Jung-Chul (Thomas) Eun

Handbook of Engineering Practice of Materials and Corrosion

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Preface

For more than 38 years of experience as an engineer specialized in metallurgy in the oil and gas industry, I have been involved in numerous project executions that are related to different industrial requirements. As I understand that identifying project definition and developing the best engineering practice in compliance with the industrial requirements are laborious process, I found it necessary to have a book that provides an overview of all the requirements of materials and corrosion engineering and decided to put my experience together.

This is a guide handbook (Engineering Practice of Materials and Corrosion-"EPMC") for materials and corrosion engineering and could be useful to experienced engineers who work in the oil and gas, chemical, and petrochemical industries. This book provides background knowledge and rationale of the engineering data based on the industrial requirements, such as codes, standards, local regulations, specifications, manuals, and common company guidelines. Throughout this book, I intended to provide simplified applications, options, and comparisons of such requirements in an integrated view.

Engineers and technicians are often faced with several different factors when working on projects, such as safety, timeline, budgets, and cost management. To satisfy these objectives, the industrial requirements are often met as minimum, and exemptions or mitigations are commonly practiced. I hope this guideline and examples provided herein will support the readers in executing the best engineering practice more effectively while meeting the project goals.

The requirements of codes, standards, and regulations will be continuously updated; however, the logical contents and rationale may rarely be changed. I also hope that the contents in this book may be useful to the readers for a long time.

Houston, TX, USA

Jung-Chul (Thomas) Eun

Cover Photo: courtesy of SK Innovation, Ulsan, Korea Refinery and Petrochemical Plants

Preview

The main purpose of this guidebook is to suggest effective engineering data which are based on the requirements in several industrial codes, standards, regulations, specifications, and regulations, such as ASME, ASTM, API, ANSI, AWS, NACE, MSS, NFPA, TEMA, PIP, NBIC, OSHA, other American standards, CSA, and foreign standards including typical requirements and recommendations in company/project specifications. One of the major purposes is to introduce practical references for a checklist as well as more detailed engineering work in one location and to provide the following:

- Typically used project's standards, guidelines, and application scope which are not covered in industrial codes and standards
- Engineering practice and experience for the limitations of codes and standards
- Engineering suggestions and test results from journals and papers with new technologies
- Case studies and various reference resources
- Correct recognition and effective spec deviation through various comparisons

All information in industrial codes and standards are based on the current version unless otherwise specified and except some foreign standards. All mechanical data which are shown in this book are for reference only. Therefore, for detail engineering of mechanical design, it is advised to find the applicable codes and standards in accordance with the project requirement and/or process conditions. Most codes and standards have the section for the reference standards which are related with themselves. In some cases, the reference standards may indicate still old versions.

The unit conversions in this book are from conversion calculation or directly each code and standard. Therefore, some converted values between the similar codes and standards may not show the same numbers in this book because the committees of codes and standards have been pursuing unit conversion by their own rounding-up system.

Many tables and figures are directly quoted from the codes and standards; however, some commentary notes which are based on the author's experience and lessons learned are added as footnotes under the tables and figures in order to optimize engineering work, promote the successful use of the full contents, minimize error and mistake, and suggest for the next version. All specified para. (paragraphs), Fig. (figures), and tables are based on this book unless otherwise noted the directly quoted code or standard. Users and readers may be able to apply "should or may" to "must/shall or should" for the requirements in this book when the user wants to utilize the contents for the project specifications.

Acknowledgments

This book was designed in accordance with industrial codes, standards, specifications, local regulations, manuals, many other resources, and work experiences. Many contents are also come from the lessons learned from my work experience as well as other people's experience. I greatly appreciate David Freier, Nasser Sheikhi, Andy Wen, Jingak Nam, Morteza Rahmanian, Tomoaki Kiso, Juan Vigil, Hundal Jung, Sooyoung Kim, Sora Han, Basim Muhidean, former co-workers, and my family (Helen, James, Eric, and Jaein) for their efforts for this book.

Thomas J.C. Eun

Work Experience with KBR, Bechtel, Foster Wheeler, Jacobs, Fluor, Exterran, Suncor Energy, GS E&C, and Hyundai Heavy Industries
P.E. for Metallic Materials
P.E. for Welding
P.E. for Mechanical Engineering
NACE Corrosion Specialist
NACE Materials Selection/Design Specialist
MS and Doctorate course work achieved for Metallurgy and BS for Mechanical Engineering

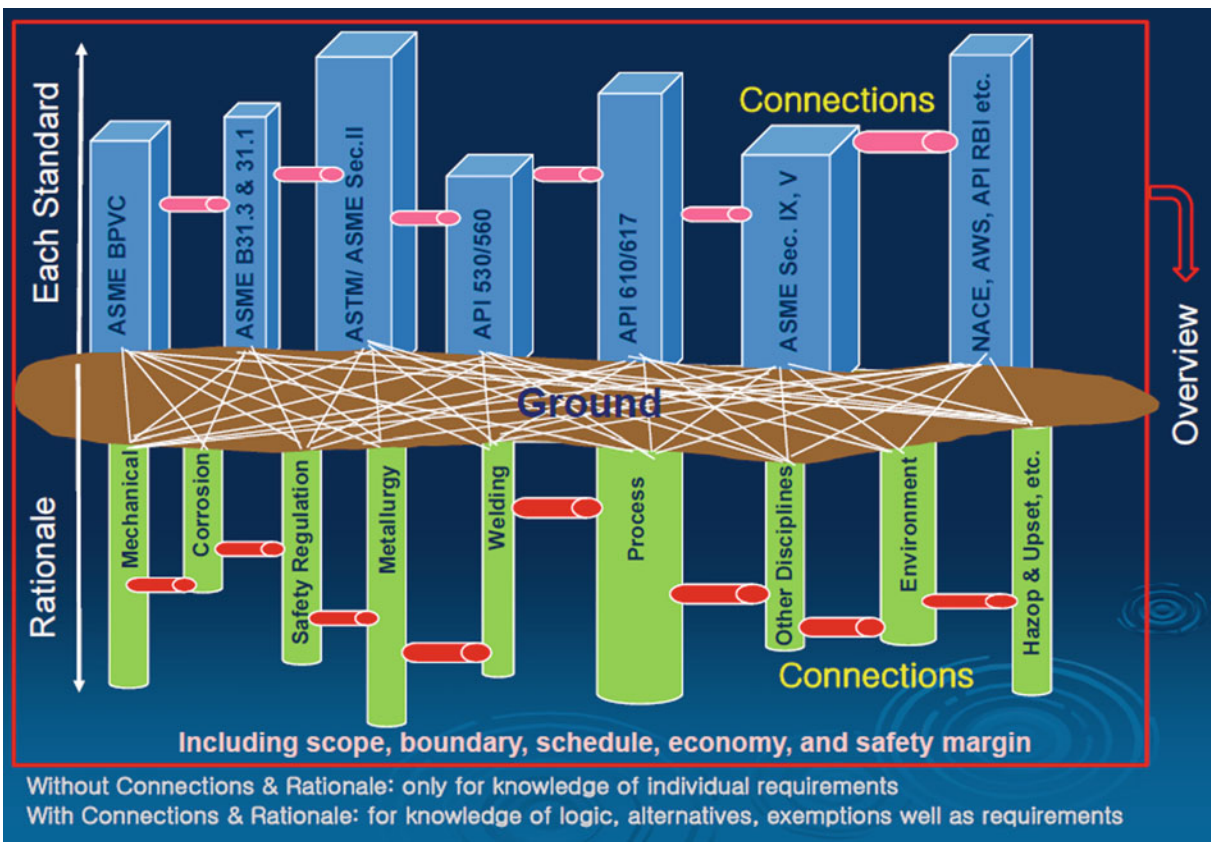
Introduction

This guide pursues not only to reduce the engineering time and mistake but also to provide one-stop sources of the applications, options, rationales, backgrounds, various references, and comparisons in an overview including scope, boundary, schedule, cost management, and safety margin (see below figure).

It also provides commentary notes, alternative applications, future trends and directions, case studies, typical project specifications, and checklists for optimization.

It consists of five sections: first section contains the principle information for mechanical and metallurgical engineers, second section contains the principle and practical information for materials in the regulations, third section contains the practical information for manufacturing and construction, fourth section contains the practical information for welding, and fifth section contains the practical information for test and inspection.

Appendices contain several other resources for design engineering and fabrication of facilities.



Contents

Abbreviations

ASHTO	American Association of State Highway and Transportation Officials
ABS	American Bureau of Shipping
ABS	Acrylonitrile-Butadiene-Styrene
A/C	Air Cooler
ACCT	ASNT Central Certification Program
ACFM	Alternating Current Field Measurement
ACI	American Cast Institute
ACSCC	Alkaline Carbonate Stress Corrosion Cracking
ADI	Austenitic Ductile Iron
AE	Acoustic Emission Test/Testing
AI	Authorized Inspector (by ASME)
AIA	Aerospace Industries Association
Air Cooler	Air-Cooled Heat Exchanger (H/EX)
AISI	American Iron and Steel Institute
AMS	Aerospace Material Specification
ALPEMA	Brazed Aluminum Plate-Fin H/EX Manufacturers' Association
ANSI	American National Standards Institute
APB	Acid-Producing Bacteria
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
(S)ASS	(Super) Austenitic Stainless Steels
ASSDA	Australian Stainless Steel Development Association
ASTM	American Society for Testing and Materials
atm (Atm)	Atmosphere
AWS	American Welding Society
AWWA	American Water Works Association
bcc	Body-Centered Cubic
bct	Body-Centered Tetragonal
BED	Basic Engineering Design
BEDD	Basic Engineering Design Data
BHN (or HBW)	Brinell Hardness
BLR	Boiler
BPS	Bonding Procedure Specification
BPV(C)	Boiler and Pressure Vessel (Code)
BSEE	Bureau of Safety and Environmental Enforcement
CA	Corrosion Allowance
CAB	Cellulose Acetate Butyrate
CAPP	Canadian Association of Petroleum Producers
COD	Crack Opening Displacement
CDW	Controlled Deposition Welding
CE (or Ceq)	Carbon Equivalent

CEN	European Committee for Standardization
CET	Critical Exposure Temperature
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CGSB	Canadian General Standards Board
CI	Cast Iron
CINI	Committee Industrial Insulation Standards
CML	Condition (or Corrosion) Monitoring Location
CMMS	Computerized Maintenance Management Software
CMRP	Certified Maintenance and Reliability Professional
CPI	Center for Public Integrity
CPVC	Chlorinated Poly(vinyl chloride) Plastics
CR	Corrosion Rate
CR	Corrosion Resistance (for fitting grade)
CRA	Corrosion Resistant Alloys
(K)CS	(Killed) Carbon Steels
CSA	Canadian Standards Association
CSEF	Creep Strength Enhanced Ferritic
CTOA	Critical Crack Tip Opening
CTOD	Crack Tip Opening Displacement
CMTR	Certified Mill Test Report
CUI	Corrosion Under Insulation
CUF	Corrosion Under Fireproofing
CVN	Charpy V Notch
dB	Decibel (Noise Level)
DBTT	Ductile-Brittle Transition Temperature
HDPE	High-Density PE
DCP	Direct Plasma (Emission Spectroscopy)
DE	Destructive Examination (↔ NDE)
DI	Ductile Iron
DH	Diffusible Hydrogen
DHT	Dehydrogenation Heat Treatment
DMT	Design Minimum Temperature (for Piping)
DNV	Det Norske Veritas
DOE	Department of Energy
DOT	Department of Transportation
D.P	Design Pressure
DPDT	Design Pressure Design Temperature
(S)DSS	(Super) Duplex Stainless Steels
D.T	Design Temperature
DW(T)T	Drop Weight (Tear) Test/Testing
EAC	Environmentally Assisted Cracking
E-CTFE	Ethylene-chlorotrifluoroethylene
ECT	Eddy Current Test/Testing
EBW	Electron Beam Welding
EFW	Electric Fusion Welded
EHS	Environment Health and Safety
EIGA	European Industrial Gas Association
EJMA	Expansion Joint Manufacturers Association
EN	European Standards (French, Norme; German, Norm)
End-User	Party as Client, Investor, Operator, or Owner
EPA	Environmental Protection Agency
EPC(M)	Engineering, Procurement, and Construction (Management)
EPEA	Environmental Protection and Enhancement Act

EPFM	Linear Elastic Fracture Mechanics
ET	Eddy Current Test/Testing
EPRI	Electric Power Research Institute
ERW	Electric Resistance Welding
ESW	Electroslag Welding
ETFE	Ethylene-Tetrafluoroethylene Copolymer
EUB	Energy and Utilities Board in Canada
EW	Explosive Welding
FAA AC	Federal Aviation Administration Advisory Circulars
FATT	Fracture Appearance Transition Temperature
FBE	Fusion Bonded Epoxy
FCAW	Flux-Cored Arc Welding
fcc	Face-Centered Cubic
FCC	Fluid Catalytic Cracking
FDIC	Federal Deposit Insurance Corporation
FEA	Finite Element Analysis
FEED	Front End Engineering Design
FEP	Perfluoro (Ethylene-Propylene) Copolymer
FERA	The Fastener Engineering and Research Association
FERC	Federal Energy Regulatory Commission
FFS	Fitness for Service
FHWA	Federal Highway Administration
FIA	Forging Industry Association
FM	Factory Manual (Insurance Company)
FM(E)CA	Failure Modes (Effects) and Criticality Analysis
FN	Ferrite Number
FRP	Fiber-Reinforced Plastics
(S)FSS	(Super) Ferritic Stainless Steels
FTA	Free Trade Agreement
GHG	Greenhouse Gas
GMAW	Gas Metal Arc Welding
GRP	Glass Fiber-Reinforced Plastic
GT	Governing Thickness
HAZ	Heat-Affected Zone
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HBW (or BHN)	Brinell Hardness
HC (or HRC)	Vickers Hardness
hcp	Hexagonal Close-Packed Structure
HDBS	Hydrostatic Design Basis Stress
HDD	Horizontal Directional Drilling
MDTD	Minimum Detectable Temperature Difference (Thermal Imaging)
HDS	Hydrostatic Design Stress
HE	Hydrogen Embrittlement
H/EX	Heat Exchanger
HEAC	Hydrogen Environmentally Assisted Cracking
HF	Hydrogen Fluoride
HHC	Highly Hazardous Chemicals
HIC	Hydrogen-Induced Cracking
HJP	Hollomon-Jaffee Parameter
HMW	High Molecular Weight
HIP	Hot Isostatic Pressing (Power Metallurgy)
HISC	Hydrogen-Induced Stress Cracking
HPHT	High Pressure-High Temperature

HRC (or Rc)	Rockwell Hardness
HSI	High Silicon Iron
HSLA	High Strength Low Alloy
HTHA	High-Temperature Hydrogen Attack
HV	Vickers Hardness
HVAC	Heating, Ventilation and Air Conditioning
Hydrotest	Hydrostatic Test/Testing
IACS	International Annealed Copper Standard
IAE	Impact Absorbing Energy
IAEA	International Atomic Energy Agency
IBC	International Building Code
IDLH	Immediately Dangerous to Life and Health
ICP	Inductively Coupled Plasma (Emission Spectroscopy)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFC	International Fire Code
IFI	Industrial Fasteners Institute
IHAC	Internal Hydrogen-Assisted Cracking
IIW	International Institute of Welding
IOW	Integrity Operating Windows
IP	Incomplete Penetration
IP	Intellectual Property
IQI	Image Quality Indicator
IRI IM	Industrial Risk Insurers Information
IRIS	Internal Rotating Inspection System
ISA	Instrument Society of America
ISO	Isometric (Drawing)
ISOPE	The International Society of Offshore and Polar Engineers
ISR	Intermediate Stress Relieving
ITP	Inspection and Test Plan
J.E.	Joint Efficient
JIP	Joint Industry Projects
JPCL	*Journal of Protective Coatings & Linings*
KDF	Knockdown Factor (for fatigue corrosion)
KLA	Knife-Line Attack
LAS	Low Alloy Steels
LBW	Laser Beam Welding
LCPTT	Lower Critical Phase Transformation Temperature
LDPE	Low Density PE
LEFM	Linear Elastic Fracture Mechanics
LEG	Liquefied Ethylene Gas
LF	Lack of Fusion
LMP	Larson-Miller Parameter = (T+460)(C+log t)/1000
LMT	Lowest Metal Temperature
LNG	Liquefied Natural Gas
LLDPE	Linear Low Density PE
LODMAT	Lowest One Day Mean Atmospheric Temperature
LPG	Liquefied Petroleum Gas
LT	Leak Test/Testing
LTC	Long, Threaded, and Coupled
LWN	Long Welding Neck
MAG	Metal Active Gas
MAP	Maximum Allowable Pressure
MAT	Maximum Allowable Temperature

MAWP	Maximum Allowable Working Pressure
MDMT	Minimum Design Metal Temperature
MDT	Maximum Design Temperature
MI	Malleable Iron
MI	Mechanical Integrity
MIC	Microbiological Induced Corrosion
Mf	Martensite finish
MFL	Magnetic Flux Leakage
MMA	Manual Metal Arc
MPT	Minimum Pressurizing Temperature
MRTD	Minimum Resolvable Temperature Difference (Thermal Imaging)
MSD	Materials Selection Diagram
MSDS	Material Safety Data Sheets
Ms	Martensite Start Point
(S)MSS	(Super) Martensitic Stainless Steels
MT	Magnetic Test/Testing
MTBF	Mean Time Before Failure
MTI	Materials Technology Institute
MTO	Material Take Off (Civil and Structures)
MTR	Mill Test Report
MTTR	Mean Time to Repair
N/A or N.A	Not Applicable
NACE	National Association of Corrosion Engineers
NACT	Normalized-Accelerated Cooled and Tempered
NAFTA	North American Free Trade Agreement
NASA	National Aeronautics and Space Administration
NBC	National Building Code of Canada
NBIC	National Board Inspection Code
NDE (or NDT)	Nondestructive Examination
NEC	National Electric Code
NEMA	National Electrical Manufacturers
NETD	Noise Equivalent Temperature Difference (Thermal Imaging)
NIST	National Institute of Standards and Technology
NPS	Nominal Pipe Size, inch
NRDM	Neutron Radiographic Dimensional Measurements
NRT(A)	Neutron Radiographic Test (Association)
NFPA	National Fire Protection Association
N-T	Normalized and Tempered
NTIW	No Tubes in Window
OEE	Overall Equipment Effectiveness
OES	Optical Emission Spectroscopy
OIML	International Organization of Legal Metrology
OMAE	International Conference on Ocean, Offshore and Arctic Engineering
O.P	Operating Pressure
O.T	Operating Temperature
OTC	Offshore Technology Conference
OSHA	Occupational Safety and Health Administration
OVHD	Overhead
para.	Paragraph
PAW	Plasma Arc Welding
PB	Polybutylene
PCC	Post Construction Committee (ASME)
PCMS	Plant Condition Management Software
PdM	Predictive Maintenance

PDP	Process Design Package
PE	Polyethylene
PED	(European) Pressure Equipment Directive
PFA	Perfluoro Alkoxyalkane
PFEP	Polyfluorinated Ethylenepropylene
PFI	Piping Fabrication Institute
PHMSA	Pipeline and Hazardous Materials Safety Administration
PHSS	Precipitation Hardening Stainless Steels
P&ID	Piping and Instrumentation Diagrams
PIP	Process Industry Practices
PM	Preventive Maintenance
PMC	Project Management Consultant
P. No.	Parent Material Number
PO	Purchasing Order
PP	Polypropylene
pp	Partial Pressure, e.g., ppCO2, ppH2S, ppH2
PPA	Polyperfluoroalkoxy Alkane
ppb	Part per Billion
PPE	Personal Protective Equipment
PPI	Plastics Pipe Institute
ppmw	Part per Million Weight
ppmv	Part per Million Volume
PQR	Procedure Qualification Record
PR	Pressure Rating
PRD	Pressure Relief Devices
PRCI	Pipeline Research Council International
PRE (or PREN)	Pitting Resistance Equivalent Number
PSEC	Partial Saturation Eddy Current Testing
PSM	Process Safety Management
PT	Dye Penetration Test/Testing
PTC	Performance Test Code (ASME)
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
PVDC	Polyvinylidene Chloride
PVDF	Polyvinylidene Fluoride
PVF	Polyvinyl Fluoride
PWHT	Post Weld Heat Treatment
QA	Quality Assurance
QC	Quality Control
QST	Quenched-Self Tempered
Q-T	Quenched and Tempered
RAGAGEP	Recognized Generally Accepted Good Engineering Practices
RAM	Reliability, Availability, and Maintainability
RBI	Risk-Based Inspection
Rebar	Reinforcement Bar (in Concrete)
RC(F)A	Root Cause (Failure) Analysis
RCM	Reliability-Centered Maintenance
REM	Rare Earth Metals
RFECT	Remote Field Eddy Current Testing
RMP	Risk Management Plan
RP	Recommended Practice
RPM	Reinforced Plastic Mortar
RT	Radiographic Test/Testing
RTF	Run-to-Failure

RTM	Real-Time Monitoring
RTP	Reinforced Thermosetting Plastics
RTR(P)	Reinforced Thermosetting Resin (Pipe)
RW	Resistance Welding
SAE	Society of Automotive Engineers
SAW	Submerged Arc Welding
SCC	Stress Corrosion Cracking
SDR	Standard Dimension Ratio
SIDR	Standard Inside Dimension Ratio
s.g.	Specific Gravity
SG	Spheroidal Graphite
SHT	Solution Heat Treatment
SIS	Swedish Institute for Standards
SMAW	Shielded Metal Arc Welding
SMRP	Society for Maintenance & Reliability Professionals
SMTS/SMYS	Specified Minimum Tensile Strength/Specified Minimum Yield Strength
SP	Standard Practice
SPC	Statistical Process Control
Spec	Specification
SQC	Statistical Quality Control
SRB	Sulfate-Reducing Bacteria
SS	Stainless Steel
SSC	Sulfide Stress Cracking
SSPC	Steel Structures Painting Council
S/T	Shell and Tubes
STD	Standard(s)
STT	Surface Tension Transfer (for Welding)
SZC	Sub-zero Cooling
TBE	Technical Bid Evaluation
TEMA	Tubular Exchanger Manufacturers Association
THG	Thermohydraulic Gripping (Mechanical Bonding)
TIG	Tungsten Inert Gas
TIR	Thermal/Infrared Test
TM	(Standard) Test Methods
TMCP	Thermomechanical Controlled Process
TML	Thickness Measurement Location
TOFD	Time of Flight Diffraction
TPM	Total Productive Maintenance
TR	Technical Report
TRIP	Transformation Induced Plasticity
T.S.	Tensile Strength
TSS	Total Suspended Solids
TT	Transformation Temperature (microstructure of metal)
TTT	Time-Temperature-Transformation (Heat Treatment)
TTT	Tube-to-Tubesheet (H/EX)
TWI	The Welding Institute (UK)
UCC	Uniform Commercial Code (US)
UOE	U (**U**-ing) forming, O molded (**O**-ing) and the enlarged diameter (**E**xpanding) combining successive processes
UBC	Uniform Building Code (US)
UBRS	User's Basic Requirements Specification
UHMW	Ultra-High Molecular Weight
UL	Underwriters Laboratories
ULDPE	Ultra-Low Density

PE UNS	Unified Numbering System
USCG	United States Coast Guard
USCO	United States Copyright Office
USPTO	United States Patent and Trademark Office
UT	Ultrasonic Test/Testing
UV	Ultraviolet
VCI	Volatile Corrosion Inhibitor
V_PCI	Vapor Phase Corrosion Inhibitor (Cortec's VCI)
VT	Visual Test/Testing
Y.S	Yield Strength
WP	Wrought Pipe (for fitting grade)
WPQ	Welding Procedure Qualification
WPS	Welding Procedure Specification
WRC	Welding Research Council
wt	Weight
WTIA	Welding Technology Institute of Australia
XRF	X-Ray Fluorescence Spectroscopy
# (lb)	Standard Flange Rating (pounds/sq. inch)

Standard Terminology and Acronyms

- ASTM A340 Terminology of Symbols and Definitions Relating to Magnetic Testing
- ASTM A941 Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys
- ASTM C125 Terminology Relating to Concrete and Concrete Aggregates
- ASTM D16 Terminology for Paint, Related Coatings, Materials, and Applications
- ASTM D4538 Terminology Relating to Protective Coating and Lining Work for Power Generation Facilities
- ASTM E6 Terminology Relating to Methods of Mechanical Testing
- ASTM E7 Terminology Relating to Metallography
- ASTM E1316 Terminology for NDE
- ASTM G40 Terminology Relating to Wear and Erosion
- NACE/ASTM G193 Terminology and Acronyms Relating to Corrosion
- MSS SP-90 Terminology for Pipe Hangers and Supports
- PIP PNC00002 Abbreviated Piping Terms and Acronyms

Definitions and Comparisons

***Conceptual Definition for Term of High Temperature**

Well – Onshore: ≥150°C (300°F)
Well – Offshore Subsea: ≥177°C (350°F)
Onshore and Offshore Topsides: ≥343–427°C (650–800°F) per Plant and/or Material

1. Industrial Code, Standard, and Local Regulation: See Table 1.2 for comparison of standards and specifications.

Industrial codes	Industrial standards	Local regulations
Mandatory standards are those that all manufacturers, design engineers, technicians, and inspectors must comply with and are typically set by industrial associations under the control of the government. Codes are typically written in what is called mandatory or "code" language. This is very similar to specification language, with which most of us are quite familiar. This is best exemplified by using the word "shall or must" in lieu of "may or should." Using a mandatory language makes the code enforceable; however, enforceability is somewhat subjective and could lead to a variety of interpretations. US Industrial Codes are widely used for project execution and maintenance in the world industries. Normally, all contents of the codes shall be applied entirely without exception once the applicable code list specifies. Good examples for industrial codes: US safety standards regarding automobile seatbelts or side-impact resistance, NBC (Building, NFPA (Fire), ASME BPVC and B31 series, etc.	Voluntary standards, on the other hand, are not regulated by the government, nor are they required to be used by the industry. Voluntary standards are considered consensus standards since they're developed using a process that allows participation by all interested stakeholders including representatives of producers, manufacturers, users, consumers, and government agencies. This is best exemplified by using the word "should or may" in lieu of "shall or must." However, once they are designated for application in the project specification, they will be mandatory standards for the project. US industrial standards are widely used for project execution and maintenance in the world industries. Normally, these standards can be applicable partially if the user requires. Good examples for industrial codes: ANSI (Standards Institute), ASTM (Testing and Materials), NIST (Standards and Technology), API (Petroleum Institute), NACE (Association for Corrosion), etc.	Local regulations are typically issued by various governments/states/provinces/municipal and representative agencies to carry out the intent of legislation enacted by the legislature of the applicable jurisdiction-Act-Law. Local regulations are mandatorily used in the applicable local regions. Good examples for industrial codes: US Federal Regulation, CFR, EUB, DOE, DOT, FERC, USCG (CG-ENG), OSHA, BSEE, NAFTA, USMCA, EHS, etc.

2. HAZID vs. HAZOP: See Sect.1.1.1.2(b) and (c) for more details.

HAZID (Hazard identification)	HAZOP (Hazard and operability)
It is to early identify the hazards or threats with more of a general risk analysis tool, which are under any possible unwanted incidents within a discipline, operation, or area. The classification made is done on the basis of probability and consequences. A HAZID study provides a qualitative analysis of a worksite in order to determine its worker safety risk level. Normally performed from evaluation stage to early define stage.	It is used to identify abnormalities in the working environment and pinpoint the root causes of the abnormalities. It deals with comprehensive and complex workplace operations, which, if malfunctions were to occur, could lead to significant injury or loss of life. It is a more detailed evaluation than HAZID. Normally performed from the define stage to early execute stage.

3. Minimum Temperatures

CET (critical exposure temperature)	MAT (minimum allowable temperature)	MDMT (minimum design metal temperature)
The lowest (coldest) metal temperature derived from either the operating or atmospheric conditions at the maximum credible coincident combination of pressure and supplemental loads that result in primary stresses. Note that operating conditions include startup, shutdown, and upset conditions. The CET may be a single temperature at the maximum credible coincident combination of pressure and primary supplemental loads [that result in general primary tensile stress (including any stresses	The lower (coldest) permissible metal temperature limit for a given material and thickness based on its resistance to brittle fracture. It may be a single temperature or an envelope of *allowable operating temperatures* as a function of pressure. The MAT is derived from mechanical design information, materials specifications, and materials data. This is the materials resistance to fracture. Typically, the MAT for the equipment will be the limiting (highest) temperature considering the effects of	The lowest *metal* temperature at which a significant load can be applied to a pressure vessel as defined by the ASME Section VIII, Division 1, UG-20. *The MDMT and the MAT are the same*, unless the service causes embrittlement of the steel (e.g., *temper embrittlement or hydrogen embrittlement*). Then, the MAT will be higher than the MDMT and become the lowest permissible temperature while under load. See Sect.1.1.12

CET (critical exposure temperature)	MAT (minimum allowable temperature)	MDMT (minimum design metal temperature)
due to net section bending) greater than 55 MPa (8 ksi)] if that is also the lowest (coldest) metal temperature for all other combinations of pressure and primary supplemental loads. If lower (colder) temperatures at lower pressures and supplemental loads are credible, the CET can be defined by an envelope of temperatures and pressures, e.g., the vapor pressure curve (depressurization) for LPG streams. The CET for atmospheric storage tanks constructed to API 650 is defined as the lower of either the lowest one-day mean atmospheric temperature plus 8 °C (15 °F) or the hydrostatic test temperature. The CET for low-pressure storage tanks constructed to API 620 should be established using the methodology for pressure vessels. The methodology for determining the CET is covered in API 579–1/ ASME FFS-1, Part 3, 3.1.5.	all the applicable potential mechanisms affecting toughness (i.e., low temperature toughness, hydrogen embrittlement, temper embrittlement, etc.). The MAT should always be below the CET. This temperature is sometimes referred to as the MPT (minimum pressurization temperature). The methodology for determining the CET is covered in API 579-1/ ASME FFS-1, Part 3, 3.1.6.	for MDMT and DMT (design minimum temperature).

4. Maximum Allowable Working Pressure (MAWP) vs. Maximum Allowable Pressure (MAP): See Sect. 1.2.5.
5. Joint Efficiency and Quality Factor: See Sect. 1.2.7.
6. Maximum Design Temperature (MDT) vs. Maximum Metal Skin Temperature (MMST): MMST shows higher temperature than MDT due to the other heat resources, such as flame in furnace/heater, while MDT is based on the maximum bulk service temperature. In many cases of fire heaters, the MMST shows 50–150 °C (90–270 °F) higher than that of the MDT. See Sect. 2.1.6.8 and 2.6.2.3 General Note e for a case of application for MMST.
7. Coating vs. Painting: The terms are often used interchangeably because there are no clear definition for each word in the codes and standards. Traditionally, the term of painting specification has been used for industrial application.

   However, currently, many end-users are changing the title to “Protective Coating (Painting) Specification” or Painting (Coating) Specification” for their specification because industrial needs are based on two purposes: functional and decoration/color-coding (safety base). The difference of the two terms may be recognized as below:

Item	Coating	Painting
Application	Not only for anticorrosion paints but frequently used for functional purposes, such as mechanical protection coatings, fire protection coatings, waterproofing coatings, wear-resistant coatings, and anticorrosion coatings, which can be used on steel, concrete, and other substrates.	More often used for decoration or color coding than the functional purpose. Many people use “painting” to cover everything. In the material terms, all paints are coatings but not all coatings are paints.
Deposit materials	Can refer to a layer of any solid or liquid film to a substrate or to the application of such a layer.	Can refer to a layer on the substrate with paint, varnish, lacquer, tar, etc. in liquid form or to the application of such a layer.
Film thickness	Used for higher thicknesses.	Used for lower thicknesses.

8. Pipe vs. Tube in Tubular Type: Pipe is for mass transfer, while tube is for heat transfer. Hence, tubes are available for small size (up to 7 inches), while pipes are for small and larger sizes. The thickness of tubes is designated by mm (inch) or gauge, but that of pipes is designed by schedule. The standard diameters are used as nominal pipe size (NPS) for pipes and outside diameter (OD) for tubes. Meanwhile, tubing material in oil and gas production is the conduit through which oil and gas are brought from the producing formations to the field surface facilities for processing (e.g., per API Spec 5CT).
9. Piping vs. Pipeline: They are the same purpose of the mass transfer, but piping is used for the pipes connected between equipment, while pipeline is used for the pipes connected between certain locations (long distance).
10. OCTG (Oil Country Tubular Goods): Drill Pipe, Casing Pipe, and Tubing (Fig. 1) – See Table 2.175 through Table 2.178 for more details.

– *Drill pipe* is a heavy seamless tube that rotates the drill bit and circulates drilling fluid. Pipe segments 9 m (30 ft) long are coupled with tool joints. Drill pipe is simultaneously subjected to high torque by drilling, axial tension by its dead weight, and internal pressure by purging of drilling fluid. Additionally, alternating bending loads due to non-vertical or deflected drilling may be superimposed on these basic loading patterns. See API Spec 5D, API RP5DP, API RP49, API Spec 16A/16R, API RP7G, API RP5A3, API RP5A5, API RP5B1, API 6A718, etc.
– *Casing pipe* lines the borehole. It is subject to axial tension by its dead weight, internal pressure by fluid purging, and external pressure by surrounding rock formations. Casing is particularly exposed to axial tension and internal pressure by the pumped oil or gas emulsion. See API RP5CT, API RP5C1, API RP5C5, API RP5A3, API RP5A5, API RP5B1, API Spec 5B, API TR5C3, API TR5C, etc.
– *Tubing* is a pipe through which the oil or gas is transported from the wellbore. Tubing segments are generally around 9 m (30 ft) long with a threaded connection on each end. See API 5CT, API RP5C5, API RP5C1, API RP5A3, API RP5A5, API RP5B1, API Spec 5B, API TR5C3, API TR5C, etc.

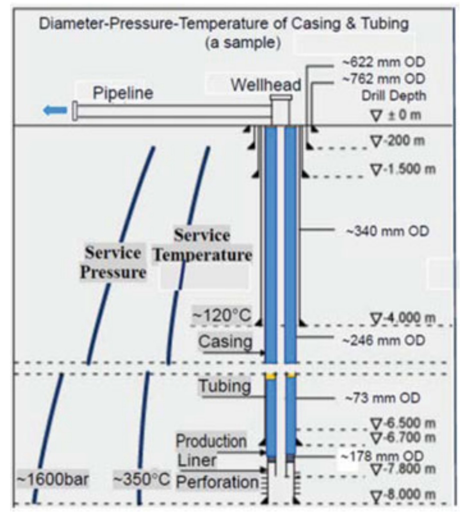


Figure 1 Deep well schematic

11. Ferrous Metal vs. Nonferrous Metal: See Table 2.2.
12. Carbon Steel vs. Low Alloy Steel: See Table 2.4.
13. Low Alloy Steel vs. High Alloy Steel: See Table 2.4.
14. Carbon Steel vs. Cast Iron: See Table 2.23.
15. Cast Steel/Alloy vs. Wrought Steel/Alloy: A steel/alloy that is wrought is one that is worked by being forged or hammered. A cast steel/alloy is when the molten alloy is poured into a mold to give it its shape and has very little strength. It is not followed by being forged or hammered any more.
16. Sensitization (Cr depletion) vs. Knife-Line Attack: See Sect. 2.1.6.3 and 4.11.6.7, respectively.
17. Ferrite Contents vs. Ferrite Number (FN): See Sect. 2.1.6.1.
18. Toughness vs. Ductility: See Sect. 1.1.10.2.
19. Tensile Strength vs. Design Stress Integrity Value: See Sect. 1.1.10.1.
20. Work Hardening vs. Precipitation (also called Aging) Hardening: See Sect. 1.1.10.2(m) and (n).
21. MTR vs. PMI: See Sect. 2.5.1.
22. Hardness vs. Hardenability:

Hardness	Hardenability
Hardness is a material property. It is the ability of a material to withstand the indent or penetration and is measured on the metal *surface* in Rockwell or Vickers. It is also used for measurement of the stiffness of a material. The softer the material, the deeper the penetration, the wider the impression. The hardness of a carbon steel depends on its carbon content; any high-carbon steel is naturally hard, no matter how it is cooled. It is usually heat-treated to give it the best combination of hardness and toughness required for a particular application. See Sect. 4.2.3 (hardness effect on weldments), Sect. 5.4.1 for hardness tests.	Hardenability is the ability of a material to become hardened *at a given depth* by various methods of hardening such as carburizing or quenching. It is firmly dependent on the quantity of carbon in that material, and actually, it does not have any measuring unit. **Hardenability** to achieve a targeted hardness *at a given depth* usually refers to the ability of alloy steels to form martensite through heat treatment and thus acquire higher strength. This ability is often not directly related to carbon content, to put it another way. For instance, an alloy steel with relatively low carbon content may be more **hardenable** than another alloy steel containing two or three times as much carbon (see Fig. 2). Jominy End-Quench Test is the most popular test methods.

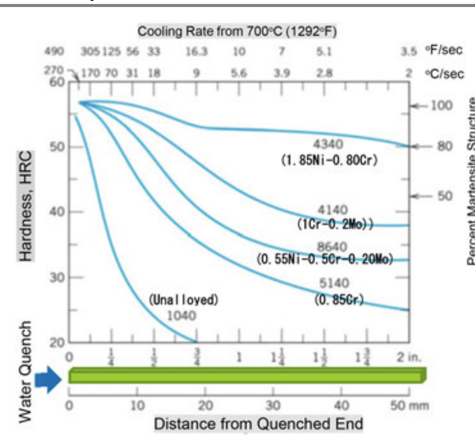


Figure 2 Hardenability curves resulted by Jominy End-Water Quench Test for five different AISI steels with 0.40%C

23. Solution Heat Treatment vs. Stabilizing Heat Treatment: See Sect. 4.12.5.
24. Standard Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys: See ASTM A941.
25. Stress Corrosion Cracking (SCC) vs. Sulfide Stress Cracking (SSC): See 2.1.6.2 for SCC. SSC which is one of the SCC failures is based on the Wet H_2S (sour) service. See ANSI/NACE MR0175/ISO 15156 and NACE MR0103/ISO17945 for SSC.
26. Lethal Service vs. EAC vs. ASME B31.3 Category "M" Service: See Sects. 1.1.11.1 and 1.1.11.2.
27. Erosion vs. Abrasion vs. Adhesive Wear (Galling): See Sect. 2.4.5.
28. Dew Point vs. Relative Humidity (RH): Dew point is the temperature at which the air is saturated (100% RH). It is dependent on only the amount of moisture in the air. RH is the % of saturation at a given temperature; it depends on moisture content and temperature. As air is heated, its ability to hold water vapor doubles with about every 11 °C increase. If air is at 100% RH at 60 °C but is heated to 93 °C, its RH decreases to about 33%. Its dew point remains at 60 °C.
29. Cold Work vs. Hot Work for Fabrication: See Sects. 3.1.4.1 and 3.1.4.2.
30. Cold Rolled vs. Hot Rolled for Base Metal

Cold rolled steel	Hot rolled steel
Cold rolled steel is essentially hot rolled steel that has had further processing. The steel is processed further in cold reduction mills, where the material is cooled (at room temperature) followed by annealing and/or tempers rolling. This process will produce steel with closer dimensional tolerances and a wider range of surface finishes. The term cold rolled is mistakenly used on all products, when actually the product name refers to the rolling of flat rolled sheet and coil products. This process results in higher YS and has four main advantages: *Cold drawing* increases the YS and TS, often eliminating further costly thermal-treatments. *Turning* gets rid of surface imperfections. *Grinding* narrows the original size tolerance range. *Polishing* improves surface finish. All cold products provide a superior surface finish and are superior in tolerance, concentricity, and straightness when compared to hot rolled steel. Cold finished bars are typically harder to work with than hot rolled due to the increased carbon content. However, this cannot be said about cold rolled sheet and hot rolled sheet. With these two products, the cold rolled product has low carbon content, and it is typically annealed, making it softer than hot rolled sheet.	Hot rolling is a mill process which involves rolling the steel at a high temperature (typically at a temperature over 927 °C (1700 °F), which is above the steel's recrystallization temperature. When steel is above the recrystallization temperature, it can be shaped and formed easily, and the steel can be made in much larger sizes. Hot rolled steel is typically cheaper than cold rolled steel due to the fact that it is often manufactured without any delays in the process, and therefore, the reheating of the steel is not required (as it is with cold rolled). When the steel cools off, it will shrink slightly, thus giving less control on the size and shape of the finished product when compared to cold rolled. *Applications*: Hot rolled products like hot rolled steel bars are used in the welding and construction trades to make railroad tracks and I-beams, for example. Hot rolled steel is used in situations where precise shapes and tolerances are not required (most weldable metals).

31. Impact Test Absorbing Energy vs. Impact Strength

    Both of them are typically defined as the amount of energy required to fracture a specimen subjected to a specific shock loading under impact at the test temperature (e.g., minimum design temperature). Impact test absorbing energy is typically described as energy (e.g., J) per standard size specimen (e.g., 1.0 cm × 0.8 cm = 0.8 cm^2) while impact strength is normally described as energy/area (e.g., J/cm^2).
32. Fracture Appearance Transition Temperature (FATT) vs. Ductile-Brittle Transition Temperature (DBTT): The FATT value is based on the change from cleavage to shear fracture appearance percentage for a broken CVN impact specimen. Commonly, $FATT_{50}$ is used, where 50 refers to 50% cleavage and 50% shear fracture appearance on a broken CVN impact specimen. The DBTT is similar except the DBTT value is based on the inflection point of a CVN impact energy test temperature curve, where the CVN upper shelf (ductile) changes to lower shelf CVN (brittle) values at a specific test temperature. Figure 3 shows the comparison of both transition temperatures.

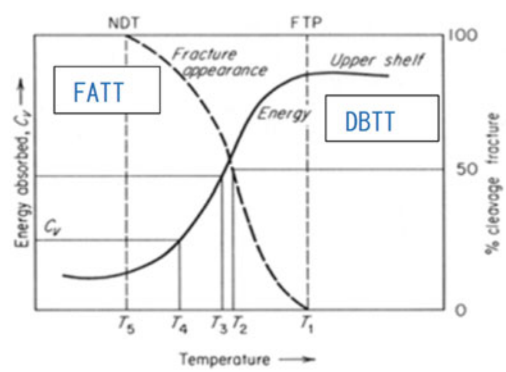


Figure 3 Comparison of both transition temperatures of FATT and DBTT. T1: Conservative, above T1 fracture is 100% fibrous. *Fracture Transition Plastic* (FTP) very demanding. T2: 50% cleavage – 50% ductile *fracture appearance transition temperature* (FATT). T3: Average of upper and lower shelf values (often approx. = T2). T4: Arbitrary value of energy absorbed (CVN), for example, 20 J (15 ft.lb) for low strength ship steel. *Ductility transition temperature.* T5: 100% cleavage fracture. *Nil ductility temperature* (NDT)

33. TEMA (Tubular Exchanger Manufacturers Association) Process Classes

Class "R"	Class "C"	Class "B"
To specify design and fabrication of unfired shell and tube H/EXs for the generally severe requirements of petroleum and related processing applications.	To specify design and fabrication of unfired shell and tube H/EXs for the generally moderate requirements of commercial and general process applications.	To specify design and fabrication of unfired shell and tube H/EXs for chemical process service.

34. Long Welding Neck (LWN) Flanges vs. Forged Nozzle

LWN flanges	Forged nozzle
Flanges have a neck outside diameter not exceeding the hub diameter specified in ASME B16.5.	A forged nozzle flange which are met: *(1)* For ASME B16.5 applications, the forged nozzle flange shall meet all dimensional requirements of a flanged fitting given in ASME B16.5 with the exception of the inside diameter. The inside diameter of the forged nozzle flange shall not exceed the inside diameter of the same size lap joint flange given in ASME B16.5. For ASME B16.47 applications, the inside diameter shall not exceed the weld hub diameter *A* given in the ASME B16.47 tables. *(2)* For ASME B16.5 applications, the outside diameter of the forged nozzle neck shall be at least equal to the hub diameter of the same size and class ASME B16.5 lap joint flange. For ASME B16.47 applications, the outside diameter of the hub shall at least equal the *X* diameter given in the ASME B16.47 tables. Larger hub diameters shall be limited to nut stop diameter dimensions. See ASME Sec. VIII, Div.1, Fig. 2–4 sketch (12) and (12a) and ASME Sec. VIII, Div.1, UG-44(j) for more details.

35. Fiber-Reinforced Plastics (FRP) vs. Glass Fiber or Fiberglass-Reinforced Plastics (GRP)

	FRP	GRP
Common	GRP is one of the FRP composite materials. Fiber is embedded in the matrix. Fiber is for strength, stiffness, and durability, while resin is for smoke penetration resistance, inter-laminar shear strength, toughness, and corrosion resistance. Thermal resistance is normally governed by resin material. ASME and ISO codes do not have different classes as FRP and GRP. Fiberglass-reinforced plastics may be interpreted as FRP or GRP.	
Fiber	Spectra 1000, carbon (CFRP), graphite, quartz, aramid, and boron.	Glass (E-glass, S-glass).
Matrix-Plastic Resin (Polymer)	Polyester, vinyl ester, epoxy (for high performance), bismaleimides/polyimides (high temperature), and furan/phenolics (high temperature and high smoke resistance).	Polyester, vinyl ester, and epoxy.
Usage	High performance application such as aircraft interiors.	Low performance applications such as producing swimming pools, shower cubicles, panels, covers, enclosures, gliders, boats, bathtubs, pipes and fittings, water tanks, pipe, surfboards, automobiles, external door skins, and roofing products.

See ASME Section X, ISO 14692, and Table 1.7 in this book for more detailed information and requirements.

36. Scale vs. Passive Film on the Metal Surface: Scales that are made by oxidation or other metallic reaction (e.g., FeS, SiCr-oxides, etc.) have heavy thickness and porous, so they are typically recognized as undesirable products even though they may provide somewhat corrosion/erosion protection in the limited condition. However, passive films made by oxidation or other metallic reaction spontaneously (e.g., Cr_2O_3, TiO_2, etc.) have ultrathin thickness and fine and dense on the CRA metal surfaces. Passive film formation is also known as passivation.
37. Zinc Embrittlement vs. Dezincification

    Zinc will be precipitated with alloy elements, such as NiZn or $NiZn_2$, which have low melting temperature, and then solidification cracking occurs (call out zinc embrittlement; see Sect. 2.1.6.6 for more details) while corrosion process that appears to selectively dissolve one of the constituents of an alloy (e.g., Zn removal in brass calls out dezincification; see Fig. 2.95 and Tables 2.178(13), 2.76, and 2.138(15) for more details).
38. Patent, Copyright, Trademark, and Registration (or Registered Trademark) for All Types of Products Including Any Distinctive Name, Symbol, or Word in the United States: USPTO (United States Patent and Trademark Office), USCO (United States Copyright Office), UCC (Uniform Law Commission). Meanwhile, Google Patents (https://patents.google.com) provides the indexes of worldwide patents and patent applications.

(source: https://smallbusiness.chron.com/differences-between-copyright-trademark-registration-780.html/
https://smallbusiness.chron.com/difference-between-copyrights-patents-3220.html/
https://www.whitecase.com/publications/article/perfecting-security-interests-united-states-patents-trademarks-and-copyrights)

	Patent	Copyright	Trademark	Registration (or registered trademark)
Purpose	To provide the right (to keep it as the originator's property) to the originator for the certain period.			
Symbol		©	**TM or SM**	®
Governing Laws	UCC, Article 9 USPTO	UCC, Article 9 USCO	Lanham Act USPTO	
Applicable Items See each law	Intellectual property – usually an invention or certain types of discoveries (mathematical equations and product formulas for example).	Literature, drama, music, art, books, videos, or intellectual property.	For words, symbols, devices, or product/company names that are used to distinguish the goods of one manufacturer or seller from that of another. Use TM (for goods) or SM (for service) if not yet registered after applied. Use ® if registered.	
Function	Patents provide the patent owner "the right to exclude others from making, using, offering for sale, or selling the invention in the U.S." according to USPTO.	Once an original piece is finished, it automatically receives copyright protection. Available to published and unpublished works, a copyright gives the owner the exclusive right to reproduce the work, prepare derivative works, distribute copies, and perform/display the work publicly. See Note 3 below.	*This trademark (™) does not protect the company from another company that produces a similar product or uses a similar name.* If such a thing were to happen, the original company would have to prove that it produced the name or design first but still may not have a legal defense without a registration.	With a registration of ®, a *trademark is protected against another company's use of the name or image.* A registered trademark is a federal and legal registration of the mark. Any future company wishing to register its own design/name/image has to check to be sure that it is not like any registered trademarks. See Note 5 below.
Registration and the Process	Patent applications can be complex and costly, and patent attorneys are often consulted to assist inventors. See Note 1 below.	Copyright registration involves filing the proper form obtained from USCO and submitting it with the required fee and work sample. See Note 4 below.	Be registered through USPTO. First, you search the online database (Trademark Electronic Search System (TESS)) to determine that your mark is not claimed. Once you have determined that your mark is unique, fill out a trademark application and present a representation of the mark. The registration process can be lengthy, taking about 4 months to *receive a response to your application.*	
Protection period after registered	Expire after 20 years of issuance to encourage competition and innovation. See Note 2 below.	Generally lasts for the life of the author(s) plus an additional 70 years.	–	Lasts 10 years but must be verified between years 5 and 6 to confirm that the trademark is still in use.

Notes
1. A patent search is perhaps the most labor-intensive process and involves searching through past patents to ensure that the property has not already been patented. Abstract definitions, detailed drawings, inventor information, inventor claims, and specifications are required, and it can take up to several years for a patent to be issued.
2. Copyrights expire depending on a number of factors, including whether the work was published or unpublished, the year of publishing, and the type of author. For example, protection of an individual author's work published after 2002 expires 70 years after the author's death. If the work is owned and published by a corporation, copyright expires 95 years from date of publication or 120 years from the date of creation, whichever comes first. Work no longer protected under copyright or created by any government office for civil use is considered in the "public domain" and may be used freely.
3. Copyrights do not cover titles, names, phrases or slogans, symbols, designs, ideas, procedures, methods, concepts, or discoveries.
4. USCO does not compare new works with those previously registered by others and only serves to provide dated evidence in cases of infringement or misuse. When infringement lawsuits are filed, the courts make the final ruling by comparing the works in question. When misuse suits arise, the court relies on copyright registration dates to prove ownership.
5. If the image is too similar and is still produced, the company is guilty of trademark infringement.

39. Seal Weld vs. Strength Weld: See Sect. 4.1.1.2 and Table 3.10.
40. Telltale Hole vs. Vent Hole: See Sect. 3.3.3.
41. Gravity vs. Viscosity of Crude Oil (based in 2012)

Gravity vs. viscosity	API definition	API gravity (density)	Typical resources	Average API gravity	Viscosity, cSt (mm^2/s)
The term of heavy oil is a reference to the high density (API Gravity) of crude oils. Viscosity is not synonymous with specific gravity (SG). There is a positive but very loose correlation (Fig. 4) between gravity and viscosity that is specific to a given oilfield – but any quantitative transform from API gravity (converted from SG) to viscosity is a rough approximation at best, and there are no transforms or rules of thumb for oils in general. *Formula to calculate API gravity* API Gravity (°) = 141.5/SG – 131.5	Light	>31.1° [<870 kg/m^3 (0.87 SG)]	Kutubu Oil	44	2.1 @20 °C
			West Texas Intermediate	40	4.9 @20 °C
			Brent Oil	38	2.86 @50 °C
			Bonny Light Oil	35.6	2.90 @50 °C
			Arab Light Oil	34.2	10.7 @20 °C
			Canadian Synthetic Crude Oil (maximum for pipeline)	33	350@15°C
			Tia Juana Light Oil	31.9	8.8 @38°C
	Medium	31.1° to <22.3° (870–920 kg/m^3) [0.87–0.92 SG]	Alaska North Slope Crude Oil	29	
			Arab Heavy Oil	27	
	Heavy	22.3–10 ° (920–1000 kg/m^3) [0.92–1.00 SG]	Alaska Viscous Oil	16–24	
			Alaska Heavy Oil	8–14	
			Tia Juana Heavy Oil	12.3	88.6 @38 °C
	Reference		*Natural Water*	*10*	
	Extra Heavy	<10° (>1000 kg/m^3 (1.00 SG)]	Venezuela (Orinoco)	10	
			Canadian Lloydminster Bitumen	9–18	
			Canadian Athabasca Bitumen	6–10	760@15 °C

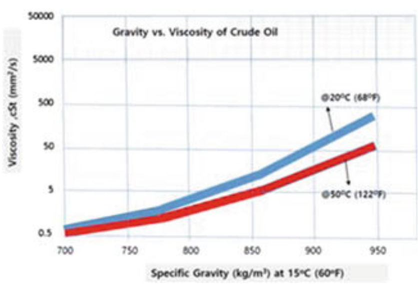


Figure 4 Gravity vs. Viscosity of crude oil (typical, but not always)

42. Sweet Crude vs. Sour Crude - Fig. 5

- Sweet crude: sulfur content ≤ 1 wt%
  (or 0.42 wt% $\leq S \leq 1$ wt%)
- Sour crude: sulfur content >1 wt%

Note: The quality of most US shale oils indicates sweet crude.

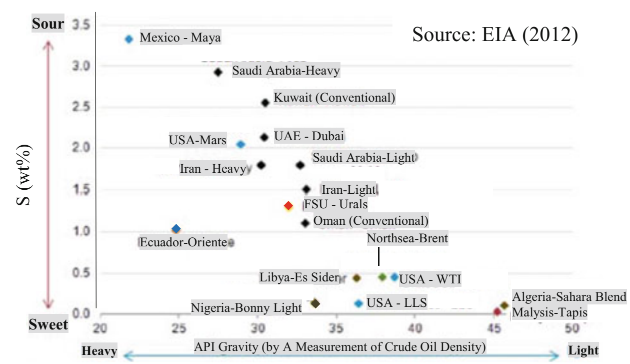


Figure 5 API gravity or several crudes per sour and sweet

43. Cold Electro-galvanizing vs. Hot-Dip Galvanizing

	Cold electro-galvanizing	Hot-dip galvanizing
Purpose and process	To provide surface protection including CP in atmosphere through metallic bonding of steel and Zn by electro-galvanizing at room temperature. Thickness: 25–400 μm (1–1.5 mil)	Galvanizing by immersing it into a molten zinc bath at temperatures of around 450 °C (840 °F). Once removed from the bath, the zinc coating on the iron or steel's exterior reacts with oxygen in the atmosphere to form zinc oxide (ZnO). ZnO further reacts with CO2 to form the protective layer known as *zinc carbonate (ZnCO3)*. Cleaning and stress relieving of the substrate are required before immersion. Thickness: 125–150 μm (5–6 mil)
Bonding, durability, abrasion resistance, and CP capabilities	Poor than the quality of hot-dip galvanizing	Excellent quality compared to cold electro-galvanizing

44. Unit Conversion
    Energy: 1 ft-lb = 1.355818 joules
    Pressure: 1 ksi = 1000 psi = 6.895 MPa = 6895 kPa = 6895 kN/m^2 = 68.94757 bar (1 bar = 14.5 psi)
    Density: 1 lb/in^3 = 27.68 ton/m^3
    Temperature (certain): °F = 1.8 × °C + 32
    Temperature (absolute or delta): °F = 1.8 × °C
    See ASME Sec. VIII, Div.2, Annex 1-C for ASME application.

Chapter 1
Design Engineering

1.1 General

1.1.1 Types and Procedure of Engineering

1.1.1.1 Types and Steps of Engineering Work

(i) Feasibility Study
(ii) Licensor Package – PDP (Process Design Package) and BED (Basic Engineering Design)
(iii) Pre-FEED (Front-End Engineering Design) or FEED
(iv) Detail Engineering (Engineering, Procurement with Fabrication)
(v) Construction and Mechanical Completion
(vi) Pre-commission
(vii) Startup
(viii) Operation and Maintenance

Normally there are five phases for Oil and Gas Process Plant Engineering as shown in Fig. 1.1. The project budget tolerance target may be decided at the Identify phase or Evaluate phase. Normally it targets that PDP stage, ± 30–50%; Pre-FEED stage, ± 10–30%; FEED stage, ± 5–15%; and EPC stage, ± 3–10%. The actual project may select more narrow tolerance, and the inflation rate for the future may not be considered. The required technical careers for materials and mechanical integrity in energy industries are shown in Tables 1.1.

1.1.1.2 Details of Major Engineering Steps

(a) Process Design Package (PDP)

Process Design Package (PDP) means the following list of text, figures, drawings and documentation relating to the design and construction of the licensed plant in the conceptual design stage:

1. *A process description* – a brief description of the process and the highlighting of special features, including an equipment list and tag numbers.
2. *A basis of design* – a concise review of feed stream basis, rates and compositions, produce specifications and battery limit conditions, safeguarding memorandum, control philosophy, operation philosophy, and a description for the operation of the licensed plant.
3. *HMB* – Heat, material, and pressure balances in utility units as well as process units.
4. *Process flow diagrams (PFD)* – major process lines and equipment, arrangement of flow sequence, major control systems, operating conditions (temperatures, pressures, and flow rates), exchanger and furnace duties, and sampling points for product sample removal.
5. *Piping and instrumentation diagrams (P&ID).* It normally shows:
   (i) A list of major equipment with principal process and mechanical data.
   (ii) A list of recommended line sizes for lines, bypasses, circulating lines, startup connections, inert gas, gas blanketing, pumpout lines, relief and safety valves except final sizing of all safety system components and their connections to the appropriate headers and sample connections (by FEED contractor), and vents and drains in process piping which are required to suit the mechanical layout of the piping (by FEED contractor).
   (iii) Minimum required instrumentation with ISA symbols.
   (iv) Control valves and manifolds.
   (v) Minimum process valving and utility system tie-ins will be shown.
   (vi) General notes for information or recommendations pertinent for EPC design.
6. *Utility flow diagrams (UFD).* It normally shows:
   (i) Lines and sizes for utility systems, such as steam, water (supply, cooling water, rain, flood, and waste), air, nitrogen, fuel oil and gas, hot oil, chemicals, dosing, etc. except sumps and drain (by FEED contractor)
   (ii) Electrical load list and single-line diagram
7. *A plot plan* – equipment layout.
8. *Column and vessel outline drawings and specifications* including vessel sketches including pressure and temperature design ratings; a nozzle schedule specifying flange or coupling rating, typical of all openings and other pertinent dimensions; and special internal (numbers, type, pitch and spacing of trays and packing).

J. -C. Eun, *Handbook of Engineering Practice of Materials and Corrosion*,
https://doi.org/10.1007/978-3-030-36430-4_1

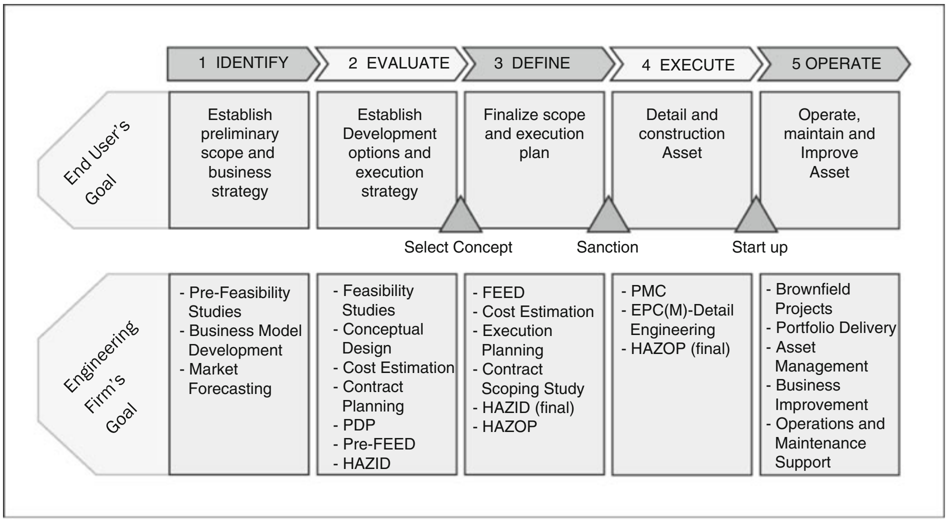


Figure 1.1 Five phases for oil and gas process plant engineering (typical). HAZID between evaluation stage and early define stage, HAZOP between define stage and early execute stage

Table 1.1 Required technical careers for materials and mechanical integrity in energy industries (typical)

Industries	Positions	Types of work	Required education backgrounds	Remark
Oil & gas (onshore & offshore – production, gas treatment, pipeline, refinery, petrochemical, chemical, LNG, fertilizer, etc.)	Technicians, Technologists, Inspectors (including NDE experts), Engineers, Supervisors/ superintendents Scientists, Professors, Instructors, Managers	Scoping study, Design (PDP, FEED, EPC, fabrication, construction, maintenance, selection of materials/coating/inhibitors, CP design, etc.), Purchasing, Inspection & Test (RBI, NDE, DE, lab, etc.), Monitoring, Data analyzing, Failure analysis (RCFA), Risk/integrity management	Mechanical, metallurgy, materials, Chemical, Civil, Electrical, Mathematics, Corrosion, Welding, Coating, CP, NDE, Others	Industrial codes and standards: See Table 1.3 Certifications: ASME, API, NACE, NBIC, AWS, P.E., etc.
Power (thermoelectric, nuclear, hydroelectric, geothermal, cogenerators, etc.)				
Chemicals (petrochemical, chemical, fine chemicals, semiconductors, etc.)				
Vehicles (aerospace, automotive, ships, military, etc.)				
Utilities (water, air, flue gas, chemicals, etc.)				

9. *Column internals (trays and packings) and loading specifications* including the number, type, pitch, and spacing of trays and packing; critical vapor-liquid loadings, stream gravities, and operating conditions; minimum tower diameters; and recommended vessel heights.
10. *Equipment duty specifications* including process criteria, general mechanical specifications and outline sketches, and condensation curves for exchangers, as required for the proper *function of the equipment*.
11. *Utility requirements*. This will include estimates of the consumption of steam, electrical power, cooling water, instrument air, inert gas, and fuel oil and gas.
12. *Environmental specifications* including tabulation of the potential emissions to air or water, a qualitative identification of pollutants and sources, and, where possible, an estimate of the quantities and concentrations.
13. *Instrument and control specifications* including instrument lists and process data sheets for minimum required instruments and controls with cause-and-effect diagrams.
14. *Piping and line specifications* including line list and designation sheets, including operating and design conditions, designation of pipe material and flange ratings, and insulation requirements.
15. *A materials list* including recommended MOC with corrosion allowances necessary for anti-corrosion or anti-corrosion protection.
16. *Reactor mechanical design*.
17. *Process guarantee conditions*.
18. *Process guarantee*.
19. *Procedure for conducting the performance test* including feedstock composition, the nature and origin of samples to be taken for analysis, and the methods of sampling, testing, and analytical procedures to be followed.
20. *Guidelines for the startup*, *operation*, *and shutdown of the licensed* plant (basis for licensed plant operating manual).
21. *Geophysical survey report*.

(b) Basic Engineering Design (BED)

The BED is conceptual or pre-FEED stage with HAZID (hazard and identification) study. The BED package is normally required by plant owner to produce and complete their Engineering, Procurement, Construction and Commissioning or Management tender package. The BED is also to be used to evaluate feasibility and budget of the project by the plant owner.

It normally covers:

1. Numbering system, process design summary, and BEDD (basic engineering design data)
2. Conceptual process studies (material balances, process flowsheets, etc.) and preliminary plot plan
3. Preliminary piping and instrument diagrams (P&ID) and material selection diagram (MSD)
4. Battery limit conditions
5. Definition and sizing of main equipment resulting in process specifications
6. Specification of effluents
7. Definition of control and safety devices
8. HAZID (hazard identification) analysis
9. In general, all of the basic studies which are required to support a BED Package containing all data needed by a competent contractor as well as to perform the detail engineering

Note: These basic engineering studies may consist of consolidating a process package initiated by an external process licensor. The BED package may be prepared in FEED stage when the PDP package is done with minimized engineering design.

(c) Front-End Engineering Design (FEED)

FEED is basic engineering which is conducted with HAZOP (hazard and operability) study after completion of conceptual design or feasibility study in evaluation stage. HAZOP is to identify abnormalities and its causes & consequences in more complicated or comprehensive processes or operations, whereas HAZID (hazard identification) is to avoid any hazardous and unwanted incidents around the entire facility more early in engineering stage. FEED is before the start of EPC (Engineering, Procurement and Construction) and provides the technical requirements as well as rough investment cost for the project. Also, these output documents may be used for government approval as well as financial approval. This work is normally contracted by EPC contractors as an optional contract or through bidding. The product of the activity is called FEED Package which amounts up to dozens of files and will be the basis of bidding for EPC contract.

It is important to reflect end-user's intentions and project-specific requirements into the FEED Package without failure, in order to avoid significant changes during EPC phase. The FEED work takes about one year in case of a large-sized project such as refinery, petrochemical, LNG, and offshore plants, etc. As it is essential to maintain close communication with the end-user, it became a common practice for end-users to station at the contractor's office during the work execution.

1. In general, the FEED phase is divided into three task areas when setting up a new plant or unit:
   (a) Provisional decision on investment by the owner or investor for the construction of a unit or plant
   (b) Production of quotations by an EPC contractor
   (c) Early phase of the basic engineering after the order has been awarded
2. The FEED phase comprises the following activities:
   (a) Mechanical data sheets of main equipment, starting from the process specifications issued during the BED and incorporating the specific requirements of codes and standards to be applied to the project of interest
   (b) Thermal rating of H/EXs
   (c) Preparation of tender packages for main equipment (long lead item)
   (d) Development of process and utility Piping and Instrumentation Diagrams (P&ID) released for detail engineering
   (e) Development of detailed plot plans and hazardous areas
   (f) Elaboration of the main piping, instrument, electrical, and civil work layouts
   (g) Process and mechanical datasheets
   (h) Applicable industrial codes and standards and project specifications
   (i) Issue the requisition of long delivery item, and complete the TBE (technical bid evaluation)

   In general, all of the studies are to be performed before ordering the main equipment (long lead item).

(d) Detail Design Engineering for New Construction and Revamping Projects

It is an engineering stage for actual construction.

It covers:

1. Scoping Study from the R
2. Purchasing of equipment (individual and bulk)
3. Thermal rating of H/EXs
4. Development of Piping and Instrumentation Diagrams released for construction
5. Development of detailed piping drawings, including isometrics and stress calculations
6. Development of detailed drawings related to instrumentation, electrical facilities, and civil works
7. Management of vendor drawings
8. Cost and schedule control

9. Startup procedures
   In general, all designs are to be performed before construction of the plant.

   The scope of this work typically includes the production of the following documentation:
   - Design basis
   - Process engineering: detailed piping and instrumentation diagrams, pump hydraulics, safety valve and rupture disc specifications, thermal design of H/EXs, and line list
   - Mechanical: general arrangement drawings for all fabricated items, lubrication list
   - Piping: piping layouts, isometric diagrams (ISO drawings), bill of material for piping items, stress analysis, and piping specification
   - Civil and structural: structural fabrication drawings, bills of quantities/MTO, foundation layouts, statutory approval drawings
   - Overall and unit plot plans
   - Detailed instrument, control system, control valve specifications, and terminal drawings
   - Electrical: list of motors and electrical consumers, power and lighting layouts, bill of quantities for bulk items
   - Enquiry specifications for packages
   - Insulation and painting specifications

1.1.2 Consideration Prior to Design

1.1.2.1 BEDD (Basic Engineering Design Data)

(a) Applicable codes and standards
(b) Local regulations
(c) Units and language
(d) Design life
(e) Plant/unit definitions (plant name & location, scope of work, assumptions, toxic materials, types of cooling or heating, winterization requirements, etc.)
(f) Field data (elevation, orientation and nature of terrain, soil, foundation type, fireproofing, specific precautions, etc.)
(g) Meteorological data (temperature, humidity, barometer pressure, wind, seismic, rainfall, snowfall, etc.)
(h) Utility conditions (steam, fuel gas, nitrogen, sir (plant & instrument), water-boiler feed, water (condensate/cooing water/utility/potable/firewater/raw water), amine (type/weight %/other data), electrical, safety, etc.)
(i) Scope of work/service/guarantee

Note: Normally the schedule is not included in BEDD categories

1.1.2.2 DPDT (design pressure-design temperature) and MDMT (minimum design metal temperature)

DPDT and MDMT should be decided at the early engineering stage because they are a fundamental input data for all facility design. In addition to normal operating condition, the following conditions should be also considered for the DPDT and MDMT.

- Alternative operation (anticipated upsets, e.g., valve outage, exothermal reaction, refractory failure, etc.)
- Startup and shutdown
- Steaming-out (purge out) and catalyst charging (if needed)
- Pressure relief (per fire and non-fire)
- Depressurization
- Metal skin temperature (e.g., fire side)
- Winterization including historical weather records and mothballing (if needed)
- Others (per code, standards, specification, etc.)

1.1.2.3 Design and selection for detail components

(a) Utilization of standard drawing approved by end-users: normally it is not necessary to confirm the strength calculation unless otherwise required because the strength of all components in standard drawing were already proved unless otherwise noted.
(b) To be considered the sequence of fabrication and assembly.

1.1.2.4 Transportation, erection, and field assembly with international and local regulation

(a) Transportation:
   1. On the sea: tide table, weather condition (e.g., hurricane, typhoon, cyclone, etc.)
   2. On the trailers: tailing/trunnion lugs direction, road survey, etc.
   3. On the train: impact factor in forward and lateral force
(b) Erection: approaching road condition, crane, gin pole, RMS (rigging master system), etc.
(c) Field assembly: dressing of removable parts, internals, top davit, etc.

1.1.2.5 Comprehension of general assembly/notes drawing – traceable for construction, maintenance, and future argument

(a) Design data
(b) Actual information as fabricated (reports of test, inspection, heat treatment, WPS, dimension, etc.)
(c) Fabrication history with hidden parts
(d) To be traceable all information of the equipment
(e) Responsibility 10–20 years per association (for seal of professional engineer)

1.1.2.6 Characteristics of requirements of code and specification – Tables 1.2 and 1.3

1.1.3 History, Governing, Updating, and Interpreting of ASME

1.1.3.1 History

The American Society of Mechanical Engineers (ASME) was founded in 1880 in the USA by prominent mechanical engineers. ASME formed its research activities in 1909, in areas such as steam tables, the properties of gases, the properties of metals, the effect of temperature on strength of materials, fluid meters, orifice coefficients, etc. By 1930, 50 years after ASME was founded, the Society had grown to more than 20,000 members, though its influence on American workers is far greater.

The Society is divided geographically into 12 regions and 200 local sections in the USA, its possessions Canada and Mexico. There are about 300 student sections at colleges and universities.

Table 1.2 Characteristics of requirements of code and specification

No.	Industry codes/standards local regulations	End-users'/contractors' specifications	Manufacturers' specifications and documents
1. Purpose	Minimum requirements for safety and welfare of public	Additional requirements for more strong safety, productivity, and maintenance of company and public including the minimum requirements of codes	Additional requirements for strong safety, productivity, and quality assurance of company and public including the minimum requirements of codes
2. Role of standardization	Minor	Strong	Moderate (focus to QA/QC)
3. Limitation & action	– Minimum or maximum – Yes or No – Required or exempt	– Minimum and/or maximum – Yes and No – Alternative	– Actual values – Yes – Fixed & result data – As built/manufactured

Table 1.3 Codes, standards, and local regulations for engineering and design mainly used in North America(1)

Targets	Codes and standards except ASTM (only for examples)
Equipment (Boilers, Pressure Vessels, Heaters, Rotating Machineries, Valves, PRD, OCTG, Subsea-Offshore Facilities), Piping, and Pipelines	ASME BPVC/Piping/The subsidiary codes and standards, API, CSAB51, BS 5500, PED, TEMA, ALPEMA, AD-2000, AS1210, PIP, PFI, PPI, PHMSA, Local Boiler/Safety Regulations, etc.
Building, geological/climatological historical data	ASCE, NBC, UBC, IBC, ACI, etc.
Corrosion, fitness for service	NACE, API, ASME FFS-1, ASTM DH25, MIL, EEMUA, etc.
Electric power, explosion prevention	IEC, NEC, UL, NEMA, IEEE, EPRI, NEMA, etc.
Energy conservation/gas	EUB, DOE, FERC, CGA, etc.
Environment, health, and safety	OSHA, EHS, etc.
Environment protection and enhancement – waste, potable water, and transportation	EPEA, EPA for protecting underground steel tanks, DOT, AWWA, etc.
Welding	ASME Sec. IX, AWS, WRC, API 1104, API RP582/1107/577, etc.
Fire fighting, fire proofing, and protection	NFPA, API RP2001/2218, UL, IFC, BS, EN, ISO, etc.
High pressure gas (LPG, LNG, etc.)	ASME, local regulations, etc.
Hot tapping	API 579-1/ASME FFS-1, API 1104/RP1107/RP2201, etc.
Inspection	NBIC, API (RBI series), AWS, ISO, BS, etc.
Nuclear	IAEA, ASME, RCCM, etc.
Tariff, tax, and insurance	FTA (NAFTA, USMCA), etc.
Using and transportation of harbors and trails	AASHTO, API, ASME, etc.
Energy – as federal regulations	FERC, CFR, CAPP, CSA, DOE, etc.
Offshore – as federal regulations	USCG (CG-ENG), BSEE, API, NACE, EEMUA, BS, ISO, etc.
Offshore – company/other country's standards & specifications	DNV, ABS, Lloyd, Norsok, etc.

Note: (1)Included foreign standards commonly used in North America

Region XIII is the region outside North America founded in 1996 which is divided into four zones. These are the Greater Europe, Asia and Pacific Rim, Latin America and the Caribbean, and Middle East and Africa zones.

The diversity of mechanical engineering in ASME can be seen in the following technical divisions and institutes.

(a) Basic Engineering Technical Group (BETG)
  - Applied Mechanics
  - Bioengineering
  - Fluids Engineering
  - Heat Transfer
  - Materials
  - Tribology

(b) Energy Conversion Group (ECG)
  - Internal Combustion Engine
  - Nuclear Engineering
  - Power
  - Advanced Energy Systems
  - Solar Energy

(c) Engineering and Technology Management Group (ETMG)
  - Management
  - Safety Engineering and Risk Analysis
  - Technology and Society

(d) Environment and Transportation Group (ETG)
  - Aerospace
  - Environmental Engineering
  - Noise Control Acoustics
  - Rail Transportation
  - Materials and Energy Recovery

(e) Manufacturing Technical Group (MTG)
  - Manufacturing Engineering
  - Materials Handling Engineering
  - Plant Engineering and Maintenance
  - Process Industries
  - Nondestructive Evaluation
  - Pressure Vessels and Piping

(f) System and Design Group (SDG)
  - Computers and Information Engineering
  - Design Engineering
  - Dynamic Systems and Control
  - Electronic and Photonic Packaging
  - Fluid Power Systems and Technology
  - Information Storage and Processing Systems
  - Microelectromechanical Systems

(g) Councils on Codes and Standards
  - Board on Performance Test Codes
  - Board on Standardization
  - Board on Pressure Technology C&S
  - Board on Nuclear Codes and Standards
  - Board on Safety Codes and Standards
  - Board on International Standards
  - Board on Conformity Assessment
  - Board on Hearings and Appeals
  - Board on Standards Technology Institute
  - Board on Council Operations

1.1.3.2 Updating and Interpreting the ASME Boiler and Pressure Vessel Codes (BPVC)

In order to keep up with the constant growth and progress of the industry, constant revisions of the Code have been required. Each new material, design, fabrication method, and protective device brings new problems to the Code Committee, requiring the technical advice of many subcommittees, in order to expedite proper additions and revisions to the Code.

Semiannually, on January 1st and July 1st, a new addendum to the Code is issued. An addendum becomes mandatory 6 months after the date of issuance. Every 3 years (2 years since 2015), on July 1st, a new edition of the Code is issued, incorporating all addenda to the previous edition. It becomes mandatory on the date of issuance.

Since the Code does not cover all the details of design, construction, and materials, pressure vessel manufacturers sometimes have difficulties in the interpretation of a certain rule, in order to meet specific customer requirements. In such cases, the inspector's office is consulted, and if he is not able to give the proper interpretation of the intent of the question, it is referred to the authorized inspector's office. If they are not able to provide a ruling, the manufacturer may request the assistance of the ASME Boiler and Pressure Vessel Committee, which meets regularly to consider inquiries of this nature. After a decision has been reached, it is forwarded to the inquiring party and also published in the Mechanical Engineering magazine. If no further criticism is received, the decision may be formally adopted as a Code Interpretation. Every 6 months, Code Interpretations are published in the form of questions and replies, and they may be included in the next addendum.

Code cases are also issued periodically. They contain rules for materials and special constructions that have not been sufficiently developed for inclusion in the Code itself. See ASME Sec. II, Part D, Appendix 5, for the code case application guidelines for the new materials. The application materials should be submitted to the following committees:

ASME BPVC & B31 series: https://cstools.asme.org/csconnect/CommitteePages.cfm

1.1.3.3 Boiler and Pressure Vessels Laws of USA (Courtesy of the Uniform BPV Laws Society)

The states, provinces, and territories in the USA and Canada have different application systems.

See the following websites for more detailed information.

- https://www.nationalboard.org/PrintAllSynopsis.aspx?Jurisdiction=Select
- https://www.scribd.com/document/52941996/NB-370

1.1.3.4 ASME Standard Base/Filler Materials – Source: http://www.wermac.org/societies/asme_astm.html

ASME and ASTM have cooperated for more than 50 years in the preparation of metallic material specifications of pressure equipment in ASME Section II (Part A, Ferrous; Part B, Nonferrous).

In 1969, AWS began the publication of specifications for welding rods, electrodes, and filler metals, hitherto issued by ASTM. ASME BPVC Committee has recognized this new arrangement and is now working with AWS on these specifications. ASME Section II, Part C, contains the welding material specifications approved for Code use.

In 1992, the ASME BPVC Committee endorsed the use of non-ASTM material for BPVC applications. It is the intent to follow the procedures and practices currently in use to implement the adoption of non-ASTM materials.

All identical specifications are indicated by the ASME organization symbols. The specifications prepared and copyrighted by ASTM, AWS, and other originating organizations are reproduced in the Code with the permission of the respective Society. The ASME BPVC Committee has given careful consideration to each new and revised specification and has made such changes as they deemed necessary to make the specification adaptable for Code usage. In addition, ASME has furnished ASTM with the basic requirements that should govern many proposed new specifications. Joint action will continue an effort to make the ASTM, AWS, and ASME specifications identical.

To assure that there will be a clear understanding on the part of the users, ASME Section II publishes both the identical specifications and those amended for Code usage in three parts every 3 years, in the same page size to match the other sections of the Code, and addenda are issued annually to provide the latest changes in ASME Section II specifications.

1.1.4 Contents of ASME

Table 1.4 shows the conventional Boiler and Pressure Vessel Codes (BPVC) which are used for fixed pressure equipment in new construction.

The ASME BPVC are recognized as the most principal requirements in design and fabrication of pressure-containing industry facilities. In addition to ASME BPVC, ASME has developed and published lots of subsidiary codes and standards for performance, fitness-for-service, nonmetals, design data, corrosion data, flare, rotating machinery, crane, examples, etc. (see below) during the last 20 years.

– BPE (bioprocessing equipment)
– BTH (below-the-hook)
– FFS (fitness-for-service)
– PCC (post-construction committee)
– PTB (example problem manuals)
– PTC (performance test codes)
– RTP (reinforced thermal plastics)
– RA (risk assessment)
– STP (standard technology publication-stress parameters)
– STS (steel stack)
– TDP (steam turbine)
– PVHO (pressure vessel human occupancy)
– Y14.5 (dimensioning and tolerancing)

Table 1.4 ASME boiler and pressure vessel codes (BPVC)

Sections	Part or subsection	Title
I	Rules of construction of power boilers	
II	**Materials**	
	Part A	Ferrous material specifications
	Part B	Nonferrous material specifications
	Part C	Specifications for welding rods, electrodes, and filler metals
	Part D	Properties (customary)
	Part D	Properties (metric)
III	**Rules for construction of nuclear facility components**	
	Subsection NCA – general requirements for division 1 and division 2	
	Appendices	
	Division 1	Subsection NB — class 1 components
		Subsection NC — class 2 components
		Subsection ND — class 3 components
		Subsection NE — class MC components
		Subsection NF — cupports
		Subsection NG — core support structures
	Division 2	Code for concrete containments
	Division 3	Containment systems for transportation and storage of spent nuclear fuel and high-level radioactive material
	Division 5	High temperature reactors
IV	Rule for construction of heating boilers	
V	Nondestructive examination	
VI	Recommended rules for the care and operation of heating boilers	
VII	Recommended guidelines for the care of power boilers	
VIII	**Rule of construction of pressure vessels**	
	Division 1	
	Division 2	Alternative rules
	Division 3	Alternative rules for construction of high pressure vessels
IX	Welding, brazing, and fusing qualifications	
X	Fiber-reinforced plastic pressure vessels	
XI	**Rules for in-service inspection of nuclear power plant components**	
	Division 1	Rules for inspection and testing of components of light-water-cooled plants
	Division 2	Requirements for reliability and integrity management (RIM) programs for nuclear power plants
XII	Rules for construction and continued service of transport tanks	

(a) SECTION VIII DIVISION 1 RULES FOR CONSTRUCTION OF PRESSURE VESSELS
SUBSECTION A GENERAL REQUIREMENTS
Part UG General Requirements for All Methods of Construction
SUBSECTION B REQUIREMENTS PERTAINING TO METHODS OF FABRICATION OF PRESSURE VESSELS
Part UW Requirements for Pressure Vessels Fabricated by Welding
Part UF Requirements for Pressure Vessels Fabricated by Forging
Part UB Requirements for Pressure Vessels Fabricated by Brazing
SUBSECTION C REQUIREMENTS PERTAINING TO CLASSES OF MATERIALS
Part UCS Requirements for Pressure Vessels Constructed of Carbon and Low Alloy Steels
Part UNF Requirements for Pressure Vessels Constructed of Nonferrous Materials
Part UHA Requirements for Pressure Vessels Constructed of High Alloy Steel
Part UCI Requirements for Pressure Vessels Constructed of Cast Iron
Part UCL Requirements for Welded Pressure Vessels Constructed of Material with Corrosion Resistant Integral Cladding, Weld Metal Overlay Cladding, or with Applied Linings
Part UCD Requirements for Pressure Vessels Constructed of Cast Ductile Iron
Part UHT Requirements for Pressure Vessels Constructed of Ferritic Steels with Tensile Properties Enhanced by Heat Treatment
Part ULW Requirements for Pressure Vessels Fabricated by Layered Construction
Part ULT Alternative Rules for Pressure Vessels Constructed of Materials Having Higher Allowable Stresses at Low Temperature
Part UHX Rules for Shell-and-Tube H/EXs
Part UIG Requirements for Pressure Vessels Constructed of Impregnated Graphite

MANDATORY APPENDICES

1. Supplementary Design Formulas
2. Rules for Bolted Flange Connections with Ring Type Gaskets
3. Definitions
4. Rounded Indications Charts Acceptance Standard for Radiographically Determined Rounded Indications in Welds
5. Flexible Shell Element Expansion Joints
6. Methods for Magnetic Particle Examination (MT)
7. Examination of Steel Castings
8. Methods for Liquid Penetrant Examination (PT)
9. Jacketed Vessels
10. Quality Control System
11. Capacity Conversions for Safety Valves
12. Ultrasonic Examination of Welds (UT)
13. Vessels of Noncircular Cross Section
14. Integral Flat Heads with a Large, Single, Circular, Centrally Located Opening
16. Submittal of Technical Inquiries to the Boiler and Pressure Vessel Committee
17. Dimpled or Embossed Assemblies
18. Adhesive Attachment of Nameplates
19. Electrically Heated or Gas Fired Jacketed Steam Kettles
20. Hubs Machined from Plate
21. Jacketed Vessels Constructed of Work-Hardened Nickel
22. Integrally Forged Vessels
23. External Pressure Design of Copper, Copper Alloy, and Titanium Alloy Condenser and H/EX Tubes with Integral Fins
24. Design Rules for Clamp Connections
25. Acceptance of Testing Laboratories and Authorized Observers for Capacity Certification of Pressure Relief Valves
26. Bellows Expansion Joints
27. Alternative Requirements for Glass-Lined Vessels
28. Alternative Corner Weld Joint Detail for Box Headers for Air-Cooled H/EXs
29. Blank
30. Rules for Drilled Holes Not Penetrating Through Vessel Wall
31. Rules for Cr–Mo Steels with Additional Requirements for Welding and Heat Treatment
32. Local Thin Areas in Cylindrical Shells and in Spherical Segments of Shells
33. Standards Units for Use in Equations
34. Requirements for Use of High Silicon Stainless Steels for Pressure Vessels
35. Rules for Mass Production of Pressure Vessels
36. Standard Test Method for Determining the Flexural Strength of Certified Materials Using Three-Point Loading
37. Standard Test Method for Determining the Tensile Strength of Certified Impregnated Graphite Materials
38. Standard Test Method for Compressive Strength of Impregnated Graphite
39. Testing the Coefficient of Permeability of Impregnated Graphite
40. Thermal Expansion Test Method for Graphite and Impregnated Graphite
41. Electric Immersion Heater Element Support Plates
42. Diffusion Bonding
43. Establishing Governing Code Editions and Cases for Pressure Vessels and Parts
44. Cold Stretching of ASS Pressure Vessels
45. Plate H/EXs
46. Rules for Use of Section VIII, Division 2

NONMANDATORY APPENDICES

- A Basis for Establishing Allowable Loads for Tube-to-Tubesheet Joints
- C Suggested Methods for Obtaining the Operating Temperature of Vessel Walls in Service
- D Suggested Good Practice Regarding Internal Structures
- E Suggested Good Practice Regarding Corrosion Allowance
- F Suggested Good Practice Regarding Linings
- G Suggested Good Practice Regarding Piping Reactions and Design of Supports and Attachments
- H Guidance to Accommodate Loadings Produced by Deflagration
- K Sectioning of Welded Joints
- L Application of Rules for Joint Efficiency in Shell and Heads of Vessels with Welded Joints
- M Installation and Operation
- P Basis for Establishing Allowable Stress Values for UCI, UCD, and ULT Materials
- R Preheating

S Design Considerations for Bolted Flange Connections
T Temperature Protection
W Guide for Preparing Manufacturer's Data Reports
Y Flat Face Flanges with Metal-to-Metal Contact Outside the Bolt Circle
DD Guide to Information Appearing on Certificate of Authorization
EE Half-Pipe Jackets
FF Guide for the Design and Operation of Quick-Actuating (Quick-Opening) Closures
GG Guidance for the Use of US Customary and SI Units in the ASME Boiler and Pressure Vessel Code
HH Tube Expanding Procedures and Qualification
JJ Flowcharts Illustrating Impact Testing Requirements and Exemptions from Impact Testing by the Rules of UHA-51
KK Guide for Preparing User's Design Requirements
LL Graphical Representations of $F_{t,\mathrm{min}}$ and $F_{t,\mathrm{max}}$
MM Alternative Marking and Stamping of Graphite Pressure Vessels
NN Guidance to the Responsibilities of the User and Designated Agent

(b) SECTION VIII DIVISION 2 RULES FOR CONSTRUCTION OF PRESSURE VESSELS; alternative rules
Part 1 General Requirements
Part 2 Responsibilities and Duties
Part 3 Materials Requirements
3.1 General Requirements
3.2 Materials Permitted For Construction of Vessel Parts
3.3 Supplemental Requirements for Ferrous Materials
3.4 Supplemental Requirements for Cr–Mo Steels
3.5 Supplemental Requirements for Q&T Steels with Enhanced Tensile Properties
3.6 Supplemental Requirements for Nonferrous Materials
3.7 Supplemental Requirements for Bolting
3.8 Supplemental Requirements for Castings
3.9 Supplemental Requirements for Hubs Machined from Plate
3.10 Material Test Requirements
3.11 Material Toughness Requirements
3.12 Allowable Design Stresses
3.13 Strength Parameters
3.14 Physical Properties
3.15 Design Fatigue Curves
3.16 Design Values for Temperatures Colder than −30 °C (−20 °F)
3.17 Nomenclature
3.18 Definitions
3.19 Tables
3.20 Figures
Annex 3-A Allowable Design Stresses
Annex 3-B Requirements for Material Procurement
Annex 3-C ISO Material Group Numbers
Annex 3-D Strength Parameters
Annex 3-E Physical Properties
Annex 3-F Design Fatigue Curves
Part 4 Design by Rule Requirements
4.1 General Requirements
4.2 Design Rules for Welded Joints
4.3 Design Rules for Shells Under Internal Pressure
4.4 Design of Shells Under External Pressure and Allowable Compressive Stresses
4.5 Design Rules for Openings in Shells and Heads
4.6 Design Rules for Flat Heads
4.7 Design Rules for Spherically Dished Bolted Covers
4.8 Design Rules for Quick-Actuating (Quick-Opening) Closures
4.9 Design Rules for Braced and Stayed Surfaces
4.10 Design Rules for Ligaments
4.11 Design Rules for Jacketed Vessels
4.12 Design Rules for Noncircular Vessels
4.13 Design Rules for Layered Vessels
4.14 Evaluation of Vessels Outside of Tolerance

4.15 Design Rules for Supports and Attachments
4.16 Design Rules for Flanged Joints
4.17 Design Rules for Clamped Connections
4.18 Design Rules for Shell and Tube Heat Exchangers
4.19 Design Rules for Bellows Expansion Joints
4.20 Design Rules for Flexible Shell Element Expansion Joints
Annex 4-B Guide for the Design and Operation of Quick-Actuating (Quick-Opening) Closures
Annex 4-C Basis for Establishing Allowable Loads for Tube-To-Tubesheet Joints
Annex 4-D Guidance to Accommodate Loadings Produced by Deflagration
Annex 4-E Tube Expanding Procedures and Qualification
Part 5 Design by Analysis Requirements
Part 6 Fabrication Requirements
6.1 General Fabrication Requirements
6.2 Welding Fabrication Requirements
6.3 Special Requirements for Tube-To-Tubesheet Welds
6.4 Preheating and Heat Treatment of Weldments
6.5 Special Requirements for Clad or Weld Overlay Linings and Lined Parts
6.6 Special Requirements for Tensile Property Enhanced Q and T Ferritic Steels
6.7 Special Requirements for Forged Fabrication
6.8 Special Fabrication Requirements for Layered Vessels
6.9 Special Fabrication Requirements for Expansion Joints
6.10 Nomenclature
6.11 Tables
6.12 Figures
Annex 6-A Positive Material Identification Practice
Part 7 Inspection and Examination Requirements
7.1 General
7.2 Responsibilities and Duties
7.3 Qualification of Nondestructive Examination Personnel
7.4 Examination of Welded Joints
7.5 Examination Method and Acceptance Criteria
7.6 Final Examination of Vessel
7.7 Leak Testing
7.8 Acoustic Emission
7.9 Tables
7.10 Figures
Annex 7-A Responsibilities and Duties for Inspection and Examination Activities
Part 8 Pressure Testing Requirements
8.1 General Requirements
8.2 Hydrostatic Testing
8.3 Pneumatic Testing
8.4 Alternative Pressure Testing
8.5 Documentation
8.6 Nomenclature
Part 9 Pressure Vessel Overpressure Protection
9.1 General Requirements
9.2 Pressure Relief Valves
9.3 Non-reclosing Pressure Relief Devices
9.4 Calculation of Rated Capacity for Different Relieving Pressures and/or Fluids
9.5 Marking and Stamping
9.6 Provisions for Installation of Pressure Relieving Devices
9.7 Overpressure Protection by Design
Annex 9-A Best Practices for the Installation and Operation of Pressure Relief Devices

(c) SECTION VIII DIVISION 3 RULES FOR CONSTRUCTION OF PRESSURE VESSELS – Alternative Rules for Construction of High Pressure Vessels
PART KG GENERAL REQUIREMENTS
PART KM MATERIAL REQUIREMENTS
PART KD DESIGN REQUIREMENTS
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M Guide to Classifying Fluid Services
N Application of ASME B31.3 Internationally
Q Quality System Program
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S Piping System Stress Analysis Examples
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Z Preparation of Technical Inquiries

(e) ASME SECTION II-PART D

Table No.	Title
1A	Sec. I; Sec. III, Cl. 2 and 3; Sec. VIII, Div. 1; and Sec. XII maximum allowable stress values S for ferrous materials
1B	Sec. I; Sec. III, Cl. 2 and 3; Sec. VIII, Div. 1; and Sec. XII maximum allowable stress values S for nonferrous materials
2A	Sec. III, Div. 1, Cl. 1 and MC; Sec. III, Div. 3, Cl. TC and SC; and Sec. VIII, Div. 2, Cl. 1 design stress intensity values Sm for ferrous materials
2B	Sec. III, Div. 1, Cl. 1; Sec. III, Div. 3, Cl. TC and SC; and Sec. VIII, Div. 2, Cl. 1 design stress intensity values Sm for nonferrous materials
3	Sec. III, Cl. 2 and 3; Sec. VIII, Div. 1 and 2; and Sec. XII maximum allowable stress values S for bolting materials
4	Sec. III, Cl. 1, TC, and SC; and Sec. VIII, Div. 2 design stress intensity values Sm for bolting materials
5A	Sec. VIII, Div. 2 maximum allowable stress values S for ferrous materials
5B	Sec. VIII, Div. 2 maximum allowable stress values S for nonferrous materials
6A	Sec. IV, For information only – maximum allowable stress values, *S*, for ferrous materials
6B	Sec. IV, For information only – maximum allowable stress values, *S*, for nonferrous materials
6C	Sec. IV, For information only – maximum allowable stress values, *S*, for lined water heater materials
6D	Sec. IV, For information only – maximum allowable stress values, *S*, for unlined water heater materials
U	Tensile strength values Su for ferrous and nonferrous materials
U-2	Sec. VIII, Div. 3 tensile strength values Su for ferrous materials
Y-1	Yield strength values Sy for ferrous and nonferrous materials
Y-2	Factors for limiting permanent strain in austenitic stainless steels, high-nickel alloy steels, nickel, and nickel alloys
TE-1	Thermal expansion for ferrous materials
TE-2	Thermal expansion for aluminum alloys
TE-3	Thermal expansion for copper alloys
TE-4	Thermal expansion for nickel alloys
TE-5	Thermal expansion for titanium alloys
TCD	Nominal coefficients of thermal conductivity (TC) and thermal diffusivity (TD)
TM-1	Moduli of elasticity, E, of ferrous materials for given temperatures
TM-2	Moduli of elasticity, E, of aluminum and aluminum alloys for given temperatures
TM-3	Moduli of elasticity, E, of copper and copper alloys for given temperatures
TM-4	Moduli of elasticity, E, of high-nickel alloys for given temperatures
TM-5	Moduli of elasticity, E, of titanium and zirconium for given temperatures
PRD	Poisson's ratio and density of materials

ASME SECTION II-PART D, *NONMANDATORY APPENDIX A*

A-100 general

A-200 metallurgical changes that can occur in service

A-201 Graphitization (occurs almost exclusively in carbon and C–Mo steels)
A-202 Softening (occurs in most ferritic alloys used for elevated temperature service)
A-203 Temper embrittlement (occurs in low alloy steels)
A-204 Strain aging (occurs in carbon and low alloy steels)
A-205 Cold working (cold strain) (effects occur in most steels but are particularly important for 300 series SS)
A-206 Relaxation cracking (strain-induced precipitation hardening)
A-207 885 °F embrittlement (occurs mostly in high-chromium stainless steels and in FSS & DSS)
A-208 Sigma-phase embrittlement (occurs mostly in high Cr SS and in the ferritic phase of DSS)
A-209 Laves and laves phase precipitation (occurs in some 300 series SS, Fe–Ni base alloys, Co-base superalloys, and in the tungsten-bearing CSEF steels)
A-210 Sensitization (carbide formation) (occurs in both the 300 series SS as well as in 400 series SS)
A-211 Thermal aging embrittlement (occurs to varying degrees in most ferrous alloys)
A-212 Radiation embrittlement (affects all materials, both ferrous and nonferrous)
A-213 Solidification cracking in Ni alloys

A-300 uniform corrosion
- A-301 General corrosion and wastage
- A-302 Atmospheric corrosion
- A-303 Galvanic corrosion
- A-304 Stray current corrosion
- A-305 High temperature corrosion
- A-306 Soil corrosion
- A-307 Caustic corrosion
- A-308 Carbon dioxide (wet CO_2) corrosion
- A-309 Concentration cell corrosion
- A-310 Differential temperature cell corrosion
- A-311 Molten salt corrosion
- A-312 Liquid metal corrosion

A-400 localized corrosion
- A-401 Pitting corrosion
- A-402 Filiform corrosion
- A-403 Crevice corrosion (and denting)
- A-404 Microbiologically influenced corrosion (MIC)

A-500 Metallurgically influenced corrosion
- A-501 Intergranular corrosion (IGC)
- A-502 Dealloying corrosion (dezincification and graphite corrosion) (occurs mainly in brasses and gray cast iron)
- A-503 Grooving (occurs mostly in ERW carbon steel pipe)

A-600 mechanically assisted corrosion
- A-601 Velocity-affected corrosion
- A-602 Erosion-corrosion
- A-603 Impingement corrosion
- A-604 Cavitation Erosion
- A-605 Corrosion fatigue

A-700 environmentally induced embrittlement and cracking
- A-701 Stress corrosion cracking (SCC) – transgranular/ intergranular/ irradiation-assisted SCC
- A-702 Hydrogen damage-HE, HIC, cracking from the precipitation of internal hydrogen, hydrogen attack, and cracking from hydride formation
- A-703 Liquid metal embrittlement (LME)
- A-704 Caustic embrittlement
- A-705 Flow-accelerated corrosion
- A-706 Sulfur embrittlement

A-800 mechanical damage mechanisms
- A-801 Fretting and wear
- A-802 Thermal fatigue
- A-803 Dynamic loading
- A-804 Anisotropy

(f) ANSI/ASME combined standards
Many ANSI standards combined with ASME standards. Table 1.5 shows the summary (ANSI/ASME xxxx) of ASME standards combined with ANSI standards. Now the description of ANSI is not necessary. For instance, the name of ASME B16.5 is enough.

1.1.5 Scope of Application in ASME

1.1.5.1 Major Applicable Scopes in ASME Sec. VIII and B31.3

Table 1.6 shows the comparison of major applicable scopes of ASME Section VIII and B31.3.

1.1.5.2 Applicable Scopes of ASME – API

Figure 1.2 shows the application scopes of each ASME and API for metal base facilities. Table 1.7 shows the application scopes of each ASME and API for non-metal base facilities.

1.1.5.3 Pressure Retaining Parts and Pressure Boundary Applied in ASME

Pressure-retaining parts include reinforcing pads, stiffeners at cone cylinder junctions, and stiffeners that resist external pressure as well as direct pressure boundary, while pressure boundary parts are only for the primary boundary separating a high pressure condition (e.g., shell, head, nozzles, etc.) from atmospheric pressure condition.

Table 1.5 The summary of ASME codes combined with ANSI standards (ANSI/: to be deleted)

Code No.	Code No.	Code No.	Code No.	Code No.
ANSI/ASME AG-1	ANSI/ASME B16.28	ANSI/ASME B30.6	ANSI/ASME B107.5M	ANSI/ASME PTC 9
ANSI/ASME A 17.1	ANSI/ASME B16.28	ANSI/ASME B30.7	ANSI/ASME B107.6	ANSI/ASME PTC 10
ANSI/ASME A 17.1. Handbook	ANSI/ASME B16.29	ANSI/ASME B30.8	ANSI/ASME B107.8M	ANSI/ASME PTC 11
ANSI/ASME A 17.2.1	ANSI/ASME B16.32	ANSI/ASME B30.9	ANSI/ASME B107.9	ANSI/ASME PTC 12.1
ANSI/ASME A 17.2.2	ANSI/ASME B16.33	ANSI/ASME B30.10	ANSI/ASME B107.11M	ANSI/ASME PTC 12.2
ANSI/ASME A 17.2.3	ANSI/ASME B16.34	ANSI/ASME B30.11	ANSI/ASME B107.12	ANSI/ASME PTC 12.3
ANSI/ASME A 17.3	ANSI/ASME B16.36	ANSI/ASME B30.12	ANSI/ASME B107.13M	ANSI/ASME PTC 12.4
ANSI/ASME A 17.4	ANSI/ASME B16.38	ANSI/ASME B30.13	ANSI/ASME B107.14M	ANSI/ASME PTC 14
ANSI/ASME A 17.5	ANSI/ASME B16.39	ANSI/ASME B30.14	ANSI/ASME B107.15	ANSI/ASME PTC 16
ANSI/ASME A 39.1	ANSI/ASME B16.40	ANSI/ASME B30.16	ANSI/ASME B107.16	ANSI/ASME PTC 17
ANSI/ASME A 90.1	ANSI/ASME B16.42	ANSI/ASME B30.17	ANSI/ASME B107.17M	ANSI/ASME PTC 18
ANSI/ASME A 112.1.2	ANSI/ASME B16.45	ANSI/ASME B30.18	ANSI/ASME B107.18M	ANSI/ASME PTC 18.1
ANSI/ASME A 112.3.1	ANSI/ASME B16.47	ANSI/ASME B30.19	ANSI/ASME B107.19	ANSI/ASME PTC 19.1
ANSI/ASME A 112.4.1	ANSI/ASME B18.1.3M	ANSI/ASME B30.20	ANSI/ASME B107.20M	ANSI/ASME PTC 19.2
ANSI/ASME A 112.6.1M	ANSI/ASME B18.2.2	ANSI/ASME B30.21	ANSI/ASME B107.21	ANSI/ASME PTC 19.3
ANSI/ASME A 112.18.1M	ANSI/ASME B18.2.3.4M	ANSI/ASME B30.22	ANSI/ASME B107.22M	ANSI/ASME PTC 19.7
ANSI/ASME A 112.19.10	ANSI/ASME B18.2.3.9M	ANSI/ASME B31G	ANSI/ASME B107.23M	ANSI/ASME PTC 19.8
ANSI/ASME A 112.19.1M	ANSI/ASME B18.3	ANSI/ASME B31.1	ANSI/ASME B133.7M	ANSI/ASME PTC 19.11
ANSI/ASME A 112.19.2M	ANSI/ASME B18.3.1M	ANSI/ASME B31.3	ANSI/ASME B133.9	ANSI/ASME PTC 19.22
ANSI/ASME A 112.19.3M	ANSI/ASME B18.3.3M	ANSI/ASME B31.4	ANSI/ASME CSO-1	ANSI/ASME PTC 19.23
ANSI/ASME A 112.19.4M	ANSI/ASME B18.3.4M	ANSI/ASME B31.5	ANSI/ASME HPS-1	ANSI/ASME PTC 20.1
ANSI/ASME A 112.19.6	ANSI/ASME B18.3.5M	ANSI/ASME B31.8	ANSI/ASME HST-1M	ANSI/ASME PTC 20.2
ANSI/ASME A 112.19.7M	ANSI/ASME B18.3.6M	ANSI/ASME B31.9	ANSI/ASME HST-2M	ANSI/ASME PTC 20.3
ANSI/ASME A 112.19.8M	ANSI/ASME B18.5	ANSI/ASME B31.11	ANSI/ASME HST-3M	ANSI/ASME PTC 21
ANSI/ASME A 112.19.9M	ANSI/ASME B18.5.2.2M	ANSI/ASME B32.3M	ANSI/ASME HST-4M	ANSI/ASME PTC 22
ANSI/ASME A 112.21.1M	ANSI/ASME B18.5.2.3M	ANSI/ASME B32.6M	ANSI/ASME HST-5M	ANSI/ASME PTC 23
ANSI/ASME A 112.21.3M	ANSI/ASME B18.6.5M	ANSI/ASME B36.10M	ANSI/ASME HST-6M	ANSI/ASME PTC 23.1
ANSI/ASME A 112.26.1M	ANSI/ASME B18.6.7M	ANSI/ASME B36.19M	ANSI/ASME MC88.1	ANSI/ASME PTC 25.3
ANSI/ASME A 112.36.2M	ANSI/ASME B18.7.1M	ANSI/ASME B40.1	ANSI/ASME MC88.2	ANSI/ASME PTC 28
ANSI/ASME B1.1	ANSI/ASME B18.8.1	ANSI/ASME B40.2	ANSI/ASME MFC-1M	ANSI/ASME PTC 29
ANSI/ASME B1.2	ANSI/ASME B18.8.2	ANSI/ASME B40.3	ANSI/ASME MFC-2M	ANSI/ASME PTC 30
ANSI/ASME B1.3M	ANSI/ASME B18.8.3M	ANSI/ASME B46.1	ANSI/ASME MFC-4M	ANSI/ASME PTC 31
ANSI/ASME B1.5	ANSI/ASME B18.8.4M	ANSI/ASME B47.1	ANSI/ASME MFC-5M	ANSI/ASME PTC 32.1
ANSI/ASME B1.7M	ANSI/ASME B18.8.5M	ANSI/ASME B56.1	ANSI/ASME MFC-6M	ANSI/ASME PTC 32.2
ANSI/ASME B1.8-1	ANSI/ASME B18.8.5M	ANSI/ASME B56.5	ANSI/ASME MFC-7M	ANSI/ASME PTC 33
ANSI/ASME B1.12	ANSI/ASME B18.8.7M	ANSI/ASME B56.6	ANSI/ASME MFC-8M	ANSI/ASME PTC 33a
ANSI/ASME B1.13M	ANSI/ASME B18.8.8M	ANSI/ASME B56.7	ANSI/ASME MFC-9M	ANSI/ASME PTC 36
ANSI/ASME B1.16M	ANSI/ASME B18.10	ANSI/ASME B56.8	ANSI/ASME MFC-10M	ANSI/ASME PTC 38
ANSI/ASME B1.20.1	ANSI/ASME B18.13	ANSI/ASME B56.9	ANSI/ASME MFC-11M	ANSI/ASME PTC 39.1
ANSI/ASME B1.20.5	ANSI/ASME B18.13.1M	ANSI/ASME B56.10	ANSI/ASME MH1.1.2	ANSI/ASME PTC 40
ANSI/ASME B1.20.7	ANSI/ASME B18.15M	ANSI/ASME B56.11.1	ANSI/ASME MH1.2.2M	ANSI/ASME PTC 42
ANSI/ASME B1.21M	ANSI/ASME B18.18.1M	ANSI/ASME B56.11.3	ANSI/ASME MH1.4.1M	ANSI/ASME PVHO-1
ANSI/ASME B1.22M	ANSI/ASME B18.18.2M	ANSI/ASME B56.11.4	ANSI/ASME MH1.5M	ANSI/ASME QE1-1
ANSI/ASME B1.30M	ANSI/ASME B18.18.3M	ANSI/ASME B56.11.5	ANSI/ASME MH1.6	ANSI/ASME QME-1
ANSI/ASME B5.1M	ANSI/ASME B18.18.4M	ANSI/ASME B73.1M	ANSI/ASME MH1.7M	ANSI/ASME QMO-1
ANSI/ASME B5.10	ANSI/ASME B18.21.1	ANSI/ASME B73.2M	ANSI/ASME MH1.9	ANSI/ASME QRO-1
ANSI/ASME B5.35	ANSI/ASME B18.21.2M	ANSI/ASME B89.1.2M	ANSI/ASME N278.1	ANSI/ASME RTP-1
ANSI/ASME B5.49M	ANSI/ASME B18.29.1	ANSI/ASME B89.1.6M	ANSI/ASME N509	ANSI/ASME SPPE-1
ANSI/ASME B5.50	ANSI/ASME B19.1	ANSI/ASME B89.1.9M	ANSI/ASME N510	ANSI/ASME SPPE-2
ANSI/ASME B5.54	ANSI/ASME B19.3	ANSI/ASME B89.1.10M	ANSI/ASME N626	ANSI/ASME STS-2
ANSI/ASME B5.55M	ANSI/ASME B20.1	ANSI/ASME B89.1.12M	ANSI/ASME N626.3	ANSI/ASME Y1.1
ANSI/ASME B5.56M	ANSI/ASME B29.1M	ANSI/ASME B89.3.4M	ANSI/ASME NOG-1	ANSI/ASME Y10.11
ANSI/ASME B15.1	ANSI/ASME B29.3M	ANSI/ASME B94.6	ANSI/ASME NQA-1	ANSI/ASME Y14.1M
ANSI/ASME B16.1	ANSI/ASME B29.4M	ANSI/ASME B94.9	ANSI/ASME NQA-3	ANSI/ASME Y14.2M
ANSI/ASME B16.3	ANSI/ASME B29.6M	ANSI/ASME B94.11M	ANSI/ASME OM	ANSI/ASME Y14.3M
ANSI/ASME B16.4	ANSI/ASME B29.8M	ANSI/ASME B94.16	ANSI/ASME PALD	ANSI/ASME Y14.4M
ANSI/ASME B16.5	ANSI/ASME B29.11M	ANSI/ASME B94.17	ANSI/ASME PTC-1	ANSI/ASME Y14.6
ANSI/ASME B16.9	ANSI/ASME B29.12M	ANSI/ASME B94.18	ANSI/ASME PTC-2	ANSI/ASME Y14.6aM
ANSI/ASME B16.10	ANSI/ASME B29.14M	ANSI/ASME B94.19	ANSI/ASME PTC 3.1	ANSI/ASME Y14.7.1
ANSI/ASME B16.11	ANSI/ASME B29.17M	ANSI/ASME B94.27.1M	ANSI/ASME PTC 3.2	ANSI/ASME Y14.8M
ANSI/ASME B16.12	ANSI/ASME B29.18M	ANSI/ASME B94.28.1M	ANSI/ASME PTC 3.3	ANSI/ASME Y14.13M
ANSI/ASME B16.14	ANSI/ASME B29.19	ANSI/ASME B94.51M	ANSI/ASME PTC 4.1	ANSI/ASME Y14.18M
ANSI/ASME B16.15	ANSI/ASME B29.23M	ANSI/ASME B94.52M	ANSI/ASME PTC 4.2	ANSI/ASME Y14.24M
ANSI/ASME B16.20	ANSI/ASME B29.24M	ANSI/ASME B94.53	ANSI/ASME PTC 4.3	ANSI/ASME Y14.32.1M
ANSI/ASME B16.21	ANSI/ASME B29.25M	ANSI/ASME B94.54	ANSI/ASME PTC 4.4	ANSI/ASME Y14.34M
ANSI/ASME B16.22	ANSI/ASME B30.1	ANSI/ASME B94.55M	ANSI/ASME PTC 6	ANSI/ASME Y14.35M
ANSI/ASME B16.23	ANSI/ASME B30.2	ANSI/ASME B96.1	ANSI/ASME PTC 6 App	ANSI/ASME Y32.2.3
ANSI/ASME B16.24	ANSI/ASME B30.3	ANSI/ASME B107.1	ANSI/ASME PTC 6R	
ANSI/ASME B16.25	ANSI/ASME B30.4	ANSI/ASME B107.2	ANSI/ASME PTC 6S	
ANSI/ASME B16.26	ANSI/ASME B30.5	ANSI/ASME B107.3	ANSI/ASME PTC 6.1	

Table 1.6 (1/3) Comparison of major applicable scopes of ASME Sec. VIII and B31.3[3]

Data	ASME Sec. VIII, Div. 1[10] /Sec. II, Part D (materials only)	ASME Sec. VIII, Div. 2 /Sec. II, Part D (materials only)	ASME Sec. VIII, Div. 3 /Sec. II, Part D (materials only)	ASME B31.3
Design pressure (DP)[1]	15–3000 psig (0.1 to 20.7 MPag)[6]	≥15 psig (0.1 MPag)	≥10,000 psig (70MPag)[7]	≥15 psig (0.1 MPag)
Max. Design temperature (DT) in Sec. II Part D and ASME B31.3	900 °C (1650 °F)	482 °C (900 °F)	482 °C (900 °F)	900 °C (1650 °F)
Materials limitation/ allowable stress in Sec. II Part D and ASME B31.3	Table 1A & 1B in Sec. II Part D No allowable stress values are reduced at min. to 343 °C (650 °F) for most ferrite steels	Table 2A & 2B in Sec. II Part D. It is more limited than Table 1	Table Y-3 (YS) and U-2 (TS) in Sec. II Part D. It is much more limited than Tables 1 & 2	Table A-1 & A-2 and Table K-1 in B31.3
Vessel & Piping Type	• Unfired steam boiler • As per combination of volume and DP • Others: see U-1	• Fixed vessel • Unfired steam boiler • Others: see U-1	• Centrally wrapped vessel • Wire wound vessel & frame • Interlocking strip wound vessel	
Size	I.D ≥ 152 mm (6 inch)	I.D ≥ 152 mm (6 inch)	–	–
Applicable non-metal materials	FRP	–	–	Solid or lined on metals Thermoplastics (Acetal, ABS, CAB, CPVC, PB, PE, PP, PVC, PVDF, PTFE, PFEP, PPA, FRP, glass, etc.)
Out of scope (special notes)	• Piping system • Pressure containers integral with machinery • Internal nonpressure parts except for attachment weld to vessel • Fire process heaters • Skirt and saddles • Design pressure > 15 psig (152 kPag)	[AG-100(b)] Other than vessels to be installed at a fixed (stationary) location unless requirements of owner [AG-121] • All out of scope in Div. 1 • Volume ≤ 120 gal (450 ℓ)-water containing • Heat input ≤200,00 Btu/hr. (58.6 kW) • Water temperature ≤ 99 °C (210 °F) • ID ≤152 mm (6 inch)	• Volume < 75 in^3 (1.23 ℓ) and • Design cycle <1000 and • All design limits of KD-2 are satisfied, • The vessel is intended to be operated at all times with supplementary protective devices to provide personnel safety	[para. 300.1.3] other than Chapter IX • piping for internal gauge pressure [$0 \leq p \leq 105$ kPa (15.2 psi)] in nonflammable/ nontoxic and −29 °C (−20 °F) ≤ D.T ≤ 185 °C (366 °F) • ASME BPVC piping components • Tubes, tube headers, crossovers, and pressure containers integral with machinery • Equipment and their internal piping/tubing
Hydrotest Pressure-Basic Concept[5]	Min. 1.3 × MAWP	[5]	Min. 1.25 × design pressure per ratio of YS/TS Max: See div. 3, KY-312	1.5* × design pressure [*1.25 for high pressure piping in Chapter IX]]
Pneumatic Test Pressure -Basic Concept[5]	Min. 1.1 × MAWP	[5]	–	1.1 × design pressure
Allowable Stress for General Membrane[8] by Design Factor (basic concept)	TS/3.5	TS/3.0 for class 1[4] TS/ 2.4 for class 2[4]	YS/1.5	TS/3
Design method	By formula (+ WRC 107 & WRC 297 + Zick's paper)	Div. 1 + local stress/fatigue analysis (FEA)	Div. 1 + local stress analysis (FEA)	By formula (and local stress analysis (FEA))
Design theory	Elastic design (membrane stress)	Elastic design (membrane + bending stress) including fatigue and local stress analysis and/or creep-rupture stress	Plastic & Elastic Design (maximum shear stress) including fatigue and local stress analysis and/or creep-rupture stress	Elastic design (membrane stress)

Table 1.6 (2/3) Comparison of major applicable scopes of ASME Section VIII and B31.3 (with code paragraphs)

Data	ASME Sec. VIII, Div. 1[10] /Sec. II, Part D (materials only)	ASME Sec. VIII, Div. 2 /Sec. II, Part D (materials only)	ASME Sec. VIII, Div. 3 /Sec. II, Part D (materials only)	ASME B31.3
Impact test	Required per UG-20 and UCS-66 & 67	More restrict than Div. 1 & B31.3 (e.g., test specimens to be selected from transverse of final forging direction for Q-T forging listed in ASME sec. VIII, Div. 2, Table 3-A.2, while standard specimen are from the longitudinal direction for other CS and LAS)[9]	More restrict than Div. 1 & 2 and B31.3 (including CTOD, K_{IC} & J_{IC})	Required per para. 323 & 423
NDE – RT – UT	Full, spot, none (by owner)	Full All plates 102 mm (4 inch) thickness and over	Full (by owner)	100%, random, spot (by owner)
Stamp	U and UM	U2	U3	PP
Additional stamp marking	W, P, B, RES, L, UB, DF, RT, HT	HT	HT, PS, WL, M, F, W, UQT, WW, SW	–
Stamp for safety relief valve	UV	–	UV3	–
For design reports, to be certified by	A.I. if it is required stamp	Requirement of Div. 1 plus professional Engineer's seal in North America	A.I. if it is required stamp	–
Min. required thickness of shells and heads/piping for general service	1.6 mm (1/16 inch)[2] excluding any corrosion allowance (see Table 1.9 in this book for more detail)	No limitation	–	No limitation, but see Table 314.2.1 for the male threaded components
Mill Undertolerance of plate	The smaller value of 0.3 mm (0.01 inch) or 6% of the ordered thickness in UG-16	No limitation	–	12.5% for pipe
Structure of contents	• Introduction-U: Scope and general • Subsection A: All vessels • Subsection B: Fabrication – UW: welding – UF: forging – UB: brazing • Subsection C: Requirement per material classes – UCS: CS and LAS – UNF: nonferrous alloy – UHA: high alloy steels – UCI: cast Iron – UCL: clad, overlay, and lining – UCD: cast ductile Iron – UHT: ferritic steel TS enhanced by HT – ULW: multi-layered vessels – ULT: higher AS materials at low temperature • Appendix – Mandatory: Appendix 1 to 31 – Non-mandatory: Appendix A to EE	• Part AG general requirements • Part AM materials requirements • Part AD design requirements • Part AF fabrication requirements • Part AR pressure relief devices • Part AI inspection and radiography • Part AT testing • Part AS marking, stamping, reports, and records • Appendix – Mandatory appendices – Non-mandatory appendices	• Part KG general requirements • Part KM materials requirements • Part KD design requirements • Part KF fabrication requirements • Part KR pressure relief devices • Part KE examination requirements • Part KT test requirements • Part KS marking, stamping, reports, and records • Appendix – Mandatory appendices – Non-mandatory appendices	• Chapter I scope and definitions • Chapter II design – Part 1 conditions and criteria – Part 2 pressure design of piping components – Part 3 fluid service requirements for piping components – Part 4 fluid service requirements for piping joints – Part 5 flexibility and support – Part 6 systems • Chapter III materials • Chapter IV standards for piping components • Chapter V fabrication, assembly, and erection • Chapter VI inspection, examination, and testing • Chapter VII nonmetallic piping and piping lined with nonmetals examination, • Chapter VIII piping for category M fluid service • Chapter IX high pressure piping

Table 1.6 (3/3) Comparison of major applicable scopes of ASME Section VIII and B31.3

Data	ASME Sec. VIII, Div. 1[10] /Sec. II, Part D (materials only)	ASME Sec. VIII, Div. 2 /Sec. II, Part D (materials only)	ASME Sec. VIII, Div. 3 /Sec. II, Part D (materials only)	ASME B31.3
Recommended applicable condition	• Static service • common vessel	• Cyclic service (fatigue analysis) • Severe discontinuity shape with local stress analysis • Pressure × Shell ID>60,000 lb./inch • Shell diameter/ thickness < 406 mm (16 in.) or thickness > 76 mm (3 in.) • Multiwall vessels	• Cyclic service (fatigue analysis) • Failure analysis (K_1c/J_1c) • Centrally wrapped vessel • Wire wound vessel/frame • Interlocking strip wound vessel 2.	Processing piping
Code basic concept	Tailor & standard/bulk made	Tailor made	Tailor made	Standard/bulk & tailor made

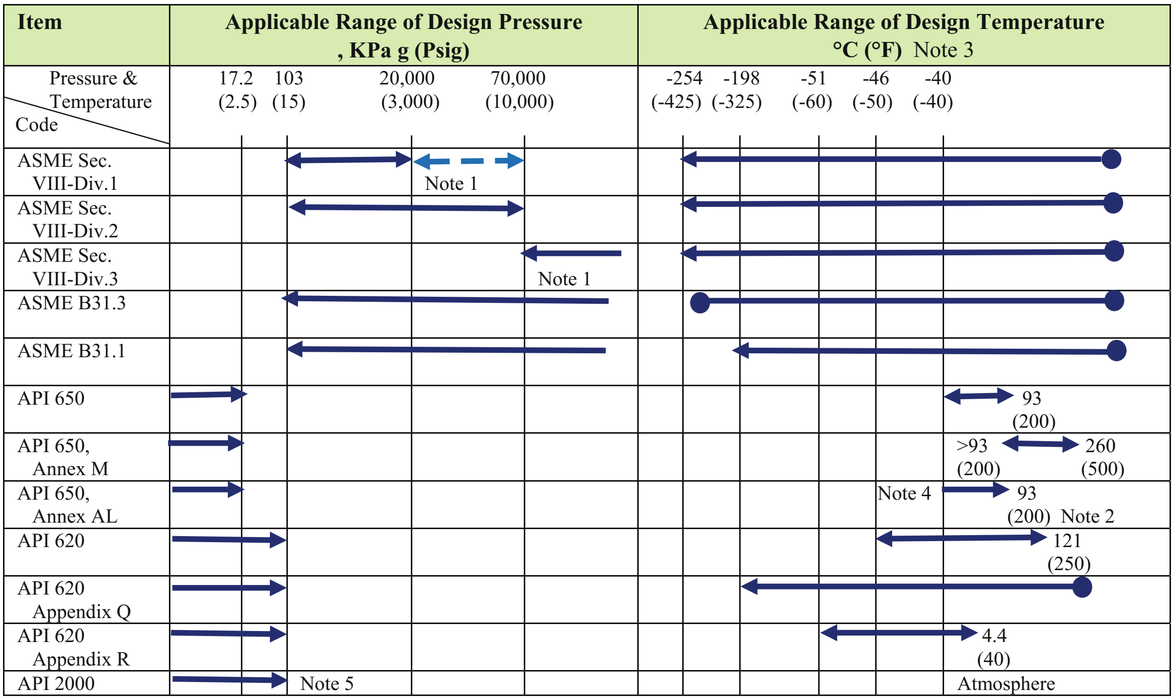
Notes:
[1]Even though the facilities are not in the application scope, it may be applied to the Codes if the end-user requests or by the manufacturer's standard
[2]Min. required thickness of shells and heads for unfired steam boilers/compressed air and steam service: 6 mm (1/4 in.)/2.4 mm (3/32 in.) excluding any corrosion allowance, respectively
[3]European Pressure Equipment Directive (PED) requires the application scope of 0.5 barg (7.5 psig) and over from May 29, 2002
[4]See Sect. 1.2.6.2
[5]See Sect. 5.5.2 in this book for more detailed information
[6]See ASME Sec. VIII, Div. 1, U-1(d) for >3000 psig. The rules of ASME Sec. VIII, Div. 1, have been formulated on the basis of design principles and construction practices applicable to vessels designed for pressures not exceeding 3000 psi (20 MPa). For pressures above 3000 psi (20 MPa), deviations from and additions to these rules usually are necessary to meet the requirements of design principles and construction practices for these higher pressures. Only in the event that after having applied these additional design principles and construction practices the vessel still complies with all of the requirements of ASME Sec. VIII, Div. 1, may it be stamped with the applicable Certification Mark with the Designator
[7]The rules of ASME Sec. VIII, Div. 3, constitute requirements for the design, construction, inspection, and overpressure protection of metallic pressure vessels with design pressures generally above 10 ksi (70 MPa). However, it is not the intent of ASME Sec. VIII, Div. 3, to establish either maximum pressure limits for ASME Sec. VIII, Div. 1 or 2, or minimum pressure limits for ASME Sec. VIII, Div. 3. Specific pressure limitations for vessels constructed to the rules of ASME Sec. VIII, Div. 3 may be imposed elsewhere in ASME Sec. VIII, Div. 3, for various types of fabrication. Whenever *Construction* appears in ASME Sec. VIII, Div. 3, it may be considered an all-inclusive term comprising materials, design, fabrication, examination, inspection, testing, certification, and pressure relief
[8]*General Membrane*: Average primary stress across solid (entire cross-) section. Excludes discontinuities and concentrations. Produced only by mechanical loads. An example of a general membrane stress is the average axial stress in a pipe (or cylindrical can) loaded in tension. See Sect. 1.2.3.3(a) for more details *Local Membrane*: Average stress across any solid (localized cross-) section. Considers discontinuities but not concentrations. Produced only by mechanical loads. An example of a local membrane stress is the average axial stress in a Category D junction, stiffener/support attached junction, cylindrical-conical junction, etc. loaded in tension. See Sect. 1.2.3.3(c) for more details
[9]Several end-users' specifications or companies' standards indicate to apply transverse direction of final working for impact test in heavy wall CS and LAS materials
[10]See ASME Sec. VIII, Div. 1, Mandatory Appendix 46, when using ASME Sec. VIII, Div. 2, to establish the thickness and other design details of a component for ASME Sec. VIII, Div. 1, pressure vessel

The internal attachments (e.g., tray support/packing support rings, vortex breaker, etc.) other than isolated chambers or differentially pressurized parts are neither pressure-retaining part nor pressure boundary in the mechanical strength calculation. So they are not covering the joint efficiency and %RT for the strength calculation (Design Section) in ASME Sec. VIII. However, once the internal/external attachments are welded on pressure boundary parts, they are considered as pressure-retaining parts per ASME Sec. IX as a part of ASME Sec. VIII (Fabrication Section).

1.1.5.4 Years of Acceptable Editions of Referenced Standards in ASME

The ASME BPVC equipment consist of many components which have their own standards. So each ASME code has the permitted substandards with applicable edition. Caution: All of substandards are not the latest version completely.

(a) Section VIII, Div. 1-2019 Edition (see Section VIII, Div. 1, Table U-3 for more details)
ASME Section VIII – Division 1 Example Problem Manual – ASME PTB-4 Latest edition
Cast Copper Alloy Pipe Flanges and Flanged Fittings, Class 150, 300, 600, 900, 1500, and 2500 – ASME B16.24 (2016)
Cast Copper Alloy Threaded Fittings, Classes 125 and 250 – ASME B16.15 Latest edition
Cast Iron Pipe Flanges and Flanged Fittings, Classes 25, 125, and 250 – ASME B16.1 (2015)
Conformity Assessment Requirements – ASME CA-1 Latest edition
Ductile Iron Pipe Flanges and Flanged Fittings, Class 150 and 300 – ASME B16.42 (2016)
Factory-Made Wrought Buttwelding Fittings – ASME B16.9 Latest edition



Notes
1. See Table 1.6, Note (6) &(7).
2. Maximum 65°C (150°F) for Alloy 5083, 5086, 5154, 5183, 5254, 5356, 5456, 5654. Ambient temperature of tanks shall have a maximum design temperature of 40°C (100°F).
3. ●—— ——● Per the maximum or minimum temperature shown the allowable stress value including the notes in Allowable Stress Tables.
4. The current code indicates -40°C (-40°F) for the minimum permissible design temperature. But it may be reduced to lower temperature in the future.
5. From full vacuum to 103.4 kPa gage (15 psig).

Figure 1.2 Applicable scopes of ASME Sec. VIII, B31.3, and API 650/620

Forged Fittings, Socket-Welding and Threaded – ASME B16.11 Latest edition
Guidelines for Pressure Boundary Bolted Flange Joint Assembly – ASME PCC-1 (2013)
Large Diameter Steel Flanges, NPS 26 through NPS 60 Metric/Inch Standard – ASME B16.47 (2017)
Marking and Labeling Systems – ANSI/UL-969 Latest edition
Metallic Gaskets for Pipe Flanges – Ring-Joint, Spiral-Wound, and Jacketed – ASME B16.20 Latest edition
Metallic Materials – Charpy Pendulum Impact Test Part 1: Test Method – ISO 148-1 (2009)
Metallic Materials – Charpy Pendulum Impact Test Part 2: Verification of Testing Machines – ISO 148-2 (2008)
Metallic Materials – Charpy Pendulum Impact Test Part 3: Preparation and Characterization of Charpy V-Notch Test Pieces for Indirect Verification of Pendulum Impact Machines – ISO 148-3 (2008)
Nuts for General Applications: Machine Screw Nuts, Hex, Square, Hex Flange, and Coupling Nuts (Inch Series) – ASME B18.2.2 Latest edition
Pipe Flanges and Flanged Fittings, NPS 1/2 through NPS 24 Metric/Inch Standard – ASME B16.5 (2013)
Pipe Threads, General Purpose (Inch) – /ASME B1.20.1 Latest edition
Pressure Relief Devices – ASME PTC 25 (2014)
Pressure Relieving and Depressurizing Systems, ANSI/API Std. 521, 5th Ed., January 2007
Qualifications for Authorized Inspection – ASME QAI-1 Latest edition
Repair of Pressure Equipment and Piping – ASME PCC-2 (2018)
Seat Tightness of Pressure Relief Valves – API Std. 527 (2014, 4th Ed.)
Standard Test Method for Flash Point by Tag Closed Tester – ASTM D56 Latest edition
Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester – ASTM D93 Latest edition
Standard Guide for Preparation of Metallographic Specimens – ASTM E3 (2011)
Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings – ASTM E125 (1963 R2008)
Standard Hardness Conversion Tables for Metal Relationship among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness – ASTM E140 Latest edition
Standard Reference Radiographs for Heavy-Walled [2 to 4 1/2-in. (51 to 114-mm)] Steel Castings – ASTM E186 (2015)

Table 1.7 Application scopes of ASME and API for non-metal base facilities (ASME RTP-1 and Section X)

Item	ASME RTP-1 (2011)	ASME Section X (2011)
Title	Reinforced thermoset plastic corrosion-resistant equipment (*Voluntary Standard*)	Fiber-reinforced plastic pressure vessels (code)
Applicable scope	*Temperature limits.* The operating temperature shall be limited to a value for which mechanical properties have been determined by the procedures in ASME RTP-1, para. 2A-300(b) and 2B-200(a), and the chemical resistance has been established by the material selection process identified in ASME RTP-1, Table 1-1, item 3. In general, maximum operating temperatures to 82 °C (180 °F) are commonly encountered, and a large body of mechanical property and chemical resistance data exists to facilitate design. Applications above 82 °C (180 °F) require that the designer recognizes and accounts for possible reduced mechanical properties at the elevated temperature and possibly decreasing mechanical properties with time as a consequence of thermal and chemical exposure. Such elevated temperature applications require special design attention, and consultation with the resin manufacturer is essential. For design purposes, properties at 23 °C (73 °F) are acceptable up to 82 °C (180 °F). Where laminates are fabricated for use at DT above 82 °C (180 °F), certification of strength and modulus per ASME STP-1, para. 2A-400(a) and (b), shall be supplied at or above the specified temperature. ; DP (external) ≤ 0.1 MPag (15pisg) ; DP (internal) ≤ 0.1 MPag (15psig) above any hydrostatic head **Dual Laminates (Appendix M-12)** • *Article A general requirements* • *Article B materials* – certified thermoplastic materials and thickness/FRP fibers/welding-extrusion, hot gas, offset, bead, acceptance defects, filler material-pigments-processing AIDS-conductive materials/acceptance inspection/measurement tools-thickness, bonding strength, high voltage & conductive spark Test/acceptance limits-including visual/dimension & shapes/welding/conductive material inspection report & log • *Article C design* – bonding resin selection/wall attachments/sheet mapping/ design stress limitations/heating & cooling design (to avoid damage) • *Article D fabrication* – machining, forming, welding & RTP overlay, visual weld defects, heat-affected zone pattern, flanges, nozzles, manways, repair procedure (Appendix M-7) • *Article E inspection and test* – high-voltage spark test & gas penetration test, final & visual inspection • *Article F shipping and handling* – Inspection • *Article G shop qualification* – Lining visual inspection acceptance criteria, Fabricable Capacity & Procedure, personnel, User's basic requirements specification (UBRS) reports • *Article H qualification of welders* – To be qualified per article G including welder qualification report/marking	; The minimum permissible temperature is to be −54 °C (−65 °F) (see ASME Sec. X, RG-112) **Class I design** — ASME does not require design calculations. Design qualification is by destructive testing of a prototype vessel. Qualification of a vessel design through the pressure testing of a prototype: ; DP ≤ 1MPag (150psig) for bag-molded, centrifugally cast, and contact-molded vessels ; DP ≤ 10MPag (1500psig) for filament-wound vessels ; DP ≤ 20MPag (3000psig) for filament-wound vessels with polar boss openings Even though a lower operating temperature is specified in the design specification, DT shall be taken as 65 °C (150 °F) for DT less than or equal to 65 °C (150 °F) or at the specified DT when the DT exceeds 65 °C (150 °F). When the DT exceeds 65 °C (150 °F), the specified DT shall not exceed 120 °C (250 °F) or 19 °C (35 °F) below the maximum use temperature (see ASME Sec. X, RM-121) of the resin, whichever is lower **Class II design** — mandatory design rules and acceptance testing by nondestructive methods. ; To comply with article RD-11 and article RT-6 in ASME Sec. X. The DP allowed under this procedure shall be as specified in RD-1120 in ASME Sec. X. ; The DT shall not be less than the interior laminate wall temperature expected under operating conditions for the part considered and shall not exceed 120 °C (250 °F) or 19 °C (35 °F) below the maximum use temperature (see ASME Sec. X, RM-121) of the resin, whichever is lower. It may be designed by rules or by stress analysis. Max.DP (psig) & ID (inch) must lie; 0.5 MPag (75 psig)*: ID 152 to 2438 mm (6 to 96 in.). 13.3 MPag (200 psig)*: ID 152 to 914 mm (6 to 36 in.), 7200/D psig: ID 914 to3658 mm 36 to 144 in.) * Designed by stress analysis acoustic emission test must be passed
Materials	– Resin matrix (resin, pigments, dyes, colorants, etc.) – per ASTM D648 & E84, RTP-1-Appendix M-2, and UBRS – Fiber reinforcement (a) Fiberglass surfacing veil (mat), organic fiber surfacing veil (mat), carbon fiber surfacing veil (mat), and fiberglass chopped strand (mat)-per RTP-1-Appendix M-1, Article A (b) Fiberglass spray-up roving and filament winding roving – -per RTP-1, Appendix M-1, Article B (c) Fiberglass woven roving fabric, fiberglass unidirectional fabric, and fiberglass nonwoven multifabric — per RTP-1, Appendix M-1, Article C (d) Fiberglass milled fiber per RTP-1, Appendix M-1, Article D (e) With the exception of surfacing veils, all fiberglass reinforcement shall be type E (f) Balsa wood core materials — per RTP-1, Appendix M-13	FRP (fiber-reinforced plastic) – ASTM D445/638/695/792/1045/1652/ 2343/ 2344/2393/2471/ 2583/2584/2992/3030/3039/ 3171/3410/3846/4097/4255/5448/ 5449/5450 – ASME B16.1/B16.5.B18.22.1

Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels – ASTM E208 (2006-R2012)
Standard Reference Radiographs for Heavy-Walled [4 1/2 to 12-in. (114 to 305-mm)] Steel Castings – ASTM E280 (2015)
Standard Reference Radiographs for Steel Castings up to 2 in. (51 mm) in Thickness – ASTM E446 (2015)
Unified Inch Screw Threads (UN and UNR Thread Form) – ASME B1.1 Latest edition
Welded and Seamless Wrought Steel Pipe – ASME B36.10M Latest edition

Metric Standards
Metric Fasteners for Use in Structural Applications – ASME B18.2.6M Latest edition
Metric Heavy Hex Screws – ASME B18.2.3.3M Latest edition
Metric Heavy Hex Bolts – ASME B18.2.3.6M Latest edition
Metric Hex Bolts – ASME B18.2.3.5M Latest edition
Metric Screw Thread – M Profile – ASME B1.13M Latest edition
Metric Screw Thread – MJ Profile – ASME B1.21M Latest edition
Standard Practices for Force Verification of Testing Machines ASTM E4 (2016)
Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods ASTM E177 (2014)
Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method – ASTM E691 (2016)
Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Ferritic-Austenitic Stainless Steel Weld Metal – ANSI/AWS A4.2M (2006)
Standard Test Method for Compressive Strength of Carbon and Graphite – ASTM C695 (2015)
Standard Terminology Relating to Manufactured Carbon and Graphite – ASTM C709 (2009)

(b) Section VIII, Div. 2, as 2019 Edition (see Section VIII, Div. 1, Table 1.1, for more details)
Conformity Assessment Requirements – ASME CA-1 Latest edition
Factory Made Wrought Steel Buttwelding Fittings – ASME B16.9 Latest Edition
Fitness-For-Service – API 579-1/ASME FFS-1 (2016)
Forged Steel Fittings, Socket-Welding, and Threaded – ASME B16.11 Latest Edition
Guidelines for Pressure Boundary Bolted Flange Joint Assembly – ASME PCC-1 (2013)
Large Diameter Steel Flanges, NPS 26 through NPS 60 Metric/Inch Standard – ASME B16.47 (2017)
Marking and Labeling Systems – ANSI/UL-969 Latest Edition
Materials and Fabrication of 2 1/4Cr–1Mo, 2 1/4Cr–1Mo–1/4V, 3Cr–1Mo, and 3Cr–1Mo–1/4V Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service – API RP 934-A (2008–2012 addendum)
Metallic Gaskets for Pipe Flanges – Ring Joint, Spiral-Wound and Jacketed – ASME B16.20 Latest Edition
Metallic materials – Charpy pendulum impact test – Part 1: Test method, ISO 148-1 (2009)
Metallic materials – Charpy pendulum impact test – Part 2: Verification of testing machines, ISO 148-2 (2008)
Metallic materials – Charpy pendulum impact test – Part 3: Preparation and characterization of Charpy V-notch test pieces for indirect verification of pendulum impact machines, ISO 148-3 (2008)
Metric Heavy Hex Screws – ASME B 18.2.3.3M Latest Edition
Metric Hex Bolts – ASME B 18.2.3.5M Latest Edition
Metric Heavy Hex Bolts – ASME B 18.2.3.6M Latest Edition
Metric Fasteners for Use in Structural Applications – ASME B18.2.6M Latest Edition
Metric Screw Threads – M Profile – ASME B 1.13M Latest Edition
Metric Screw Threads – MJ Profile – ASME B 1.21M Latest Edition
Nuts for General Applications: Machine Screw Nuts, Hex, Square, Hex Flange, and Coupling Nuts (Inch Series) – ASME/ANSI B18.2.2 Latest Edition
Pipe Threads, General Purpose, Inch – ASME B1.20.1 Latest Edition
Pipe Flanges and Flanged Fittings, NPS 1/2 through NPS 24 Metric/Inch Standard – ASME B16.5 (2013)
Pressure Relief Devices – ASME PTC 25 (2014)
Qualifications for Authorized Inspection – ASME QAI-1 Latest Edition
Repair of Pressure Equipment and Piping – ASME PCC-2 (2018)
Seat Tightness of Pressure Relief Valves – API Standard 527 (2014)
Standard Hardness Conversion Tables for Metals Relationship among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness – ASTM E140 Latest Edition
Standard Practice for Fabricating and Checking Al Alloy Ultrasonic Standard Reference Blocks – ASTM E127 (2015)
Standard Practice for Ultrasonic Examination of Steel Forgings – SA-388/SA-388M Latest edition
Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Austenitic-Ferrite Stainless Steel Weld Metal – AWS 4.2M (2006)
Standard Reference Photographs for Magnetic Particle Indications on Ferrous Casting – ASTM E125 (1963 R2008)
Standard Reference Radiographs for Heavy-Walled (2 to 4 1/2 in. (51 to 114 mm)) Steel Castings – ASTM E186 (2015)
Standard Reference Radiographs for Heavy-Walled (4 1/2 to 12 in. (114 to 305 mm)) Steel Castings – ASTM E280 (2015)
Standard Reference Radiographs for High Strength Copper-Base and Nickel-Copper Alloy Castings – ASTM E272 (2015)
Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials – ASTM E139 Latest edition

Standard Test Method of Conducting Drop Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steel – ASTM E208 (2006-R2012)
Standard Reference Radiographs for Steel Castings up to 2 in. (51 mm) in Thickness – ASTM E446 (2015)
Unified Inch Screw Threads (UN and UNR Thread Form) – ASME B1.1 Latest Edition

(c) ASME B31.3 (2016)
See ASME B31.3, Table 326.1, and Appendix E for component and reference standards, respectively.

1.1.6 Limitations and Requirements for Wall Thickness

The mass of a metal component impacts lots of properties of the metal, such as strength, hardenability, toughness, heat treatment (holding time), weldability, formability, castability, uniform metallic microstructures, impurity, corrosion resistance, etc. In most cases the quality, ability, and threshold of the thicker metal show poor properties compared to those of thinner metal. Therefore, industrial standards have many requirements in terms of the thickness of the component.

1.1.6.1 Minimum Thickness Requirements

The minimum wall thickness shall be based on the minimum required thickness including the required corrosion allowance from the strength calculation of the applicable codes and standards. In addition, codes, standards, and specifications require the minimum thicknesses for stability during fabrication, construction, and operation as below. The selected thickness shall meet all of them.

Tables 1.8, 1.9, 1.10, 1.11, 1.12, 1.13, 1.14, 1.15, and 1.16 show the permissible mill tolerances and the minimum thicknesses required in ASME and API.

Table 1.12 shows typical requirements of some company standards (for reference) for H-EX.

Table 1.8 Mill tolerance of base metal in ASME and API

Materials	Maximum mill tolerance [paragraph in each code and standard]		
	Sec. VIII, Div. 1	B31.3	API 5L
Plates	Not more than the smaller value of 0.25 mm (0.01 inch) or 6% of the ordered thickness [UG-16 *(c)(2)*]	–	–
Pipes	If pipe or tube is ordered by its nominal wall thickness, the manufacturing undertolerance On wall thickness shall be taken into account except for nozzle wall reinforcement area requirements in accordance with UG-37 and UG-40. [UG-16*(d)*]	12.5% mill tolerance [Table S301.3.1]	[Table J.4] Tolerances for wall thickness (t_W)(1) *Seamless* ; $t_W \leq 4$ mm (0.157 in.): +0.6 mm/ -0.5 mm (+0.024 in./ –0.020 in.) ; 4 mm (0.157 in.) < $t_W \leq 10$ mm (0.394 in.): + 0.150 t_W and –0.125 t_W ; 10 mm (0.394 in.) < t_W < 25 mm (0.984 in.): ± 0.125 t_W ; $t_W \geq 25$ mm (0.984 in.): + 3.7 mm (0.146 in.) or + 0.1 t_W, whichever is the greater(2), − 3.0 mm (0.120 in.) or – 0.1 t_W, whichever is the greater(2) *HFW Pipe*(3) ; $t_W \leq 6$ mm (0.236 in.): ± 0.4 mm (0.016 in.) ; 6 mm (0.236 in.) < $t_W \leq 15$ mm (0.591 in.): ± 0.7 (0.028 in.) ; $t_W \geq 15$ mm (0.591 in.): ± 1.0 mm (0.039 in.) *SAW Pipe*(3) ; $t_W \leq 6$ mm (0.236 in.): ± 0.5 mm (0.020 in.) ; 6 mm (0.236 in.) < $t_W \leq 10$ mm (0.394 in.): ± 0.7 (0.028 in.) ; 10 mm (0.394 in.) < $t_W \leq 20$ mm (0.787 in.): ± 1.0 (0.039 in.) ; t_W > 20 mm (0.591 in.): +1.5 mm (0.060 in.) and − 1.0 (0.039 in.)
Tubes	(4)		
Heater tubes	See API 530, 5.7- per ASTM specification (12.5%)		

Notes: HFW = helical fusion welded
(1)If the purchase order specifies a minus tolerance for wall thickness smaller than the applicable value given in this table, the plus tolerance for t_W shall be increased by an amount sufficient to maintain the applicable tolerance range. See API 5L for more restrictions
(2)For pipe with $D \geq 355.6$ mm (14.0 in.) and $t_W \geq 25.0$ mm (0.984 in.), the tolerance is ±12.5%
(3)The plus tolerance for wall thickness does not apply to the weld area
(4)Wall thickness requirements in ASTM materials:

- ASTM A450, Table 2 Permitted Variations in Wall Thickness for Seamless Cold-Drawn Low Carbon Steel H/EX and Condenser Tubes
- ASTM A1016, Table 2 Permitted Variations in Wall Thickness for Ferritic Alloy Steel, Austenitic Alloy Steel, and SS Tubes
- ASTM B751, Table 1 Permitted Variations in Wall Thickness for Ni and Ni Alloy Welded Tubes
- ASTM B829, Table 2 Permissible Variations in Wall Thickness of Seamless Cold-Worked Pipe and Tube for Ni and Ni Alloy Seamless Pipe and Tube
- ASTM B111, Tables 11 and 12 Wall Thickness Tolerance for Cu and Cu-Alloy Seamless Condenser Tubes and Ferrule Stock
- ASTM B395, Tables 11 and 12 Wall Thickness Tolerance for U-Bend Seamless Cu and Cu Alloy H/EX and Condenser Tubes
- ASTM B706, Table 5 Wall Thickness Tolerance for Seamless Cu Alloy (UNS No. C69100) Pipe and Tube
- ASTM B338, Table 5 Wall Thickness Tolerance for Seamless and Welded Ti and Ti Alloy Tubes for Condensers and H/EXs

Table 1.9 Minimum thickness requirements (excluded CA) of pressure components in ASME Codes (after strength calculation and fabrication)

Equipment or Materials	Minimum Thickness Exclusive of CA [Paragraph in Each Code]		
	Sec. VIII, Div. 1	Sec. VIII, Div. 2	B31.3
Pressure-retaining components – general regardless of material unless otherwise specified below	1.5 mm (1/16 in.) after fabrication [UG-16] 6 mm (1/4 in.) unfired steam boilers [UG-16]	1.6 mm (1/16 in.) after fabrication [4.1.2]	(1)
Tubes(1) of Plate-type H/EX	No limits [UG-16]	No limits [4.1.2]	–
Tubes of air cooler or cooling tower H/EX	No limits in tubes protected by fins or mechanical means and tube OD of 9.5–38 mm (3/8 to 1 ½ in.) [UG-16]	No limits for (i) tubes protected by fins or other mechanical means and (ii) tube OD of 10–38 mm (0.375 to 1.5 in.) But, minimum thickness of 0.5 mm (0.022 in.) for tubes. [4.1.2]	–
Inner pipe (NPS 6 and less) of double pipe H/EX	No limits [UG-16]	No limits [4.1.2]	–
CS and LAS-shell & heads	2.5 mm (3/32 in.) for shells and heads used for compressed air, steam, and water service in non-lethal service. Minimum thickness of 0.5 mm (0.022 in.) for tubes. [UG-16, UCS-23]	2.4 mm (0.094 in.) exclusive of any CA for CS/LAS vessel for compressed air service, steam service, and water service. [4.1.2]	–
After final heat treating for enhanced Q-T ferritic steels	6 mm (1/4 in.) for welded joints in WPQ [UHT-82 *(f) (5)*]	1.6 mm (1/16 in.) for formed steels [6.6.4], 6 mm (1/4 in.) for welded joints in WPQ [6.6.5.2(d)(5)]	–
Clad plates	Same as for CS and LAS based on total thickness for clad construction and the base plate thickness for applied-lining construction. [UCL-20]	–	–
Low temperature −5, 8, 9% Ni steels	5 mm (max. 50.8 in.) [3/16 in. (max. 2 in.)] for the base metal at welds [ULT-16(b)]	–	(1)
Layered cylinders	3.2 mm (1/8 in.) of each layer [ULW-16]	3.2 mm (1/8 in.) of each layer [4.13.4.4]	–
Nozzle/fitting neck	See [Table UG-45] per each nozzle size and [Table UW-16.1] for each fitting size	See [Table 4.5.2] per each nozzle size	(1)
Expansion joints & flexible shell	3 mm (1/8 in.) for CS/LAS [5–2]	3.2 mm (1/8 in.) for CS/LAS [4.20.2]	(1)
Flange with nut stops	–	12.7 mm (1/2 in.) for hub [4.16.10]	–
At opening area for attachment welds	See Table 1.17 in this book	–	–
Repaired section of casting	See [Table UCI-78.1] per each CI NPS plug, [Table UCD-78.1 & 78.2] per each cast ductile Iron NPS plug & curvature of cylinder/cone	–	–
External threaded components	–	–	Per size [Table 314.2.1]

General Notes: (not specified)
a. CA = corrosion allowance
b. tmin = minimum required thickness in UG-27 or 1-1
c. The minimum thickness of plate after forming and without allowances for corrosion shall not be less than the minimum thickness allowed for the type of materials being used. (See Code para. UG-16, UG-25, and UCS-25)
Note: (1)Minimum thickness should be decided by the strength calculation
Commentary Notes
(a)[General Practice] Tube wall due to the bending process may be thinned, and then the tube wall is not sufficient to meet the minimum wall thickness for the required tube gauge specified on the data sheet or strength calculation sheet. Therefore, if required to maintain minimum tube wall thickness, the inner two rows of U-tubes should have a wall thickness 1 gauge thicker than the remaining tubes
(b)TEMA (shell & tube type H/EX): See Table 1.10 in this book for the minimum tube wall thickness
(c)API 660 (shell & tube type H/EX): min. 1.5 mm (1/16 in.) for undiluted thickness for weld overlay. See Table 1.11 and Table 1.12 in this book for the minimum tube wall thickness (after bending for U-tubes)
(d)API 661 (air coolers): See Table 1.13 in this book for the minimum tube wall thickness, Table 1.14 in this book for the minimum header thickness, and Table 1.15 in this book for the minimum nozzle neck thickness
(e)API 530 (heater tubes): See Table 1.16 in this book for the minimum tube wall thickness
(f)ASME codes do not have the requirements for minimum thickness of nonpressure components

Table 1.10 Minimum required thicknesses of shell plates in TEMA

Materials	Class	Min, thickness (including the corrosion allowance), mm (inch)
Carbon steel	R	9.5 (3/8)
	C & B	7.9 (5/16)
Alloy	R, C, and B	3.2 (1/8)

Table 1.17 shows the minimum wall thickness for attachment welds at openings shall not be less than that shown for the nearest equivalent nominal pipe size. Table 1.18 shows the minimum thickness of external threaded components in piping system.

Minimum wall thickness for valve components: Most valve standards specify the minimum wall thickness for the components per nominal size, pressure class, and material (e.g., body, bonnet, etc. See API STD 600 series valve standards).

Table 1.11 Minimum required wall thickness of tubes in API 660, Table 1, modified (Shell & Tubes H/EX)

Tube material	Minimum required wall thickness, mm (inch) – Note 1, 2, & 3
CS, low Cr steels (Cr ≤ 9%), Al alloys	2.11 (0.083)
Copper and copper alloys	1.65 (0.065)
High alloy & steel [ASS, DSS, nonferrous alloys]	1.473 (0.058)
High alloy steel [FSS & MSS]	1.473 (0.058)
Titanium	1.067 (0.042)

Notes
1. Tubes shall be furnished on either a minimum wall basis or an average wall basis, provided the tube thickness is not less than that specified above
2. For low-fin tubing, this shall be the minimum thickness at the root diameter
3. See API 660, Table 6, for Maximum allowable tube wall thickness reduction for roller-expanded tube-to-tubesheet joints for shell and tube type H/EXs

Commentary Notes (General)
a. If required to maintain a minimum tube wall thickness, the inner two rows (smallest U-bend radius) of U-tubes should have a wall thickness one gauge thicker as a minimum than the remaining tubes. Normally, for larger tube diameter, more thinning is expected
b. The minimum bend diameter (inner diameter) of U-bends should be greater than or equal to 3 times the tube outside diameter
c. For sulfur condensers, tubes should have an outside diameter of 38 mm (1–1/2 inches) minimum, with a tube wall thickness not less than 3.4 mm (0.134 inch)
d. See Sect. 3.1.7.2 and Table 3.9 for more requirements including maximum allowable tube wall thickness reduction for roller-expanded tube-to-tubesheet joints

Table 1.12 Minimum required tube thicknesses of H-EX [(1)(2)] Only for Reference in Case of Severe Corrosion/Erosion Circuits

	Tube Outside Diameter		
Material	0.75 inch	1 inch	1.25 or 1.5 inch
CS and low Cr steels (Cr ≤ 9%)	2.1 mm (0.083 inch)	2.77 mm (0.109 inch)	2.77 mm (0.109 inch)
Copper and copper alloys	1.65 mm (0.065 inch)	2.1 mm (0.083 inch)	2.77 mm (0.109 inch)
ASS & DSS, Nickel-Based Alloys[(3)]	1.65 mm (0.065 inch)	1.65 mm (0.065 inch)	2.1 mm (0.083 inch)
FSS and MSS[(3)]	1.65 mm (0.065 inch)	2.1 mm (0.083 inch)	2.77 mm (0.109 inch)
Titanium	1.24 mm (0.049 inch)	1.24 mm (0.049 inch)	–

Notes
(1) 0.049 inch is the thinnest wall acceptable for any material
(2) If required to maintain a minimum tube wall thickness, the inner two rows of U-tubes shall have a wall thickness one gauge thicker than the remaining tubes
(3) Average wall thicknesses are shown

Table 1.13 Minimum required wall thickness of tubes in API 661, Table 5 (air cooler)

Tube material	Minimum required wall thickness, mm (inch)[(1)]
Carbon steel or ferritic low alloy steel (max.9%Cr)	2.11 (0.083)
High alloy steels [ASS, FSS, DSS]	1.65 (0.065)
Nonferrous material	1.65 (0.065)
Titanium	1.24 (0.049)

Note:[(1)]For embedded fin tubes, this thickness shall be measured from the bottom of the groove to the inner wall. Greater wall thickness may be required for severe services or certain tube configurations

Table 1.14 Minimum required thicknesses of header in API 661, Table 1 (Air Cooler)

	Minimum thickness, mm (inch)[(1)]	
Component	CS and LAS	High alloy steel or other metals
Tubesheet	19 (1/4)	16 (5/8)
Plug sheet	19 (1/4)	16 (5/8)
Top, bottom, and end plates	12 (1/2)	10 (3/8)
Removable cover plates	25 (1)	22 (7/8)
Pass partition plates and stay plates	12 (1/2)	6 (1/4)

Notes
[(1)]The thickness indicated for any carbon or low alloy steel component includes a corrosion allowance of up to 3 mm (1/8 inch). The thickness indicated for any component of high alloy steel or other material does not include a corrosion allowance. The thickness is based on an expanded tube-to-tubesheet joint with one groove

Commentary Notes
[(a)]The minimum thickness of solid metal plug gaskets should be 1.5 mm (0.060 in)
[(b)]The minimum thickness of expanded metal mesh: 2 mm (0.07 inch) for nominal size 40 mm (1.5 inch) and 3 mm (0.110 inch) for nominal size 50 mm (2 inch)
[(c)]Fan decks should be designed for a live load of 2500 N/m2 (50 lbf/ft^2) with a minimum thickness of 2.7 mm (12 gauge USS; 0.105 in)

Table 1.15 Minimum nozzle neck nominal thickness in API 661, Table 3[(1)] (air cooler)

Pipe size, DN (NPS)	Nozzle neck thickness, mm (inch)	Pipe size, DN (NPS)	Nozzle neck thickness, mm (inch)
20 (3/4)	5.56 (0.219)	100 (4)	13.49 (0.531)
25 (1)	6.35 (0.250)	150 (6)	10.97 (0.432)
40 (1 ½)	7.14 (0.281)	200 (8)	12.70 (0.500)
50 (2)	8.74 (0.344)	250 (10)	15.09 (0.594)
80 (3)	11.13 (0.438)	300 (12)	17.48 (0.688)

Note: [(1)]The data in this table are taken from ASME B36.10M, using Sch.160 for sizes up to DN 100 (NPS 4) and Sch.80 for the larger sizes

Table 1.16 Minimum allowable thickness of new tubes in API 530, Table 1 (fired heater)

Tube outside diameter		Minimum thickness			
		Ferritic steel tubes		Austenitic steel tubes	
mm	(inch)	mm	(inch)	mm	(inch)
60.3	(2.375)	3.4	(0.135)	2.4	(0.095)
73.0	(2.875)	4.5	(0.178)	2.7	(0.105)
88.9	(3.50)	4.8	(0.189)	2.7	(0.105)
101.6	(4.00)	5.0	(0.198)	2.7	(0.105)
114.3	(4.50)	5.3	(0.207)	2.7	(0.105)
141.3	(5.563)	5.7	(0.226)	3.0	(0.117)
168.3	(6.625)	6.2	(0.245)	3.0	(0.117)
219.1	(8.625)	7.2	(0.282)	3.3	(0.130)
273.1	(10.75)	8.1	(0.319)	3.7	(0.144)

Table 1.17 Minimum thickness requirements for attachment welds at openings (ASME Sec. VIII, Div. 1, Table UW-16.1)

NPS	mm	inch
1/8	2.7	0.11
1/4	2.7	0.11
3/8	2.7	0.11
1/2	3.6	0.14
3/4	4.2	0.16
1	5.5	0.22
1 1/4	7.5	0.30
1 1/2	7.5	0.30
2	7.9	0.31
2 1/2	9.5	0.37
3	9.5	0.38

Table 1.18 Minimum thickness of external threaded components (ASME B31.3, Table 314.2.1)

Fluid category	Notch-sensitive material	Size range[(1)] NPS [DN]	Min. wall[(2)]	Notes (see general note as well)
Normal for CS	Yes	≤1½ [≤40]	Sch.80	(1) For sizes >DN 50 (NPS 2), the joint shall be safeguarded (see Appendix G) for a fluid service that is flammable, toxic, or damaging to human tissue (2) Nominal wall thicknesses is listed for Sch. 40 and 80 in ASME B36.10M and for Sch. 40S in ASME B36.19M
		2 [50]	Sch.40	
		2 ½ to 6 [65–150]	Sch.40	
Normal for ASS	No	≤2 [≤50]	Sch.40S	
		2 ½ to 6 [65–150]	Sch.40S	
Category D	Either	≤300 [≤12]	Per B31.3, 304.1.1	

General Notes: Use the greater of B31.3, 304.1.1, or thickness shown in this Table

Table 1.19 Maximum thickness requirements in codes and standards

Item	Codes and standards
For manufacturing limits (thickness, size, and weight) of the base metal – see Tables 2.173 through 2.202 in this book	Each ASTM (or others) standard material
Several maximum thickness requirements (main body, parts, and attachments) for PWHT exemption	ASME Section VIII, Div. 1, Table UCS-56-xx ASME Section VIII, Div. 2, Tables 6.8 through 6.15
Maximum thickness requirements for CVN impact test exemption	ASME BPVC, B31.xx, etc.
For essential variables (max. permissible thickness from PQR test) for WPS/PQR ASME Section IX	ASME Section IX
For vessels made of 5%, 8%, and 9% nickel steels, the maximum thickness of the base metal at welds shall be 51 mm (2 in.)	ASME Section VIII, Div. 1, ULT-16(b), and Table ULT-23
For jacket closures design, the closure design is limited to a maximum thickness *trc* of 16 mm (5/8 in.)	ASME Section VIII, Div. 1, MA-9, 9-5(c)(1) ASME Section VIII, Div. 2, Table 4.11.1
Maximum thickness of 17.5Cr–17.5Ni–5.3Si (UNS S30601) at the welds shall not exceed 25 mm (1 in.)	ASME Section VIII, Div. 1, MA-34, Table 34-2
Maximum thickness of governing welded joints for NDE application per material group	ASME Section VIII, Div. 2, Tables 7.1 & 7.2
Maximum thickness of tube wall and fin wall (to avoid pressure drop due to smaller ID)	During thermal-rating for H/EXs and boiler tubes or to consider the bending, tube expansion, and commercial manufacturing capacity
Maximum coating thickness of each layer	Per manufacturer's standards
Others (max. misalignment/max. weld deposit height)	ASME BPVC, B31.xx, etc.

1.1.6.2 Maximum Thickness Requirements

Table 1.19 shows the requirements according to the thickness in ASME BPVC, B31 series, and ASTM.

1.1.7 ASME Code Stamps

Table 1.20 shows the summary of ASME BPVC Stamps. Table 1.21 shows the ASME Code Stamps' list and symbols.

Table 1.20 Summary of ASME BPVC stamps

Section No.	Title	Stamps
I	Power boiler	S, M, E, A, V, PP, PRT
III	Subsection NCA-8000	N, NV, NPT, NA, N3, NS
IV	Heating boilers	H, HLW, HV, PRT
VIII	Pressure vessel	Div. 1: U, UM, UV, UD Div. 2: U2 Div. 3: U3, UV3, UD3
X	Fiber-reinforced plastic pressure vessels	RP
XII	Continued Service of Transport Tanks	T, TV, TD, PRT
NBIC	National Board Inspection Code	R, VR, NR

Notes: The owner's certificates are not listed in this table
1. See Table 1.21 for the detailed information about stamping authorization, procedures, etc.
2. ASME has two marking symbols below

: ASME Collective Membership and ASME Standard Material Mark

: ASME Single Certification Mark

Table 1.21 (1/4) List of stamps by ASME codes

Class	Symbol (up to 2012)	Symbol (since 2011)	Products	Applicable code sections	Remark
A		A	Assembly of power boiler	Section I power boilers Section II: Part C materials for welding Section V NDE Section IX welding B 31.1 power piping CA-1 conformity assessment requirements	Notes 3, 4
M		M	Miniature boiler	Section I power boilers Section II: Parts A, B, C, D Section IX welding B 31.1 power piping CA-1 conformity assessment requirements	Note 4
PRT	–	PRT	Parts fabrication	Section I power boilers Section IV heating boilers Section XII transport tanks	
S		S	Power boiler [alternative stamp below] PP & S	Section I power boilers Section II: Parts A, B, C, D materials Section V NDE Section IX welding B 31.1 power piping CA-1 conformity assessment requirements	Notes 3, 4
PP ("qp")		PP	Power piping [alternative stamp below] PP & S		
E		E	Electric boiler (assembled without welding)	Section I power boilers Section II: Parts A, B, D materials B 31.1 power piping CA-1 conformity assessment requirements	Notes 3, 4

Source: ASME NB57 modified

Table 1.21 (2/4) List of stamps by ASME codes

Class	Symbol (up to 2012)	Symbol (since 2011)	Products	Applicable code sections	Remark
V	V	ASME V	Boiler safety valve**	Section 1 power boilers Section II: Parts A, B, C, D materials Section IX welding PTC 25 pressure relief devices CA-1 conformity assessment requirements	Note 3
HV	HV	ASME HV	Heating boiler safety valves	Section II: Parts A, B, C materials Section IV heating boilers Section IX welding PTC 25 pressure relief devices	Note 3
HLW	HLW	ASME HLW	Lined portable water heater	Section II: Parts A, B, C materials Section IV heating boilers Section IX welding	
H	H	ASME H	Cast iron sectional heating boiler*	Section IV heating boilers	
H			Field assembly of heating boiler	Section IV heating boilers Section IX welding qualifications	
H			Heating boilers, except cast Iron	Section II: Parts A, B, C Section IV heating boilers Section IX welding	
U	U	ASME U	Pressure vessel div. 1 (note 5)	Section II: Parts A, B, C, D materials Section V NDE Section VIII, Div. 1, pressure vessels Section IX welding	
UM	UM	ASME UM	Miniature pressure vessel div. 1*		Note 1
UV	UV	ASME UV	Pressure vessel safety valve manf. or assembly**	Section II: Parts A, B, C, D materials Section VIII, Div. 1 or Div. 2, pressure vessels & Alternative Section IX welding PTC 25 pressure relief devices	Note 3
UV3	UV3	ASME UV3	Pressure vessel safety valve manf. or assembly**	Section II: Parts A, B, C, D materials Section VIII, Div. 3, high pressure and special vessels Section IX welding PTC 25 pressure relief devices	Note 3
U2	U2	ASME U2	Pressure vessel div. 2 (note 5)	Section II: Parts A, B, C, D materials Section V NDE Section VIII, Div. 2, pressure vessels-alternative Section IX welding	
U3	U3	ASME U3	Pressure vessel Div. 3 (Note 5)	Section II: Parts A, B, C, D materials Section VIII, Div. 3, high pressure and special vessels Section V NDE Section IX welding	
UD	UD	ASME UD	Rupture disk**	Section II: Parts A, B, C, D materials Section VIII, Div. 1, pressure vessels Section IX welding PTC 25 pressure relief devices	Note 3
UD3	–	ASME UD3	High pressure vessel relief devices	Section III, Div. 3, high pressure and special vessels	
RP	RP	ASME RP	Fiberglass-reinforced plastic pressure vessel (note 7)	Section X FRP pressure vessels	
RTP	RTP	ASME RTP	Reinforced thermoset plastic corrosion-resistant equipment	RTP-1 FRP corrosion-resistant equipment	

Source: ASME NB57 modified

Table 1.21 (3/4) List of stamps by ASME codes

Class	Symbol (up to 2012)	Symbol (since 2011)	Products	Applicable code sections	Remark
N		N	Vessel, concrete vessel, pump, line valve, storage tank, piping systems, support structures constructed for nuclear power plants	Section II: Part D (N and NA only) Section III: Subsection NCA and appendices May also apply the following: Subsection NB – class 1 components Subsection NC – class 2 components Subsection ND – class 3 components Subsection NE – class MC components Subsection NF – cupports Subsection NG – core supports Subsection NH – class 1 components in elevated temperature service Division 2 concrete reactor vessels and containments Division 3 containment systems for storage and transport packaging of spent nuclear fuel and high-level radioactive materials and waste Section V NDE Section IX welding NQA-1 Quality Assurance for Nuclear Facilities	Note 8
NA		NA	All items constructed for nuclear power plants		
NPT		NPT	Tubular products welded with filler metal, piping subassembly, etc. Constructed for nuclear power plants; but must be relevant to construction of nuclear power plant		
NS	–	NS	Nuclear support		
N3		N3	Nuclear components	Section II, Part D Section III, Div. 3, high pressure and special vessels Section V NDE Section IX welding NQA-1 quality assurance for nuclear facilities May also apply the following: Subsection NB – class 1 components Subsection NC – class 2 components Subsection ND – class 3 components Subsection NE – class MC components Subsection NF – supports Subsection NG – core supports Subsection NH – class 1 components in elevated temperature service Subsection NCA, Div. 1 & 2, (general requirements) Division 2 concrete reactor vessels and containments	Note 8
NV		NV	Nuclear safety and pressure relief valves	Section II: Parts A, B, D Section III subsection NCA and appendices May also apply the following: Subsection NB – class 1 components Subsection NC – class 2 components Subsection ND – class 3 components Subsection NH – class 1 component in elevated temperature service Section V NDE Section IX welding PTC 25 pressure relief devices NQA-1 quality assurance for nuclear facilities	Note 8
R	–	R	Repair and/or alteration of boilers, pressure vessels, and other pressure-retaining items	NBIC, part 3, section 1	Note 2
VR	–	VR	*Repair pressure relief valves*	NBIC, part 3, section 1 and supplements 7 and 8	Note 2
NR	–	NR	Repair and replacement of nuclear components	NBIC, part 3, section 1	Note 2

Source: ASME NB57 modified

Table 1.21 (4/4) List of stamps by ASME codes

Class	Symbol (up to 2012)	Symbol (since 2011)	Products	Applicable code sections	Remark
T	T	ASME T	Transport tanks: "T" stamp	Section II, parts A, B, C, D materials Section V NDE Section IX welding Section XII transport tanks	Note 6
TV	TV	ASME TV	Transport tanks safety valves: "TV" stamp	Section II, parts A, B, C, D materials Section IX welding Section XII transport tanks PTC 25 pressure relief devices	Note 3
TD	TD	ASME TD	Transport tanks pressure relief Devices: "TD" stamp**	Section II, parts A, B, C, D materials Section IX welding Section XII transport tanks PTC 25 pressure relief devices	Note 3

Source: ASME NB57 modified

Notes:

1. Vessels stamped with the "UM" symbol are vessels that are exempt from inspection by authorized inspectors, the manufacturer being responsible for the design, fabrication, inspection, and testing of the vessel. However, these vessels are limited in size and design, fabrication, inspection, and testing, e.g., in size and design pressure up to 0.14 m^3 (5 ft^3) volume and 1.72 MPag (250 psig) or 0.04 m^3 (1.5 ft^3) and 4.14 MPag (600 psig). The Certificate of Authorization for using the "UM" stamp must be renewed annually. Some local jurisdictions do not recognize the "UM" stamp and require inspection by an authorized inspector
2. "R," "VR," and "NR" stamps are doing under the National Board of Boiler and Pressure Vessel Inspectors, while other stamps are doing under the American Society of Mechanical Engineers:
   "R": see http://www.nationalboard.org/Index.aspx?pageID=115&ID=160
   "VR": see http://www.nationalboard.org/Index.aspx?pageID=115&ID=161
   "NR": see http://www.nationalboard.org/Index.aspx?pageID=115&ID=162
3. Sections II, V, and IX are not required for assemblers; Section II, Part C, and Sections V and IX are not required for manufacturers if welding, brazing, and fusing are not within the scope of their work
4. The PRT Certification is for manufacturers of parts who do not perform or assume any design responsibility for the parts they manufacture
5. References for Pressure Vessels in ASME:
   - B36.10M Welded and Seamless Wrought Steel Pipe
   - B36.19M Stainless Steel Pipe [Div. 1 & 2 only]
   - B46.1 Surface Texture (Surface Roughness, Waviness, and Lay) [Div. 3 only]
   - NQA-1 Quality Assurance Program Requirements for Nuclear Facilities [Div. 1 & 2 only]
   - PCC-1 Guidelines for Pressure Boundary Bolted Flange Joint Assembly
   - PCC-2 Repair of Pressure Equipment and Piping [Div. 1 only]
   - PTC 25 Pressure Relief Devices
   - QAI-1 Qualifications for Authorized Inspection
   - API 579-1/ASME FFS-1 Fitness-For-Service [Div. 2 & 3 only]
6. References for Transport Tanks in ASME:
   - Section VIII, Div. 1 & 2, Pressure Vessels and Alternative
   - Section II, Parts A, B, C, and D Materials
   - Section V NDE
   - Section IX Welding
   - B36.10M Welded and Seamless Wrought Steel Pipe
   - B1.1 Unified Inch Screw Threads (UN and UNR Thread Form)
   - B1.20.1 Pipe Threads, General Purpose, Inch
   - B18.2.2 Square and Hex Nuts
   - PTC 25 Pressure Relief Devices
   - QAI-1 Qualifications for Authorized Inspection
7. References for FRP Vessels in ASME:
   - Section V NDE
   - B16.1 Gray Iron Pipe Flanges and Flanged Fittings: Classes 25, 125, and 250
   - B16.5 Pipe Flanges and Flanged Fittings: NPS 1/2 through NPS 24 Metric/Inch Standard
   - B18.22.1 Plain Washers
8. References for Nuclear Facility Components in ASME
   - Section II, Parts A, B, C, and D Materials
   - Section V NDE
   - Section IX Welding
   - Section XI Rules for In-service Inspection of Nuclear Power Plant Components
   - B36.10M Welded and Seamless Wrought Steel Pipe
   - B36.19M Stainless Steel Pipe
   - NQA-1 Quality Assurance Program Requirements for Nuclear Facilities
   - QAI-1 Qualifications for Authorized Inspection
   - RA-S Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications [For Nuclear In-service]

*Components not subject to Authorized Inspection, annual audit by the AIA

**Components not subject to Authorized Inspection, triennial audit by ASME

Table 1.22 Short checklist to complete a design calculation according to the ASME Sec. VIII, Div. 1

Items	Paragraph
1. Computer program verification	
2. Drawing + calculation	
2.1 ASME code edition and addenda	
2.2 Unit	Appendix GG
2.3 Design – operational data, elastic/plastic design	
2.4 MDMT	UG-20 (b)
2.5 Materials	UG-4 thru UG-15
2.6 Dimensions (ID, T, OD, etc.)	UG-16
2.7 Loads	UG-22 (a) to (j)
2.8 Restrictions	UW-2
2.9 MAWP & MAP	UG-23
2.10 Code cases	
3. Test pressure (minimum)	
3.2 Hydrostatic test	UG-99
3.3 Pneumatic test	UG-100
3.4 RT examination	UW-11 table UW-12
3.5 NDE (corner joint, joggle joint)	UG-93 (d), UW-13 (e)
4. Corrosion allowance	UG-25 or as otherwise agreed
5. Inspection openings	UG-46
6. Check whether design calculations have been made for all pressure-bearing parts	
7. Minimum wall thickness	UG-16 (b) (1)-(5)
7.1 Shell	UG-16 (b) (1)-(5)
7.2 Dished head	UG-16 (b) (1)-(5)
7.3 Nozzle	UG-16 (d) UG-40
7.4 Remaining wall thickness underneath tapped holes	UG-43 (d)
8. Minimum weld dimensions	
8.1 Flange attachment to the nozzle	Figure 2-4 App. 2
8.2 Nozzle attachment to the shell or head	UW-16

1.1.8 Check List for Materials in ASME Sec. VIII, Div. 1

Table 1.22 shows a short checklist to complete a design calculation according to the ASME Sec. VIII, Division 1. It is only to illustrate some of the types of construction in ASME Sec. VIII, Div. 1. This should be used only as a quick reference. The applicable edition, addenda, interpretations, and code cases of the Code should be considered and confirmed according to the governing year.

1.1.9 Categorization of Services in Codes

1.1.9.1 General Categorization

Tables 1.23, 1.24, and 1.25 show service categories classified in pressure vessels (ASME Sec. VIII Div. 1), process piping (ASME B31.3), and pipeline (ISO 13623), respectively. Each code has more specific requirements per the category.

1.1.9.2 Lethal Services

Most codes and standards specify more strict requirements (e.g., in PWHT, test and inspection, toughness, material quality) for safety control of pressure equipment and piping containing lethal service.

ASME Sec. VIII, Div. 1, UW-2, Endnotes 65 & 85 indicate that "lethal substances" meant poisonous gases or liquids of such a nature that a very small amount of the gas or of the vapor of the liquid mixed or unmixed with air is dangerous to life when inhaled. For purposes of this Division, this class includes substances of this nature which are stored under pressure or may generate a pressure if stored in a closed vessel. Eventually, ASME codes do not specially call out the services which are defined as lethal. This is the responsibility of vessel user-process engineer. Table 1.26 shows a group of chemicals which are listed as Class A poisons by the Code of Federal Regulations (CFR), Title 49. These materials in their pure state (100% concentration) would undoubtedly be considered lethal by the Code.

For these materials in solution with other non-lethal components, however, the process engineer must make a judgment as to the minimum concentration of the lethal component in solution above which the solution would be considered lethal with regard to Code rules

Table 1.23 Categorization of services in pressure vessels (ASME Sec. VIII Div. 1)

Service	Requirements (simplified)	Code paragraph
Air	All pressure vessels for use with compressed air (used in UG-46 is not intended to include air that has had moisture removed to provide an atmospheric dew point of −46 °C (50 °F) or less), except as permitted otherwise in UG-46, shall be provided with suitable inspection opening. The minimum thickness of shells and heads used in compressed air service, steam service, and water service, made from materials listed in Table UCS-23, shall be 2.5 mm (3/32 inch) exclusive of any corrosion allowance	UG-46 (a) UG-16(b)(4)
Flammable and/or noxious gases and liquids	Expanded connections shall not be used as a method of attachment to vessels used for the processing or storage of flammable and/or noxious gases and liquids unless the connections are seal-welded	UG-43 (f)
Lethal substances[(1)]	Butt-welded joints in vessels to contain lethal substances shall be fully radiographed. No ERW is allowed for pressure vessel. When fabricated of CS or LAS, the vessel shall be postweld heat-treated The joints of various categories shall conform to paragraph UW-2 Steel plates conforming to material specifications, SA-36, SA/CSA-G40.21 38W, SA-283, shall not be used for pressure parts in pressure vessels See Table 1.28 in this book for more details	UW-2(a) UCS-6(b)(1)
Steam	The minimum thickness of shells and heads used in compressed air service, steam service, and water service, made from materials listed in Table UCS-23, shall be 2.5 mm (3/32 inch) exclusive of any corrosion allowance	UG-16(b)(4)
Unfired steam boilers[(2)]	Steel plates conforming to material specifications, SA-36, SA/CSA-G40.21 38W, SA-283, shall not be used for pressure parts in unfired steam boilers	UCS-6(b)(1)
Water[(3)]	The minimum thickness of shells and heads used in compressed air service, steam service, and water service, made from materials listed in Table UCS-23, shall be 2.5 mm (3/32 inch) exclusive of any corrosion allowance	UG-16(b)(4)

Notes:
[(1)]The lethal substances mean poisonous gases or liquids of such a nature that a very small amount of the gas or of the vapor of the liquid mixed or unmixed with air is dangerous to life when inhaled, for example, bromoacetone, chloropicrin, cyanogen, ethyldichlorarsine, hydrogen cyanide, methyldichlorasine, mustard gas, nitric oxide, nitrogen dioxide, nitrogen peroxide, nitrogen tetroxide, and phosgene for Class A poisons in US Federal Regulation, Title 49. Wet H_2S (sour) service is not normally recognized as lethal service because it is only a metal failure issue. See 1.1.9 (2) for more details
[(2)]Unfired steam boilers may also be constructed in accordance with the rules of ASME Sec. I
[(3)]Vessels in water service excluded from the jurisdictions of the code are listed in ASME Sec. VIII, Div. 1, U-*1 (c)(2)(−f) & (−g)*

Table 1.24 Categorization of services in process piping (ASME B31.3)

Service	Requirements (simplified)	Remark
Severe cyclic conditions	Applying to specific piping components or joints for which the owner or the designer determines that construction to better resist fatigue loading is warranted. See B31.3, Appendix F, and para. F301.10.3 for guidance on designating piping as being under severe cyclic conditions	
Category D fluid service (utility)	A fluid service in which all of the following apply: *(1)* The fluid handled is nonflammable, nontoxic, and not damaging to human tissues as defined in B31.3, 300.2 *(2)* The design gauge pressure does not exceed 1035 kPa (150 psi) *(3)* The design temperature is not greater than 186 °C (366 °F) *(4)* The fluid temperature caused by anything other than atmospheric conditions is not less than −29 °C (−20 °F)	Lowest cost Usually not fire resistant Usually not blowout resistant
Category M fluid service (lethal)	A fluid service in which both of the following apply: *(1)* The fluid is so highly toxic that a single exposure to a very small quantity of the fluid, caused by leakage, can produce serious irreversible harm to persons by breathing or bodily contact, even when prompt restorative measures are taken *(2)* After consideration of piping design, experience, service conditions, and location, the owner determines that the requirements for normal fluid service do not sufficiently provide the leak tightness required to protect personnel from exposure	High cost Usually fire resistant Usually blowout resistant See Fig. 1.3 guide for classifying M fluid service
Elevated temperature fluid service	A fluid service in which the piping metal temperature has a design or sustained operating temperature equal to or greater than *Tcr* as defined in ASME B31.3, Table 302.3.5, General Note (b)	
High pressure fluid service	A fluid service for which the owner specifies the use of ASME B31.3, Chapter IX, for piping design and construction; see also ASME B31.3, K300	High cost Usually fire resistant Usually blowout resistant
High purity fluid service	A fluid service that requires alternative methods of fabrication, inspection, examination, and testing not covered elsewhere in the code, with the intent to produce a controlled level of cleanness. The term thus applies to piping systems defined for other purposes as high purity, ultra-high purity, hygienic, or aseptic	
Normal fluid service (process)	A fluid service pertaining to most piping covered by B31.3, i.e., not subject to the rules for category D, category M in B31.3, elevated temperature, high pressure, or high purity fluid service	Moderate cost May be fire resistant or not May be blowout resistant or not

Table 1.25 Categorization of fluids in petroleum and natural gas transportation pipeline (ISO 13623)

Category	Requirements (simplified)
Category A	Typically non-flammable water-based fluids
Category B	Flammable and/or toxic fluids which are liquids at ambient temperature and at atmospheric pressure conditions. Typical examples are oil and petroleum products. Methanol is an example of a flammable and toxic fluid
Category C	Non-flammable fluids which are non-toxic gases at ambient temperature and atmospheric pressure conditions. Typical examples are nitrogen, carbon dioxide, argon, and air
Category D	Non-toxic, single-phase natural gas
Category E	Flammable and/or toxic fluids which are gases at ambient temperature and atmospheric pressure conditions and are conveyed as gases and/or liquids. Typical examples are hydrogen, natural gas (not otherwise covered in category D), ethane, ethylene, liquefied petroleum gas (such as propane and butane), natural gas liquids, ammonia, and chlorine

Table 1.26 Class A poisons

Bromoacetone
Chloropicrin
Cyanogen
Ethyldichlorarsine
Hydrogen cyanide
Methyldichlorarsine
Mustard gas
Nitric oxide
Nitrogen dioxide
Nitrogen peroxide
Nitrogen tetroxide
Phosgene

Meanwhile, there are many of Occupational Safety and Health Administration (OSHA)'s toxic HHC (highly hazardous chemicals) and Environment Protection Safety (EPA)'s toxic environment health and safety (EHS) that would fall into this "Lethal Service" category. But there is a much better rationale to use to establish those substances which could be considered "lethal," that is, the Immediately Dangerous to Life and Health (IDLH) values used by the National Institute for Occupational Safety and Health (NIOSH) which has been established by OSHA

The OSHA definition is part of a legal standard, which is the minimum legal requirement. Table 1.27 shows the IDLH value samples listed in OSHA as a recommendation for lethal service. However, users or employers are encouraged to apply proper judgment to avoid taking unnecessary risks under their responsibility, even if the only immediate hazard is "reversible," such as temporary pain, disorientation, nausea, or non-toxic contamination.

The H_2S gas can be in lethal service in accordance with Table 1.27, but wet H_2S dissolved completely in water will not be a lethal service.

Once "lethal service" is designated in the datasheets of facilities, ASME codes address several requirements as shown in Table 1.28.

Table 1.27 (1/4) IDLH value samples (as a lowest) listed in NIOSH (OSHA) (heavy metals not included)

Substance	IDLH value	Substance	IDLH value
Acetaldehyde	2000 ppm	Chlorinated diphenyl oxide	5 mg/m^3
Acetylene tetrabromide	8 ppm	Chlorine	10 ppm
Acetic acid	50 ppm	Chlorine dioxide	5 ppm
Acetic anhydride	200 ppm	Chlorine trifluoride	20 ppm
Acetone	2500 ppm [LEL]	Chloroacetaldehyde	45 ppm
Acetonitrile	500 ppm	α-Chloroacetophenone	15 mg/m^3
Acrolein	2 ppm	Chlorobenzene	1000 ppm
Acrylonitrile	85 ppm	o-Chlorobenzylidene malononitrile	2 mg/m^3 [UC]
Aldrin	25 mg/m^3	Chlorobromomethane	2000 ppm
Allyl alcohol	20 ppm	Chlorodiphenyl (42% chlorine)	5 mg/m^3
Allyl chloride	250 ppm	Chlorodiphenyl (54% chlorine)	5 mg/m^3 [UC]
Allyl glycidyl ether	50 ppm	Chloroform	500 ppm
2-Aminopyridine	5 ppm [UC]	1-Chloro-1-nitropropane	100 ppm
Ammonia	300 ppm	Chloropicrin	2 ppm
Ammonium sulfamate	1500 mg/m^3	β-Chloroprene	300 ppm
n-Amyl acetate	1000 ppm	Chromic acid and chromates	15 mg Cr(VI)/m^3
sec-Amyl acetate	1000 ppm	Coal tar pitch volatiles	80 mg/m^3
Aniline	100 ppm [UC]	Crag (r) herbicide	500 mg/m^3
o-Anisidine	50 mg/m^3 [UC]	Cresol (o, m, p isomers)	250 ppm
p-Anisidine	50 mg/m^3 [UC]	Crotonaldehyde	50 ppm
ANTU	100 mg/m^3 [UC]	Cumene	900 ppm [LEL]
Arsine	3 ppm	Cyanides (as CN)	25 mg/m^3 (as CN)
Azinphosmethyl	10 mg/m^3	Cyclohexane	1300 ppm [LEL]
Benzene	500 ppm	Cyclohexanol	400 ppm
Benzoyl peroxide	1500 mg/m^3	Cyclohexanone	700 ppm
Benzyl chloride	10 ppm [UC]	Cyclohexene	2000 ppm

Table 1.27 (2/4) IDLH value samples (as a lowest) listed in NIOSH (OSHA) (heavy metals not included)

Substance	IDLH value	Substance	IDLH value
Boron oxide	2000 mg/m^3	Cyclopentadiene	750 ppm
Boron trifluoride	25 ppm	2,4-D	100 mg/m^3
Bromine	3 ppm	DDT	500 mg/m^3
Bromoform	850 ppm	Decaborane	15 mg/m^3
1,3-Butadiene	2000 ppm [LEL]	Demeton	10 mg/m^3
2-Butanone	3000 ppm [UC]	Diacetone alcohol	1800 ppm [LEL]
2-Butoxyethanol	700 ppm [UC]	Diazomethane	2 ppm
n-Butyl acetate	1700 ppm [LEL]	Diborane	15 ppm
sec-Butyl acetate	1700 ppm [LEL]	Dibutyl phosphate	30 ppm
tert-Butyl acetate	1500 ppm [LEL]	Dibutyl phthalate	4000 mg/m^3
n-Butyl alcohol	1400 ppm [LEL]	o-Dichlorobenzene	200 ppm
sec-Butyl alcohol	2000 ppm	p-Dichlorobenzene	150 ppm
tert-Butyl alcohol	1600 ppm	Dichlorodifluoromethane	15,000 ppm
n-Butylamine	300 ppm	1,3-Dichloro-5,5-dimethylhydantoin	5 mg/m^3
tert-Butyl chromate	15 mg Cr(VI)/m^3	1,1-Dichloroethane	3000 ppm
n-Butyl glycidyl ether	250 ppm	1,2-Dichloroethylene	1000 ppm
n-Butyl mercaptan	500 ppm	Dichloroethyl ether	100 ppm
p-tert-Butyltoluene	100 ppm	Dichloromonofluoromethane	5000 ppm
Calcium arsenate (as As)	5 mg as/m^3	1,1-Dichloro-1-nitroethane	25 ppm
Calcium oxide	25 mg/m^3	Dichlorotetrafluoroethane	15,000 ppm
Camphor (synthetic)	200 mg/m^3 [UC]	Dichlorvos	100 mg/m^3
Carbaryl	100 mg/m^3	Dieldrin	50 mg/m^3
Carbon black	1750 mg/m^3	Diethylamine	200 ppm
Carbon dioxide	40,000 ppm (4% in a volume of air)	2-Diethylaminoethanol	100 ppm
Carbon disulfide	500 ppm	Difluorodibromomethane	2000 ppm
Carbon monoxide	1200 ppm	Diglycidyl ether	10 ppm
Carbon tetrachloride	200 ppm	Diisobutyl ketone	500 ppm
Chlordane	100 mg/m^3	Diisopropylamine	200 ppm
Chlorinated camphene	200 mg/m^3 [UC]	Dimethyl acetamide	300 ppm
Dimethylamine	500 ppm	Hydrogen chloride	50 ppm
N,N-Dimethylaniline	100 ppm	Hydrogen fluoride (as F)	30 ppm
Dimethyl-1,2-dibromo-2,2-dichloroethyl phosphate	200 mg/m^3	Hydrogen peroxide	75 ppm
Dimethylformamide	500 ppm	Hydrogen selenide (as Se)	1 ppm
1,1-Dimethylhydrazine	15 ppm	Hydrogen sulfide	100 ppm
Dimethyl phthalate	2000 mg/m^3	Hydroquinone	50 mg/m^3
Dimethyl sulfate	7 ppm	Isoamyl acetate	1000 ppm
Dinitrobenzene (o, m, p isomers)	50 mg/m^3	Isoamyl alcohol (primary & secondary)	500 ppm
Dinitro-o-cresol	5 mg/m^3 [UC]	Isobutyl acetate	1300 ppm [LEL]
Dinitrotoluene	50 mg/m^3	Isobutyl alcohol	1600 ppm
Di-sec-octyl phthalate	5000 mg/m^3	Isophorone	200 ppm
Dioxane	500 ppm	Isopropyl acetate	1800 ppm
Diphenyl	100 mg/m^3	Isopropyl alcohol	2000 ppm [LEL]
Dipropylene glycol methyl ether	600 ppm	Isopropylamine	750 ppm
Endrin	2 mg/m^3	Isopropyl ether	1400 ppm [LEL]
Epichlorohydrin	75 ppm	Isopropyl glycidyl ether	400 ppm
EPN	5 mg/m^3	Ketene	5 ppm
Ethanolamine	30 ppm	Lindane	50 mg/m^3
2-Ethoxyethanol	500 ppm	Lithium hydride	0.5 mg/m^3
2-Ethoxyethyl acetate	500 ppm	Magnesium oxide fume	750 mg/m^3
Ethyl acetate	2000 ppm [LEL]	Malathion	250 mg/m^3
Ethyl acrylate	300 ppm	Maleic anhydride	10 mg/m^3
Ethyl alcohol	3300 ppm [LEL]	Mesityl oxide	1400 ppm [LEL]
Ethylamine	600 ppm	Methyl acrylate	250 ppm
Ethyl benzene	800 ppm [LEL]	Methylamine	100 ppm
Ethyl bromide	2000 ppm	Methoxychlor	5000 mg/m^3

Table 1.27 (3/4) IDLH value samples (as a lowest) listed in NIOSH (OSHA) (heavy metals not included)

Substance	IDLH value	Substance	IDLH value
Ethyl butyl ketone	1000 ppm	Methyl acetate	3100 ppm [LEL]
Ethyl chloride	3800 ppm [LEL]	Methyl acetylene	1700 ppm [LEL]
Ethylene chlorohydrin	7 ppm	Methyl acetylene-propadiene mixture	3400 ppm [LEL]
Ethylenediamine	1000 ppm	Methyl acrylate	250 ppm
Ethylene dibromide	100 ppm	Methylal	2200 ppm [LEL]
Ethylene dichloride	50 ppm	Methyl alcohol	6000 ppm
Ethyl ether	1900 ppm [LEL]	Methylamine	100 ppm [UC]
Ethyl formate	1500 ppm	Methyl (amyl) ketone	800 ppm
Ethylene glycol dinitrate	75 mg/m^3	Methyl bromide	250 ppm
Ethyleneimine	100 ppm	Methyl cellosolve (r)	200 ppm
Ethyl mercaptan	500 ppm	Methyl cellosolve (r) acetate	200 ppm
N-Ethylmorpholine	100 ppm	Methyl chloride	2000 ppm
Ethylene oxide	800 ppm [UC]	Methyl chloroform	700 ppm
Ethyl silicate	700 ppm	Methylcyclohexanol	500 ppm
Ferbam	800 mg/m^3	o-Methylcyclohexanone	600 ppm
Ferrovanadium dust	500 mg/m^3	Methylene bisphenyl isocyanate	75 mg/m^3
Fluorides (as F)	250 mg F/m^3	Methylene chloride	2300 ppm
Fluorine	25 ppm	Methyl formate	4500 ppm
Fluorotrichloromethane	2000 ppm	5-Methyl-3-heptanone	100 ppm
Formaldehyde	20 ppm	Methyl hydrazine	20 ppm
Formic acid	30 ppm	Methyl iodide	100 ppm
Furfural	100 ppm	Methyl isobutyl carbinol	400 ppm
Furfuryl alcohol	75 ppm	Methyl isocyanate	3 ppm
Glycidol	150 ppm	Methyl mercaptan	150 ppm
Heptachlor	35 mg/m^3	Methyl methacrylate	1000 ppm
n-Heptane	750 ppm	Methyl styrene	700 ppm
Hexachloroethane	300 ppm	Mica	1500 mg/m^3
Hexachloronaphthalene	2 mg/m^3 [UC]	Monomethyl aniline	100 ppm
n-Hexane	1100 ppm [LEL]	Morpholine	1400 ppm [LEL]
2-Hexanone	1600 ppm	Naphtha (coal tar)	1000 ppm [LEL]
Hexone	500 ppm	Naphthalene	250 ppm
sec-Hexyl acetate	500 ppm	Nickel carbonyl (as Ni)	2 ppm
Hydrazine	50 ppm	Nicotine	5 mg/m^3
Hydrogen bromide	30 ppm	Nitric acid	25 ppm
Nitric oxide	100 ppm	Quinone	100 mg/m^3
p-Nitroaniline	300 mg/m^3 [UC]	Ronnel	300 mg/m^3
Nitrobenzene	200 ppm	Rotenone	2500 mg/m^3
p-Nitrochlorobenzene	100 mg/m^3	Selenium hexafluoride	2 ppm
Nitroethane	1000 ppm [UC]	Soapstone	3000 mg/m^3
Nitrogen dioxide	20 ppm	Sodium fluoroacetate	2.5 mg/m^3
Nitrogen trifluoride	1000 ppm	Sodium hydroxide	10 mg/m^3
Nitroglycerine	75 mg/m^3	Stibine	5 ppm
Nitromethane	750 ppm	Stoddard solvent	20,000 mg/m^3
1-Nitropropane	1000 ppm	Strychnine	3 mg/m^3 [UC]
2-Nitropropane	100 ppm	Styrene	700 ppm
Nitrotoluene (o, m, p isomers)	200 ppm	Sulfur dioxide	100 ppm
Octachloronaphthalene	Unknown [UC]	Sulfur monochloride	5 ppm
Octane	1000 ppm [LEL]	Sulfur pentafluoride	1 ppm
Oil mist (mineral)	2500 mg/m^3	Sulfuric acid	15 mg/m^3
Osmium tetroxide (as Os)	1 mg Os/m^3 [UC]	Sulfuryl fluoride	200 ppm
Oxalic acid	500 mg/m^3 [UC]	Talc	1000 mg/m^3
Oxygen difluoride	0.5 ppm	TEDP	10 mg/m^3
Ozone	5 ppm	Tellurium hexafluoride	1 ppm
Paraquat	1 mg/m^3	TEPP	5 mg/m^3
Parathion	10 mg/m^3	Terphenyl (o, m, p isomers)	500 mg/m^3

Table 1.27 (4/4) IDLH value samples (as a lowest) listed in NIOSH (OSHA) (heavy metals not included)

Substance	IDLH value	Substance	IDLH value
Pentaborane	1 ppm	1,1,1,2-Tetrachloro-2,2-difluoroethane	2000 ppm
Perchloromethyl mercaptan	10 ppm	1,1,2,2-Tetrachloro-1,2-difluoroethane	2000 ppm
Pentachlorophenol	2.5 mg/m^3	1,1,2,2-Tetrachloroethane	100 ppm
n-Pentane	1500 ppm [LEL]	Tetrachloroethylene	150 ppm
2-Pentanone	1500 ppm	Tetrachloronaphthalene	Unknown [UC]
Perchloromethyl mercaptan	10 ppm [UC]	Tetraethyl lead (as Pb)	40 mg Pb/m^3 [UC]
Perchloryl fluoride	100 ppm	Tetrahydrofuran	2000 ppm [LEL]
Phenol	250 ppm	Tetramethyl lead (as Pb)	40 mg Pb/m^3 [UC]
p-Phenylenediamine	25 mg/m^3	Tetramethyl succinonitrile	5 ppm
Phenyl ether (vapor)	100 ppm	Tetranitromethane	4 ppm
Phenyl ether-biphenyl mixture (vapor)	10 ppm	Tetryl	750 mg/m^3
Phenyl glycidyl ether	100 ppm	Thiram	100 mg/m^3
Phenylhydrazine	15 ppm	Titanium dioxide	5000 mg/m^3
Phosdrin	4 ppm	Toluene	500 ppm
Phosgene	2 ppm	Toluene-2,4-diisocyanate	2.5 ppm
Phosphine	50 ppm	o-Toluidine	50 ppm
Phosphoric acid	1000 mg/m^3	Tributyl phosphate	30 ppm
Phosphorus (yellow)	5 mg/m^3	1,1,2-Trichloroethane	100 ppm
Phosphorus pentachloride	70 mg/m^3	Trichloroethylene	1000 ppm [UC]
Phosphorus pentasulfide	250 mg/m^3	1,2,3-Trichloropropane	100 ppm
Phosphorus trichloride	25 ppm	1,1,2-Trichloro-1,2,2-trifluoroethane	2000 ppm
Phthalic anhydride	60 mg/m^3	Triethylamine	200 ppm
Picric acid	75 mg/m^3	Trifluorobromomethane	40,000 ppm
Pindone	100 mg/m^3	2,4,6-Trinitrotoluene	500 mg/m^3
Portland cement	5000 mg/m^3	Triorthocresyl phosphate	40 mg/m^3 [UC]
Propane	2100 ppm [LEL]	Triphenyl phosphate	1000 mg/m^3
n-Propyl acetate	1700 ppm	Turpentine	800 ppm
n-Propyl alcohol	800 ppm	Uranium (soluble compounds, as U)	10 mg U/m^3
Propylene dichloride	400 ppm	Vinyl toluene	400 ppm
Propylene imine	100 ppm	Warfarin	100 mg/m^3
Propylene oxide	400 ppm	Xylene (o, m, p isomers)	900 ppm
n-Propyl nitrate	500 ppm	Xylidine	50 ppm
Pyrethrum	5000 mg/m^3 [UC]	Zinc chloride fume	50 mg/m^3
Pyridine	1000 ppm	Zinc oxide	500 mg/m^3

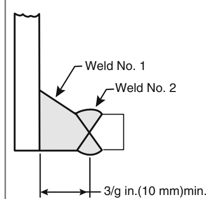
Legend
LEL lower explosive (flammable) limit in air, % by volume (at room temperature unless otherwise noted), *UC* uncertainty

Table 1.28 (1/3) Section for lethal service requirements in ASME Sec. VIII, Div. 1, and PTB-4

Paragraph	Requirements for lethal service (brief extracts)	Remark
U-2(a)(2)	Definition of lethal services. See UW-2(a).	
UG-16(b)(5)(−a)	The tube walls for air cooler and cooling tower H/EX to be ≥1.5 mm (1/16 in.).	
UG-24(a)(6)(−a)	Casting and cast iron (UCI-2) and ductile cast iron (UCD-2) vessels are prohibited.	
UG-24(a)(6)(−b)	The quality factor for nonferrous castings for lethal service shall not exceed 90%.	
UG-24(a)(6)(−c)	The quality factor for lethal service shall not exceed 100%.	
UG-25(e)	Telltale holes shall not be used in vessels that are to contain lethal substances [see UW-2(a)], except as permitted by ULW-76 for vent holes in layered construction.	See Sect. 3.3.3 in this book.
UG-99(g)(4)	The visual inspection of joints and connections for leaks at the test pressure divided by 1.3 cannot be waived.	
UG-99(k)(3), UG-100(k)(3), Appendix 27-4	The internal & external surfaces of vessel shall not be painted and shall not be internally lined by mechanical or welded attachments prior to the hydrotest or pneumatic test for the vessel containing lethal service.	
UG-100(d)(4)	Pneumatic test visual leak inspection cannot be waived. See code cases 2046-2, 2055-2, and 2407 regarding pneumatic instead of hydrostatic testing.	
UG-100(e)(3)	Do not paint or line prior to the pneumatic test.	
UG-100(d)(3)	Do not paint (internal & external) prior to the pneumatic test for the vessel containing lethal service.	

All paragraphs, appendix, figures, and eq. designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

Table 1.28 (2/3) Section of lethal service requirements in ASME Sec. VIII, Div. 1, and PTB-4 (cont'd)

Paragraph	Requirements (brief extracts)	Remark
UG-116(c)	"L" stamping must be added to the nameplate.	
UG-120(d)(1)	"Lethal service" is added to the data report.	
UW-2(a)	Definition of lethal services. See Sect. 1.1.9.2 in this book. All butt-welded joints shall be full RT per UW-51 except below. ERW pipe or tube is not permitted to be used as a shell or nozzles. PWHT is required for CS and LAS vessels. When a vessel is to contain fluids of such a nature that a very small amount mixed or unmixed with air is dangerous to life when inhaled, it shall be the responsibility of the user and/or his designated agent to determine if it is lethal.	The decision for service category is a responsibility of the user and/or his designated agent.
UW-2(a)(1)(a)	Except for welded tubes and pipes internal to H/EX shells, the weld category A joints shall be type 1[(1)].	
UW-2(a)(1)(b)	*The weld Category B & C* joints shall be type no. (1) or type no. (2)[(1)].	
UW-2(a)(1)(c)	*The weld category C joints for lap joint stub ends* shall be as follows: 1. The finished stub end shall be attached to its adjacent shell with a type no. (1) or type no. (2) joint[(1)]. The finished stub end can be made from forging or can be machined from plate material. [UW-13(h).] 2. The lap joint stub end shall be fabricated as follows: (a) The weld is made in two steps as shown in Figure UW-13.5. (b) Before making weld no. 2, weld no. 1 is examined by full RT, regardless of size. The weld and fusion between the weld buildup and neck are examined by UT per appendix 12. (c) Weld no. 2 is examined by full RT. 3. The finished stub end may either conform to ASME B16.9 dimensional requirements or be made to a non-standard size, provided all requirements of ASME Sec. VIII, Div. 1, are met.	 **Figure UW13.5 lab joint stub ends for lethal service** See code interpretation BC-79-680/VIII-80-111.
UW-2(a)(1)(d)	*All joints of weld category D* shall be full penetration welds.	
UW-2(a)(2)	RT of the welded seam in H/EX tubes and pipes, to a material specification permitted by ASME Sec. VIII, Div. 1, which are butt welded without the addition of filler metal may be waived, provided the tube or pipe is totally enclosed within a shell of a vessel which meets the requirements of UW-2(a).	Most end-users indicate "not allow to use no-filler metal welding."
UW-2(a)(3)	If the H/EX is exposed to lethal service only at one side, the lethal service requirements may not be applicable to the other side under the following conditions: 1. The tubes shall be seamless; or 2. Tubes are butt welded without addition of filler metal and receive in lieu of full RT all of the following nondestructive testing and examination: *(a)* Hydrotest per the applicable specification *(b)* Pneumatic test under water per the applicable material specification or, if not specified, in accordance with ASME SA-688 (seamless and welded ASS feedwater heater tubes) *(c)* UT or nondestructive electric examination of sufficient sensitivity to detect surface calibration notches in any direction in accordance with ASME SA-557 (ERW CS Feedwater heater tubes), S1 (UT-round tubing), or S3 (Eddy-current test) No improvement in longitudinal joint efficiency is permitted because of the additional nondestructive tests.	
UW-2(a)(4)	All elements of a combination vessel in contact with a lethal substance shall be constructed to the rules for lethal service.	
UW-11(a)(1)	All butt welds in shell and head to be full RT.	
UB-3	Brazed vessels shall not be used.	Brazed vessels
UCS-6(b)(1)	Do not use SA-36, SA/CSA-G40.21 38W, or SA-283-A/B/C/D.	
UCS-79(d)(1)	Stress-relieving requirements for >5% extreme fiber elongation after cold formed for CS (P.1-Gr. 1& 2).	
UCI-2 and UCD-2	Cast iron shall not be used.	Cast (ductile) Iron

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

Table 1.28 (3/3) Section of lethal service requirements in ASME Sec. VIII, Div. 1, and PTB-4 (cont'd)

Paragraph	Requirements (brief extracts)	Remark
UIG-2(c)	Metal parts used in conjunction with impregnated graphite pressure vessels, including those for lethal service, shall be constructed per UIG.	Impregnated graphite pressure vessels
UIG-23(b)	The maximum allowable tensile stress value to be used in design shall be 80% of the determined value at the design temperature, divided by a design factor of 6.0 (7.0 for lethal service; see UIG-60).	
UIG-60	Shall meet the following additional requirements in lethal service: *(a)* The design factor shall be 7.0 for lethal service. *(b)* In addition to the testing requirements in Table UIG-84-1, all graphite components, excluding tubes, shall be tested per UIG-84 requirements at room temperature to determine mechanical properties. *(c)* All interior corners of pressure components shall have a 13 mm (1/2 in.) minimum radius. *(d)* Exposed graphite shall be shielded with a metal shroud. This shroud shall be constructed per UIG but is exempt from NDE and pressure testing requirements. *(e)* Hydrotest pressure shall not be less than 1.75MAWP. It is strongly recommended that owners/users monitor the permeability of graphite equipment.	
UIG-99	Completed pressure vessels shall be subjected to a hydrostatic test per the requirements of UG-99, except that the test pressure shall not be less than 1.5 × design pressure (1.75 × for lethal service vessels).	
ULW-1 & ULW-26 (b)(4)	The lethal restrictions of layered vessels apply to the inner shell and heads only.	
UHX-19.1(b)	H/EX markings. "L-T" for tube side = lethal service on tube side.	H/EX
Appendix 2-5(d), 2-6	For vessels in lethal service, the maximum bolt spacing shall not exceed the value calculated per Bsmax = $2a + 6\ t/(m + 0.5)$ (eq. (3)) and Bsc = $[Bs/(2a + t)]^{1/2}$ (eq. (7)).	Flange design-bolt space
Appendix 2-14(a)	The flange rigidity rules should not be used as an alternative in lethal service.	Flange rigidity
Appendix 7-1	100% quality factor.	Steel castings
Appendix 7-5	The certification for castings for lethal service shall indicate the nature, location, and extent of any repairs.	
Appendix 9-8	Where only the inner vessel is subjected to lethal service, the requirements of UW-2 shall apply only to welds in the inner vessel and those welds attaching the jacket to the inner vessel.	Jacketed vessels
Appendix 17-2(a)	Dimpled or embossed assemblies shall not be used.	Dimpled or embossed assemblies
Appendix 35-3(c)	The rules of UG-90(c)(1) inspection and tests shall be applied.	Mass production of pressure vessels
Appendix 35-7(d)	Single-chamber pressure vessels, constructed by a manufacturer under the provisions of UG-90(c)(2), shall not be constructed and stamped for lethal service.	
Appendix W, Table W-3	To apply the U-forms: Instructions for the preparation of manufacturer's data reports	U-forms
Endnotes 65 & 85	Definition of lethal service	

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified
Notes: All RT shall be performed per UW-51
(1)See Table 1.54 in this book

Table 1.29 shows several code cases for lethal services in ASME BPVC.
Table 1.30 shows the old interpretations and PTB (problem manuals) for lethal service in ASME BPVC.

1.1.9.3 Environmentally Assisted Cracking (EAC) Services

The term of EAC is used only for the integrity of the material, not for health and safety of human being. The facilities in EAC can be readily and/or catastrophically brittle-failed without recognition or symptom before their designed life time. Therefore, the prevention of any EAC shall be considered at the beginning stage of the facilities' design, while general/uniform corrosion of the selected material can be controlled by corrosion allowance for the design life time of the components.

– Wet H_2S (sour)/HF/Amine/Caustic/Carbonate/Ethanol/Anhydrous Ammonia/Nitrate/Sulfate/Hydrogen (per end-user's experience): Hardness Control and/or SR and/or PWHT are required for CS and LAS. See Sect. 4.12.3.15 for PWHT requirements of CS in EAC environments.
– Polythionic Acid-/Severe Chloride-Assisted SCC: Solution Heat Treatment and Thermally Stabilized Heat Treatment are required as per the Materials after fabrication of 300 series SS.
– Fatigue/Cyclic/Low Temperature (brittle fracture)/Creep-Rupture Services as well as metallurgical embrittlement conditions are normally considered as a separated cracking environment.

1.1.9.4 Unfired Steam

Vessels in which steam is generated by the use of heat resulting from operation of a processing system containing a number of pressure vessels such as used in the manufacture of chemical and petroleum products. See ASME Sec. VIII, Div. 1, U-1(g)(2)(b), for more details.

Table 1.29 Code cases for lethal service in ASME BPVC

Code case No.	Requirements	Remark
1750–27	ASTM A126 for bodies, bonnets, yokes, housings, and holders of pressure relief devices sec. I; Sec. VIII, Div. 1; and Sec. X-2016	Shall not be used
2249	N02200 & N02201 – Use of vacuum furnace brazing for lethal service, Sec. VIII, Div. 1-1997	Per DP, DT, vessel volume, ID, etc.
2318	Slip-on flanges for nuclear material fluidized bed reactors, Sec. VIII, Div. I-1999	Per thickness, material, flange type, MAWP, etc.
2321-1	Exemption from PWHT for tube-to-tubesheet seal welds between P-No. 4 or 5A and P-No. 8 or 4X, Sec. VIII, Div. 1-2002	Not acceptable
2324-1	Use of automated ultrasound leak detection system in lieu of visual inspections required by UG-100(d) Sec. VIII, Div. 1-2012	Not acceptable
2334	Single-fillet lap joint Tubesheet to Shell connection of Shell and tube H/EX, Sec. VIII, Div. 1-2000	Not acceptable
2346-1 & 2537	Alternative rules for ellipsoidal or Torispherical heads having integral backing strip attached to Shell, Sec. VIII, Div. 1-2003 & 2005	Not acceptable
2377	Full RT of SA-612 (P. No.10C-Gr.1) steel plate ($t > 5/8''$), Sec. VIII, Div. 1–2003	No exemption
2421	Single-fillet joints in H/EX tube welds (category B joint), Sec. VIII, Div. 1-2003	Not acceptable
2437-1	Diffusion bonded, flat plate, microchannel H/EXs, microchannel, Sec. VIII, Div. 1-2005	This code case is not used
2527	Pneumatic testing of pressure vessels, U-1(j), UM Vessels-2007 in lieu of UG-29(f)(2) and UG-100	Not acceptable
2621-1	Diffusion bonding for microchannel H/EXs, Sec. VIII, Div. 1-2009	Not applicable
2751	Hemispherical head attached to cylindrical Shell having integral backing ring that is part of the Shell, Sec. VIII, Div. 1-2012	Not acceptable
2766	Determination of MAWP for plate H/EXs without performing proof testing or design calculation for the gasketed plate pack, Sec. VIII, Div. 1 & 2 -2013	Shall not be used
2867	Use of sintered silicon carbide (S-SiC) for pressure boundary parts for frame-and-plate-type pressure vessels, Sec. VIII, Div. 1-2016	This code case is not used

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

Table 1.30 (1/5) Interpretations and PTB (problem manuals) for lethal service in ASME BPVC

Interpretation or record No.	Requirements for lethal service (all para. below are from the code)	Year issued
VIII-1-83-77R (BC-82-679)	ERW (electric resistance welded) pipe may only be used if the long seam is radiographed Q. Can ERW pipe be used for the shell of a pressure vessel designed for lethal service under UW-2(a) in Sec. VIII, Div. 1, whether or not radiographic examination is performed on the ERW welded seam? A. No. see UW-2(a). The provisions of UW-2(a)(2) and (3) do not apply.	1992
VIII-82-65 (record BC-82-126)	Volumetric examination of category D joints is not always required Q. In Sec. VIII, - Div. 1, construction, is volumetric examination required for category D welds in lethal service? A. No, unless nozzle designs of the types shown in Fig. UW-16.1 and sketches (f-1) through (f-4) are incorporated into the design (see UW-11).	1982
VIII-80-82 (record BC-80-422)	Ferrous metal in Sec. VIII, Div. 2, Table AD-155.1, Note (5) Q. A Sec. VIII, Div. 2, vessel made of ferrous material other than austenitic is to be in lethal service and, therefore, must be postweld heat-treated. Is it permissible to pressure test this vessel at the same temperature as the impact test temperature which is colder than that determined by Note (5) of Table AD-155.1? A. No.	1980
VIII-79-18 (record BC-79-16)	Double chambers in Sec. VIII, Div. 1, UW-2 Q. If a Sec. VIII, Div. 1, pressure vessel contains two independent pressure chambers of which one chamber is for a special service, such as lethal service, must the independent chamber which is not in the special service also comply with the special requirements such as those of UW-2(a)? A. As covered in UG-19(a), the independent chamber which is not in a special service, such as lethal service, need not comply with the special requirements such as those of UW-2(a). However, if there are common parts between the two chambers, they must satisfy the special requirements such as those of UW-2(a). Also see UG-116(d), (k), and (l) concerning marking and UG-120 (b) and (d) concerning data reports.	1979
VIII-79-34 (record BC-79-247)	Double chambers in Sec. VIII, Div. 1, UW-2 and Fig. UW-13.1, Sketch (f) Q. A two-chambered vessel is constructed with an intermediate head attachment per Fig. UW-13.1 sketch (f) as the pressure barrier between the chambers. Can the chamber exerting pressure on the convex side of this head be used in lethal service per UW-2 when at the same time the other chamber is not? A. No. The intermediate head attachment does not satisfy the requirements of UW-2(a)(2) which specifies that such a category B joint should be of type no. (1) or (2) of Table UW-12.	1979

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

Table 1.30 (2/5) Interpretations and PTB (problem manuals) for lethal service in ASME BPVC (cont'd)

Interpretation or (record) No.	Requirements for lethal service (all para. below are from the code)	Year issued
VIII-77-76 (record BC-77-398)	Q. What are the specific substances considered lethal under the service restrictions of UW-2 of Sec. VIII, Div. 1? A. Sec. VIII, Div. 1, provides a definition of lethal substance in the footnotes of UW-2. A list of lethal substances is not provided since the responsibility of determining whether a substance is lethal as defined by Sec. VIII, Div. 1, rests with the user and/or his designated agent. If such a substance is determined as lethal, the vessel manufacturer shall be advised.	1977
VIII-2-13-01 (record 11-1370)	Fluid service category Q. Does ASME Sec. VIII, Div. 2, include a fluid service category that has been defined as "lethal"? A. No; see 2.2.2 in Sec. VIII, Div. 2.	2012
VIII-1-98-91 (record BC-99-478)	Jacketed glass-lined vessel in appendix 27, UW-2(a), and UCS-56 Q. All P-No. 1 materials are used to construct a type 2 jacketed glass-lined vessel under Appendix 27 of Section VIII, Division 1. The internal chamber will contain a lethal substance and has successfully passed examination in accordance with UW-11(a) and UW-51. The internal chamber will be subjected to multiple temperature cycles in accordance with 27-4(a)(3) for completion of the glassing operation. Can these multiple elevated temperature cycles be substituted for heat treatment and documentation requirements of UW-2(a) and UCS-56? A. Yes.	2000
VIII-1-83-365 & VIII-2-83-46 (record BC-85-194)	Packed joints for lethal service applications Q1. Do the rules of Section VIII, Division 1 or Division 2, prohibit the use of packed joints in vessels constructed to lethal service requirements [e.g., UW-2(a)]? A1. No; however, consideration of the appropriateness of such connections in a particular installation is the responsibility of the user or his designated agent [e.g., U-2(a)]. Note: This interpretation also appears as VIII-2-83-46.	1985
VIII-1-01-42 (record BC-01-225)	Appendix 13, Fig. 13-2 and Fig. UW-13.3 Q. Can Fig. UW-13.3 sketches (a) and (b) be used for the construction of noncircular vessels requiring the use of type no. (1) or (2) butt welds for the category C joints [e.g., to satisfy lethal service requirements of UW-2(a)(1)(b)]? A. Yes; see U-2(g).	2001
VIII-1-04-48 (record BC-04-1205)	Cone >30° and corner joints not permitted Background: Consider a vessel, constructed according to the rules of sec. VIII, div. 1, containing a cone with a half-apex angle exceeding 30 deg. the cone is attached to a cylindrical shell at its large end and to a nozzle at its small end. Both ends are full-penetration welds, and neither contains knuckle transitions. Q. Is it permitted to use these joints in a vessel that has been designated for lethal service as per UW-2(a)? A. No.	2005
VIII-1-92-112 (record BC-92-352)	Full RT of category C and D butt welds is required except for UW-11(a)(4) Q. Are category C and D butt welds required to be fully radiographed when the vessel is to be stamped for lethal service? A. Yes, except for those category C butt welds exempted under UW-11(a)(4).	1992
VIII-1-92-194 (record BC-93-684)	Full penetration angle joints are not permitted in UW-2(a)(1)(b) Q. A H/EX consisting of rectangular header boxes is designed in accordance with Appendix 13 of Sec. VIII, Div. 1. Each header has full penetration angle joints located at the four corners. The end plates are attached by a single-sided full penetration angle joint. Do these types of joints meet the requirements of UW-2(a)(1)(b) for lethal service when interpretable radiographs can be produced for the full length of the welds? A. No.	1994
VIII-1-92-211 (record BC-94-180)	Figure UW-13.2 attachments are not permissible Q. Can any of the attachment details shown in Fig. UW-13.2 of Sec. VIII, Div. 1, be used for lethal service? A. No; see UW-2(a)(1)(b).	1994
VIII-1-98-113 (record BC-00-100)	Permissible reinforced pad (repad) and flange pad arrangements in UW-2(a)(1)(d) Q. Can reinforced pads attached with fillet welds as shown in Fig. UW-16.1 sketches (a-2) and (h) of Section VIII, Division 1, be used on vessels designed for lethal service per UW-2(a)(1)(d)? A. Yes.	2000
VIII-1-98-23 (record BC-97-522)	Figure UW-16.1 (a) and (c) are permissible nozzle attachments; others are not discussed Q. Can the attachment details shown in Fig. UW-16.1 sketch (a) or (c) be used on a vessel intended for use in lethal service? A. Yes.	1998
VIII-77-62 (record BC-77-350)	Butt weld in nozzle in Sec. VIII, Div. 1, UW-11(a)(4) and UW-2(a) Q. Do the provisions of UW-11(a)(4) override the requirements of UW-2(a) for the exemption of certain butt welds in nozzles where a vessel is in lethal service? A. It is the intent of Sec. VIII, Div. 1, category B and C butt welds in nozzles and communicating chambers that exceed neither 10 in. nominal pipe size nor 1–1/8 wall thickness be excluded from the provisions of radiography, even though the vessel is in lethal service. This overrides the provisions of UW-2(a).	1977

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Table 1.30 (3/5) Interpretations and PTB (problem manuals) for lethal service in ASME BPVC (cont'd)

Interpretation or (record) No.	Requirements for lethal service (all para. below are from the code)	Year issued
VIII-80-02 (record BC-79-639)	Do not use corner joints from Fig. UW-13.2 – redesign to create butt joints that can be radiographed Q. Is the joint configuration illustrated in Sec. VIII Div. 1, Fig. UW-13.2, sketches (b) and (c) of Sec. VIII, Div. 1, acceptable when used to join side plates in a box header designed for lethal service? A. No. The last sentence of the first paragraph of UW-2(a) lists the types of joints which may be used with various categories of welded joints. The three categories of joints which are used to join the sides of a box header in lethal service and the type of joint are: Category A (longitudinal welded joint) must be type 1 (butt); category B (circumferential welded joint) must be type 1 or type 2 (butt); and category C, the same as category B. Since the joint must be a butt joint, the types shown in Fig. UW-13.2, sketches (b) and (c), are not permitted for lethal service.	1980
VIII-1-86-148 (record BC-87-162)	Sec. VIII, Div. 1, UG-116(f), RT 1 Q. A pressure vessel is being built in accordance with the requirements of Sec. VIII, Div. 1, and has the following characteristics: (1) The vessel will not contain lethal substances. Does this vessel satisfy the requirements of UW-11(a), and should it have RT 1 placed under the code symbol? A. Yes.	1987
VIII-81-78 (record BC-81-263)	Requirements for tube-to-tubesheet (TTT) joints in lethal services in Sec. VIII-1, UW-2(a)(1)(b) Q. Can a category C weld joint utilize the tubesheet-to-shell or tubesheet-to-channel details of Fig. UW-13.2 sketch (h), (i), (j), (k), or (l) without radiography or dye penetrant examination? A. If there are no special service restrictions such as lethal, which requires the category C joints to be butt joints, or any other special limits, the category C joint may be made without RT or PT.	1981
VIII-1-83-10 (record BC-82-164)	Requirements for tube-to-tubesheet (TTT) joints in lethal services in Sec. VIII-1, UW-2, UW-3, and Appendix A Background – The questions apply to welded TTT joints where one or both sides of a heat exchanger are in lethal service as defined in UW-2(a) and are as follows: Q1. Do such joints fall under any of the joint categories of UW-3? A1. No. Q2. Is radiographic examination required? A2. No. Q3. Other than visual, is any nondestructive examination required? A3. Not unless the requirements of UHA-34 or UHT-57 are applicable. Q4. For welding processes permitted by UW-27, are there any special requirements concerning the use or absence of filler metal? A4. No. Q5. Are welded or seal-welded joints required? A5. No. Q6. Must the provisions of nonmandatory Appendix A concerning TTT joints be satisfied? A6. No, but they are acceptable where applicable. The details of the joint are the responsibility of the vessel manufacturer, after consideration of the service information furnished to him by the user. See UW-2(a).	1982
VIII-1-04-73 (record BC-05-032)	PWHT of Table UCS-56 Q. A pressure vessel is constructed of P-No. 3, Gr. 1 & 2 materials with a nominal thickness not exceeding 16 mm (5/8 in.). A satisfactory welding procedure qualification in accordance with UCS-56(a) has been made in equal or greater thickness than the production weld. The vessel is not in lethal service, nor is PWHT a service requirement. All other requirements of UCS-56(a) have been met. Is PWHT required per Table UCS-56 of Sec. VIII, Div. 1, for this vessel? A. No.	2005
VIII-78-21 (record BC-77-805)	PWHT in Sec. VIII, Div. 1, UW-2 and UCS-56 Q. For H/EX parts of P-No. 1 material, is PWHT required if the vessel is operating in non-lethal service? A. Such H/EX parts would be required to be postweld heat-treated under the conditions given in Table UCS-56 below that specified in Note (2)(a) and Note (3) in Table UCS-56.	1978
(record 15-634 & 14-1910)	PWHT requirement for clad vessels for lethal service Q. For a P No 1 material, does Table UCS-56-1, General Note (b)(3)(e), provide an exemption to postweld heat treatment of the weld overlay cladding applied to a carbon steel vessel that is designated to be in lethal service? A. Yes.	2015
VIII-1-98-108 (record BC-00-080)	PWHT in UCL-51 and Table UCS-56 Q. A pressure vessel is constructed of P-No. 1 and P-No. 8 materials and is intended for lethal service. The vessel is PWHT. After PWHT, but before performing the hydrotest, the interior of the vessel has a stainless steel lining applied using plug welds. Does Note (2)(c)(5) of Table UCS-56 in Sec. VIII, Div. 1, permit the liner to be applied after the vessel has been PWHT without the need to perform any additional heat treatment? A. Yes, provided that the preheat requirements are met.	2000
VIII-1-86-45 (record BC-85-602)	Heat treatment of test specimens in Section VIII-1, UCS-85(b) Q. Can the test specimen requirements of UCS-85(b) be waived for flued openings in a shell made by the following condition? (1) The vessel is not used to contain a lethal substance. A. No.	1986
(Record 15-1154)	Full RT does not include the reinforcing rings per UG-29 Q. Is it the intent of paragraph UW-2(a) in Section VIII, Division 1, that butt welds in stiffening rings which are designed per UG-29 and are attached to lethal service vessels shall be fully radiographed? A. No.	2015

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

Table 1.30 (4/5) Interpretations and PTB (problem manuals) for lethal service in ASME BPVC (cont'd)

Interpretation or (record) No.	Requirements for lethal service (all para. below are from the code)	Year issued
(Record 15-1215)	RT requirements Q. Does paragraph UW-2(a) prohibit the use of ultrasonic examination in lieu of radiography when the qualifying conditions of paragraph UW-51(a)(4) are met? A. No.	2015
VIII-1-95-137 (record BC-96-334)	Full RT and PWHT in UW-2(a), UCL-34, and UCL-35 Q. Are the requirements in UW-2(a) of Section VIII, Division 1, for performing full radiography and postweld heat treatment on vessels which are to contain lethal substances applicable regardless of the calculated pressure and thickness for the vessel? A. Yes.	1997
VIII-77-30	RT in Sec. VIII, Div. 1, UW-11, UW-12 Q. Do the service restrictions of UW-2(a) for lethal substances and UW-2(c) for unfired steam boilers with design pressures exceeding 50 psi permit the use of partial radiography under UW-11(a)(5)(b)? A. For lethal substances, all butt welds in vessels are required to be examined radiographically for their full length as prescribed in UW-11(a)(1) except as provided in UW-11 (a)(4) which permits no RT for category B and C butt welds in nozzles and communicating chambers that exceed neither 10 in. nominal pipe size nor 1-1/8 in. wall thickness.	1977
VIII-81-85 (record BC-81-320)	Pipe to vessel with fillet weld in Sec. VIII, - Div. 1, UW-16(g)(3)(a) Q. Is it permissible to attach a pipe to a vessel using a fillet weld deposited from the outside only in lieu of using a threaded fitting as shown in Fig. UW-16.2, sketch (k), if the attachment meets the limitations specified in UW-16(g)(3)(a) and is not designed for lethal service? A. Yes.	1981
VIII-1-04-43 (record BC-04-1043)	Fillet welds to flat cover Q1. With reference to interpretation VIII-1-95-128, are the welds used to attach heater elements to flat covers in flanged immersion heaters classified by UW-3 as a category A, B, C, or D joint? A1. No. Q2. If the answer to Question (1) is no, then can a fillet weld be used to attach a heater element to a flat cover in a flanged immersion heater intended for lethal service as defined in UW-2(a)? A2. Yes.	2004
(Record 15-1264)	Non-circular vessel and closures Q1. Is the weld that attaches a flat plate end closure to a non-circular pressure vessel categorized as category C in accordance with UW-3? A1. Yes. Q2. If the vessel is designated as being in lethal service, are all the requirements of UW-2(a) applicable to the weld that attaches a flat plate end closure to a non-circular vessel? A2. Yes.	2015
VIII-1-95-138 (record BC-96-341A)	Flange type in UW-2(a)(1)(c) and Appendix 2, Fig. 2-4 Sketch (7) Q. Would an integral type flange shown in Fig. 2-4 sketch (7) in Sec. VIII, Div. 1, be acceptable for lethal service if the requirements of UW-2(a)(1)(c) are met? A. No.	1997
VIII-1-86-84 (record BC-86-286)	Flange type in Sec. VIII, Div. 1, UW-2(a)(1) Q1. A flange is welded to a nozzle in a vessel for lethal service. Is the construction shown in Fig. UW-13.2 sketch (m) permissible? A1. No. Q2. A flange is welded to a nozzle in a vessel intended for lethal service. Is the construction shown in Fig. 2-4 sketches (7), (8), (8a), (8b), and (9) permissible? A2. No.	1986
VIII-1-86-86 (record BC-86-293)	Nozzle type in Section VIII, Division 1, UW-16(f)(3)(a) and UCI-23(b) Q. Is it permissible to attach a nozzle consisting of a pipe welded to an ANSI bolted flange at one end and attached at the other end to a vessel, using a fillet weld deposited from the outside only in lieu of using a threaded fitting as shown in Fig. UW-16.2 sketch (1), if the attachment meets the limitations specified in UW-16(f)(3)(a) and is not designed for lethal service? A. No.	1986
(Record 15-1288)	Lethal and non-lethal sections of H/EXs per UW-2(a)(3) Q. A floating head H/EX with TEMA rear-end head type "S" has the tube side fluid specified as lethal service, but the shell side fluid is not. The shell cover of the floating end is not directly exposed to the tubeside "lethal" fluid. Is it required that the category A, B, C and D welds in shell cover satisfy the requirements of UW-2(a) if the provisions of UW-2(a)(3) are satisfied? A. No.	2015
VIII-1-16-42 (record 16-689)	Telltale holes on the nozzle repad in lethal service Q. Paragraph UG-25(e) prohibits the use of telltale holes that are intended to provide some positive indication when the thickness has been reduced to a dangerous degree due to corrosion. Does the same lethal service restriction apply to the telltale holes required by paragraph UG-37(g)? A. No.	2016

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

Table 1.30 (5/5) Interpretations and PTB (problem manuals) for lethal service in ASME BPVC (cont'd)

Interpretation or (record) No.	Requirements for lethal service (all para. below are from the code)	Year issued
VIII-79-48 (record BC-79-361)	Internals of H/EX in Sec. VIII, Div. 1, UW-2(a), Footnote 10 Q. Under the rules of UW-2(a) of Section VIII, Division 1, including footnote 10, is it required that both the shell side and channel side of a shell and tube heat exchanger be designed for lethal service if only one side is designated as lethal service, regardless of whether the tubes in the bundle are seamless or butt welded without the addition of filler metal? A. No. The generalized reply to this question is as follows: An independent chamber as covered in UG-19(a) of Sec. VIII, Div. 1, which is not in a special service, such as lethal service, need not comply with the special requirements such as those of UW-2(a). However, if there are common parts between the two chambers, they must satisfy the special requirements such as those of UW-2(a).	1979
VIII-1-16-39 (record 16-65)	Dished cover with bolting flanges in Fig. 1-6(d) is category C Q. For a dished cover that is welded to a bolting flange similar to Figure 1-6(d), shall the weld joining the dished cover to the bolting flange be considered as a category C weld joint that would be subjected to the service restrictions found in paragraph UW-2? A. Yes.	2016
VIII-1-16-72 (record 16–1569)	RT marking Q. A vessel is constructed using type no. 3 joints, as described in Table UW-12. All welds noted in UW-11(a) are fully radiographed. Does this vessel meet the requirements of RT 4 as described in UG-116(e)(4)? A. Yes.	2016
VIII-1-17-11 (record 16-2956)	UG-82(b) does not prohibit attachments after hydrotest per UG-99(g) Q. Do the rules of UG-82(b) prohibit attachments from extending over pressure-retaining welds for vessels in lethal service and subject to inspection after hydrotest per UG-99(g)? A. No.	2017

All paragraphs, appendices, figures, and tables designated in this table are based on ASME Sec. VIII, Div. 1, unless otherwise specified

1.1.9.5 Cyclic Service

A cycle is a relationship between stress and strain that is established by the specified loading at a location in a vessel or component. More than one stress-strain cycle may be produced at a location, either within an event or in transition between two events, and the accumulated fatigue damage of the stress-strain cycles determines the adequacy for the specified operation at that location. This determination shall be made with respect to the stabilized stress-strain cycle. The service is exposed to fatigue load from fluctuating pressure, temperature, vibration, or their combination – a service in which fatigue becomes significant due to the cyclic nature of the mechanical and/or thermal loads. A screening criteria is provided in Table 1.64 which can be used to determine if a fatigue analysis should be included as part of the vessel design.

1.1.10 Properties of Materials

See ASTM E6 for standard terminologies of principal terms used for mechanical tests.

1.1.10.1 Mechanical Properties

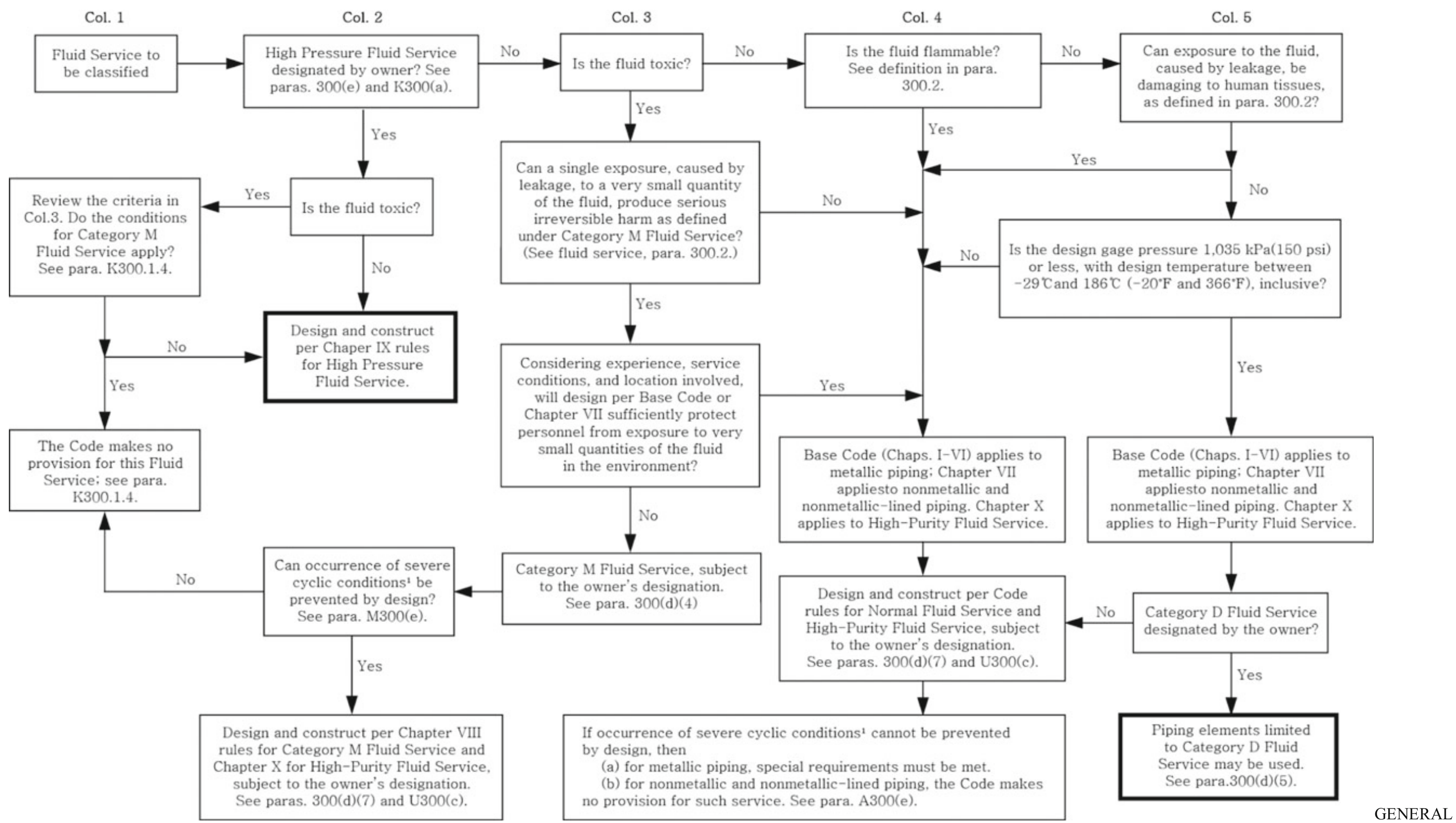
See Sect. 4.2.4 for residual stress due to welding and Sect. 4.12.3.2 for residual stress due to post-fabrication.

(a) *Strength*: An ability of a metal to maintain heavy loads (or force) without breaking. For example, steel is strong, but lead is weak.
(b) *Tensile Stress* (TS), psi or MPa: See individual material code and ASME Sec. II, Part D, for the values (as specified minimum tensile strength) in the following tables.
   - ASME Sec. II, Part D, Table 1A/2A: for ferrous materials (other than below)
   - ASME Sec. II, Part D, Table 1B/2B: for nonferrous materials (other than below)
   - ASME Sec. II, Part D, Tables 3 and 4: for bolting
   - ASME Sec. II, Part D, Table U: hot tensile strength at elevated temperature

   For the values as a specified minimum tensile strength for piping design, see the following tables.
   - B31.3, Table A-1/1M and A-2/2M
   - B31.1, Table A-1 to A-10

Tensile strength is the most important property of the materials for the design of facilities. The maximum stress value (the ultimate tensile stress in Fig. 1.4a) is when the section area of the specimen has just begun to reduce without additional load in tensile test. The fractional change in length in Fig. 1.4a is called the strain, and $\Delta\ell / \ell$ indicates elongation of the material.

As TS is higher, the required thickness of facility may be decreased. However, the values are highly limited in SCC (stress corrosion cracking), SSC (sulfide stress corrosion cracking), low temperature, and lethal service. As TS is close to YS (low elongation), the material



NOTES:
(a) See paras. 300(b)(1), 300(d)(4) and (5), and 300(e) for decisions the owner must make. Other decisions are the designer's responsibility; see para. 300(b)(2).
(b) The term "fluid service" is defined in para. 300.2.
NOTE: (1) Severe cyclic conditions are defined in para. 300.2. Requirements are found in Chapter II, Parts 3 and 4, and in paras. 323.4.2 and 241.4.3.

Figure 1.3 Guide for classifying M fluid service in ASME B31.3, Fig.M-300 (all paragraphs are from B31.3)

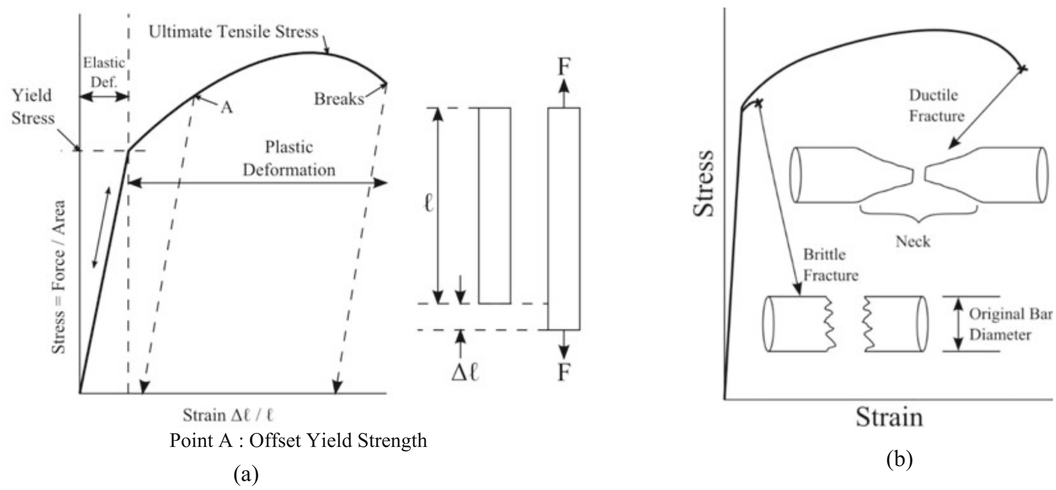


Figure 1.4 Stress-strain curves by tensile test. (**a**) Stress-strain curves during tensile test. (**b**) Brittle-ductile fractures during tensile test

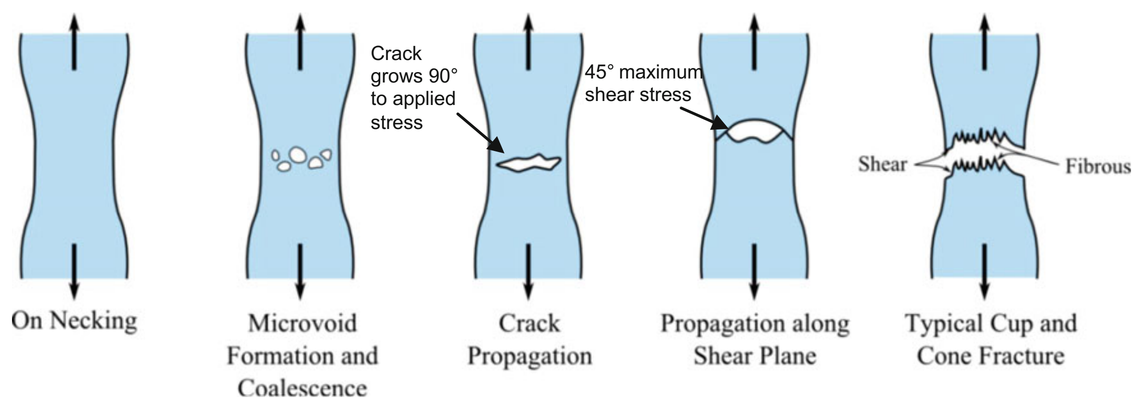


Figure 1.5 Stages in cup and cone fracture mode

may readily fail in brittle fracture mode as shown in Fig. 1.4b. Cast irons which have very low elongation have readily failed in the brittle fracture mode.

Ductile fracture is a much less serious problem in engineering materials since failure can be detected beforehand due to observable plastic deformation prior to failure.

- Under uniaxial tensile force, after necking, microvoids form and coalesce to form crack, which then propagates in the direction normal to the tensile axis.
- The crack then rapidly propagates through the periphery along the shear plane at 45°, leaving the cub and cone fracture.

Figure 1.5 shows the stages in cup and cone fracture mode of ductile carbon steel under tensile load.

Tension Tests in ASTM

- ASTM A20 General Requirements for Steel Plates for Pressure Vessels (at room temperature)
- ASTM A370 Standard Test Methods and Definitions for Mechanical Testing of Steel Products
- ASTM E8 Test Methods for Tension Testing of Metallic Materials
- ASTM E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials (Hot Tensile)
- ASTM A770 Through-Thickness Tension Testing of Steel Plates for Special Applications
- ASTM D638 Test Method for Tensile Properties of Plastics
- ASTM D882 Test Method for Tensile Properties of Thin Plastic Sheeting
- ASTM D1708 Test Method for Tensile Properties of Plastics by Use of Microtensile Specimens

Figure 1.6 shows the facture modes of ductile and brittle failure per stress/load type.

Most components of fixed equipment, piping, and structures are under tensile and bending stress/load condition, while some components (i.e., shaft) in rotating equipment are under torsional stress and bending stress/load condition.

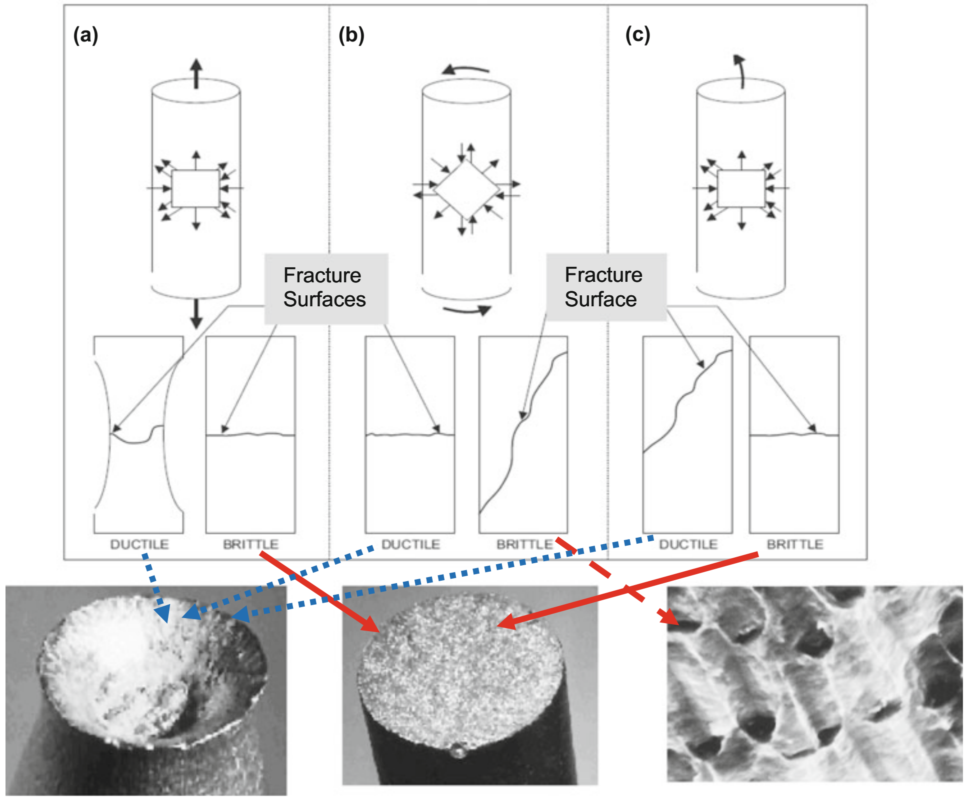


Figure 1.6 Ductile and brittle failure mode per stress (load) type. (**a**) Tensile stress. (**b**) Torsional stress. (**c**) Bending stress

(c) *Yield Stress* (YS), psi or MPa: See individual material code and ASME Sec. II, Part D, for the values (as specified minimum yield strength) in the following tables:
- Table 1A/2A: for ferrous materials (other than below)
- Table 1B/2B: for nonferrous materials (other than below)
- Tables 3 and 4: for bolting
- Table Y-1: hot yield strength at elevated temperature
- Table Y-2: factors for limiting permanent strain in nickel, high nickel alloys, and high alloy steels for hot yield strength at elevated temperature. This table lists multiplying factors that, when applied to the yield strength values shown in Table Y-1, will give a value that will result in lower levels of permanent strain. If this value is less than the maximum allowable stress value listed in Table 1A, 1B, 5A, or 5B, or the design stress intensity value listed in Table 2A or 2B, the lower value shall be used.

For the values specified as minimum yield strength for piping design, see the following tables:
- B31.3, Table A-1/1M and A-2/2M
- B31.1, Table A-1 to A-10

The maximum stress is the value which can be taken max 0.2% permanent strain (0.002 strain offset-$\Delta\ell$ in Fig. 1.4) after unloading in tensile test. As the value is higher, the facility cost may be decreased. However, the higher values may be more susceptible to cracking environments (e.g., SCC, SSC, caustic service, low temperature, etc.).

The increases in temperature complicate the analysis of what happens during the welding cycle, and thus understanding of factors contributes to understanding weldment distortion.

The yield strength (YS) values can be obtained from ASME Sec. VIII, Div. 1, UG28(c)(2), Step 3, in accordance with several nomenclatures in ASME Sec. VIII, Div. 1, UHX (H/EXs), when you cannot obtain the values at the high temperature.

UG28(c)(2), Step 3, suggests that the value is twice the B value in ASME Sec. II, Part D, (Figure HA-1, 2, and 6 or NFN-6-6, 9, and 13 for 650 °C (1200 °F) for cylindrical/tubular types. For types (i.e., tubesheet, floating head, etc.) other than cylindrical/tubular shape, the YS data in API STD 530 may be used.

As the value is higher, the required thickness of facility may be decreased. However, the higher values may be more susceptible to cracking environments (e.g., SCC, SSC, caustic service, low temperature, etc.).

Figure 1.7 shows that the mechanical properties are changed as per the temperatures.

Ratio of Yield Strength (YS) to Tensile Strength (TS)

As higher YS/TS value, it is easier not only work hardening but decreasing of toughness/fatigue stress and resistance of SCC and hydrogen embrittlement.

(d) *Design Stress Intensity Values* (for ASME Sec. III, Class 1, TC and SC)

1. Design stress intensity values for Sec. III, Class 1 materials listed in Tables 2A, 2B, and 4 and Sec. II, Part D, Subpart 1, shall be used. The materials shall not be used at temperatures that exceed the temperature limit in the applicability column of the stress tables. The values in the tables may be interpolated for intermediate temperatures. Only materials whose P-numbers are listed in ASME Sec. VIII, Div. 3, Table WB-4622.1-1, shall be used.
2. The design of a containment shall be determined so that the primary membrane and primary membrane plus bending stress intensities due to any combination of design loading do not exceed the maximum design stress intensity value permitted at the design temperature. These design stress intensity values may be interpolated for an intermediate design temperature as shown in Fig. 1.8.

(e) *Maximum Allowable Stress* (A.S), psi:

A.S. is normally calculated from tensile and yield strength by the following concept:

1. The values have the design safety margin from tensile and yield strength (f: safety factor).
2. The lesser value of TS/f (f = 3.5 for Div. 1, 3.0 for Div. 2) or 2/3 YS for the pressure vessels.
3. A.S. below room temperature is applied to the values at room temperature in ASME Sec. II, Part D, except ASME Sec. VIII, Div. 1, Part ULT, for low temperature that covers 5, 8, and 9 Ni steels, 304 SS, and 5083-O Aluminum alloy.
4. For a welded tube or pipe, use the allowable stress for the equivalent seamless product in ASME Sec. VIII, Div. 1, Part UHX (H/EXs). When the allowable stress for the equivalent seamless product is not available, divide the allowable stress of the welded product by 0.85.

The following codes for several facilities indicate the maximum allowable stresses for facility design:

– ASME Sec. II, Part D, and Sec. VIII, Div. 1, Part ULT, for low temperature (pressure vessels)
– B31.3 Table A-1/1M and A-2/2M (process piping)
– B31.1 Table A-1 to A-10 (power piping)
– API 650 Table 3-2 (tanks)
– API 530 Figure E.4 to F.19 (elastic and creep & rupture stress for heaters)
– API Spec 6A for derating factor at elevated temperature for surface wellhead and tree equipment

See Sect. 1.2.3.10 for more detailed criteria of establishing allowable stress values.

(f) *Elongation*: See ASME Sec. II, Parts A and B, for the values. Higher values give more increased formability and toughness. Conventional cast irons other than C.I. or malleable C.I. do not have elongation.

(g) *Elastic (or Young's) Modulus*, E: See ASME Sec. II, Part D, Table TM-1 to TM-5, B31.3 Table C-6, B31.1, Table C-1 & C-2 for the values, WRC Bulletin 503, and Appendix A.5 in this book. The E values are obtained from the slope of the curve in elastic zone of Fig. 1.4 (tensile test) or other methods.

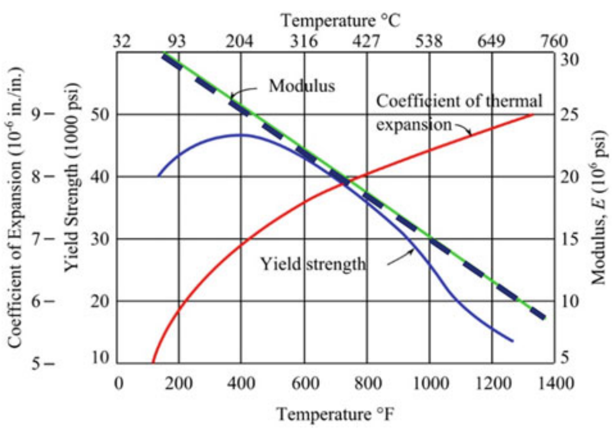


Figure 1.7 Changes in the physical properties of moderate carbon steel (trend)

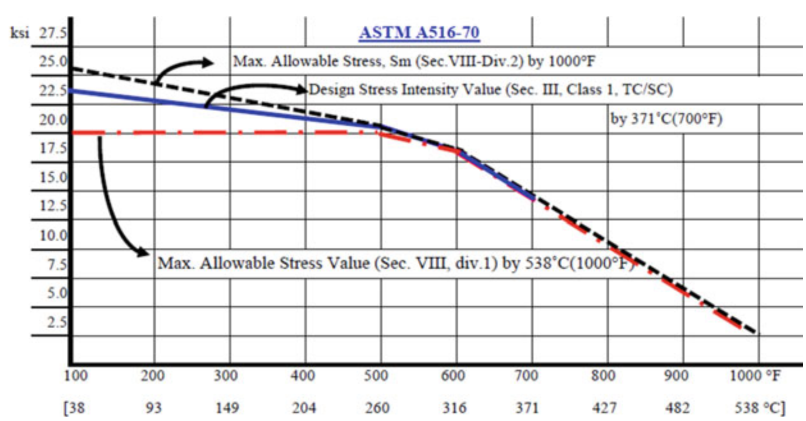


Figure 1.8 Maximum allowable stress and design stress intensity values as per temperature and codes

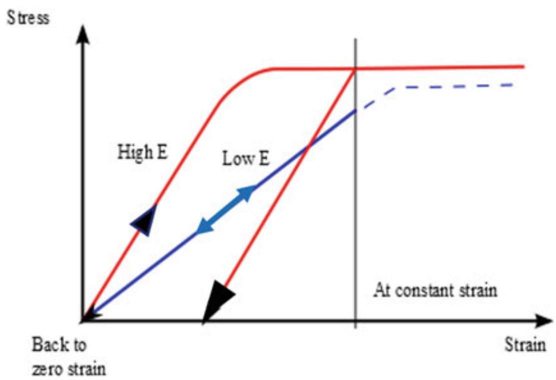


Figure 1.9 Back to zero strain of low elastic modulus pipe

Table 1.31 Poisson's ratio of several metals (typical values)

Materials	Poisson's ratio
Cork	0.0
Concrete	0.1
Carbon steels	0.25–0.35 (0.33 for low carbon)*
Aluminum alloys	0.31
Copper	0.33
Stainless steels	0.28
Titanium	0.31
Tungsten	0.27

Source: ASM Metal Handbook, Vol.1
*Note: 1. The maximum value for all materials is 0.52. 0.30 for low carbon steel in API 579-1/ASME FFS-1

$$E = \Delta\ \text{Stress}/\Delta\ \text{Strain}\ [\text{unit : psi}]$$

This is typically used to perform stress analysis of a statically intermediate component. The low elastic modulus will be obstacles to designing the structure for buckling resistance; however it may be selected in the fatigue stress design because it is readily back to zero strain, for instance, subsea risers which are under great fatigue stress (Fig. 1.9). Meanwhile, shear modulus (modulus of rigidity, G) describes an object's tendency to shear (the deformation of shape at constant volume) when acted upon by opposing forces; it is defined as shear stress over shear strain. See below for Stiffness (Rigidity), G.

(h) *Flexibility and Stiffness* (modulus of rigidity or modulus of elasticity in shear, G)
They can be evaluated from the results of tensile test. See ASME B31.1 and 31.3, Appendix D.

$$\text{Strain}\,(\varepsilon) = \delta/L \qquad \delta = \frac{PL}{EA}$$

where P, load (lb); L, original length of specimen (in); E, elastic modulus (=load/stain ratio) (psi); A, section area of specimen (in^2); δ, the magnitude of transformation (in); and ν, Poisson's ratio

$$\text{Flexibility} = \frac{L}{EA}\,[\text{ft/lbf}] \quad \text{Stiffness (Rigidity)}, G = \frac{E}{2\,(1+\nu)}\,[\text{psi}]$$

Especially, the stiffness has an important value in the evaluation of bending and twisting of beams.

(i) *Poisson's Ratio* (ν) – Table 1.31
It means one of the deformation ratio per direction of bar in the tensile test.
Poisson's ratio, ν = strain in the x direction (contraction ratio)/strain in the y direction (expansion ratio)
Also, see ASME Sec. II Part D, Table PRD, WRC 503 (Physical Properties), AISC, ASTM C469/C623/D638/E132, ISO 527 and Appendix A.4 in this book for more detailed values.

(j) *Bending Stress*
Bending stress is the normal stress that is induced at a point in a body subjected to loads that cause it to bend. The variation may or may not be linear across the section thickness. When a load is applied perpendicular to the length of a beam (with two supports on each end), bending moments are induced in the beam. Flexural theory states that most materials will exhibit linear-plastic behavior, i.e., they will respond to an applied load by deflecting in accordance with Hooke's Law and will return to their original shape and form when the load is removed. This stress-strain relation exists only up to a certain load, after which the material will undergo some irretrievable deformation. Hooke's Law states that deformation of an object under loading is proportional to the magnitude of the load.

Materials which are said to be "elastic" become distorted when they are compressed, stretched, or bent.

This behavior is due to the forces that different parts of a member exert on each other when a structure is subjected to loads. A simply supported beam of length L subjected to a concentrated transverse load P at midspan would exhibit vertical deflection (and start to curve) due to bending caused by the two reaction loads at the supports. At midspan, the top of the beam would be the location at which the maximum compression occurs due to contraction in the top fibers. The bottom of the beam would experience maximum tension due to the elongation in the bottom fibers.

The maximum bending moment due to applied transverse load P occurs at midspan of a beam of length L and is given by the following equation (Fig. 1.10):

$$M_{\max} = \frac{Px}{2} = \frac{P}{2}\cdot\frac{L}{2} = \frac{PL}{4}$$

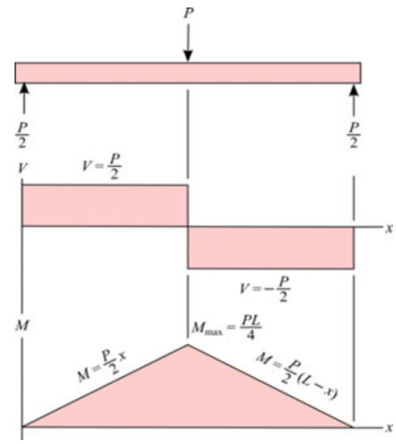


Figure 1.10 Bending stress distribution on a simple beam

Bending Tests in ASTM

- ASTM A370 Standard Test Methods and Definitions for Mechanical Testing of Steel Products
- ASTM A615 Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement
- ASTM A720 Test Method for Ductility of Nonoriented Electrical Steel
- ASTM B490 Standard Practice for Micrometer Bend Test for Ductility of Electrodeposits
- ASTM E190 Test Method for Guided Bend Test for Ductility of Welds
- ASTM E290 Test Methods for Bend Testing of Material for Ductility
- ASTM E855 Test Methods for Bend Testing of Metallic Flat Materials for Spring Applications Involving Static Loading
- ASTM D522 Test Methods for Mandrel Bend Test of Attached Organic Coatings
- ASTM D790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
- ASTM D6272 Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending

(k) *Shear Stress*

Shear strength is the strength against a shear force that tends to produce a sliding failure on a material along a plane that is parallel to the direction of the force. The shear strength of a component is important for designing the dimensions and materials to be used for the manufacture/construction of the component, such as steel beams, bolts, or concrete beam. In general: ductile materials (fcc structural metals) fail in shear, whereas brittle materials (e.g., cast iron) fail in tension.

$$\text{Shear stress } (\tau) = (\sigma_1 - \sigma_2)/2$$

σ_1 = major principal stress
σ_2 = minor principal stress

In bolt shear load calculation, the shear strength is:

$$\text{Shear strength } (\tau) = \text{Force}/(\text{Cross} - \text{SectionArea at Bolt Root})$$

Shear Strength Tests in ASTM and ISO

- ASTM B769 Test Method for Shear Testing of Aluminum Alloys
- ASTM B831 Test Method for Shear Testing of Thin Aluminum Alloy Products
- ASTM D732 Test Method for Shear Strength of Plastics by Punch Tool
- ASTM D4255 Test Method for Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method
- ASTM D5379 Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method
- ASTM D7078 Test Method for Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method
- ASTM G146 Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High Pressure-High Temperature Refinery Hydrogen Service
- ISO 3597 Textile-glass-reinforced plastics – determination of mechanical properties on rods made of roving-reinforced resin
- ISO 12579 Timber structures (glued laminated timber) – method of test for shear strength of glue lines
- ISO 14130 Fiber-reinforced plastic composites – determination of apparent laminar shear strength by short-beam method

Effect of Shear Stress on Metal Surface for Erosion Corrosion: see Sect. 2.4.5.2.

Fatigue Stress: see Sect. 1.3.2.
Creep-Rupture Stress: see Sect. 1.3.3.

1.1.10.2 Metallurgical Properties

(a) *Ductility*: An extent to which a metal can be deformed without fracture in rolling, extrusion, etc. An ability of metal to stretch or bend without breaking. An ability of metal to flow plastically before fracture. Soft iron, soft steel, and copper are ductile metals. It is related to the elongation and reduction of area in tensile test.

Ductility Tests in ASTM

- ASTM A720 Test Method for Ductility of Nonoriented Electrical Steel
- ASTM B490 Standard Practice for Micrometer Bend Test for Ductility of Electrodeposits

- ASTM E208 Test Method for Conducting Drop Weight Test for Nil-Ductility Transition Temperature of Ferritic Steels
- ASTM STP919 Drop Weight Test for Determination of Nil-Ductility Transition Temperature: User's Experience with ASTM Method E 208
- ASTM E290 Test Methods for Bend Testing of Material for Ductility
- ASTM D113 Test Method for Ductility of Bituminous Materials

(b) *Toughness*: An ability to absorb energy in the plastic range. A property of metal that will not permit it to tear or shear (cut) easily and will allow it to stretch without breaking. It is a main issue for material property in low temperature service. See Sect. 2.2 for low temperature impact tests and Sect. 5.2.3 for several fracture toughness tests and applicable standards.

(c) *Brittleness*: A property of metal that will allow it to shatter and fail without elongation easily. Metals, such as cast iron or cast aluminum and some very hard steels, are brittle. It is a main issue for material property and pressure test in low temperature service, as well as in MPT, welding, aging, cold forming, etc.

(d) *Hardness*: An ability of metal to resist plastic deformation, wear, or cutting action. Hardness is to be controlled by surface hardening (e.g., surface metallizing) as well as one of the original mechanical properties (e.g., tensile and yield strength). It should be controlled as high hardness value in erosion and wearing environments. However, it should be controlled as low hardness value to prevent (catastrophic) failure in SCC, hydrogen, low temperature, and cyclic environment.

There are several hardness measuring test methods, such as Brinell, Vickers, Rockwell, etc. See Sect. 5.4.1 for more details and specific requirements for hardness.

Meanwhile, Shore durometer hardness unit is used for elastomer and resin materials (see ASTM D2240).

Table 1.32 shows an approximate equivalent tensile strength as per the hardness number (Brinell and Vickers) for carbon and low alloy steels in annealed, normalized, and quenched-tempered conditions.

Hardness Test Methods and Conversion Tables for Several Materials (Including Nonmetals) see Sect. 5.4.1.2(b) and Appendix A.2 in this book.

Hardness Conversion for DSS (Including Super DSS) ASTM E140 does not address for DSS.

- HRC = 0.091 HV – 2.4

(e) *Hardenability*: A property of metal that allows it to be easily to hardened during working such as heat treatment, hot and cold work, etc.

(f) *Bendability*: A property of metal that allows it to bend without failure and heavy residual stress.

(g) *Wear Resistance*: A property of metal that allows it to endure wearing. See Sect. 2.1.7.7 for hardfacing.

Table 1.32 Approximate equivalent hardness number and tensile strength for carbon and low alloy steels in annealed, normalized, and quenched-tempered conditions

Brinell Hardness No. (3000 kg load)	Vickers Hardness No.	Approximate TS		Brinell Hardness No. (3000 kg load)	Vickers Hardness No. (MPa)	Approximate TS	
		(MPa)	(ksi)			(MPa)	(ksi)
441	470	1572	228	265	280	889	129
433	460	1538	223	261	275	876	127
425	450	1496	217	256	270	855	124
415	440	1462	212	252	265	841	122
405	430	1413	205	247	260	827	120
397	420	1372	199	243	255	807	117
388	410	1331	193	238	250	793	115
379	400	1289	187	233	245	770	113
369	390	1248	181	228	240	765	111
360	380	1207	175	219	230	731	106
350	370	1172	170	209	220	696	101
341	360	1131	164	200	210	669	97
331	350	1096	159	190	200	634	92
322	340	1069	155	181	190	607	86
313	330	1034	150	171	180	579	84
303	320	1007	146	162	170	545	79
294	310	979	142	152	160	517	75
284	300	951	138	143	150	490	71
280	295	938	136	133	140	455	66
275	290	917	133	124	130	427	62
270	285	903	131	114	120	393	57

Commentary Notes:
(1) Based on API 579/ASME FFS-1, Table F.1, unless otherwise noted below
(2) This table should not be used for the purpose of strength calculation
(3) Surface hardness values may be different with that in the metal core. Especially the values may be greatly different after local heating or fire

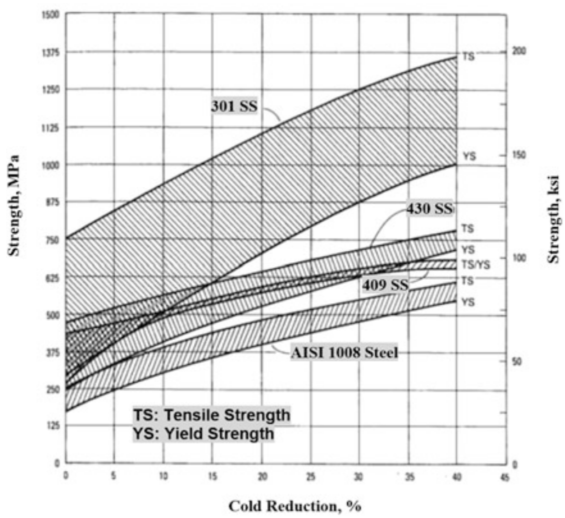


Figure 1.11 Cold work hardening of several metals. (Source: ASM Metal Handbook, Vol.1)

(h) *Machinability*: A property of metal that allows it to be easily machined through the lathe, milling, etc.

(i) *Malleability*: A property of metal that allows it to be rolled, forged, hammered, or shaped without cracking or breaking. Copper is a very malleable metal.

(j) *Graphitization*: A phenomenon is dissociated from Fe_3C (cementite) to Fe + 3C after several hundred or thousand hours at high temperature [>427 °C (800 °F) for carbon steels] of carbon and low alloy steels. This phenomenon decreases strength greatly. See Sect. 2.3.1 for more details.

(k) *Melting Temperature*: The higher the melting temperature, the more difficult it is to form and weld and hence the need for more energy for the working. See Appendix A.3 for the melting temperatures of several metals.

(l) *Grain Size*: The grain size of a metal is an important material characteristic for strength, toughness, formability, directionality, corrosion resistance, texture, and surface appearance. As the average grain size decreases, the metal becomes stronger (more resistant to plastic flow), and as the grain size increases, the opposite effect on strength occurs. In general, for a given alloy and thickness, ductility increases with grain size, and strength decreases. This occurs because the smaller the grains, the shorter the distance the dislocations can move, and then it can be economically fabricated into the desired part. See Sect. 2.1.1.12 for general characteristics of grain size and Sect. 2.1.1.5 for effects in low temperature toughness.

(m) *Work Hardening*: It is an increase in mechanical strength due to plastic deformation on cold work as shown in Fig. 1.11. In metallic solids, a permanent change of shape is usually carried out on a microscopic scale by defects called dislocations which are created by stress, rearranging the material by moving through it. At low temperature, these defects do not anneal out of the material, but build up as the material is being worked, interfering with one another's motion and thereby increasing the strength. Any material with a reasonably high melting point can be strengthened in this fashion. It is often exploited to harden alloys that are not amenable to heat treatment, including low carbon steel. Conversely, since the low melting point of indium makes it immune to work hardening at room temperature, it can be used as a gasket material in high-vacuum systems. A material's work hardenability can be predicted by analyzing a stress-strain curve or studied in context by performing a hardness test before and after the proposed cold work process. See Sect. 2.1.6.12 for strain (or deformation)-induced martensite and permeability of stainless steels after cold work. API 660, 9.9.2 states that if austenitic stainless steel (ASS), duplex stainless steel (DSS), titanium, cupro-nickel or nickel-based alloy tubes are specified, the tube holes shall be machined in accordance with TEMA (8th edition), Table RCB-7.41, column (b) (Special Close Fit).

API 661, Table 11 also requires the Special Close Fit if ASS, DSS, titanium, copper-nickel, or nickel-based alloy tubes are specified. The close fit requirement is to minimize work hardening effects. ASME (or other facility codes/standards) requires the release of residual stresses from work hardening. See Sect. 4.12.3 for heat treatment (PWHT or Stress Relieving) requirements for several metals in various industrial codes and standards.

(n) *Precipitation* (Aging) *Hardening*: It is a technique where heat is applied to a malleable material, such as some aluminum, magnesium, nickel, and titanium alloys and some stainless steels (e.g., 17-4 PHSS, 17-7 PHSS), in order to strengthen it. The technique hardens the alloy by creating solid impurities, called precipitates (secondary metallic compounds), which stop the movement of dislocations in the crystal lattice structure. Dislocations are the primary cause of plasticity in a material; thus, the absence of dislocations increases the material's yield strength. Creating precipitation-hardened materials starts with heating the material to a very high temperature in order to dissolve the precipitate. It takes 1–20 hours for the precipitate to completely dissolve. Supersaturation of the solution is achieved through quenching. Quenching can be completed in water, air, or some mixture of air and water. As an important step in solid solution strengthening, it leaves the material softer and more prepared for the next phase of precipitation hardening.

1.1.10.3 Physical Properties

(a) *Thermal Conductivity* (TC): See ASME Sec. II Part D, Table TCD, WRC Bulletin 503, and Appendix A.3 & A.6 and the notes in this book.

The thermal conductivity of metals is quite high. The unit is Btu·ft/hr·ft^{2}·°F (Btu/hr·ft·°F or W/m·°K or W/m·°C). At a given temperature, the thermal and electrical conductivities of metals are proportional, but raising the temperature increases the thermal conductivity while decreasing the electrical conductivity. This behavior is quantified in Wiedemann-Franz law:

$$K/\sigma = LT \text{ or } L = K/\sigma T \text{ Wiedemann-Franzl Law}$$

where the constant of proportionality L is called the Lorenz number, K is thermal conductivity, and σ is electrical conductivity.

With higher TC (K), the required size of heat transferring facilities, such as H/EXs, evaporators and fin tubes of radiator, etc., can be reduced. However, it may be not easy to weld materials with high thermal conductivity due to the rapid cooling in fusion zone. 1 Btu/hr·ft·°F = 1.731 W/m·°K = 1.731 W/m·°C

(b) *Thermal Diffusivity* (TD): See ASME Sec. II Part D, Table TCD, General Notes, and WRC Bulletin 503.
The actual heat diffusion value considered the density and specific heat of the materials. It is used to evaluate the cooling rate during welding and hot work and perform a transient thermal heat transfer analysis of a component. The relation of thermal diffusivity (ft^2/hr) and thermal conductivity (Btu/hr ft °F or W/m °K) is as below:

$$TD = \frac{TC\ [Btu/hr \times ft \times {}^0F]}{Density\ [lb/ft^3] \times Specific\ Heat\ [Btu/lb \times {}^0F]}$$

(c) *Electric Conductivity and Resistivity*
Electrical conductivity is a measure of how well a material accommodates the movement of an electric charge, while electrical resistivity is a fundamental property of a material that quantifies how strongly that material opposes the flow of electric current. It is the ratio of current density to electric field strength. Its SI-derived unit is Siemens per meter (S/m) or % IACS (International Annealed Copper Standard). The conductivity of the annealed copper (5.8108×10^7 S/m) = 100% IACS at 20 °C.

Table 1.33 shows the electric conductivities and resistivities of several materials.

This electric conductivity value is normally proportionated to thermal conductivity.

(d) *Density* (*Specific Gravity*): See ASME Sec. II Part D, Table PRD, for the values.
The useful value for the analysis of weight, corrosion rate, etc. The material density is required to perform a transient thermal heat transfer analysis of a component. See Appendix A.3 and the notes for density of several metals.

(e) *Thermal Expansion Coefficient* (TEC): See Sec. II Part D, Table TE series, B31.3 Table C-1, 3, 5, B31.1 Table B-1, WRC Bulletin 503, ASM Metal Handbook, Vol.1, Thermal properties of metals for the values, and Appendix A.3 & A.7 and the notes in this book. See ASTM E831 for the test. As higher TEC, the deformation during hot working or cyclic heating is easier. Also, crack may occur by thermal shock [see Fig. 1.17 and Sect. 2.2.1.13] due to magnitude of temperature differential. This is required to perform thermal stress analysis of a component.

Figure 1.12 shows the mean coefficients of thermal expansion as a function of temperature for transition butt-weld materials in several metals. Meanwhile the mixing point on piping with magnitude of temperature differential ($\Delta T > 150$ °C) may require the use of thermal sleeve to avoid thermal shock.

Table 1.33 Electric conductivity and resistivity of several materials at 20 °C

Metals	Electrical conductivity σ (S/m)	Electrical resistivity ρ (Ω.m)	Metals	Electrical conductivity σ (S/m)	Electrical resistivity ρ (Ω.m)
Silver (Ag)	63.0×10^6	1.59×10^{-8}	Mercury (Hg)	1.02×10^6	98.00×10^{-8}
Copper (Cu)	59.6×10^6	1.68×10^{-8}	Manganese (Mn)	0.69×10^6	144.0×10^{-8}
Annealed copper (Cu)	58.0×10^6	1.72×10^{-8}	Nichrome (3)	0.67×10^6	110.0×10^{-8}
Gold (Au)	45.2×10^6	2.44×10^{-8}	Carbon (amorphous)	1.25×10^3 to 2.00×10^3	5×10^{-4} to 8×10^{-4}
Aluminum (Al)	37.8×10^6	2.65×10^{-8}	Carbon (graphite)	3.3×10^2 to 3.0×10^5	5×10^{-6} to 3×10^{-3}
Calcium (Ca)	29.8×10^6	3.36×10^{-8}	GaAs(4)	1×10^{-8} to 1×10^3	1×10^{-3} to 1×10^8
Tungsten (W)	17.9×10^6	5.60×10^{-8}	Germanium (Ge)	2.17	4.6×10^{-1}
Zinc (Zn)	16.9×10^6	5.90×10^{-8}	Water (seawater)	4.8	2.0×10^{-1}
Nickel (Ni)	14.3×10^6	6.99×10^{-8}	Water (drinking)	5×10^{-4} to 5×10^{-2}	2×10^1 to 2×10^3
Lithium (Li)	10.8×10^6	9.28×10^{-8}	Silicon (Si)	1.56×10^{-3}	6.4×10^2
Iron (Fe)	10.0×10^6	9.70×10^{-8}	Wood (damp)	0.1×10^{-3} to 1.0×10^{-3}	0.1×10^4 to 1.0×10^4
Platinum (Pt)	9.43×10^6	10.60×10^{-8}	Water (deionized)	5.50×10^{-6}	1.8×10^5
Tin (Sn)	9.17×10^6	10.90×10^{-8}	Glass	1×10^{-15} to 1×10^{-11}	1×10^{11} to 1×10^{15}
Gallium (Ga)	7.10×10^6	14.00×10^{-8}	Carbon (diamond)	$\leq 1 \times 10^{-13}$	1×10^{12}
Niobium (Nb)	7.00×10^6	14.00×10^{-8}	Hard rubber	$\leq 1 \times 10^{-14}$	1×10^{13}
CS	6.99×10^6	14.30×10^{-8}	Air	$\leq \leq 1 \times 10^{-9}$	1×10^9 to 1×10^{15}
Lead (Pb)	4.55×10^6	22.00×10^{-8}	Wood (dried)	1×10^{-16} to 1×10^{-14}	1×10^{14} to 1×10^{16}
Titanium (Ti)	2.38×10^6	42.00×10^{-8}	Sulfur (S)	1×10^{-16}	1×10^{15}
Manganin(1)	2.07×10^6	48.20×10^{-8}	PET (5)	1×10^{-21}	1×10^{21}
Constantan(2)	2.04×10^6	49.20×10^{-8}	Teflon	1×10^{-25} to 1×10^{-23}	1×10^{23} to 1×10^{25}
304 SS	1.45×10^6	69.00×10^{-8}			

Notes: Source: Ohring, Milton, Engineering Materials Science." New York: Academic Press, 1995
(1)Manganin®: alloy with 84%Cu-12%Mn-4%Ni or 86%Cu-12%Mn-2%Ni
(2)Constantan (known as Eureka, Advance, or Ferry): 55%Cu-45%Ni
(3)Nichrome®: alloy with 80%Ni-20%Cr
(4)GaAs (gallium arsenide): a compound of elements gallium (Ga) and arsenic (As)
(5)PET: polyethylene terephthalate

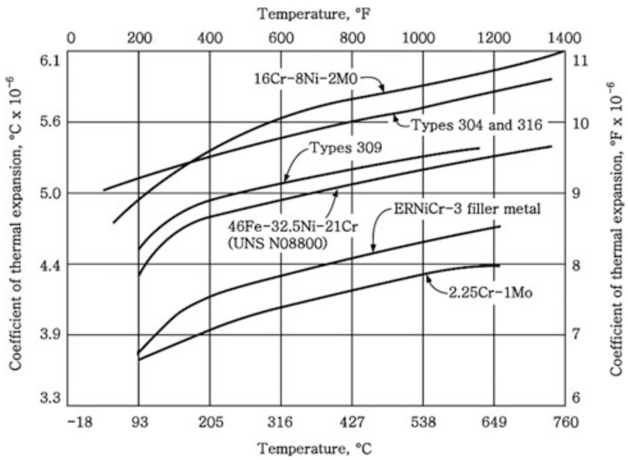


Figure 1.12 Mean coefficients of thermal expansion as a function of temperature for transition butt-weld materials. (Source: Ohring, Milton, Engineering Materials Science, New York, Academic Press, 1995)

(f) *Specific Heat*, Btu/lb/°F or kJ/kg °K:
Specific heat capacity is the amount of heat required to change temperature of 1 kg of a substance by *one degree*. Specific heat may be measured in kJ/kg K or Btu/lb°C. Specific heat capacity represents the amount of energy required to raise 1 kg by 1 °C and can be thought of as the ability of a substance to absorb heat. Therefore the SI unit of specific heat capacity is kJ/kg K (kJ/kg °C). Water has a very large specific heat capacity (4.19 kJ/kg °C) compared with many fluids. Specific heat capacities for different materials can be found in Table 1.34 and Appendix A.3.

(g) *Permeability of Metal* (μ):
Permeability of metal refers to its ability of being permeable. It is also called relative permeability or magnetic constant which is a constant of proportionality that exists between magnetic induction and magnetic field intensity. This constant (μ) is equal to approximately 1.257×10^{-6} henry per meter (H/m) in free space (vacuum). Materials are classified per permeability (concentrated magnetic flux) as below.
– Paramagnetic materials with a factor of more than 1 but less than or equal to 10
– Ferromagnetic materials with a factor of more than 10

The permeability factors of some substances change with the rising or falling of temperature, cold or hot work, or intensity of the applied magnetic field.

1. Customary Units
Convert the fluxmeter reading to intrinsic induction Bi and calculate the permeability as follows:

$$\mu = 1 + \frac{B_i}{H}$$

where:

μ = permeability of the test specimen
Bi = intrinsic induction of the test specimen, G
H = magnetic field strength, Oe (oersted)

Table 1.34 Specific heat of several metals

Metal	Symbol	Specific Heat Capacity – c_p		
		(kJ/kg °K)	(kcal/ kg°C)	($Btu/lb_m°F$)
Aluminum	Al	0.91	0.22	0.22
Antimony	Sb	0.21	0.05	0.05
Beryllium	Be	1.83	0.44	0.44
Bismuth	B	0.13	0.03	0.03
Cadmium	Cd	0.23	0.05	0.05
Carbon steel	CS	0.49	0.14	0.14
Cast Iron	CI	0.46	0.11	0.11
Chromium	Cr	0.46	0.11	0.11
Cobalt	Co	0.42	0.10	0.10
Copper	Cu	0.39	0.09	0.09
Gold	Au	0.13	0.03	0.03
Iridium	Ir	0.13	0.03	0.03
Iron	Fe	0.46	0.11	0.11
Lead	Pb	0.13	0.03	0.03
Magnesium	Mg	1.05	0.24	0.24
Manganese	Mn	0.48	0.11	0.11
Mercury	Hg	0.14	0.03	0.03
Mercury	Hg	0.14	0.03	0.03
Molybdenum	Mo	0.25	0.06	0.06
Nickel	Ni	0.54	0.13	0.13
Niobium (columbium)	Nb (Cb)	0.27	0.06	0.06
Osmium	Os	0.13	0.03	0.03
Platinum	Pt	0.13	0.03	0.03
Plutonium	Pu	0.13	0.03	0.03
Potassium	K	0.75	0.18	0.18
Rhodium	Rh	0.24	0.06	0.06
Selenium	Se	0.32	0.08	0.08
Silicon	Si	0.71	0.17	0.17
Silver	Ag	0.23	0.06	0.06
Sodium	Na	1.21	0.29	0.29
Tantalum	Ta	0.14	0.03	0.03
Thorium	Th	0.13	0.03	0.03
Tin	Sn	0.21	0.05	0.05
Titanium	Ti	0.54	0.13	0.13
Tungsten	W	0.13	0.03	0.03
Uranium	U	0.12	0.03	0.03
Vanadium	V	0.39	0.09	0.09
Zinc	Zn	0.39	0.09	0.09
Wrought Iron		0.50	0.12	0.12

Sources: Ohring, Milton, Engineering Materials Science, New York, Academic Press, 1995
Note: 1 kJ/kg °K = 1 J/g °K = 0.2388 kcal/kg°C = 0.2388 cal/g°C = 0.2388 $Btu/lb_m°F$

2. SI Units
   Convert the fluxmeter that is the magnetic polarization J and calculate the permeability as follows:

$$\mu_r = 1 + \frac{J}{\Gamma_m H}$$

where:

μr = relative permeability of the test specimen
J = magnetic polarization, T
$\Gamma_m = 4\pi \times 10^{-7}$ H/m
H = magnetic field strength, A/m

Permeability Standards in ASTM for Permeability of Metal (μ)

- ASTM A342 TM for Permeability of Weakly Magnetic Materials
- ASTM A772 TM for AC Magnetic Permeability of Materials Using Sinusoidal Current
- ASTM A799 TM for Steel Castings, Stainless, Instrument Calibration, for Estimating Ferrite Content
- ASTM D6539 TM for Measurement of the Permeability of Unsaturated Porous Materials by Flowing Air

1.1.10.4 Tracking Numbering System of Base Metal

(a) Heat Number: the number of metal with one chemical composition, produced by a recognized production process from a single primary melt of metal. Remelted ingot material is not recognized as a separate heat unless it is produced from a melt having a different chemical composition than the other heats.
(b) Lot (Serial) No.: The number of cut piece with the same heat number (tracking no by mill maker). The following classes are considered:
   - *Casting lot*: single production pour from a master heat
   - *Wrought lot*: quantity of metal made by melting followed by working or by working and heat treatment as a unique batch. Different lots may come from the same heat and may be made into different product forms. Lot definitions are expected to be found in the applicable material specifications.

1.1.11 Minimum Design Metal Temperature (MDMT) and Design Minimum Temperature (DMT)

MDMT for equipment and DMT for piping are to be considered in the selection of materials for pressure vessels, storage tanks, H/EXs, piping, pipelines, and structural steels. The MDMT or DMT should be as cold as or colder than the lowest temperature of the contacting process fluid under all kinds of operating conditions including upset. When colder temperatures are possible due to auto-refrigeration effects, the acceptability of the co-incident pressure-temperature shall be determined by the applicable code (e.g., ASME Sec. VIII, Div. 1, UCS-66, or ASME B31.3, 323.2.2). Temperature variations such as those caused by startup, cool down, shutdown, planned depressurizing, planned venting, and failure of control systems should be considered.

The MDMT or DMT for a component in contact with two fluids that have different temperatures should be determined by considering the heat transfer areas and the heat transfer capacities of both fluids. If single fluid flow operation is possible, the design metal temperature should be the coldest temperature of the fluid.

The MDMT or DMT is considered as the same temperature with DBTT (ductile-brittle transition temperature with 50% ductile-50% brittle mode after impact test) of the metal unless otherwise noted in the definition.

The following design guidelines for MDMT or DMT are recommended for each facility:

1.1.11.1 MDMT Decision of Pressure Vessels Designed as per ASME Section VIII (Recommendation)

The following factors may be used for the determination of MDMT:

(a) ASME Section VIII, Section VIII, Div. 1, UG-20, (b), shall be complied.
(b) The MDMT should not be warmer than −7 °C (20 °F) unless otherwise specified.
(c) The lowest (coldest) temperature resulting from the following factors should be determined as a minimum and should be used as the MDMT when the temperature so determined is colder than the default value established in (a) above.
   1. The lowest one day mean atmospheric temperature (LODMAT): However, LODMAT temperature numbers colder than −29 °C (−20 °F) may be considered as equal to −29 °C (−20 °F) when the material is insulated or located at the inside of service container.
   2. The coldest operating temperature coincident with full (normal) operating pressure (specified by process engineering).
   3. The coldest temperature resulting from a possible process upset. The depressurization condition (results in auto-refrigeration) may be considered as MDMT; however, ASME Section VIII, Div. 1, Figure UCS-66.1(M), may be used to mitigate the impact test requirements.
   4. The applicable end-user's specification or manual.
   5. For equipment where auto-refrigeration is a consideration, an MDMT established according to each code.

Note: More than one MDMT may be assigned to a pressure vessel with sections operating at different process conditions.

1.1.11.2 DMT of Piping Systems and Components Designed as per ASME B31.3

The concepts of material toughness rules in ASME B31.3 are essentially the same as those in Section VIII, Divisions 1 and 2. The coldest temperature results from a possible process upset. The depressurization condition (results in auto-refrigeration) may be considered as DMT; however, ASME B31.3, Fig. 323.2.2B, may be used to mitigate the impact test requirements. See Appendix A for more details.

1.1.11.3 MDMT (or DMT) of Nonpressure Components (Recommendation)

The material for nonpressure parts welded directly to carbon steel pressure parts should be as follows:

(a) Materials that are to be an essential to the structural integrity or support of a vessel, tank, or component (such as skirts, saddles, legs, support lugs, lifting lugs) shall meet the temperature limits in Table 2.14 and shall be impact tested if not exempted as stated in the applicable codes.
(b) Materials for attachments that transmit loads to pressure-retaining components (such as platform clips, tray supports, pipe guide clips, ladder clips, etc.) should be fabricated from materials as indicated in Table 2.14 for the applicable MDMT. However, the impact test may or may not be required per company standards. Structural steel attachments that are not subject to the cold process temperature should comply with the applicable structure codes and company standards.
(c) Material for minor attachments (insulation studs, minor clips, light davits) may be used with non-impact-tested weldable carbon steel.

1.1.11.4 DMT of Structural Steel

Normally the LODMAT is applied with applicable codes/standards.

1.1.12 Nominal Thickness and Governing Thickness (GT)

The materials may have different mechanical and metallurgical properties in accordance with thickness (called “mass effect”). Codes and standards suggest several different requirements as per thickness, e.g., heat treatment, welding, toughness, fabrication, etc. However, the thickness from the weld joint or shaped products may not be readily defined. Therefore, the codes and standards also specify the nominal thickness and governing thickness to define effectively the requirements as per thickness.

1.1.12.1 ASME Sec. VIII, Div. 1

Appendix 3-2: Nominal thickness is defined except as defined in UW-40(f) and modified in UW-11(g); the nominal thickness is the thickness selected as commercially available and supplied to the manufacturer. For plate material, the nominal thickness shall be, at the manufacturer’s option, either the thickness shown on the Material Test Report (MTR in UG-93(a)(1)) before forming or the measured thickness of the plate at the joint or location under consideration.

UW-40(f) defines the nominal thickness used for welding and heat treatment application.

UHA-51 defines the nominal thickness used for CVN impact test exemption as below.

For product forms other than plate and pipe, the nominal material thickness shall be determined as follows:

– Castings: maximum thickness between two cast coincidental surfaces
– Hollow cylindrical forgings: maximum radial thickness
– Disk forgings: maximum thickness, including the length of an integral hub if a hub is present
– Weld neck flanges: the larger of the thickness of the flange ring or the neck

ASME Sec. VIII, Div. 1, also defines the governing thickness (GT) for impact test requirements. See Sect. 2.2.2.2 in this book for the GT defined for impact test requirements.

1.1.12.2 ASME Sec. VIII, Div. 2

ASME Sec. VIII, Div. 2, defines the governing thickness (GT) for PWHT effects of impact test requirements and material restrictions. See Fig. 2.135 in this book for the GT for PWHT effect for impact test and Sect. 2.2.2.2 in this book for the GT defined for impact test requirements.

1.1.12.3 ASME B31.3

The thickness definition specified for PWHT and impact test requirements is controlled by “control thickness” due to branch connections mostly in all piping system. In addition, the definition of “governing thickness” is also applied for high pressure piping (in B31.3, Section K.).

All Pressure Piping

(a) The term *control thickness* as used in Table 4.127 and Table 4.127a in this book is the lesser of
   1. the thickness of the weld
   2. the thickness of the materials being joined at the weld or the thickness of the pressure-containing material if the weld is attaching a nonpressure containing material to a pressure-containing material
(b) Thickness of the weld, which is a factor in determining the control thickness, is defined as follows:
   1. Groove welds (girth and longitudinal) – the thicker of the two butting ends after weld preparation, including I.D. machining
   2. Fillet welds – the throat thickness of the weld

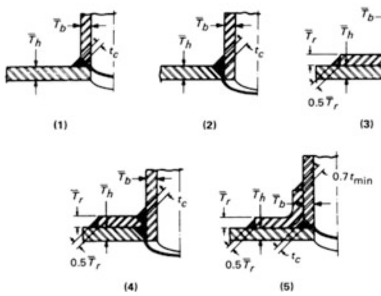


Figure 1.13 Branch welds in piping. (Source: ASME B31.3, Fig. 328.5.4D)

3. Partial penetration welds – the depth of the weld groove
4. Material repair welds – the depth of the cavity to be repaired
5. Branch welds – the dimension existing in the plane intersecting the longitudinal axes, calculated as indicated for each detail using the thickness through the weld for the details shown in Figs. 1.13 and 1.14 in this book.
   This thickness shall be computed using the following formulas:
   (−a) For Fig. 1.13, use:
      illustration (1) p $Tb + tc$
      illustration (2) p $Th + tc$
      illustration (3) p greater of $Tb + tc$ or $Tr + tc$
      illustration (4) p $Th + Tr + tc$
      illustration (5) p $Tb + tc$
   (−b) For Fig. 1.14, use $Tm + tc$ for all illustrations.

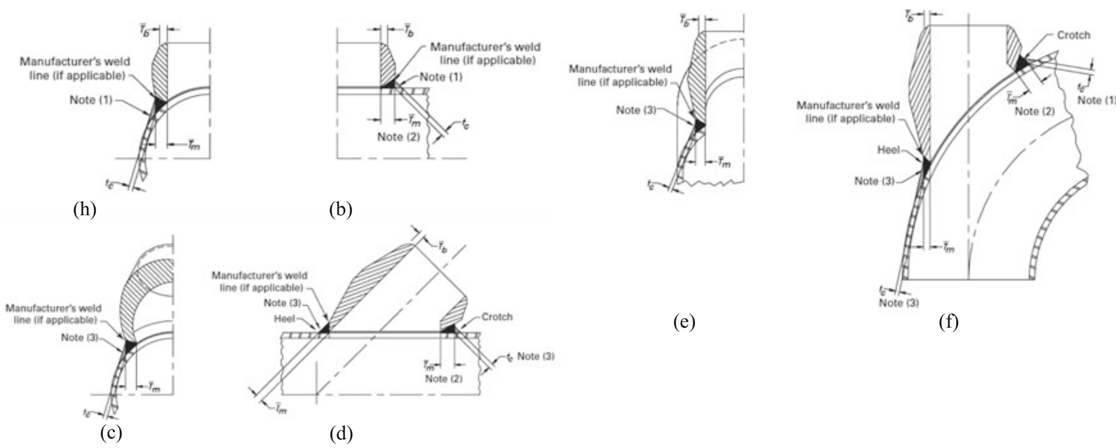


Figure 1.14 Integrally reinforced branch connection in piping. (Source: ASME B31.3, Fig. 328.5.4F). (**a**) Transverse. (**b**) Longitudinal. (**c**) Transverse. (**d**) Longitudinal. (**e**) Transverse. (**f**) Longitudinal

(c) The term nominal material thickness as used in Table 4.127a is the thicker of the materials being joined at the weld.
   High Pressure Piping: normally ASME B16.5 Class 2500 rating, but not always

K331.1.3 Governing Thickness. When components are joined by welding, the thickness to be used in applying the heat treatment provisions of Table 4.127 in this book shall be that of the thicker component measured at the joint, except as follows:

In the case of fillet welds used for the attachment of external nonpressure parts, such as lugs or other pipe supporting elements, heat treatment is required when the thickness through the weld and base metal in any plane is more than twice the minimum material thickness requiring heat treatment (even though the thickness of the components at the joint is less than the minimum thickness) except as follows:

(a) Not required for P-No. 1 materials when weld throat thickness is 16 mm (5/8 in.) or less, regardless of base metal thickness.
(b) Not required for P-No. 3, 4, 5, 10A, and 10B materials when weld throat thickness is 6 mm (1/4 in.) or less, regardless of base metal thickness, provided that not less than the recommended minimum preheat is applied and the specified minimum tensile strength of the base metal is less than 490 MPa (71 ksi).
(c) Not required for ferritic materials when welds are made with filler metal that does not air harden. Austenitic welding materials may be used for welds to ferritic materials when the effects of service conditions, such as differential thermal expansion due to elevated temperature, or corrosion, will not adversely affect the weldment.

Code Interpretation 25–30
Subject: ASME B31.3, 331.1.3(a)(2) and (c), Preheat and PWHT Governing Thickness (B31.3-2014)
Date Issued: April 28, 2015
File: 15-616

Question (1): In ASME B31.3, 331.1.3(a)(2), does the phrase “the thickness of the materials being joined at the weld” mean the nominal thickness of the materials being joined at the weld?
Reply (1): Yes.

Question (2): In ASME B31.3, 331.1.3(a)(2), does the phrase "the thickness of the pressure-containing material" mean the nominal thickness of the pressure-containing material?
Reply (2): Yes.
Question (3): In ASME B31.3, para. 331.1.3(c), does the phrase "the thicker of the materials being joined at the weld" mean the nominal thickness at the weld of the thicker of the materials being joined?
Reply (3): Yes.

1.1.13 Guidelines on the Approval of New Materials Unregistered in the ASME BPVC

To apply ASME BPVC with new material unregistered in ASME Section II, Part D, Code Case application shall be approved in accordance with ASME Sec. II, Part C, Appendix 5. The inquirer shall identify to the ASME BPVC Committee the following:

(a) The Section or Sections and Divisions of the ASME BPVC in which the new material is to be approved
(b) The temperature range of intended application
(c) Whether cyclic service is to be considered
(d) Whether external pressure is to be considered

For Mechanical Properties Data shall be provided over the required range of test temperatures from at least three heats of material meeting all of the requirements of the applicable specifications. Data submitted on three heats of one wrought product form for which coverage is requested may be considered to be applicable for all other wrought product forms having the same chemistry.

For wrought materials and especially for those materials whose mechanical properties are enhanced by heat treatment, forming practices, or a combination thereof, and for other materials for which the mechanical properties may be reasonably expected to be thickness dependent, data from one additional lot from material of at least 75% of the maximum thickness for which coverage is requested shall be submitted. If no maximum thickness is given, information shall be provided to support the suitability of the thickness used for the tested samples.

For Charpy V-Notch Impact Test For steels, nickel alloys, cobalt alloys, and aluminum alloys, data shall be provided at room temperature and 56 °C (100 °F) intervals, beginning at 93–38 °C (200–100 °F) above the maximum intended use temperature, unless the maximum intended use temperature does not exceed 38 °C (100 °F). For copper alloys, titanium alloys, and zirconium alloys, the test data shall be provided at room temperature, 66 °C (150 °F), and 93 °C (200 °F), and then at 56 °C (100 °F) intervals, to 56 °C (100 °F) above the maximum intended use temperature, unless the maximum intended use temperature does not exceed 38 °C (100 °F).

For Fatigue Service If the material is to be used in components that operate under compressive loads (e.g., external pressure), stress-strain (S-N) plots (tension or compression) shall be furnished for each of the three heats of material at 100 °F intervals from room temperature up to 56 °C (100 °F) above the maximum temperature desired. Engineering stress-strain (S-N) data shall be provided in the form of stress-strain plots and digitized data, from which the plots were derived, in tabular form up to 1.2% strain. Digitized data shall be provided at intervals no greater than 0.01% strain.

For Welding Data The following three types of welding information are required for a new base metal for use in welded construction in an ASME BPVC:

– Data on weldability
– Data on strength and toughness in the time-independent regime
– Data on strength in the time-dependent regime

The following welding information shall be provided by the Inquirer, to support the request for a Code Case for, or incorporation of, a new base material for use in elevated temperature service:

(i) When there is one or more AWS, ASME, or equivalent consumable specification and classification suitable for use with the new base material and when such consumable/process combinations can produce welds and weldments that have both good weldability and as high or higher strengths as the base metal over the range of expected service temperatures, no time-dependent test data is required.
(ii) When there is no such suitable consumable having an AWS, ASME, or equivalent specification and classification, or when it is necessary or desirable to use a new, perhaps nominally matching, welding consumable, the following information shall be provided to the Committee:
   – Chemistry ranges for each element specified for the consumable to be used
   – Creep-rupture data for weldments made with one lot of consumables for each process

See ASME Sec. II, Part C, Appendix 5, for more details.

1.1.14 Guidelines on Multiple Marking of Materials in the ASME BPVC

In many cases, using material that is identified with two or more specifications (or grades, classes, or types) may be permitted even if they have different strengths or even if one of them is not permitted for use in the construction code of application. The ASME Committee has addressed variants of these questions in several interpretations: I-89-11, IIA-92-08, VIII-1-89-269, and VIII-1-89-197.

Dual or multiple marking is not acceptable if two or more specifications to which the material is marked have mutually exclusive requirements.

This prohibition includes more than just chemistry and property requirements. One example is SA-515 and SA-516; the former requires melting to coarse grain practice, while the latter requires melting to fine grain practice.

Another example is SA-213 TP304L and TP304H; the carbon content ranges of these grades have no overlap.

See ASME Sec. II, Part C, Appendix 7, for more details.

1.2 Conventional Design

1.2.1 Elastic Design and Plastic Design

1.2.1.1 Elastic Design (Plane-Stress Design)

The elastic design is based on preventing failure by bursting when the pressure is at its maximum near the end of the design life after the corrosion allowance has been used up (to be designed in elastic zone of the materials (<Yield Strength)).

1.2.1.2 Plastic Design (Plane-Strain Design)

The plastic design is based on preventing failure by creep-rupture during the design life (by API 530) (to be designed up to the plastic zone of the materials ($\geq$Yield Strength)). Slight deformation may be considered for the design with the life time of facilities. (e.g., bracing of surface condensers, stress intensity analysis of fracture toughness, and dam door of water power plants).

1.2.1.3 Elastic and Plastic Design (Plane-Stress and Strain Design)

The more severe condition after performed each design should be decided.

1.2.2 Equipment Life Time (See Table 1.35)

Table 1.35 Equipment life time (common design base in oil refinery plants) (see Notes)

Facilities	Condition	Design life time	Remark
Pressure vessel	Erection weight $\geq$ 50 ton	20–30 years	
	Erection weight < 50 ton	15–25 years	
Pressure vessel internals (tray, packing, etc.)	Tray, packing, etc.	5–20 years	Variable according to maintenance plan
Heater tubes	API 530/560	100,000 hours	Minimum
H/EX body	Shell and channels	15–25 years	
H/EX bundle	Run length $\leq$ 2 years	5–10 years	
	Run length > 2 years	10 years	
Piping	General lines	15–20 years	Including valves
	Tall tower overhead lines	15–30 years	
Pipelines	Aboveground	15–25 years	
	Underground	30–50 years	
Pumps, compressors	API standards	15–25 years	
Tank	Small diameter	15–25 years	
	Large diameter	20–30 years	
Package item		20–30 years	
Nuclear power plant		40–100 years	
Bridges		50–100 years	
Building		40–100 years	

Notes
1. The fatigue stress by required cycles and load may control the design life
2. The corrosion allowance normally controls the design life

1.2.3 *Stresses for Design*

1.2.3.1 Comprehension of Stress-Strain Curve

The shape and magnitude of the stress-strain curve (Fig. 1.15) of a metal will depend on its composition, heat treatment, prior history of plastic deformation, and the strain rate, temperature, and state of stress imposed during the testing. The parameters, which are used to describe the stress-strain curve of a metal, are the *tensile strength, yield strength or yield point, percent elongation, and reduction of area*. The first two are strength parameters; the last two indicate ductility. Unless the creep and rupture design (e.g., heaters, boilers, high temperature reactors, etc.) is considered, most facilities are designed at the elastic region.

See API Spec 16R for the definition of several types of stresses in the design of marine (offshore) drilling riser couplings.

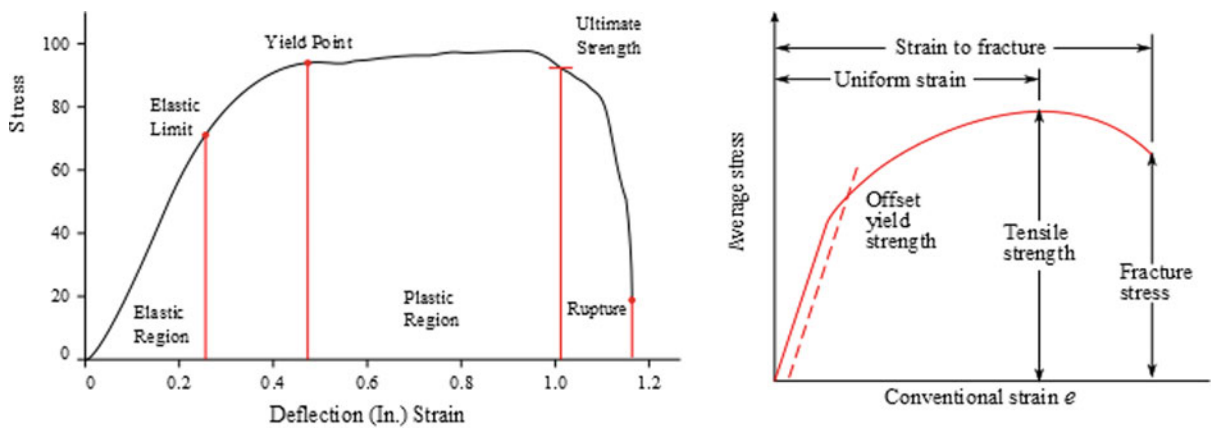


Figure 1.15 Stress-strain curve for ductile material

1.2.3.2 Classes of Stresses for Some Typical Cases in ASME (See Table 1.36)

Table 1.36 (1/2) Classes of stresses for some typical cases (ASME Sec. VIII, Div. 2, Table 5.6)

Vessel components	Location	Origin of stress	Type of stress[5]	Classification
Any shell including cylinders, cones, spheres, and formed heads	Shell plate remote From discontinuities	Internal pressure	General membrane Gradient through plate thickness	*Pm* *Q*
		Axial thermal gradient	Membrane Bending	*Q* *Q*
	Near nozzle or other opening	Net-section axial force and/or bending moment applied to the nozzle and/or internal pressure	Local membrane Bending Peak (fillet or corner)	P_L *Q* *F*
	Any location	Temperature difference between Shell and head	Membrane Bending	*Q* *Q*
	Shell distortions; out of roundness and dents	Internal pressure	Membrane Bending	P_m *Q*
Cylindrical or conical shell	Any section across Entire vessel	Net-section axial force, bending Moment applied to the cylinder or cone, and/or internal pressure	Membrane stress averaged through the thickness, remote from discontinuities; stress component perpendicular to cross section	*Pm*
			Bending stress through the thickness; stress component perpendicular to cross section	*Pb*
	Junction with head or flange or other opening	Internal pressure	Membrane Bending	P_L *Q*
Dished head or conical head	Crown	Internal pressure	Membrane Bending	*Pm* *Pb*
	Knuckle or junction to shell	Internal pressure	Membrane Bending	P_L[1] *Q*
Flat head	Center region	Internal pressure	Membrane Bending	*Pm* *Pb*
	Junction to shell	Internal pressure	Membrane Bending	P_L *Q*[2]

Table 1.36 (2/2) Classes of stresses for some typical cases (ASME Sec. VIII, Div. 2, Table 5.6)

Vessel components	Location	Origin of stress	Type of stress[5]	Classification
Perforated heads or shells	Typical ligament in a uniform pattern	Pressure	Membrane (average through cross section). Bending (averaged through width of ligament., but gradient through plate) Peak	*Pm* *Pb* *F*
	Isolated or a typical ligament	Pressure	Membrane (averaged through cross section) Bending (averaged through width of ligament., but gradient through plate) Peak	*Q* *Pb* *F*
Nozzles	Within the limits of reinforcement given by ASME Sec. VIII, Div. 2, 4.5	Pressure and external loads and moments including those attributable to restrained free end displacements of attached piping	General membrane Bending (other than gross structural discontinuity stresses) averaged through nozzle thickness	*Pm* *Pm*
	Outside the limits of reinforcement given by ASME Sec. VIII, Div. 2, 4.5	Pressure and external axial, shear, and torsional loads including those attributable to restrained free end displacements of attached piping	General membrane	*Pm*
		Pressure and external loads and moments, excluding those attributable to restrained free end displacements of attached piping	Membrane Bending	P_L *Pb*
		Pressure and all external loads and moments	Membrane Bending Peak	*Pm* *Q* *F*
	Nozzle wall	Gross structural discontinuities	Membrane Bending Peak	P_L *Q* *F*
		Differential expansion	Membrane Bending Peak	*Q* *Q* *F*
Cladding	Any	Differential expansion	Membrane Bending	*F* *F*
Any	Any	Radial temperature distribution[3]	Equivalent linear stress[4] Nonlinear portion of stress distribution	*Q* *F*
Any	Any	Any	Stress concentration (notch effect)	*F*

Abbreviations:
F = additional equivalent stress produced by a stress concentration or a thermal stress over and above the nominal (P + Q) stress level, P_m = general primary membrane equivalent stress, P_L = local primary membrane equivalent stress, P_b = primary bending equivalent stress, S = allowable stress at design temperature (Sec. II, Part D), S_{PS} = primary + secondary stress = max.[3S, 2Sy], Sy = YS = yield stress, Q = secondary equivalent stress

Notes: (with Fig. 1.16)
[1]Consideration shall be given to the possibility of wrinkling and excessive deformation in vessels with large diameter-to-thickness ratio
[2]If the bending moment at the edge is required to maintain the bending stress in the center region within acceptable limits, the edge bending is classified as *Pb*; otherwise, it is classified as *Q*
[3]Consider possibility of thermal stress ratchet
[4]Equivalent linear stress is defined as the linear stress distribution that has the same net bending moment as the actual stress distribution. See Table 1.6 Note (8) for the definitions of General Membrane and Local Membrane
[5]Consider possibility of thermal stress ratchet*

**Thermal Stress*: A self-balancing stress produced by a non-uniform distribution of temperature or by differing thermal coefficients of expansion. For the purpose of establishing allowable stresses, two types of thermal stress are recognized, depending on the volume or area in which distortion takes place

(i) A general thermal stress that is associated with distortion of the structure in which it occurs. If a stress of this type, neglecting stress concentrations, exceeds twice the yield strength of the material, the elastic analysis may be invalid, and successive thermal cycles may produce incremental distortion. Therefore, this type is classified as a secondary stress. Examples of general thermal stress are the stress produced by an axial temperature distribution in a cylindrical shell, the stress produced by the temperature difference between a nozzle and the shell to which it is attached, and the equivalent linear stress produced by the radial temperature distribution in a cylindrical shell

(ii) A local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint and are therefore classified as local stresses. Examples of local thermal stresses are the stress in a small hot spot in a vessel wall, the difference between the non-linear portion of a through-wall temperature gradient in a cylindrical shell, and the thermal stress in a cladding material that has a coefficient of expansion different from that of the base metal

Ratcheting: A progressive incremental inelastic deformation or strain that can occur in a component subjected to variations of mechanical stress, thermal stress, or both (thermal stress ratcheting is partly or wholly caused by thermal stress). Ratcheting is produced by a sustained load acting over the full cross section of a component, in combination with a strain controlled cyclic load or temperature distribution that is alternately applied and removed. Ratcheting causes cyclic straining of the material, which can result in failure by fatigue, and at the same time produces cyclic incremental growth of a structure, which could ultimately lead to collapse (Fig. 1.16)

Stress Category	Primary			Secondary Membrane Plus Bending	Peak
	General Membrane	Local Membrane	Bending		
Description (For examples, see ASME Sec. VIII, Div.2, Table 5.2).	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities/ concentrations. Produced only by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations	1.Increment added to primary or secondary stress by a concentration (e.g., notch). 2. Certain thermal stresses which may cause fatigue but not distortion cot distortion of vessel shape.
Symbol	P_m	P_L	P_b	Q	F

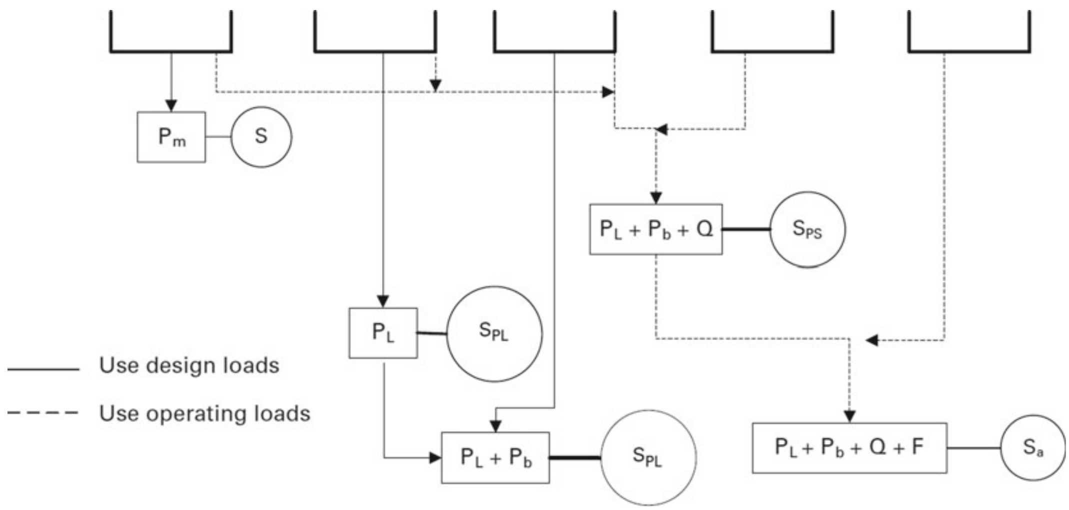


Figure 1.16 Stress categories and limits of equivalent stress (ASME Sec. VIII, Div. 2, Fig. 5.1). (See ASME Sec. VIII, Div.3, Fig. 9-200-1 for Div.3 Vessel)

1.2.3.3 Primary Stress

Primary stresses are developed in each component of a vessel due to sustained internal and external loads. The fundamental characteristic of primary stresses is that they are not self-limiting. In other words, no redistribution of load or reduction of stress will occur despite yielding within the component. Primary stresses are not reduced by the deformations they produce. Therefore, primary stresses that exceed the yield strength of the material will cause failure either by gross plastic deformation or by bursting.

Primary stresses are further divided into primary membrane stresses and primary bending stresses because different stress limits are applied for design, depending on the type of primary stress.

(a) Primary Membrane Stress

Primary membrane stresses are tensile or compressive stresses that are essentially uniform through the thickness.

Consequently, gross plastic deformation will occur when these stresses exceed the yield strength of the material. Examples of primary membrane stresses in pressure vessel shells are:

- Circumferential and longitudinal stress attributable to internal pressure.
- Longitudinal stress in horizontal vessels due to bending between saddle supports.
- Axial compression due to the weight of a vertical vessel.
- Stresses in a nozzle neck in the area of reinforcement due to internal pressure and to external forces and moments attributable to piping connections. Exceptions are those related to discontinuity effects.
- Axial tensile and compressive stresses due to wind and earthquake loads.

A thermal stress is not classified as a primary stress. Primary membrane stress is divided into general and local categories. A general primary membrane stress is one that is distributed in the structure such that no redistribution of load occurs as a result of yielding. Examples of primary stress are general membrane stress in a circular, cylindrical, or spherical shell due to internal pressure or to distributed live loads and the bending stress in the central portion of a flat head due to pressure.

The design limit for primary membrane stresses is the maximum allowable design stress for the material of construction at the design temperature. Continuous primary membrane stresses cannot exceed two thirds of the yield strength. However, stresses that act intermittently and for relatively short durations (e.g., those attributable to wind and earthquake loads) can be increased to 1.2 times the maximum allowable design stress.

(b) Primary Bending Stresses

Primary bending stresses vary from tension to compression through the cross section of a pressure vessel shell component. They are generally at a maximum at the surface. Higher average stresses are required to produce failure by plastic deformation in bending than for uniform tensile or compressive loads. Bending stresses are most likely to be the predominant primary stress in the following cases:

(i) The bending stress in the center of a flat head
(ii) The bending stress between the ligaments of closely spaced openings

The stress limits for components, when primary bending stresses predominate, are 1.5 times the maximum allowable design stress for the material of construction at the design temperature. This higher stress limit is usually incorporated into the design rules and equations for components that conform to the acceptable design details depicted in the ASME Code. The allowable design stress can be multiplied by 1.5 only if a stress analysis is made of the component.

(c) Local Primary Membrane Stress

A local primary membrane stress is a subcategory of primary membrane stress that is developed by sustained internal and external loads similar to primary membrane stresses. A local primary membrane stress exceeds the stress limit for a primary membrane stress, but as the higher stress is localized, it can be redistributed to the surrounding portions of the pressure vessel if yielding occurs, although the redistribution of stress upon localized yielding normally prevents failure of the pressure vessel. The plastic deformation associated with such yielding is unacceptable. Therefore, the stress limit for a localized stress of the material of construction at the design temperature can be as high as the minimum yield strength.

In order to prevent excessive elastic distortion, a local primary membrane stress is not permitted to extend in a longitudinal direction more than $(Rt_S)^{1/2}$, where R is the radius of curvature of the vessel component and t_S is its thickness. Furthermore, individual regions of localized stress must be separated by at least $2.5 \times (Rt_S)^{1/2}$.

Examples of local primary membrane stresses in pressure vessels are:

(i) Membrane stress at head-to-shell junctions
(ii) Membrane stress at conical-transition-to-cylindrical-shell junctions
(iii) Membrane stress in the shell at nozzles
(iv) Membrane stress at vessel supports or external attachments

1.2.3.4 Secondary Stresses

Secondary stresses differ from primary stresses because they are self-limiting. Secondary stresses develop at structural discontinuities.

Examples of secondary stresses are:

(i) Bending stresses at head-to-shell junctions
(ii) Bending stress at conical-transition-to-cylindrical-shell junction
(iii) Bending stress in the shell at nozzles
(iv) Bending stress at vessel supports and external attachments
(v) Thermal stresses produced by temperature gradients in the shell, by differences in temperature between the nozzle and shell, or by differences in temperature between ID and OD of tubes of heaters or boilers

Unlike primary stresses, secondary stresses are reduced in magnitude by the local yielding, before gross plastic deformation or bursting can occur. The first application of load during hydrotest will generally suffice to significantly reduce the secondary stresses in a pressure vessel, but subsequent load applications could further reduce the secondary stresses.

The stress limit for secondary stresses is typically 3.0 times the maximum allowable design stress for the material of construction at the design temperature in pressure vessel. Therefore, the secondary stress is permitted to be as high as twice the yield strength, but it is reduced in magnitude by local yielding. Unless a detailed stress analysis is made, structural discontinuities that develop secondary stresses should be separated by a distance of at least $2.5 \times (Rt_S)^{1/2}$ to avoid additive effects that could increase the total secondary stress above 3.0 times the maximum allowable design stress.

A distinction must be made between local primary membrane stresses. Local primary membrane stresses also develop at structural discontinuities and are essentially self-limiting. However, they are categorized as primary stresses because the plastic deformation associated with the yielding (required to redistribute the local membrane stress) may be excessive. Therefore, in effect, the membrane component of the stress developed by the self-constraint at structural discontinuities is categorized as a primary stress, whereas the bending component of the stress is categorized as a secondary stress.

Transients during heating up and cooling down can lead to excessive thermal gradients on materials, particularly on thick-walled vessels, resulting in excessive stresses on the material. These stresses can be tensile or compressive in nature. Tensile stress pulls an object apart. Compressive stress compresses or pushes an object. Thermal stresses tend to be cyclic in nature (heating followed by cooling, followed by heating, etc.), fatiguing the materials or components subjected to the stress.

Thermal stresses are of particular concern in thick-walled ($0.025 \leq t$/OD, normally <0.05)* vessels and components because of the magnitude of the stresses involved. Vessel design, construction, and application factor determine if a vessel has thin-walled (t/OD < 0.005), medium-walled ($0.005 \leq t$/OD < 0.025), or thick-walled thickness.

*API 530 (calculation of fired heater tube thickness) requires thermal stress between inside and outside of the tubes when t/OD < 0.15 in elastic range. This methodology may be also used for the analysis of thermal shock. (See Sect. 2.2.1.13.)

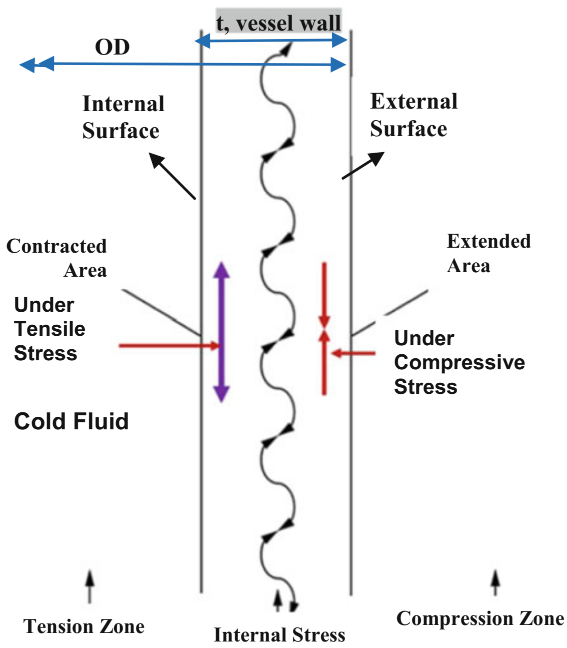


Figure 1.17 Thermal stresses on a thick-walled vessel

When a thick-walled vessel is rapidly heated or cooled, one part of the vessel's wall may try to expand or contract, while the adjacent wall section, which has a delayed response to the temperature change, tries to restrain it. Therefore, both sections of the vessel wall are stressed, compressive stress on one side and tensile stress on the other side, as illustrated in Fig. 1.17.

1.2.3.5 Peak Stresses

Peak stresses in pressure vessels are generally the highest stresses that exist in the various separate components of a vessel. They are distinguished from primary and secondary stresses in that they do not produce significant distortion, but they need not be localized nor necessarily self-limiting. They are developed at location of high stress concentration (i.e., acute structural discontinuities) as below and by certain types of thermal stress. Peak stress is of consequence only worth regard to the possible initiation of fatigue failure if the material lacks adequate toughness. The stress limit for peak stresses is 3 times the allowable design stress for the material of construction.

(i) Stress at corners and fillets of nozzles
(ii) Thermal stresses in the shell related to cladding or weld overlay
(iii) Thermal stresses in the shell due to rapid change in temperature of vessel contents

1.2.3.6 Discontinuity Stresses

(a) General

Pressure vessels consist of axially symmetrical elements of different geometries and thicknesses and sometimes different materials. If these individual components were allowed to expand freely as separate sections under internal pressure, each element would have an edge radial displacement and an edge rotation that would differ from those of the adjacent component. However, since all these components form a continuous structure and must deflect and rotate together, the differences in movement at junctions result in local deformations and induce local stresses. Other items, such as stiffening rings and internal bulkheads, also affect the cylinder deformation and introduce local stresses.

Stresses created by the interaction of two shell components at their junction (i.e., an abrupt change in geometry of the vessel shell or a structural discontinuity) are called discontinuity stresses. Under static loads, such as constant internal pressure, and with ductile materials, discontinuity stresses can be kept low by proper design. They become important, however, under cyclic loads or at low temperatures where the ductility of the material is reduced. Discontinuity stresses must be added to membrane stresses developed by other loads.

There are two categories of structural discontinuities: gross and local.

- Gross structural discontinuities affect a relatively large portion of a structure and have significant effect on the overall stress pattern. All of the junctions between shell components fall into this category.
- Local structural discontinuities are sources of stress or strain intensification that affect only a small volume of material and do not have a significant effect upon the overall stress pattern.

  They usually produce peak stresses.

(b) Calculation of Discontinuity Stresses

Discontinuity stresses can be evaluated using the general bending theory of thin cylindrical shells. Since this method uses edge forces and moments as unknown quantities, it is called the Force Method.

(c) Discontinuities in Cylindrical Shells

Discontinuities in cylindrical shells occur when the shell is constructed of portions of different thicknesses and/or different materials. If the cylinder is long enough, the effect of the edge forces will dissipate to a small value within short distance, and their overall effect on the shell can be neglected.

1.2.3.7 Shear Stress, τ

$\tau = F$ (force applied)/A (area to which the force is applied)

Acceptance in ASME Sec. VIII, Div. 1

; Groove Welding: 70% allowable stress of base metal

; Fillet Welding: 55% allowable stress of base metal

1.2.3.8 Stress Values in ASME Sec. II, Part D – See Table 1.37

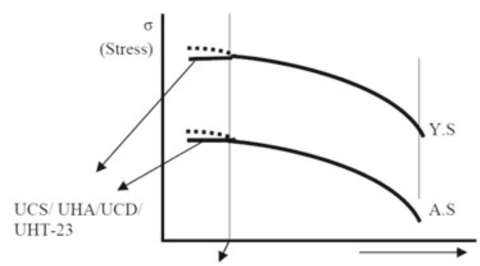
Table 1.37 Tables for stress values in ASME Sec. II, Part D

All table numbers here come from ASME Sec. II, Part D.

Materials	Condition	Div. 1	Div. 2	Div. 3
Ferrous materials	Test at atmospheric temperature	Table 1A for TS, YS, AS (Note 3)	Table 2A for TS, YS, AS (Note 3)	–
	Test at high temperature	Table U for TS Table Y-1 for YS (except Div. 3) Table Y-3 for YS (only for Div. 3) (Note 2)		
Nonferrous materials	Test at atmospheric temperature	Table 1B for TS, YS, AS (Note 3)	Table 2B for TS, YS, AS (Note 4)	–
	Test at high temperature	Table U for TS Table Y-1 for YS (except Div. 3) Table Y-3 for YS (only for Div. 3) (Note 2)		
Cr-Si-V steels	Test at atmospheric temperature	–	–	Table U-2 for TS
Bolting materials	Test at atmospheric temperature	Table 3 for AS (Note 4)	Table 3 for AS (Note 4) Table 4 for SI (Note 1, 4)	Table Y-3 for YS

Legends: TS tensile strength, YS yield strength, AS maximum allowable stress, SI stress intensity value
Notes: 1: Use with ASME Sec. VIII, Div. 2, Appendices 4, 5, and 6
2: Different maximum temperature limitations
3: Appendix 1 – basis for establishing stress values in Table 1A and B
4: Appendix 2 – basis for establishing stress values in Tables 2A, B, 3, and 4

Figure 1.18 Allowable stresses of low temperature service metals in ASME Sec. VIII, Div. 1



Temperature

▪▪▪▪▪▪▪Sec. VIII, Div.1, ULT-23

states the higher strength (-----)values can be used for the following materials;
(1) 5%, 8%, 9% Ni Steel (SA645, 353, 553, 333, 334)
(2) Austenitic Stainless (SA-240)
(3) Aluminum Alloys (5803-O)

The Minimum Temperature in the Table for A.S.

Allowable Stress and Minimum Tensile Strength Values for Parts ▪▪▪▪▪▪▪
: See ASME Sec. VIII Div.1, Appendix AA (page A-79 to A83)
Table ULT-23 Maximum Allowable Stress Values (5%, 8%, 9% Ni steels, 304SS, and Aluminum 5083-O)
Table ULT-82 Minimum Tensile Strength Requirements for WPQ Tests

1.2.3.9 Allowable Stresses of Low Temperature Service Metals in ASME Sec. VIII, Div. 1

However, ASME Sec. VIII, Div. 2, 3.16, and several end-user standards are indicated below.

For design temperatures colder than −30 °C (−20 °F), the allowable design stress values and strength parameter values to be used in design shall not exceed those given in the pertinent tables in Section II, Part D, for −30 °C to 40 °C (−20 °F to 100 °F), unless specifically addressed in the project specifications and datasheets (Fig. 1.18).

1.2.3.10 Criteria for Establishing Allowable Stress Values (Tables 1.38, 1.39, 1.40, 1.41, 1.42, 1.43, and 1.44)

(a) ASME BPVC

The allowable stress values in ASME Sec. II, Part D, Tables 1A and 1B, are established for the most common standard materials. In the determination of allowable stress values for materials, the ASME Committee is guided by successful experience in service, insofar as evidence of satisfactory performance is available. Such evidence is considered equivalent to test data where operating conditions are known with reasonable certainty. In the evaluation of new materials, the ASME Committee is guided to a certain extent by the comparison of test information with available data on successful applications of similar materials.

Nomenclature (for Tables 1.38, 1.39, 1.40, 1.41, 1.42, 1.43, and 1.44)*:*

$F\ avg$ = multiplier applied to average stress for rupture in 100,000 hr. at 816 °C (1500 °F) and below, F avg = 0.67.
Above 816 °C (1500 °F), it is determined from the slope of the log time-to-rupture versus log stress plot at 100,000 hr. such that log $Favg = 1/n$, but it may not exceed 0.67.
R_T = ratio of the average temperature-dependent trend curve value of tensile strength to the room temperature tensile strength
R_Y = ratio of the average temperature-dependent trend curve value of yield strength to the room temperature yield strength

Table 1.38 Criteria for establishing allowable stress values

Product/material	≤Room temperature		>Room temperature (note 2)						
	(a) Tensile strength	(b) Yield strength	(c) Tensile strength		(d) Yield strength		(e) Stress rupture		(f) Creep rate
Wrought or cast ferrous and nonferrous	$S_T/3.5$	2/3 S_Y	$S_T/3.5$	(1.1/3.5) S_T R_T	2/3 S_Y	2/3 S_Y R_Y *or 0.9* S_Y R_Y *(Note 1)*	F_{avg} $S_{R\ avg}$	0.8$S_{R\ min}$	1.0 S_C
Welded pipe or tube, ferrous and nonferrous	(0.85/3.5) S_T	2/3 × 0.85S_Y	(0.85/3.5) S_T	(1.1×0.85)/3.5 × S_T R_T	2/3 × 0.85S_Y	2/3 × 0.85 S_Y R_Y *or 0.9 × 0.85* S_Y R_Y *(Note 1)*	(F_{avg}×0.85) $S_{R\ avg}$	(0.8 × 0.85) $S_{R\ min}$	0.85 S_C

Source: ASME Sec. II, Part D, Mandatory Appendix Table 1-100 for Table 1A & 1B modified

Notes:

(1) Two sets of allowable stress values may be provided for ASS in ASME Sec. II, Part D, Table 1A, and nickel alloys and cobalt alloys in ASME Sec. II, Part D, Table 1B, having *SY/ST* ratio < 0.625. The lower values are not specifically identified by a footnote. These lower values do not exceed 2/3 of the yield strength at temperature. The higher alternative allowable stresses are identified by a footnote. These higher stresses may exceed 2/3 but do not exceed 90% of the yield strength at temperature. The higher values should be used only where slightly higher deformation is not in itself objectionable. These higher stresses are not recommended for the design of flanges or for other strain-sensitive applications

Commentary Notes:

(2) The maximum allowable stress shall be the lowest value [between (a) and (b) or between (c) and (d) for elastic design and between (e) and (f) for creep-rupture design] obtained from the criteria in this table

Table 1.39 Criteria for establishing allowable stress values of casting

Product/material	Table	Below room temperature (Note 1)		Room temperature and above (Note 1)			
		(a) Tensile strength	(b) Yield strength	(c) Tensile strength		(d) Yield strength	
Cast iron	UCI-23	S_T /10	NA	S_T /10	*1.1*/10 $S_T R_T$	NA	NA
Nodular iron	UCD-23	S_T /5	2/3 S_Y	S_T /5	*1.1*/5 $S_T R_T$	2/3 S_Y	2/3 $S_Y R_Y$
Wrought or cast ferrous and nonferrous	ULT-23	S_T R_T /3.5	2/3 $S_Y R_Y$	NA	NA	NA	NA

Source: ASME Sec. VIII, Div. 1, Nonmandatory, Appendix P modified

Commentary Note (1) The maximum allowable stress shall be the lowest value [between (a) and (b) or between (c) and (d) for elastic design] obtained from the criteria in Table 1.30 above

Table 1.40 Maximum allowable stress values in tension for cast iron

Spec. No.	Class	Specified Min. Tensile Strength, ksi (MPa)	Maximum Allowable Stress, MPa (ksi), For Metal Temperature Not Exceeding		Ext. Press. Chart Figure No. (Note 1)
			230 °C (450 °F) and colder	345 °C (650 °F)	
SA-667	. . .	20 (138)	13.8 (2.0)	N.R	CI-1
SA-278	20	20 (138)	13.8 (2.0)	N.R	CI-1
SA-278	25	25 (172)	17.2 (2.5)	N.R	CI-1
SA-278	30	30 (207)	20.7 (3.0)	N.R	CI-1
SA-278	35	35 (241)	24.1 (3.5)	N.R	CI-1
SA-278	40	40 (276)	27.6 (4.0)	27.6 (4.0)	CI-1
SA-278	45	45 (310)	31.0 (4.5)	31.0 (4.5)	CI-1
SA-278	50	50 (345)	34.5 (5.0)	34.5 (5.0)	CI-1
SA-47	Grade 32510	50 (345)	34.5 (5.0)	34.5 (5.0)	CI-1
SA-278	55	55 (379)	37.9 (5.5)	37.9 (5.5)	CI-1
SA-278	60	60 (414)	41.4 (6.0)	41.4 (6.0)	CI-1
SA-476	. . .	80 (552)	55.2 (8.0)	N.R	CI-1
SA-748	20	16 (110)	11.0 (1.6)	N.R	CI-1
SA-748	25	20 (138)	13.8 (2.0)	N.R	CI-1
SA-748	30	24 (165)	16.5 (2.4)	N.R	CI-1
SA-748	35	28 (193)	19.3 (2.8)	N.R	CI-1

Source: Table UCI-23 in ASME Sec. VIII, Div. 1, modified

Commentary Note: N.R. = not recommended unless otherwise approved by the end-user

(1) See Figure CI-1 in Subpart 3 of ASME Sec. II, Part D

Table 1.41 Criteria for establishing design stress intensity/allowable stress values for ASME Sec. II, Part D, Tables 2A and 2B

Product/Material	Room Temperature and Below (Note 2)		Above Room Temperature (Note 2)			
	Tensile Strength (a)	Yield Strength (b)	Tensile Strength (c)		Yield Strength (d)	
Wrought or cast, ferrous and nonferrous	1/3 S_T	2/3 S_Y	1/3 S_T	(1.1/3) $S_T R_T$	2/3 S_Y	2/3 $S_Y R_Y$ or 0.9 $S_Y R_Y$ [Note(1)]
Welded pipe or tube, ferrous and nonferrous	(0.85/3) S_T	(2/3 × 0.85) S_Y	0.85/3 S_T	(1.1 × 0.85/3) $S_T R_T$	(2/3 × 0.85) S_Y	(2/3 × 0.85) $S_Y R_Y$ or (0.9 × 0.85) $S_Y R_Y$ [Note(1)]

Source: ASME Sec. II, Part D, Table 2–100(a) modified

Notes: 2/3 × 0.85 = 0.567, 0.85/3 = 28.333, 1.1 × 0.85/3 = 31.167, 0.9 × 0.85 = 0.765

(1) For ASS, nickel alloys, and cobalt alloys having an S_Y/S_T ratio less than 0.625, see the design stress intensity values in ASME Sec. II, Part D, Tables 2A and B, may exceed 2/3 and may be as high as 90% of the YS at temperature

Commentary Notes:

(2) The maximum allowable stress shall be the lowest value [between (a) and (b) or between (c) and (d) for elastic design] obtained from the criteria in Table 1.41

Table 1.42 Criteria for establishing design stress intensity/allowable stress values for ASME Sec. II, Part D, Table 3

Product/material	Room temperature and below (Note 2)		Above room temperature (Note 2)						
	(a) Tensile strength	(b) Yield strength	(c) Tensile strength		(d) Yield strength		(e) Stress rupture		(f) Creep rate
Bolting, annealed ferrous and nonferrous	1/4 S_T	2/3 S_Y	1/4 S_T	(1.1 /4) $S_T R_T$	2/3 S_Y	2/3 $S_Y R_Y$	F_{avg} S_{Ravg}	0.8 S_{Rmin}	1.0 Sc
Bolting, with strength enhanced by heat treatment or strain hardening, ferrous and nonferrous [Note(1)]	1/5 S_T	1/4 S_Y	1/5 S_T	(1.1 /4) $S_T R_T$	1/4 S_Y	2/3 $S_Y R_Y$	F_{avg} S_{Ravg}	0.8 S_{Rmin}	1.0 Sc

Source: ASME Sec. II, Part D, Table 2–100(b) modified

Notes: 1.1/4 = 0.275

(1) For materials whose strength has been enhanced by heat treatment or by strain hardening, the criteria shown shall govern unless the values are lower than for the annealed material, in which case the annealed values shall be used

Commentary Notes:

(2) The maximum allowable stress shall be the lowest value [between (a) and (b) or between (c) and (d) for elastic design and between (e) and (f) for creep-rupture design] obtained from the criteria in Table 1.42. See Sect. 1.3.3 in this book for creep-rupture condition

Table 1.43 Criteria for establishing design stress intensity/allowable stress values for ASME Sec. II, Part D, Table 4

Product/Material (ferrous and nonferrous metals)	Room Temperature and Below(2)		Above Room Temperature(2)	
	(a) Tensile Strength	(b) Yield Strength	(c) Tensile Strength	(d) Yield Strength
Bolting, with strength not enhanced by heat treatment or strain hardening	1/4 S_T	2/3 S_Y	(1/1.4) $S_T R_T$	2/3 $S_Y R_Y$
Bolting, with strength enhanced by heat treatment or strain hardening(1)	NA	NA	NA	1/3 $S_Y R_Y$

Source: ASME Sec. II, Part D, Table 2–100(c)

Notes: 1/1.4 = 0.714

(1)For materials whose strength has been enhanced by heat treatment or by strain hardening, the criteria shown shall govern unless the values are lower than for material whose strength is not enhanced by heat treatment or strain hardening, in which case the values for the material whose strength has not been enhanced by heat treatment or strain hardening shall be used

(2)The maximum allowable stress shall be the lowest value [between (a) and (b) or between (c) and (d) for elastic design] obtained from the criteria in Table 1.43

$S_{R\ avg}$ = average stress to cause rupture at the end of 100,000 hr
$S_{R\ min}$ = minimum stress to cause rupture at the end of 100,000 hr
$S_{C\ avg}$ = average stress to produce a creep rate of 0.01%/1000 hr
S_T = specified minimum tensile strength at room temperature
S_Y = specified minimum yield strength at room temperature
n = a negative number equal to Δ log time-to-rupture divided by Δ log stress at 100,000 hr
NA = not applicable

Table 1.44 Criteria for establishing design stress intensity/allowable stress values for ASME Sec. II, Part D, Tables 5A and 5B

Product/Material	Below Room Temperature		Room Temperature and Above [(2)]			
	(a) Tensile Strength	(b) Yield Strength	(c) Tensile Strength	(d) Yield Strength	(e) Stress Rupture	(f) Creep Rate
All wrought or cast ferrous and nonferrous product forms except bolting	S_T /2.4	S_Y /1.5	S_T /2.4	$R_Y S_Y$/1.5	Min. ($F_{avg} S_{R\ avg}$ or 0.8 S_{Rmin})	1.0 $S_{C\ avg}$
All wrought or cast austenitic and similar nonferrous product forms except bolting[(1)]	S_T /2.4	S_Y /1.5	S_T /2.4	Min. (S_Y/1.5 or 0.9 $S_Y R_Y$)	Min. ($F_{avg} S_{R\ avg}$ or 0.8 $S_{R\ min}$)	1.0 $S_{C\ avg}$

Source: ASME Sec. II, Part D, Table 10–100

General Notes: When using this stress basis criterion to determine the allowable stresses for a specific material as a function of temperature, the derived allowable stress at a higher temperature can never be greater than the derived allowable stress at a lower temperature

Notes: 1/2.4 = 0.417, 1/1.5 = 0.667 S_Y = YS

[(1)] These higher stress values were established at temperatures where the short-time tensile properties govern, to permit the use of these materials where slightly greater deformation is acceptable. The stress values in this range exceed 2/3 YS but do not exceed 90% YS at temperature. These stress values are not recommended for the flanges of gasketed joints or other applications where slight amounts of distortion can cause leakage or malfunction. ASME Sec. II, Part D, Table Y-2, lists multiplying factors that, when applied to the yield strength values shown in ASME Sec. II, Part D, Table Y-1, will give allowable stresses that will result in lower values of permanent strain

[(2)] The maximum allowable stress shall be the lowest value [between (a) and (b) or between (c) and (d) for elastic design and between (e) and (f) for creep-rupture design] obtained from the criteria in Table 1.44. See Sect. 1.3.3 in this book for creep-rupture condition

(b) API
API Spec 6A/ISO 10423 (Specification for Wellhead and Christmas Tree Equipment) allows the use of design allowable stresses for non-standard materials in pressure-containing components below:
; S_t (maximum allowable general primary membrane stress intensity at hydrostatic test pressure)
= min (5/6 SMYS, 2/3 SMTS, min.)
; S_m (design stress intensity at rated working pressure) = min (2/3 SMYS, 1/2 SMTS)
; S_s (maximum combined primary and secondary stress intensity) = min (2 SMYS, SMTS)

See API TR 6AF1 for Technical Report on Temperature Derating on API Flanges per Load Combination.

1.2.3.11 Allowable Stresses in ASME B31.3 (Similar in Other B31.xx Series)

The allowable stress is reduced as the service temperature is becoming higher up to the temperature (see Table 2.15) limited by code. The higher strength of material at high temperature may be a major concern for engineers to reduce the thickness and flange rating unless the project/user specifications require limitations. Materials unlisted in B31.3, Table A-1(M) and A-2(M), may be used as per below.

; For a material that conforms to ASME B31.3, para. 323.1.2, the TS and YS at temperature shall be derived by multiplying the average expected TS and YS at temperature by the ratio divided by the average expected TS and YS at room temperature. Unlisted materials may be used provided they conform to a published specification covering chemistry, physical and mechanical properties, method and process of manufacture, heat treatment, and quality control and otherwise meet the requirements of this Code. See also ASME BPVC Section II, Part D, Appendix 5. Allowable stresses shall be determined in accordance with the applicable allowable stress basis of this Code or a more conservative basis. Basis for design stresses of ferritic steels (other than bolting, gray iron, malleable iron) is to get the lower of 1/3TS or 2/3YS in general service except 2/3YS in high pressure service (Chapter IX – Part K). See ASME B31.3, para. A302.3, for allowable stresses of non-metallic materials.

1.2.3.12 Allowable Variations in Elevated Temperature Service (See ASME B31.3 Appendix V as well)

The allowable stress can be different even though it is the same material because the most critical factor for selection of allowable stress value is the design (safety) factor as per the applicable code (type of facility) as seen in Table 1.45 (e.g., of SA-106B).

1.2.4 Strength Calculation

1.2.4.1 Requirements of Strength Calculation in ASME Sec. VIII, Div. 1, TEMA, API, and Others (Table 1.46)

1.2.4.2 Circumferential (Hoop) Stress ($R/t \geq 10$) and Longitudinal (Axial or Meriodic) Stress (Table 1.47)

Where

R = inside radius
D = inside diameter
P = internal pressure
t = minimum required thickness
σ_L = longitudinal (axial or meriodic) stress
σ_C = circumferential (hoop) stress
S = allowable stress at design temperature in ASME Sec. II, Part D
E = joint efficiency
C.A. = corrosion allowance

Table 1.45 Allowable stresses of ASME Sec. VIII and B31.3 (e.g., SA-106B)[1] [2]

Data	ASME Sec. VIII Division 1	ASME Sec. VIII Division 2, Class 1[5]	ASME Sec. VIII Division 2, Class 2[5]	ASME B31.3 Table A-1	ASME B31.3 Table K-1
Tensile strength/yield strength, ksi	60/35	60/35	60/35	60/35	60/35
Allowable stresses, ksi	17.1	20.0	(3)	19.9	23.3
At 38 °C (100 °F)	17.1	20.0	23.3	19.9	21.9
At 93 °C (200 °F)	17.1	20.0	21.4	19.9	20.7
At 149 °C (300 °F)	17.1	19.9	20.6	19.9	19.9
At 204 °C (400 °F)	17.1	19.0	19.9	19.0	19.0
At 260 °C (500 °F)	17.1	17.9	19.0	17.9	17.3
At 316 °C (600 °F)	15.6	16.8	17.9	16.7	16.7
At 371 °C (700 °F)	10.8	–	16.8	11.4	–
At 427 °C (800 °F)	5.9	–	–	5.9	–
At 482 °C (900 °F)	2.5	–	–	2.5	–
At 538 °C (1000 °F)	–	–	–	1.0	–
At 593 °C (1100 °F)			–		
Design factor	3.5	3.0	2.4	3.0	2.4
Max. design temperature (DT) in Sec. II, Part D	538 °C (1000 °F)[4]	371 °C (700 °F)	371 °C (700 °F)	593 °C (1100 °F)[4]	371 °C (700 °F)

Notes (*)
[1]The designated TS and YS at room temperature are the inherent values for a certain material regardless of codes and standards
[2]Allowable stresses are variable values in accordance with the applicable codes and standards
[3]Based on YS/1.5 for general membrane. The value of 1 × YS is used for local membrane
General membrane: Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads
Local membrane: Average stress across any solid section. Consider discontinuities but not concentrations. Produced only by mechanical loads
[4]All carbon steels are limited up to 427°C (800°F) when graphitization is expected due to long-term exposure
[5]See Table 1.52 in this book

Table 1.46 (1/2) Requirements of strength calculation in ASME Sec. VIII, TEMA, API, and others

Facilities	Parts	Condition	Codes or codes interpretation (ASME & others)	Other references and remark
Pressure Vessels and H/EXs	Shell, pipe, tube	Int. pressure	Div. 1 UG 27	
	Shell, pipe, tube	Ext. pressure	Div. 1 UG 28	
	2:1 head	Int. pressure	Div. 1 UG 32(d)	Div. 1 UW 11 to 13 (FigureUW13 & 13.1), 51, 52, UG 81, UCS-79
	Hemispherical head	Int. pressure	Div. 1 UG 32(f), (l), Table ULT-23, App.1-3	
	Torispherical head	Int. pressure	Div. 1 UG 32(e)	
	Heads	Ext. pressure	Div. 1 UG 33, UCS-33, UNF-33, UHA-31, UCI-32 & 33, UCL-23(b) & (C), 26, UCD-32 & 33, App.L	
	Cone	Int. pressure	Div. 1 UG 32(g), (h), App.1-8	
	Cone	Ext. pressure	Div. 1 UG 33(f)	
	Flat cover	Int. pressure	Div. 1 UG 34	
	Bolted heads (spherically dished covers)	Int. pressure	Div. 1 App.1-6	
	Bolted flange connections	Int. pressure	Div. 1 UG11, 34, 44 App.2 & 5	
	Nozzle neck	Int. & ext. pressure	Div. 1 UG 36	
	Reinforcing/stiffening rings	Ext. pressure	Div. 1 UG 29 & 30	*3
	Nozzle openings and reinforcing pad	Int. pressure	Div. 1 UG 37 to 39, 40 to 42, UW 14 to 16, App.1-7	
	Nozzle local stress analysis	Ext. load	WRC 107 and 297	*4
	Jacket	Int. & ext. pressure	Div. 1 App. 9, 17, UG-36, 45, 46, 47, 99, 101	
	Special flanges	Int. pressure	Div. 1 App. 2 and Y	
	Expansion joints	Int. pressure	Div. 1 UHX-16 & 17, App. 5 & 26 and EJMA	*17, Thermal cycle
	Head with continuous rings	Int. & ext. pressure	*17	*4
	Int. manhole cover in vessel	Int. & ext. pressure	*17	
	Nozzle & reinforcing pad on multi-open area	Int. pressure	Div. 1 UG 42, *17	
	Noncircular cross section	Int. pressure	Div. 1 App. 13	
	Multiwall	Int. pressure	Div. 1 Part ULW	
	Wind & seismic load	Ext. load	ASCE 7, NBC, UBC	

Table 1.46 (2/2) Requirements of strength calculation in ASME Sec. VIII, Div. 1, TEMA, API, and others (cont'd)

Facilities	Parts	Condition	Codes or codes interpretation (ASME & others)	Other references and remark
Bin	Body	Self & ext. load		*8
Supports and lugs	2 saddles	Self & ext. load	Div. 1, App. G L.P. Zick analysis, *14	*4, *8
	Lifting lugs	Erection load	*17	*4, *8
	Setting lugs	Self & ext. load		*4, *8
	Legs	Self & ext. load	AISC/CISC	*4, *8
	Reinforcing ring on rectangular tanks	Self & ext. load	*17	*3
	Top davit	Lifting load	*18	*8
	Fatigue analysis: FEM	Self, int., & ext. load	Div. 2, 3.15, Annex 3-F & 5-B/C/F, and software	
	Braced and stayed	Self, int., & ext. pressure	Div. 1 UG-47, 48 to 50, UW-19, 83, App.17, *8	
	Knee brace for platform or pipeline supports	Ext. load		*8
	Shear load in bolted connection	Ext. load		*8
H/EXs	Components	Int. & ext. pressure	TEMA Div. 1 Part UHX API 660 & 661	ALTEMA for cryogenic service
	Tubesheets	Int. & ext. pressure	Div. 1, App. AA and TEMA	
Surface condenser	All		HEI	
Piping	Fatigue	Cyclic	B31.3 Para 304.1.2, A319.1.1, F301.10, and K304.8	ASME B31 series
	Straight pipe	Int. pressure	B31.3 Para 304.1 and K304.1	
	Bends (curved and mitered segments)	Int. pressure	B31.3 Para 304.2 and K304.2	
	Branch connection	Int. pressure	B31.3 Para 304.3 and K304.3 & Appendix H	
	Closures	Int. pressure	B31.3 Para 304.4, A304.4, M306.6, K304.4, and /Div. 2	
	Flexibility analysis	Int. pressure	B31.3 Para 319.3, A319.3, and Appendix C	
	Reaction	Int. pressure	B31.3 Para 319.5	
	Expansion joints	Int. pressure	B31.3 Appendix X	Thermal cycle
	Differential thermal expansion	Int. pressure	B31.3, 301.7.3, 313, 331.1.3, K331.1.3, F309, App. L	
	Stress analysis	Int. pressure	Software	
Flange	Flange MAWP	Int. & ext. pressure	ASME B16.5	
Storage tanks	Components	Self, int., & ext. pressure	API 650, 620, 2000	
Safety valve Devices	Safety relief valves	Int. pressure	Div. 1, UG-125 through 137 and App. 11 B31.3 Para 301.2.2, 322.6, 345.5.1, K322.6.3, and K345.1	ASME B31 series
Fired heater			API 530 & 560	
Steel stack			ASME STS-1	
FRP vessel			ASME Sec. X	
Thermoplastic			ASME RTP-1	

*References (Other than codes and standards)

1. Bruce E. Ball and Will J. Carter, CASTI Guidebook to ASME Sec. VIII Div. 1 – Pressure Vessel, CASTI, 2002
2. Robert Chuse and Bryce E. Carson, Pressure Vessels-The ASME Code Simplified, McGraw-Hill, Inc.1993
3. Eugene F. Megyesy, Pressure Vessel Handbook, PVHP, Inc. 8th Edition
4. Henry H. Bednar, Pressure Vessel Design Handbook, VNR company, 1981
5. Anthony L. Kohan, Pressure Vessel Systems, McGraw-Hill, Inc.1987
6. Warren C. Young, Roark's Formulas for Stress and Strain, McGraw-Hill, Inc. 6th Edition
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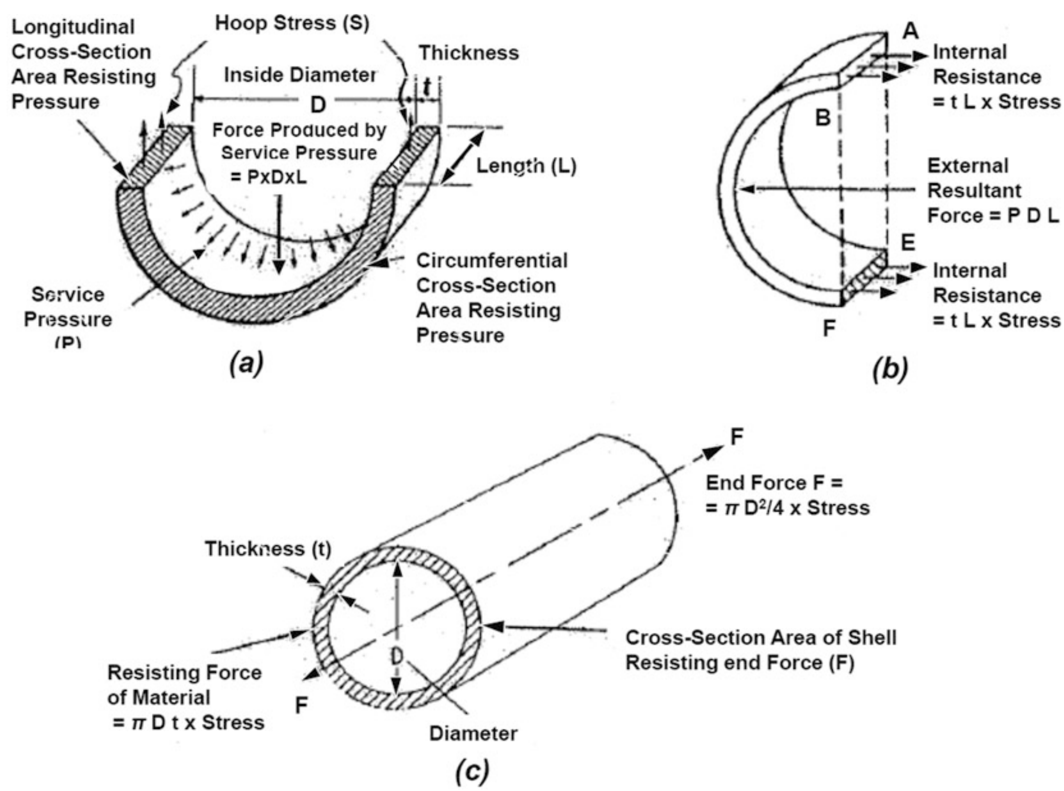
11. Pressure Vessel Manuals, Several Companies and Project Specifications

12. A.J. Heinze, Pressure Vessel Design for Process Engineers, Hydrocarbon Processing, May 1979
13. Manual of Steel Structure, AISI, 8th Edition
14. "Stresses in Large Cylindrical Pressure Vessels on Two Saddle Supports," p. 959, *Pressure Vessels and Piping: Design and Analysis, A Decade of Progress,* Volume Two, published by ASME
15. HEI
16. ASCE 7, NBC, UBC
17. JIS Pressure Vessel Interpretation
18. JPI: Japan Petroleum Institute
19. The Most Popular Software ™ or ®;
    - Pressure Vessels and H/EX's Strength Calculation: PV Elite, COMPRESS, etc.
    - H/EX's Mechanical Design: B-JAC, etc.
    - H/EX's Thermal Calculation: HTRI & HTFS, etc.
    - Piping Stress and Flexibility Analysis: CAESAR II, CAEPIPE v5.1J, TRILEX, etc.
    - Offshore Fixed Structures: SACS, etc.
    - Offshore Risers: Flexcom, OrcaFlex, etc.
    - FEA: ANSYS, FE/Pipe, NozzlePRO, ALGOR, Abaqus FEA, Nastran, etc.
    - Floating Systems: WAMIT, etc.
    - Acoustic Programs: PULS, PULSIM, etc.

Table 1.47 Circumferential (hoop) stress ($R/t \geq 10$) and longitudinal (axial or meriodic) stress

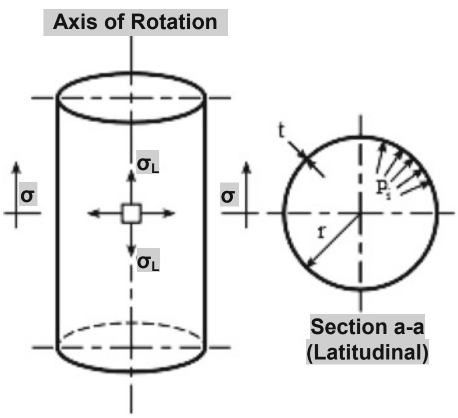
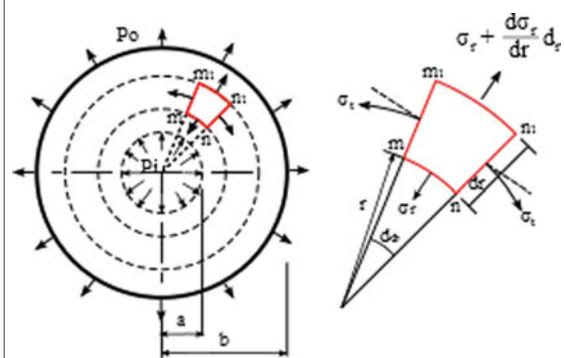
Circumferential (hoop) stress – (a) & (b)	Longitudinal (axial or meriodic) stress – (c)



Force = $PDL = \sigma_L(2tL)$ = stress of material ~~2~~ PR ~~L~~ = ~~2~~ t ~~L~~ σ_L	Force = $P\pi D^2/4 = \sigma_L(\pi Dt)$ = stress of material $P \pi R^{\not 2} = 2\sigma_L(\pi$ ~~R~~ $t)$
$\sigma_C = PR/t$	$\sigma_L = PR/2t$
t = PR/(SE-0.6P) + C.A. – code calculation formula	$t = PR/2$(SE-0.6P) + C.A.
The hoop stress (σ_C) is always greater and determines the required thickness of the shell	

1.2.4.3 Effect of Thick and Thin Thickness in Internal Pressure (Table 1.48)

Table 1.48 Effect of thick and thin thickness in internal pressure

Thin thickness effect in internal pressure ($R/t \geq 10$)	Thick thickness effect in internal pressure ($R/t < 10$)
	
Where R = inside radius for thin thickness P = internal pressure t = minimum required thickness σ_L = longitudinal (meriodic) stress σ_C = circumferential (hoop) stress	Where r = any radius, a = inside radius b = outside radius for thick thickness P = internal pressure σ_t = circumferential (hoop) stress σ_r = radial stress
$\sigma_L = PR/2t$ $\quad$ $\sigma_C = PR/t$	$\sigma_t = a^2P\,(1 + b^2/r^2)/(b^2 - a^2)$ $\sigma_r = a^2P\,(1 - b^2/r^2)/(b^2 - a^2)$ $\sigma_{t\ max} = P\,(a^2 + b^2)/(b^2 - a^2)$; maximum tensile stress at the inner surface
The hoop stress (σ_C) is always greater and determines the required thickness of the shell	The radial stress (σ_t) is always a compressive stress and smaller than the maximum tensile stress ($\sigma_{t\ max}$). $\sigma_{t\ max}$ is always greater than the internal pressure but approaches this value as the wall thickness increases. The difference between the minimum tensile stress at the outside surface and the maximum tensile stress at the inside surface is the magnitude of the internal pressure. Therefore, for the very high internal pressures, it is necessary to use comparably high-yield strength materials
There is little difference between the maximum tensile stress given by the thick-cylinder equation and that given by the thin-cylinder or average stress equation	The difference between the values of the two equations is significant
For example, at a wall thickness of $R/t = 10$, the maximum stress is only 5% higher than the average stress. "−0.6P" factor is used in code calculation formula for compensation of the difference (≤5%) maximum stress and average stress	For example, at a wall thickness of $R/t = 6$, the maximum stress is 37% higher than the average stress
Conventional calculation formula	*ASME BPVC equations approximate the more accurate thick-wall equations and used for all thickness*

1.2.4.4 Equations for Pressure Vessels under Internal Pressure in ASME Sec. VIII, Div. 1 (Courtesy of Pressure Vessel Handbook-modified). See Table 1.49 and ASME BPVC Code Case 2260–2 Alternative Rules for Design of Ellipsoidal and Torispherical Formed Heads

1.2.5 Maximum Allowable Working Pressure (MAWP) and Maximum Allowable Pressure (MAP)

1.2.5.1 MAWP (Maximum Allowable Working Pressure)

(a) Definition and Application

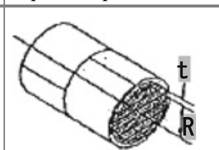
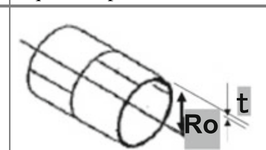
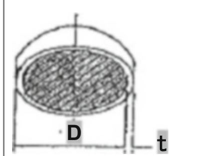
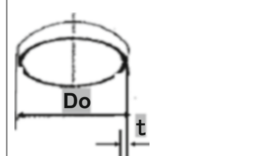
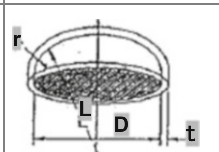
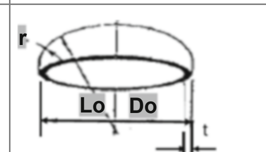
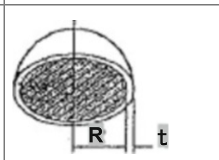
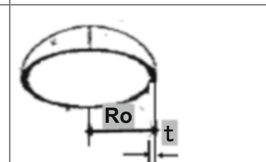
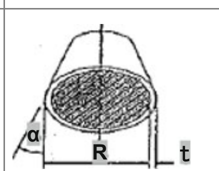
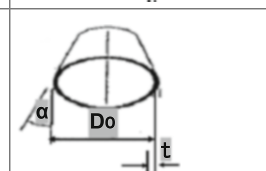
MAWP is required to be displayed on a pressure vessel's nameplate and is defined in the Code as, "the maximum pressure permissible at the top of the vessel in its normal operating positions (as hot and corroded) at the designated coincident temperature specified for that pressure." The MAWP is not the same as the design pressure (pd), which provides the basis for the design of the vessel. The MAWP is determined from the design (internal or external pressure) of the vessel as described below and is not used for the design.

The MAWP of a vessel should not normally be limited by the MAWP of a minor component, such as a flange or nozzle. For example, if an ASME B16.5 flange has a lower pressure rating than the MAWP for the shell and head components, the flange should be upgraded to the next higher class. However, this upgrading can cause complications if the associated piping class calls for lower pressure flanges, and a nonstandard flange must be added to the pipe mating to the vessel. These factors must be evaluated for each specific circumstance.

Table 1.49 Equations for pressure vessel components calculation under internal pressure in ASME Sec. VIII, Div. 1

Notation		
α = half apex angle of cone section, deg.	L = inside spherical or crown radius	r = inside knuckle radius
D = inside diameter of the head skirt; or inside length of the major axis of an ellipsoidal head; or inside diameter of a conical head at the point under consideration, measured perpendicular to the longitudinal axis	Lo = outside spherical or crown radius	t = minimum required thickness of head after forming
	M = factor	
	P = internal design pressure or MAWP	Ts = minimum specified thickness of head after
	Or MAP	Forming (ts $\geq t$)
	R = inside radius as seen above	S = allowable stress of the material at design temperature
Do = outside diameter	Ro = outside radius as seen above	
E = lowest joint efficiency in weld seams	Lo = outside spherical or crown radius	

Item	Imperial unit	SI unit	Metric unit
α	deg.	deg.	deg.
D, Do, L, R, Ro, r, t	inch	mm	mm
P, MAWP, MAP	psi	Pa	Kgf/cm^2
S	psi	Pa	Kgf/cm^2

Components	Equations per inside dimension (UG)		Equations per outside dimension	
Cylindrical shell with longitudinal joints (ts ≤ 0.5R or P ≤ 0.385SE)		$t = \frac{PR}{SE - 0.6P}$ $P = \frac{SEt}{R + 0.6t}$		$t = \frac{PRo}{SE + 0.4*P}$ $P = \frac{SEt}{Ro - 0.4*t}$
Ellipsoidal Head (ts/L ≥ 0.002) (Note 1,2,6)		$t = \frac{PD}{2SE - 0.2P}$ $P = \frac{2SEt}{D + 0.2t}$		$t = \frac{PDo}{2SE + 1.8P}$ $P = \frac{SEt}{Do - 0.8t}$
Dished (Torispherical) Head (Note 1,3,5,6)		$t = \frac{PLM}{SE - 0.6P}$ $P = \frac{2SEt}{LM + 0.2t}$		$t = \frac{PLoM}{2SE + P(M - 0.2)}$ $P = \frac{2SEt}{LM + 0.2t}$
Sphere or Hemispherical Head (ts ≤ 0.356R or P ≤ 0.665SE) (Note 2)		$t = \frac{PR}{2SE - 0.2P}$ $P = \frac{2SEt}{R + 0.2t}$		$t = \frac{PRo}{2SE + 0.8P}$ $P = \frac{2SEt}{Ro - 0.8t}$
Cone & Conical Section (α ≤ 30 deg.) (Note 4 & 5)		$t = \frac{PD}{2\cos\alpha(SE - 0.6P)}$ $P = \frac{2SEt\cos\alpha}{D + 1.2t\cos\alpha}$		$t = \frac{PDo}{2\cos\alpha(SE + 0.4P)}$ $P = \frac{2SEt\cos\alpha}{Do + 0.8t\cos\alpha}$

	Factor *M*																
L/r	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	13.0	14.0	15.0	16.0	16.67
M	1.39	1.41	1.44	1.46	1.48	1.50	1.52	1.54	1.56	1.58	1.60	1.62	1.65	1.69	1.72	1.75	1.77

Notes: Longitudinal stresses (corcumferential joints) are not considered in this Table. * See Coefficient, Y for ASME B31.xx.

1. For ellipsoidal or torispherical heads with ts/L < 0.002, the rules of ASME Sec. VIII, Div. 1, 1-4(f), shall also be met
2. An acceptable approximation of a 2:1 ellipsoidal head is one with a knuckle radius of 0.17D and a spherical radius of 0.90D
3. Torispherical heads made of materials having a specified minimum tensile strength exceeding 485 MPa (70,000 psi) shall be designed using a value of *S* equal to 138 MPa (20,000 psi) at room temperature and reduced in proportion to the reduction in maximum allowable stress values at temperature for the material (see ASME Sec. VIII, Div. 1, UG-23)
4. Conical heads or sections having a half apex-angle *α* greater than 30 deg. without a transition knuckle shall comply with ASME Sec. VIII, Div. 1, eq. (4), and 1-5(g)
5. *Toriconical Heads and Sections*. The required thickness of the conical portion of a toriconical head or section, in which the knuckle radius is neither less than 6% of the outside diameter of the head skirt nor less than three times the knuckle thickness, shall be determined by ASME Sec. VIII, Div. 1, eq. (f)(4), in (f) above, using Di in place of D. The required thickness of the knuckle shall be determined by ASME Sec. VIII, Div. 1, eq. 1-4(d)(3), in which L = Di/ 2cos α
6. See ASME BPVC Code Case 2260-1 for Alternative Rules for Design of Ellipsoidal and Torispherical Formed Heads per Sec. VIII, Div. 1, and ASME BPVC Code Case 2261 for Alternative Rules for Design of Ellipsoidal and Torispherical Formed Heads per Sec. VIII, Div. 2

Meanwhile, the term of maximum allowable external working pressure (MAEWP) is also used for the maximum external pressure permissible acting on the vessel (corroded fully per design, no more corrosion allowance) in normal operating position at design temperature.

(b) Calculation of MAWP in ASME

The actual thicknesses of the various vessel components will usually be thicker than the thickness calculated using the component design pressure (p). It is usually more economic to obtain the required thickness plus corrosion allowance by purchasing the next thicker commercial size of plate, pipe, or ASME B16.5 flange than to have the components specially fabricated to the exact thicknesses required. Therefore, the MAWP permitted (without exceeding the maximum allowable design stress) for the material at the design temperature will usually be somewhat higher than the design pressure (Pd). The Code allows calculating a MAWP based on this extra thickness, adjusted for the hydrostatic head (Ph), for each vessel component, using the lowest MAWP for any component as the MAWP for the vessel.

If a MAWP is not calculated for the actual component thicknesses in this described manner, the design pressure (pd) must be used for the MAWP on the nameplate. When the design pressure (Pd) is used for the MAWP on the nameplate, the extra thickness should be added to the corrosion allowance for each component of the vessel.

1.2.5.2 MAP (Maximum Allowable Pressure) in ASME

(a) Definition and Application

The MAP is defined as the highest permissible pressure as determined by the design formulas for a component using the nominal thickness less corrosion allowance (new (uncorroded) and cold condition) and the maximum allowable stress value from Table 1A of Sec. II, Part D, at the MDMT. For ferritic steel flanges defined in UCS-66(c), the flange rating at the warmer MDMT or 38 °C (100 °F) may be used as the MAP.

MAP can be used for hydrotest of a new equipment. A ratio of the maximum design pressure at the MDMT to the maximum allowable pressure (MAP) at the MDMT in ASME Sec. VIII, Div. 1, UCS-66(b)(1)(b) and (i)(2), is used for reduction MDMT without impact testing.

(b) Calculation of MAP

MAP in new (uncorroded) condition is calculated with the allowable stresses at MDMT, whereas MAWP is considering the allowable stresses at the designated coincident temperature (Table 1.50).

Table 1.50 Basic comparison of MAWP and MAP

	MAWP (maximum allowable working pressure)	MAP (maximum allowable pressure)
Working Condition	Hot and Corroded	New and Cold
Basic Concept of Calculation	For Maintenance During Operation	For New Construction
For example, Vessel with 3 mm CA Design Pressure = 950 psia (t_{min} = 23.5 mm excluded CA)	MAWP = 960 psia (based on t_{nor} – CA = 27–3 = 24 mm)	MAP = 1050 psia (based on t_{nor} = 27 mm)

1.2.6 Design Factors and Pressure Vessel Classes

1.2.6.1 Allowable Stresses Calculated at Room Temperature: Depends on the Design Factor of Each Code (Table 1.51).

Table 1.51 Allowable stresses calculated at room temperature

Data	Elongation, %	ASME Sec. VIII, Div. 1*1	ASME Sec. VIII, Div. 2*1	ASME B31.3	Remark
Allowable Stress Basic Concept		The lesser of TS/**3.5** or 2/3 × YS	The lesser of TS/**3** or 2/3 × YS	The lesser of TS/**3** or 2/3 × YS	
SA-516-70 YS/TS = 38/70	30	YS: 2/3 × 38 = 25.3 TS: 70/3.5 = *20.0*	YS: 2/3 × 38 = 25.3 TS: 70/3 = *23.3*	YS: 2/3 × 38 = 25.3 TS: 70/3 = *23.3*	The value by TS is governed for allowable stress of carbon steels
SA-516–60 YS/TS = 32/60	30	YS: 2/3 × 32 = 21.3 TS: 60/3.5 = *17.1*	YS: 2/3 × 32 = 21.3 TS: 60/3 = *20.0*	YS: 2/3× 32 = 21.3 TS: 60/3 = *20.0*	
SA-106B YS/TS = 35/60	30	YS: 2/3 × 35 = 23.3 TS: 60/3.5 = *17.1*	YS: 2/3 × 35 = 23.3 TS: 60/3 = *20.0*	YS: 2/3 × 35 = 23.3 TS: 60/3 = *20.0*	
SA240–304 YS/TS = 30/70	40	YS: 2/3 × 30 = *20.0* TS: 70/3.5 = *20.0*	YS: 2/3 × 30 = *20.0* TS: 70/3 = 23.3	YS: 2/3 × 30 = *20.0* TS: 70/3 = 23.3	The value by YS is governed for allowable stress of ASS
SA240–304 L YS/TS = 25/70	40	YS: 2/3 × 25 = *16.7* TS: 70/3.5 = 20.0	YS: 2/3 × 25 = *16.7* TS: 70/3 = 23.3	YS: 2/3 × 25 = *16.7* TS: 70/3 = 23.3	
SA240–316 YS/TS = 30/75	40	YS: 2/3 × 30 = *20.0* TS: 75/3.5 = *20.0*	YS: 2/3 × 30 = *20.0* TS: 75/3 = 25.0	YS: 2/3 × 30 = *20.0* TS: 75/3 = 25.0	

Notes:
1. Bolting materials in ASME Sec. VIII, –2001 Add: The lesser of TS/4 or 2/3 × YS
2. Actual design margin for elastic design is 1/3 × YS

1.2.6.2 Pressure Vessel Classes and Design Factor of ASME Sec. VIII, Div. 2 (Table 1.52)

Table 1.52 Pressure vessel classes and design factor of ASME Sec. VIII, Div. 2

Classes	Design factor for TS	Design factor for YS	P.E. stamp required[(1)]	Part 5 be used to supersede the design rules	Allowable stress in ASME Sec. II-D, Subpart 1	Maximum ratio of membrane stress to yield during hydrotest
Class 1	3.0	1.5	No	No[(2)]	Table 2A or Table 2B	0.9
Class 2	2.4	1.5	Yes	Yes	Table 5A or Table 5B	0.95

Notes: P.E., certified professional engineer; UDS, user's design specification; MDR, manufacturer's design report
(1) To certify the UDS and MDR unless fatigue analysis is required. See Code Case 2891 for more information
(2) Part 5 cannot be used to overrule the rules in Part 4

1.2.7 Joint Efficiency and Quality Factor

1.2.7.1 Joint Efficiency

The consideration that must be made is the ratio of the strength of the joint compared to the strength of the base metal. This ratio is called "joint efficiency" or "joint quality factor." An efficient joint is one that is just as strong as the base metal.

(a) Pressure Vessels
Table 1.53 shows the joint efficiency (J.E) and Code Reference in ASME Sec. VIII, Div. 1.
Table 1.54 shows the summary of the requirements for Joint Category, RT, Joint Efficiency, PWHT of Pressure Vessels-ASME Sec. VIII, Div. 1.
Table 1.55 shows the examples for typical application of joint efficiency as per RT applied for each major joint in ASME Sec. VIII, Div. 1.
(b) Weld Joint Quality Factor (Ej) in Piping: B31.3; Para. 302.3.4, K302.3.4; and Table A-1B
1. Basic Quality Factors
The Ej tabulated in ASME B31.3 Table A-1B are basic factors for straight or spiral longitudinal welded joints for pressure retaining components in B31.3 Table 302.3.4. The following example for ASTM A358 (EFW Austenitic Cr-Ni SS Pipe for High Temperature Service and General Applications) in ASME B31.3, Table 1–1B, shows that the Ej is designated between 0.85 and 1.0 per class (Table 1.56).
2. Increased Quality Factors
ASME B31.3, Table 302.3.4, also indicates higher joint quality factors which may be substituted for those in Table A-1B for certain kinds of welds if additional examination is performed beyond that required by the product specification (Table 1.57).

1.2.7.2 Casting Quality Factor (*Ec*) in ASME B31.3, 303.3.2, 302.3.3, K302.3.3, and Table A-1A

The Casting Quality Factors (*Ec*) are applied for cast components not having pressure-temperature ratings established by standards in ASME B31.3, Table 326.1.

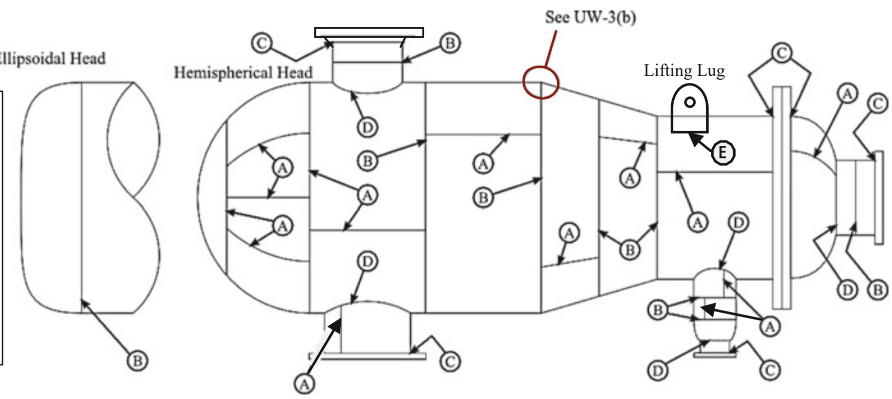
(a) Basic Quality Factors (*Ec*)
The following basic quality factors in Table 1.58 are to be considered.
(b) Increased Casting Quality Factors – B31.3, Table 302.3.3C
The quality factors may be increased when supplementary examinations are applied as in Table 1.59.

Table 1.53 Joint efficiency (J.E) and code reference in ASME Sec. VIII, Div. 1

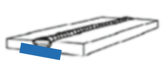
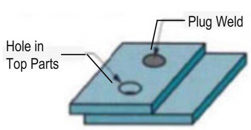
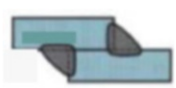
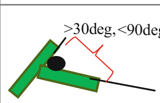
Types of joint and radiography (weld type as per Table 1.54)	J.E.	Paragraph
Double-welded butt joints (Type 1) Fully radiographed Spot-radiographed No radiograph	1.0 0.85 0.70	UW-11 UW-51, UW-35 UW-12, UW-52 Table UW-12
Single-welded butt joints (backing strip left in place) (Type 2) Fully radiographed Spot-radiographed No radiograph	0.90 0.80 0.65	UW-52 UCS-25 UW-51 UW-52
Single-welded butt joints no backing strip (Type 3) limited to circumferential joints only, not over 16 mm (5/8 inch) thick and not over 600 mm (24 in.) OD – no radiograph	0.60	Table UW-12
Fillet weld lap joints and single-welded butt circumferential joints	Per component	Table UW-12
Seamless vessel sections or heads (spot-radiographed)	1.0	UW-12(d)
Seamless vessel sections or heads (no radiography)	0.85	UW-12(d)

Table 1.54 Weld category, RT, joint efficiency, PWHT of pressure vessels – ASME Sec. VIII, Div. 1

Joint categories are the same as in ASME Sec.VIII, Div.2. But, Category "E" is from Div.2.



To the joints under certain conditions, special requirements apply, which are the same for joints designated by identical letters. These special requirements, which are based on service, material, thickness, and other design conditions, are tabulated below. Joint efficiency is 1.0 for butt joint in compression. See General Notes for Type No. as per the weld joint description

Joint Types	Weld Joint Sketch	Limitations [Specified paragraphs and Figures are based on ASME Sec. VIII, Div. 1]	Joint Category	J.E per RT Type		
				Full[a]	Spot[b]	None
(1)		None	A, B, C, D	1.00	0.85	0.70
(2)		*(a)* None except as in *(b)* below	A, B, C, D	0.90	0.80	0.65
		(b) Circumferential butt joints with one plate offset; see UW-13 (b)(4) and Fig. UW-13.1, sketch (i)	A, B, C	0.90	0.80	0.65
(3)		Circumferential butt joints only, not over 16 mm (5/8 in.) thick and not over 600 mm (24 in.) OD	A, B, C	N/A	N/A	0.60
(4)		*(a)* Longitudinal joints not over 10 mm (3/8 in.) thick	A	N/A	N/A	0.55
		(b) Circumferential joints not over 16 mm (5/8 in.) thick	B, C[c]	N/A	N/A	0.55
(5)		*(a)* Circumferential joints[d] for attachment of heads not over 600 mm (24 in.) OD to shells not over 13 mm (1/2 in.) thick	B	N/A	N/A	0.50
		(b) Circumferential joints for the attachment to shells of jackets not over 16 mm (5/8 in.) in nominal thickness where the distance from the center of the plug weld to the edge of the plate is not less than 1.5 times the diameter of the hole for the plug	C	N/A	N/A	0.50
(6)		*(a)* For the attachment of head convex to pressure to shells not over 16 mm (5/8 in.) required thickness, only with use of fillet weld on inside of shell	A, B	N/A	N/A	0.45
		(b) For attachment of heads having pressure on either side to shells not over 600 mm (24 in.) ID and not over 6 mm (1/4 in.) required thickness with fillet weld on outside of head flange only	A, B	N/A	N/A	0.45
(7)		As limited by Fig. UW-13.2 and Fig. UW-16.1	C, D[e]	N/A	N/A	N/A
(8)		Design per U-2(g) for Category B and C joints	B, C, D	N/A	N/A	N/A
(9)	Corner joints made with partial penetration welds with or without cover fillet welds	Not described in Div. 1				
(10)	Fillet Joints	Not described in Div. 1				

General Notes: $E = 1.00$ for butt joints in compression

a. Some welding processes require UT in addition to RT, and other processes require UT in lieu of RT. See ASME Sec. VIII, Div. 1, UW-11 for some additional requirements and limitations that may apply

b. Joint efficiency assignment rules of ASME Sec. VIII, Div. 1, UW-12(d) and UW-12(e), shall be considered and may further reduce the joint efficiencies to be used in the required thickness calculations

c. The rules of ASME Sec. VIII, Div. 1, UW-12(f), may be used in lieu of the rules of this table at the manufacturer's option

d. Joint descriptions per joint type are below

Joint Types	Joint Description
(1)	Butt joints as attained by double-welding or by other means which will obtain the same quality of deposited weld metal on the inside and outside weld surfaces to agree with requirements of UW-35. Welds using metal backing strips which remain in place are excluded
(2)	Single-welded butt joint with backing strip other than those included under Type (1) above
(3)	Single-welded butt joint without use of backing strip
(4)	Double full fillet lap joint. This joint is not applicable for bolted flanged connection of Category C joint
(5)	Single full fillet lap joints with plug welds conforming to UW-17
(6)	Single full fillet lap joints without plug welds
(7)	Corner joints made with full penetration welds with or without cover fillet welds
(8)	Angle joints made with a full penetration weld where the cone half-apex angle is greater than 30 deg.
(9)*	Corner joints made with partial penetration welds with or without cover fillet welds
(10)*	Fillet welds

Notes: *designated in ASME Sec. VIII, Div. 2, only
[a]Full RT: see ASME Sec. VIII, Div. 1, UW-12(a) and UW-51
[b]Spot RT: see ASME Sec. VIII, Div. 1, UW-12(b) and UW-52
[c]For Type No. 4 Category C joint, limitation not applicable for bolted flange connections
[d]Joints attaching hemispherical heads to shells are excluded
[e]There is no joint efficiency *E* in the design equations of ASME Sec. VIII, Div. 1, for Category C and D corner joints. When needed, a value of *E* not greater than 1.00 may be used

Table 1.55 (1/3) Sample cases of joint efficiencies and RT – ASME Sec. VIII, Div. 1 (for reference)

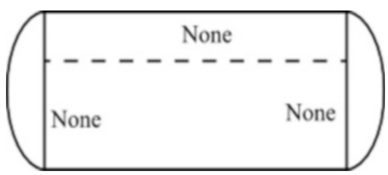
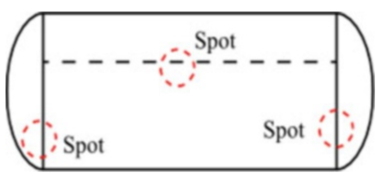
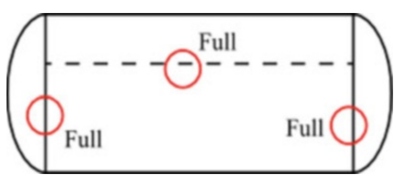
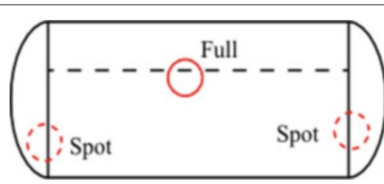
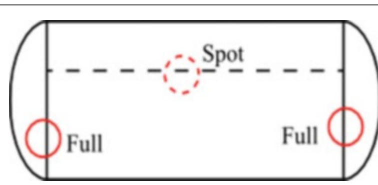
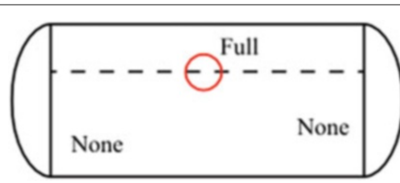
Examples with seamless heads and rolled shell – all joints Type 1 in Table UW-12		
Case	RT Combination	Detail Application
A1		No circumferential seam RT No long seam RT UW-11(a)(5) NOT met for the long seam UW-11(a)(5)(b) NOT met for the circumferential seam UW-11(a)(5)(b) NOT met E head = 0.85 from UW-12(d) E shell = 0.7 from Table UW-12
A2		Spot circumferential seam RT Spot long seam RT UW-11(a)(5) NOT met for the long seam UW-11(a)(5)(b) is met for the circumferential seam UW-11(a)(5)(b) NOT met E head = 0.85 from UW-12(d) E shell = 0.85 from Table UW-12
A3		Full circumferential seam RT Full long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for the circumferential seam UW-11(a)(5)(b) is met E head = 1.0 from UW-12(d) E shell = 1.0 from Table UW-12
A4		Spot circumferential seam RT Full long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for the circumferential seam UW-11(a)(5)(b) is met E head = 1.0 from UW-12(d) E shell = 1.0 from Table UW-12
A5		Full circumferential seam RT Spot long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) NOT met for the circumferential seam UW-11(a)(5)(b) is NOT met E head = 0.85 from UW-12(d) E shell = 0.85 from Table UW-12
A6		No circumferential seam RT Full long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) NOT met for the circumferential seam UW-11(a)(5)(b) is NOT met E head = 0.85 from UW-12(d) E shell = 0.85 from UW-12(d)

Table 1.55 (2/3) Sample cases of joint efficiencies and RT – ASME Sec. VIII, Div. 1 (for reference)

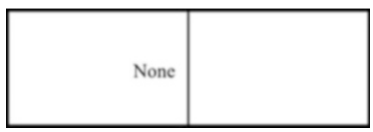
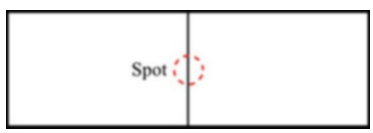
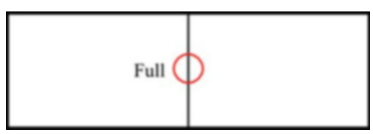
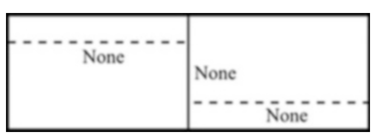
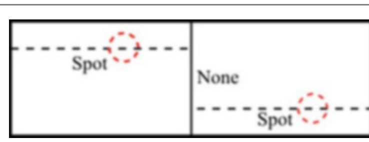
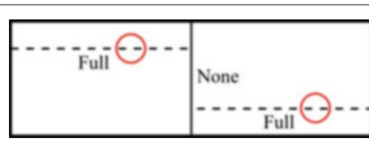
Examples with seamless heads and seamless (piping) shell – all joints type 1 in Table UW-12		
Case	RT combination	Detail application
B1		No circumferential seam RT Long seam is seamless UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) NOT met for circumferential weld UW-11(a)(5)(b) is NOT met E head = 0.85 from UW-12(d) E shell = 0.85 from UW-12(d)
B2		Spot circumferential seam RT Long seam is seamless UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is met E head = 1.0 from UW-12(d) E shell = 1.0 from UW-12(d)
B3		Full circumferential seam RT Long seam is seamless UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is met E head = 1.0 from UW-12(d) E shell = 1.0 from UW-12(d)
C1		Two seamless pipes No circumferential seam RT Long seam is seamless UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) NOT met for circumferential seam UW-11(a)(5)(b) is NOT met E Pipe = 0.85 from UW-12(d)
C2		Two seamless pipes Spot circumferential seam RT Long seam is seamless UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is met E Pipe = 1.0 from UW-12(d)
C3		Two seamless pipes Full circumferential seam RT Long seam is seamless UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is met E Pipe = 1.0 from UW-12(d)
C4		Two welded shells No circumferential seam RT No long seam RT UW-11(a)(5) is NOT met for the long seam UW-11(a)(5)(b) is NOT met for circumferential seam UW-11(a)(5)(b) is NOT met E Pipe = 0.7 from Table UW-12(d)
C5		Two welded shells No circumferential seam RT Spot long seam RT UW-11(a)(5) is NOT met for the long seam UW-11(a)(5)(b) is NOT met for circumferential seam UW-11(a)(5)(b) is NOT met E Pipe = 0.85 from UW-12(d)
C6		Two welded shells No circumferential seam RT Full long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is NOT met for circumferential seam UW-11(a)(5)(b) is NOT met E Pipe = 0.85 from UW-12(d)

Table 1.55 (3/3) Sample cases of joint efficiencies and RT – ASME Sec. VIII, Div. 1 (for reference)

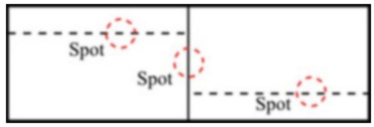
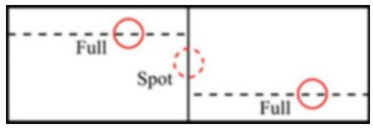
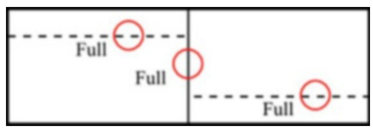
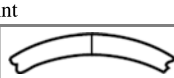
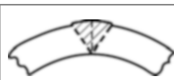
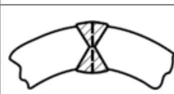
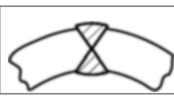
Examples with two shells – circumferential joint type 1 in Table UW-12 (cont'd)		
Case	RT Combination	Detail Application
C7		Two welded shells Spot circumferential seam RT Spot long seam RT UW-11(a)(5) is NOT met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is NOT met E Pipe = 0.85 from UW-12(d)
C8		Two welded shells Spot circumferential seam RT Full long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is met E Pipe = 1.0 from Table UW-12
C9		Two welded shells Full circumferential seam RT Full long seam RT UW-11(a)(5) is met for the long seam UW-11(a)(5)(b) is met for circumferential seam UW-11(a)(5)(b) is met E Pipe = 1.0 from Table UW-12

Table 1.56 Weld joint quality factor (Ej) in piping (ASME B31.3)

Class (see Note)	Ej
1, 3, 4	1.00
5	0.90
2	0.85

Notes:
Class 1: double butt welded with filler metal in all passes, 100% RT
Class 2: double butt welded with filler metal in all passes, No RT
Class 3: single butt welded with filler metal in all passes, 100% RT
Class 4: single butt welded, weld pass exposed to the inside pipe surface without the additional filler metal, 100% RT
Class 5: double butt welded with filler metal in all passes, spot RT

Table 1.57 Longitudinal weld joint increased quality factor, *Ej* (ASME B31.3 Table 302.3.4)

Type of weld joint		Type of weld seam	Examination	Factor, *Ej*
1. Furnace butt weld, continuous weld		Straight	As required by listed specification	0.60 Note (1)
2. Electric resistance weld (ERW)		Straight or spiral (helical seam)	As required by listed specification	0.85 Note (1)
3. Electric fusion weld (EFW)				
(a) Straight butt weld (with or without filler metal)		Straight or spiral (helical seam)	As required by listed specification or ASME B31.3	0.80
			Note (2)	0.90
			Note (3)	1.00
(b) Double butt weld (with or without filler metal)		Straight or spiral (helical seam) [except as provided in 4 (specific specification) below]	As required by listed specification or ASME B31.3	0.85
			Note (2)	0.90
			Note (3)	1.00
4. Specific specification				
(i)API 5L, EFW, double butt seam		Straight (with one or two seams) or spiral (helical seam)	As required by specification	0.95
			Note (3)	1.00

Notes:
(1) It is not permitted to increase the joint quality factor by additional examination for joint 1 or 2
(2) Additionally spot RT in accordance with ASME B31.3, para. 341.5.1
(3) Additionally 100% RT in accordance with ASME B31.3, para. 344.5.1, and Table 341.3.2

Table 1.58 Basic quality factors, *Ec* (ASME B31.3 Table A-1A modified)

Materials (ASTM) – example	*Ec*
(Austenitic, Ferritic) Ductile Iron Castings – ASTM A395/536/571 Steel Castings for Fusion Welding – ASTM A216 High Temperature Steel & Alloy Castings – ASTM A217 Low Temperature Steel Castings – ASTM A352 ASS Castings and Steel Castings – ASTM A351/A487 Copper and Copper Alloy Castings – ASTM B61/62/148/584 Nickel Alloy Castings – ASTM A494 Aluminum Alloy Castings – ASTM B26, Temper T6/T71	0.80
Centrifugally SS Cast Pipe – ASTM A451	0.90
Gray and Malleable Iron Castings – ASTM A47/48/126/197/278 Centrifugally Low Alloy Cast Pipe – ASTM A426 Aluminum Alloy Castings – ASTM B26, Temper F	1.0

Table 1.59 Increased casting quality factors, *Ec* (ASME B31.3, Table 302.3.3C, and Code Case modified)

Materials	*Ec*	Remark
Ductile Cast Iron, UNS F33100: Except as permitted in (c). *(c)* The casting quality factor may be increased by performing supplementary examination(s) listed in ASME B31.3, Table 302.3.3(c). The casting shall have first been visually examined as required by MSS SP-55, Quality Standard for Steel Castings for Valves, Flanges, Fittings, and Other Piping Components — Visual Method	0.80	ASME Code Case B31 Case 196 (2007)
Machine all surfaces to 6.3 μm Ra (250 μ in. *Ra* per ASME B46.1) finish, thus increasing the effectiveness of surface examination	0.85	
Examine all surfaces of each casting (ferromagnetic material only) by MT per ASTM E709 (method), MSS-SP-53, Table 1 (acceptance) Examine all surfaces of each casting (ferromagnetic material only) by PT per ASTM E165 (method), MSS-SP-93, Table 1 (acceptance)	0.85	
Machine all surfaces to 6.3 μm Ra (250 μ in. *Ra* per ASME B46.1) finish, thus increasing the effectiveness of surface examination, and (a) or (b) below: (a) Examine all surfaces of each casting (ferromagnetic material only) by MT per ASTM E709 (method), MSS-SP-53, Table 1 (acceptance) (b) Examine all surfaces of each casting (ferromagnetic material only) by PT per ASTM E165 (method), MSS-SP-93, Table 1 (acceptance)	0.90	
(c) Full UT each casting per ASTM E114 (method), no evidence of depth of defects, over 5% of wall thickness (acceptance) (d) Full RT per ASTM E94 (method), B31.3, Table 302.3.3D (acceptance)	0.95	
Machine all surfaces to 6.3 μm Ra (250 μ in. *Ra* per ASME B46.1) finish, thus increasing the effectiveness of surface examination, and (c) or (d) below: (c) Full UT each casting per ASTM E114 (method), no evidence of depth of defects, over 5% of wall thickness (acceptance) (d) Full RT per ASTM E94 (method), B31.3, Table 302.3.3D (acceptance)	1.0	
(a) or (b) and *(c) or (d)* (a) Examine all surfaces of each casting (ferromagnetic material only) by MT per ASTM E709 (method), MSS-SP-53, Table 1 (acceptance) (b) Examine all surfaces of each casting (ferromagnetic material only) by PT per ASTM E165 (method), MSS-SP-93, Table 1 (acceptance) (c) Full UT each casting per ASTM E114 (method), no evidence of depth of defects, over 5% of wall thickness (acceptance) (d) Full RT per ASTM E94 (method), B31.3, Table 302.3.3D (acceptance)	1.0	

General Notes: Applicable standards
ASME B46.1 Surface Texture (Surface Roughness, Waviness, and Lay)
ASTM E94 Guide for Radiographic Examination
ASTM E114 Practice for Ultrasonic Pulse-Echo Straight-Beam Contact Testing
ASTM E125 Reference Photographs for Magnetic Particle Indications on Ferrous Castings
ASTM E165 Practice for Liquid Penetrant Examination for General Industry
ASTM E709 Guide for Magnetic Particle Testing
MSS SP-53 Quality Standard for Steel Castings and Forgings for Valves, Flanges, Fittings, and Other Piping Components — Magnetic Particle Examination Method
MSS SP-93 Quality Standard for Steel Castings and Forgings for Valves, Flanges, Fittings, and Other Piping Components — Liquid Penetrant Examination Method

1.2.8 *Pressure Relief Devices (PRD)*

Table 1.60 shows international PRD standards for pressure vessels and piping to prevent overpressure.

Table 1.61 and Table 1.62 show the summary of requirements for Pressure Relief Devices (PRD) in ASME Section VIII and B31.3.

Table 1.60 Most common standards for Pressure Relief Devices (PRD) used in several countries

Country	Standard No.	Description
USA	ASME BPVC/ API Tanks	I-Power PV, III-Nuclear Power PV, VIII-Unfired PV/ API STD 620 & 2000
	ASME B31.xx Piping	B31.1 Power, B31.3 Process
	ASME PTC 25	Pressure Relief Devices (PRD)
	API STD 520	Sizing selection and installation of pressure relieving devices in refineries, Part 1 Design, Part 2 Installation
	API STD 521	Guide for pressure relieving and depressurizing systems
	API STD 526 & 527	Flanged Steel Pressure Relief Valves & Seat Tightness of Pressure Relief Valves
	API RP 576/ NB-18	Inspection of Pressure Relieving Devices/ PRD Certification
Germany	A. D. Merkblatt A2	Pressure vessel equipment safety devices against excess pressure – safety valves
	TRD 421	Technical equipment for steam boilers safeguards against excessive pressure – safety valves for boilers of groups I, III, & IV
	TRD 721	Technical equipment for steam boilers safeguards against excessive pressure – safety valves for steam boilers group II
UK	BS 6759	Part 1 specification for safety valves for steam and hot water Part 2 specification for safety valves for compressed air and inert gas Part 3 specification for safety valves for process fluids
France	AFNOR NFE-E 29–411 to 416	Safety and relief valves
Korea	KS B 6216	Spring loaded safety valves for steam boilers and pressure vessels
Japan	JIS B 8210	Safety devices for protection against excessive pressure – safety valves
Australia	SAA AS1271	Safety valves, other valves, liquid level gauges, and other fittings for boilers and unfired pressure vessels

Table 1.61 (1/2) Set-Pressure and Material Requirements of Pressure Relief Devices in ASME Sec. VIII, Div.1

Item	Requirements in Sec. VIII, Div.1	Remarks (Sec. VIII, Div.1)		
Geneal & Detail	[UG-125 through 140] To prevent overpressure See Note 1 for Materials Selection. Nonreclosing Rupture Disk Devices: See UG-127(a) Nonreclosing Pin Devices: See UG-127(b) Nonreclosing Spring Loaded Devices: See UG-127(c)	[Simplified Concept of PRD Pressure-for reference]		
		Pressure Vessel Pressures (P)		**Typical PRD Pressures (P)**
		Max. Allowable accumulation P, fire sizing	121%	Max. relieving P, fire sizing
		Max. allowable accumulation P, multiple PRDs	116%	Max. relieving P, multiple PRDs
		Max. allowable accumulation P, non-fire sizing	110%	Max. relieving P, single PRD
			105%	Max. allowable set P, multiple PRDs
		MAWP (base)	100%	Max. allowable set P, single PRDs
		Typical max. allowable operating P	90%	

Table 1.61 (2/2) Set-Pressure and Material Requirements of Pressure Relief Devices in ASME Sec. VIII, Div.1

Item	Requirements in Sec. VIII, Div.1	Remarks (Sec. VIII, Div.1)
General for Other than unfired steam boilers [UG-125 (c) and UG-127 (d)(3)]	To prevent the pressure (P) > 10% or 20 KPa (3 psi), whichever is greater, above the MAWP except below; 1. In multi PRDs, the P > 16% or 30 KPa (4psi), whichever is greater. 2. In additional hazard by exposure, supplement PRDs shall be installed, more than 21% MAWP. 3. Nonreclosing PRD-aggregate capacity: PRD intended primarily for protection against exposure are excluded above (1) & (2), provided (i) more than 20% above MAWP, (ii) set P ≤ MAWP, (iii) vessel has sufficient ullage, (iv) MAWP (PRD set P) is greater than the vapor P of liquefied compressed gas at the max. anticipated temperature. And when the MAWP < 105 kPa (15 psi), in no case shall the P be allowed to rise more than 21% above the MAWP.	*Note* 1. from ASME Sec. VIII, Div.1, UG-136, (b) Material Selections 1 Cast iron seats and disks are not permitted. 2. Adjacent sliding surfaces such as guides and disks or disk holders shall both be of corrosion resistant material. Springs of corrosion resistant material or having a corrosion resistant coating are required. The seats and disks of pressure relief valves shall be of suitable material to resist corrosion by the fluid to be contained. The Manufacturer shall consider the potential for galling and the effects on the performance of the pressure relief valve in the selection of materials for sliding surfaces. The Manufacturer shall consider the potential for brinelling and the effects on the performance of the pressure relief valve in the selection of materials for the seating surfaces. *NOTE: The degree of corrosion resistance, appropriate to the intended service, shall be a matter of agreement between the Manufacturer and the user or his designated agent.* 3. Materials used in bodies, bonnets or yokes, and body-to-bonnet or body-to-yoke bolting, shall be listed in ASME Sec. II and Sec.VIII, Div.1. Bodies, bonnets or yokes, and body-to-bonnet or body-to-yoke bolting shall meet all applicable requirements of Subsection C. 4. Materials used in all other parts required for the pressure relieving or retaining function shall be (a) Listed in ASME Sec. II; or (b) Listed in ASTM specifications; or (c) Controlled by the Manufacturer of the pressure relief valve by a specification ensuring control of chemical and physical properties and quality at least equivalent to ASTM standards.
PRD Capacity [UG-133]	The capacity at relieving P > 110% relieving P	
Set Pressure (P) of PRD [UG-134]	(a) Single relief device ; ≤ 100% MAWP Multiple relief devices ; one ≤ 100% MAWP, others ≤ 105% MAWP (b) Device for exposure to fire or other sources of external heat : ≤ 110% MAWP	
Tolerance of Set Pressure (P) of PRD [UG-134 & 126]	1. The tolerance shall not exceed ±2 psi (15 kPa) for P ≤70 psi (500 kPa) and ±3% for P > 70 psi (500 kPa), except as covered in (2) below. 2. The tolerance which comply with UG-125(c)(3)-Devices for exposure to fire or other sources of external heat shall be within −0%, +10%. *(e)* The burst P tolerance for rupture disk devices at the specified disk temperature shall not exceed ±2 psi (15 kPa) of marked burst P ≤ 40 psi (300 kPa) and ±5% of marked burst P >40 psi (300 kPa). *(f)* The tolerance for pin devices shall not exceed ±2 psi (15 kPa) of marked set P ≤40 psi (300 kPa) and ±5% of marked set P >40 psi (300 kPa) at specified pin temperature.	
Pressure (P) Relief Valves [UG-126]	(a) To be direct spring loaded type (b) Pilot operated pressure relief valves may be used when the self-actuated and main valve will open automatically at not over the set P and will discharge its full rated capacity if some essential part of the pilot should fail. (c) Set P: ≤15 kPa (2 psi) for P ≤ 500 kPa (70 psi) and 3% for P >500 kPa (70 psi).	
Non-reclosing PRD – Breaking Pin	[UG-127(b)(3) Pin Devices] The set P to be ≥90% of the set P of the pressure relief valve. [UG-127(c) Spring Loaded Nonclosing PRD] The tolerance on opening point < ± 5%.	
Non-reclosing PRD- Spring loaded	[UG-127(a) Rupture Disk Devices and UG-127(b) Pin Devices] The set P tolerance to be ≤ ± 15 kPa (± 2 psi) for marked set P up to and including 300 kPa (40 psi) and ±5% for marked set pressures above 300 kPa (40 psi).	
Liquid Pressure Relief Valves	[UG-128] Any liquid pressure relief valve used shall be at least NPS 1/2 (DN 15).	
Other min. Requirements	[UG-136] for Pressure Relief Valves [UG-137] for Rupture Disk Devices [UG-138] for Pin Devices	
Other Reference	Section 2 of ASME PTC 25	

Table 1.62 Requirements of pressure relief devices (PRD safety valve) in ASME B31.3

Item	ASME B31.3 including ASME Sec. VIII, Div. 1, partially
One or More Stop Valves in Pressure Relief (PR) Piping	[ASME B31.3, 322.1] *(a)* A full-area stop valve may be installed on the inlet side of a PRD. A full area stop valve may be placed on the discharge side of a PRD when its discharge is connected to a common header with other discharge lines from other pressure-relieving devices. Stop valves of less than full area may be used on both the inlet side and discharge side of PRD as outlined herein if the stop valves are of such type and size that the increase in pressure drop will not reduce the relieving capacity below that required, nor adversely affect the proper operation of the PRD. Or *(b)* Stop valves to be used in pressure relief piping shall be so constructed or positively controlled that the closing of the maximum number of block valves possible at one time will not reduce the PR capacity provided by the unaffected relieving devices below the required relieving capacity. Or *(c)* As an alternative to (b) above, stop valves shall be so constructed and arranged that they can be locked or sealed in either the open or closed position.
Pressure Relief Discharge Piping	[ASME B31.3, 322.6.2] Discharge lines from PR safety devices shall be designed to facilitate drainage. When discharging directly to the atmosphere, discharge shall not impinge on other piping or equipment and shall be directed away from platforms and other areas used by personnel.
Pressure Relief Devices	[ASME B31.3, 322.6.3] (a) PR devices required by para. 301.2.2(a) shall be ASME Sec. VIII, Div. 1, UG-125(c), UG-126 through 128,and UG-132 through 136 excluding UG-135(e) and 136(c) Design pressure, MAWP; piping system, vessel (b) Relief set pressure; per Sec. VIII, Div. 1, except the following: (1) With owner's approval the set pressure may exceed the limits in Sec. VIII, Div. 1 (2) For a liquid thermal expansion relief device which protects only a blocked-in portion of a piping system, the set pressure ≤ the lesser of the system test pressure or 120% of design pressure (c) The max. relieving pressure shall be as per Sec. VIII, Div. 1, with the exception that the allowance in para. 302.2.4 (f) are permitted, provided that all other requirements of para. 302.2.4 are also met. [B31.3, 345.5.2] PRD for Pneumatic Test: Set Pressure ≤ the lesser of 345 kPa or 10% test pressure

1.2.9 Design and Selection for Detail Components

1. Utilization of standard drawing approved by end-users: Normally it is not necessary to confirm the strength calculation unless otherwise required because the strength of all components in standard drawing was already proved unless otherwise noted.
2. To be considered the sequence of fabrication and assembly.
   ; Delivery condition, hydrotest condition, shop equipment capacity, raw material size, cutting plan, etc.

1.2.10 Transportation, Erection, and Field Assembly

1. Transportation:
   (a) On the sea: tide table, weather condition (e.g., hurricane, typhoon, cyclone, etc.)
   (b) On the trailers: tailing/trunnion lugs direction, road survey
   (c) On the train: impact factor in forward and lateral force
2. Erection: approaching road condition, crane, gin pole, RMS (rigging master system)
3. Field assembly: Dressing of removable parts, internals, top davit

1.2.11 Comprehension of General Assembly/Notes Drawing

Traceable for construction, maintenance, and future argument

(a) Design data from end-users
(b) Actual information as fabricated (reports of test, inspection, heat treatment, WPS, dimension, etc.)
(c) Fabrication history with hidden parts
(d) To be traceable all information of the equipment
(e) Responsibility 20 years (for seal of the registered P.E.)

1.2.12 Development of Piping Materials Classes

1.2.12.1 Piping Material Engineer's Responsibilities

The piping material engineer's responsibilities vary from company to company. Here is a list of typical functions that he or she is expected to perform:

(a) Develop the project piping classes for all process and utility services.
(b) Write specifications for fabrication, shop and field testing, insulation, and painting.
(c) Create and maintain all data sheets for process and utility valves.
(d) Create a list of piping specials, such as hoses and hose couplings, steam traps, and interlocks.
(e) Create and maintain data sheets for these piping special (SP) items.
(f) Assemble a piping material requisition with all additional documents.
(g) Review offers from vendors and create a technical bid evaluation.
(h) Make a technical recommendation.
(i) After placement of a purchase order, review and approve documentation from vendors related to piping components.
(j) When required, visit the vendor's premises to attend kickoff meetings, the testing of piping components, or clarification meetings.
(k) Liaise with the following departments: Piping Design and Stress, Process, Instrumentation, Vessels, Mechanical, Structural, Procurement, and Material Control.

1.2.12.2 Development of the Project Piping Classes

(a) All process plants have two types of principal piping systems:
   (i) Process (major plant fluids, flammable, toxic, corrosive) piping systems and utility piping systems.
   (ii) Process piping systems are the arteries of a process plant. They receive the feedstock, carry the product through the various items of process equipment for treatment, and finally deliver the refined fluid to the battery limits for transportation to the next facility for further refinement. Process piping systems can be further divided into primary process, which is the main process flow, and secondary process, which applies to the various recycling systems.
(b) Utility piping systems are to support the primary process, falling into five groups:
   (i) Support – instrument air, cooling water, steam, and treated water
   (ii) Maintenance – plant air, nitrogen, and fuel oil/gas
   (iii) Protection – foam and firewater

Table 1.63 Several factors and their combinations for piping material classes

Categories	Basic Types	Others
Materials	See Table 2.11	Seamless, welded
Service	Fluids (sour, amine, HF, hydrogen, caustic, carbonic acid, etc.) per specific requirements Corrosion, Erosion, Non-corrosive, Utilities, etc.	Included specific requirements (chemical composition, hardness, test & inspection, heat treatment, etc.)
Pressure Rating (psi)	#150, 300, (400), 600, 900, 1500, and 2500	or SI Unit
Temperature Range per Each Material	Cryogenic (<−46 °C), low temperature (up to −46 °C below −29 °C), common temperature (−29 °C to 400–800 °C), high temperature (>600–800 °C)	1. Elevated temperature: D.T for highest 2. DMT/MDMT: lowest
Corrosion Allowance	0 mm, 0.5 mm, 1 mm, 1.5 mm, 3 mm, 4.5 mm, 6 mm	or equivalent US customary unit
PWHT	No & Yes	per codes or project specifications
Pipe Size	NPS ½ inch to NPS 48 inch (or higher)	
Other Requirements	Mill fabrication (killed, vacuum degassing, etc.), valve trim materials, gasket materials, seating materials, bolting materials, specific heat treatment, welding, NDE, special assemblies, etc.	Service velocity (min. & max.), minimum curvature. See Sect. 1.4.2 for more details

(ii) Cleanness – lube oil and chemicals
(iii) Living – potable water

(c) Piping classes. Each piping system is allocated a piping class, which lists all the components required to construct the piping. A piping material class consists a specific condition from several combinations in Table 1.63.

After analyzing these characteristics, process and utility piping systems can be grouped into individual piping class. This standardization or optimization has benefits in the procurement, inspection, construction, and maintenance. Too little optimization increases the number of piping classes, making the paperwork at all stages of the project (including maintenance) difficult to handle and leading to confusion, resulting in mistakes. Too much optimization reduces the number of piping classes, however, as the piping class must satisfy the characteristics of the most severe service and use the most expensive material. This means that less-severe services are constructed using more expensive material, because the piping class is over-specified. It is the responsibility of the piping material engineer to fine-tune this optimization to the benefit of the project.

A typical oil and gas separation process plant may have about 20 process piping classes and a similar number of utility piping classes in one unit. More complex petrochemical facilities require a greater number of piping classes to cover the various process streams and their numerous temperature and pressure ranges. Sometimes it is not uncommon for process plants such as these to have in excess of 40–50 process and piping classes.

1.3 Advanced Design

1.3.1 Stress Analysis and Finite Element Analysis (FEA)

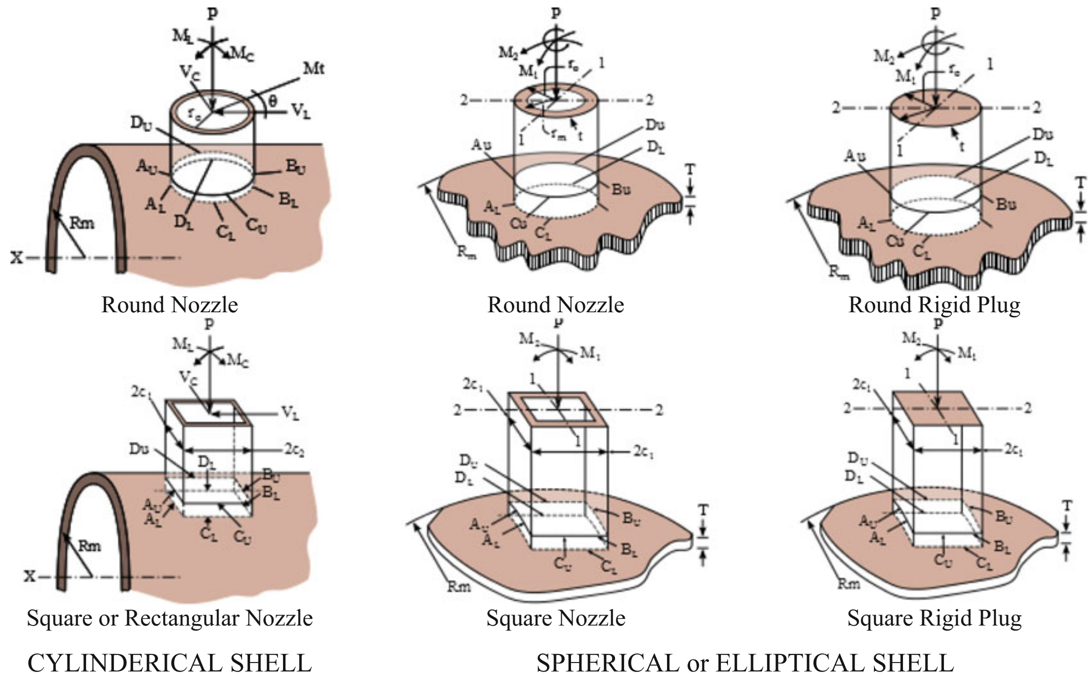
This module calculates "local" stresses per WRC 107 standard on the shell of the vessel, tank, or pipe. Typically, such local stress analysis is performed to ensure that piping loads will not overstress the vessel wall at the nozzle/vessel junction resulting in cracked welds or damage to the vessel. WRC does not specify stress allowable, only how to calculate stresses. So we have built in to this module as well as in the WRC 297 module automatic load combinations and stress allowable per ASME Sec. 8, Div. 1 or Div. 2. ASME Sec. 8 is the pressure vessel design code.

1.3.1.1 WRC 107/ WRC 537

WRC 107 (1st edition in 1979) can handle both spherical and cylindrical shells, with either a hollow attachment (like a nozzle) or solid attachment (like a lug). Figure 1.19 shows the forces and moments on the attachment of pressure vessel in WRC 107. Meanwhile, WRC 537 in 2010 was published for Precision Equations and Enhanced Diagrams for Local Stresses in Spherical and Cylindrical Shells due to External Loadings to facilitate implementation of the widely required and used relations found in WRC 107.

1.3.1.2 WRC 297

This module is the same as WRC 107, but using WRC 297 method for calculating local stresses. This module also has built-in stress allowable and load combinations per ASME Sec. VIII. The main differences between WRC 107 and WRC 297 are that WRC 297 can be used only for cylindrical shells, not spherical shells, and only with a round hollow attachment. Although WRC 297 is limited for those applications, WRC 297 design rules allow stress calculations for thinner wall shells than WRC 107, such as thin-walled vessels and tanks.



Rm = Mean radius of spherical shell or mean radius of cylindrical shell, in	P = Concentrated radial load or total distributed radial load, lb
Mx = External overturning moment in the x direction	r_o = outside radius of cylindrical attachment, in
Θ = Angle around attachment, degrees	r_m = mean radius of cylindrical attachment, in

Figure 1.19 Forces and moments on attachment of pressure vessel (WRC 107 & WRC 537)

Both WRC 107 and 297 have certain limits of shell diameter vs. attachment diameter and wall thickness limitations. See the web site for the Pressure Vessel Research Council for more information on WRC standards.

1.3.1.3 Finite Element Analysis (FEA) – Courtesy J.W. Jones, FEA of Pressure Vessels, NBIC

The use of finite element methods to design and analyze pressure vessels is a relatively recent development in the overall historical perspective of the ASME Code. The finite element method first became a useful tool for the designer in the early 1960s. The advent of the ASME Nuclear Code (Section III), which first appeared in about 1964, provided for a "design by analysis" procedure. Until this time, the pressure vessel design codes all used the "design by formula" approach, which is essentially now used in ASME Sec. VIII, Div. 1. The design by formula method provides explicit rules for calculating wall thicknesses of heads, shells, reinforcement around openings, and other details of a vessel. There are additional rules to handle such features as discontinuities between different components (i.e., the 3:1 taper rule) and allowable construction details are illustrated. The shortcoming of these rules is, of course, that they cannot cover every conceivable detail that the designer may want to use. For example, ASME Sec. VIII, Div. 1, gives numerous warnings and admonitions that the designer shall consider the effects of thermal gradients, piping loads, nozzle loads, rapidly fluctuating loads, seismic, wind, etc., but unfortunately there are few specific guidelines or formulas included in the code to cover such items. Further, the allowable stresses given in the code are based on a rather simplistic average membrane stress. Other loads, such as thermal loads, for example, cause a different type of stress that cannot be limited to the S values in the code, if a reasonable design is to be developed.

ASME Sec. III and Sec. VIII, Div. 2, which came out several years after ASME Sec. III, both use the concept of design by analysis. These rules provide the designer/analyst with a variety of stress limits, each developed to protect against a different mode of failure. Stresses are classified into categories such as Primary, Secondary, Peak, etc. Each category of stress is subjected to different stress limits.

1.3.2 Fatigue Analysis

Fatigue is the condition leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material. The maximum allowable stresses will be gradually reduced as per the fatigue loads. See Sect. 2.3.10 for thermal fatigue and Sect. 2.4.2.11 for fatigue corrosion-knockdown factor (KDF).

1.3.2.1 Fatigue Analysis for Pressure Vessels

Allowable stress value after long-term operation with high cycle (by dynamic: 10^5~10^8, e.g., vehicles, bridge, rotating machineries, heat-exchanger tube vibration, subsea risers, pipelines, etc.) or low cycle (by thermal: 10^3~10^4, e.g., pressure vessel, heat-exchanger, boilers, heater, etc.) is decreasing as shown in Figs. 1.20, 1.21, 1.22, 1.23, 1.24, 1.25, 1.26, 1.27, 1.28, 1.29. Figure 1.20 typically illustrates the trends of the S-N curves in corrosive services. Figures 1.21, 1.22, 1.23, 1.24, 1.25, 1.26, 1.27, 1.28, 1.29 show the S-N curves in non-corrosive services (in air) and non-creep zones. The interpolation may be applicable when the YS (as SMYS) of TS (as SMTS) is between two curves. Several other factors, such as weld surface condition, notch effects, metal temperature differential (ASME Sec. VIII, Div. 2, Table 5.8), and aging effects (by high dislocation density, 2nd phase precipitations, etc.), can additionally decrease the fatigue stress/life. Figure 1.30 shows a typical failure mode of fatigue crack and stress-concentrated crack. Typically, fatigue cracks appear in 45° direction or through fusion weld, while stress-concentrated cracks propagate through-thickness direction.

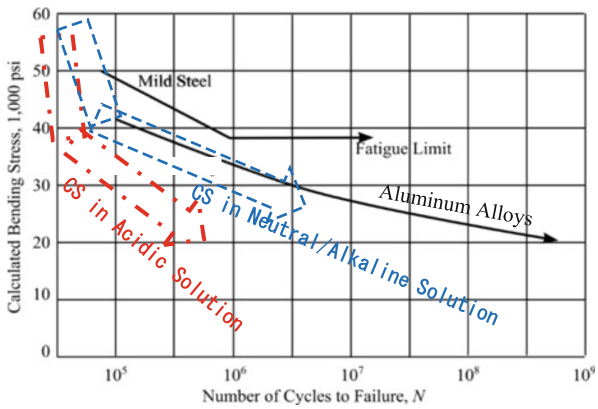


Figure 1.20 Fatigue S-N curve of metals (trend in air)

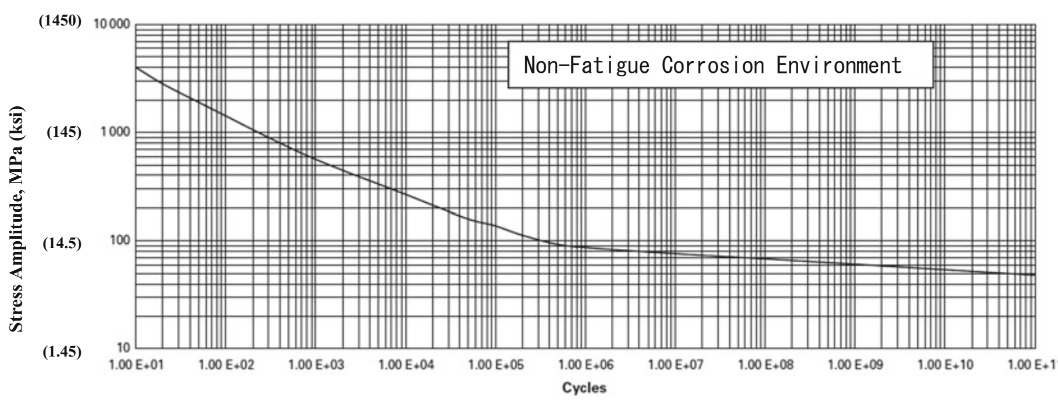


Figure 1.21 Fatigue S-N curve for carbon, low alloy, series 4XX, high alloy, and high tensile strength steels for temperatures not exceeding 371 °C (700 °F) – TS $\leq$ 552 MPa (80 ksi) (ASME Sec. VIII, Div. 2, Figure 3-F.1M)

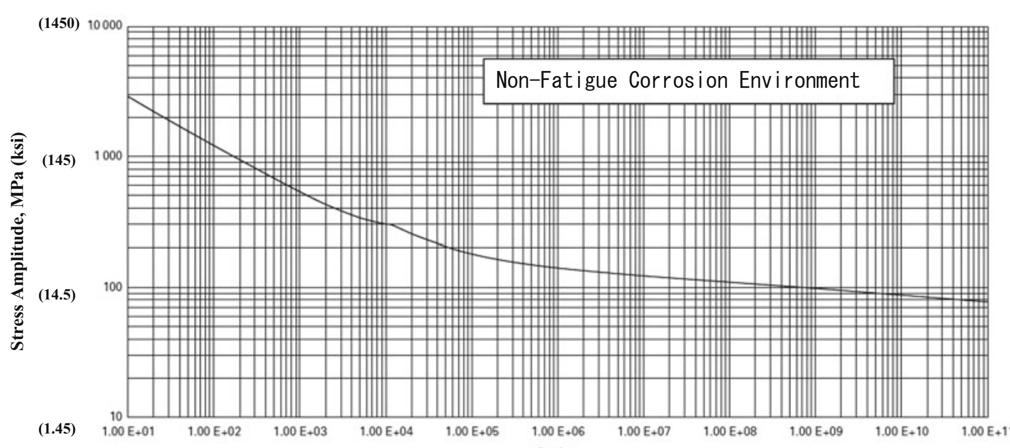


Figure 1.22 Fatigue S-N curve for carbon, low alloy, series 4XX, high alloy, and high tensile strength steels for temperatures not exceeding 371 °C (700 °F) – TS = 793–892 MPa (115–130 ksi) (ASME Sec. VIII, Div. 2, Figure 3-F.2M)

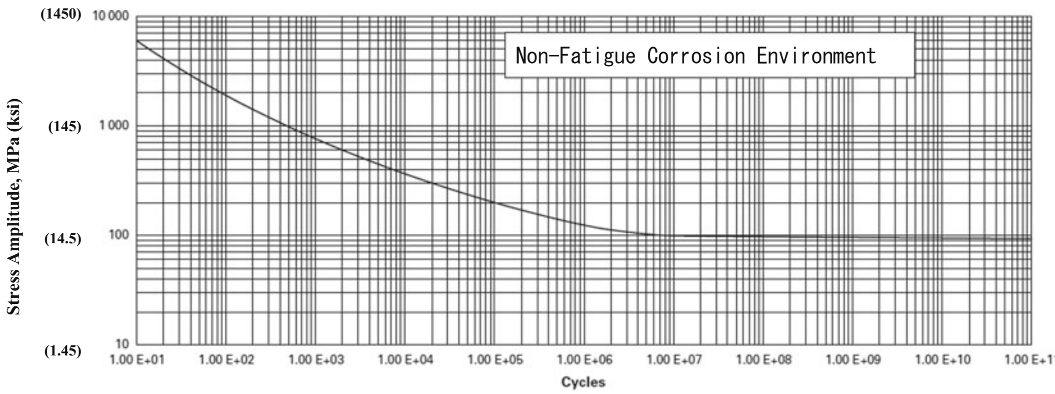


Figure 1.23 Fatigue S-N curve for series 3xx high alloy steels, Ni-Cr-Fe Alloy, Ni-Fe-Cr Alloy, and Ni-Cu alloy for temperatures not exceeding 427 °C (800 °F) (ASME Sec. VIII, Div. 2, Figure 3-F.3M)

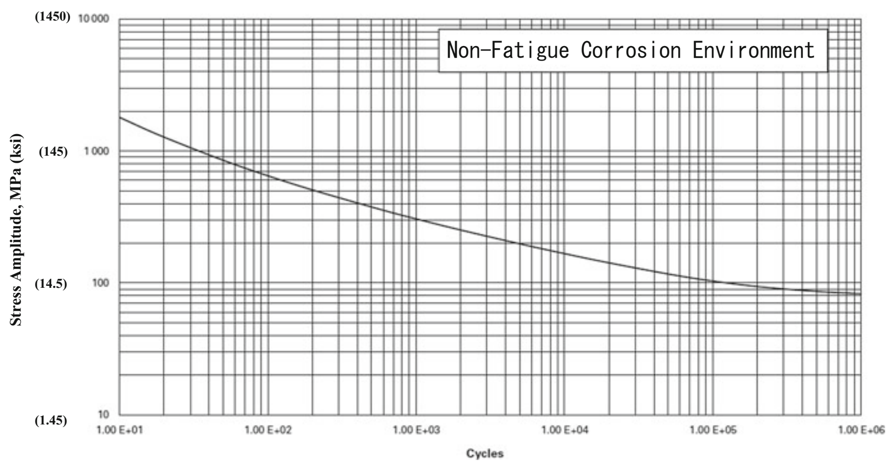


Figure 1.24 Fatigue S-N curve for wrought 70–30 Cu-Ni for temperatures not exceeding 371 °C (700 °F) – YS $\leq$ 134 MPa (18 ksi) (ASME Sec. VIII, Div. 2, Figure 3-F.4M)

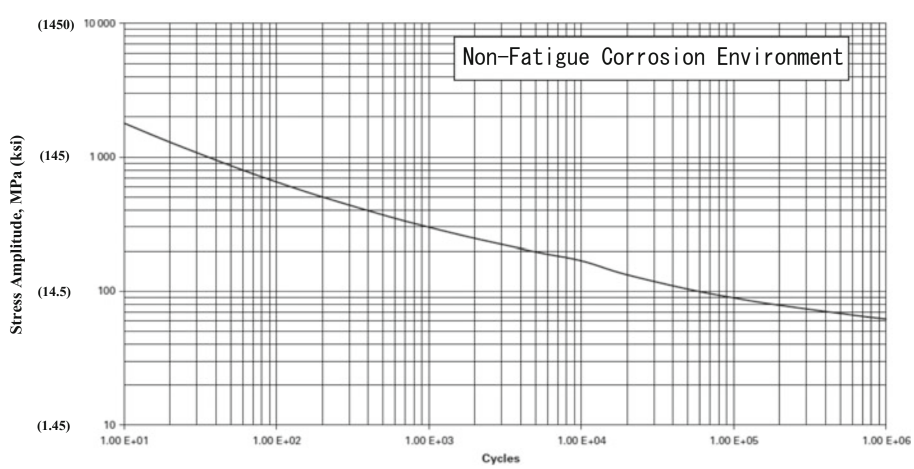


Figure 1.25 Fatigue S-N curve for wrought 70–30 Cu-Ni for temperatures not exceeding 371 °C (700 °F) – YS = 207 MPa (30 ksi) (ASME Sec. VIII, Div. 2, Figure 3-F.5M)

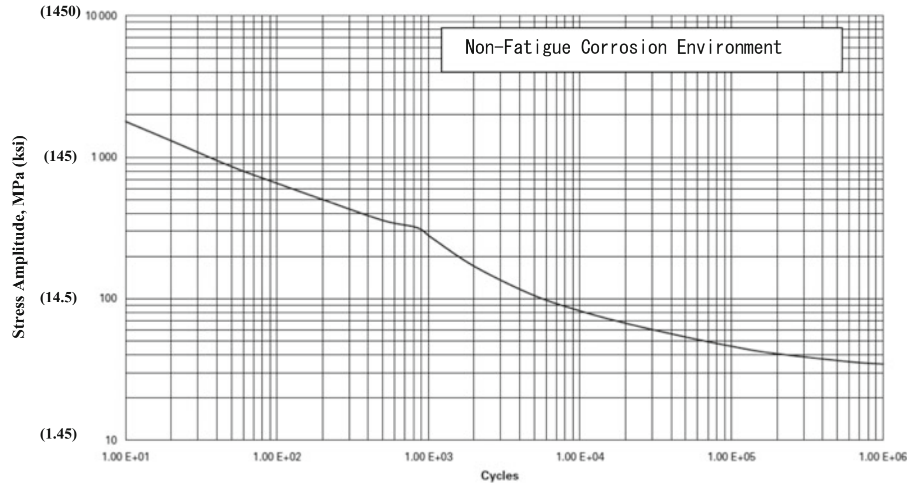


Figure 1.26 Fatigue S-N curve for wrought 70–30 Cu-Ni for temperatures not exceeding 371 °C (700 °F) – YS = 310 MPa (45 ksi) (ASME Sec. VIII, Div. 2, Figure 3-F.6M)

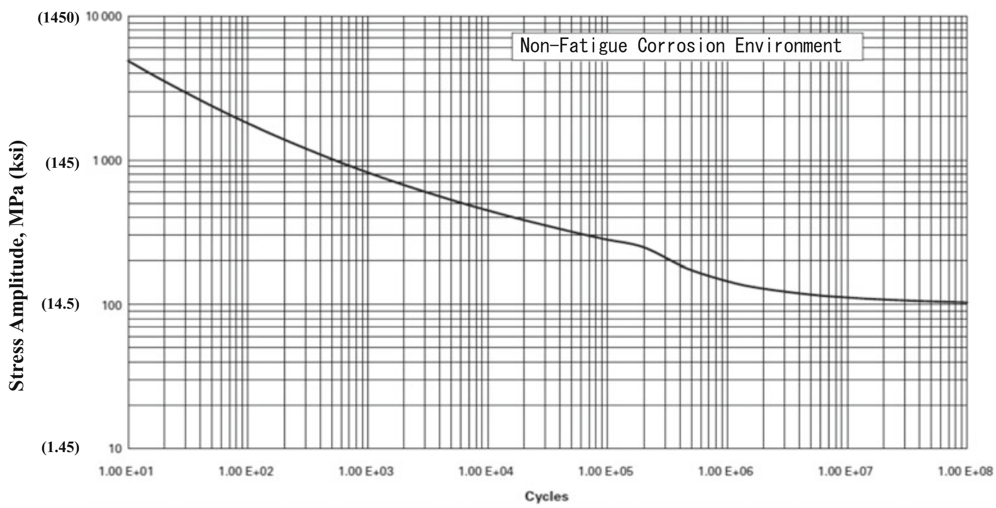


Figure 1.27 Fatigue S-N curve for Ni-Cr-Mo-Fe, alloys X, G, C-4, and C-276 for temperatures not exceeding 427 °C (800 °F) (ASME Sec. VIII, Div. 2, Figure 3-F.7M)

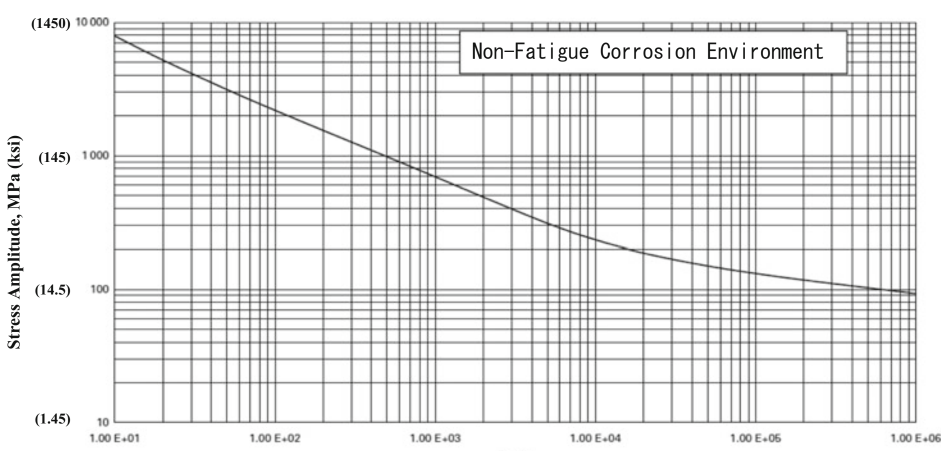


Figure 1.28 Fatigue S-N curve for high strength bolting for temperatures not exceeding 371 °C (700 °F) – maximum nominal stress $\leq 2.7S_M$, S_M = *membrane stress* (ASME Sec. VIII, Div. 2, Figure 3-F.8M)

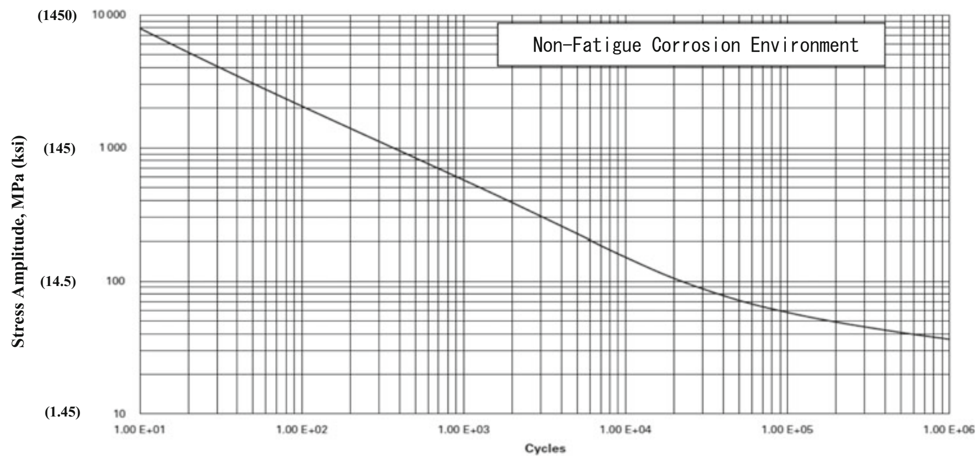


Figure 1.29 Fatigue S-N curve for high strength bolting for temperatures not exceeding 371 °C (700 °F) – maximum nominal stress >2.7S_M, S_M = *membrane stress* (ASME Sec. VIII, Div. 2, Figure 3-F.9M)

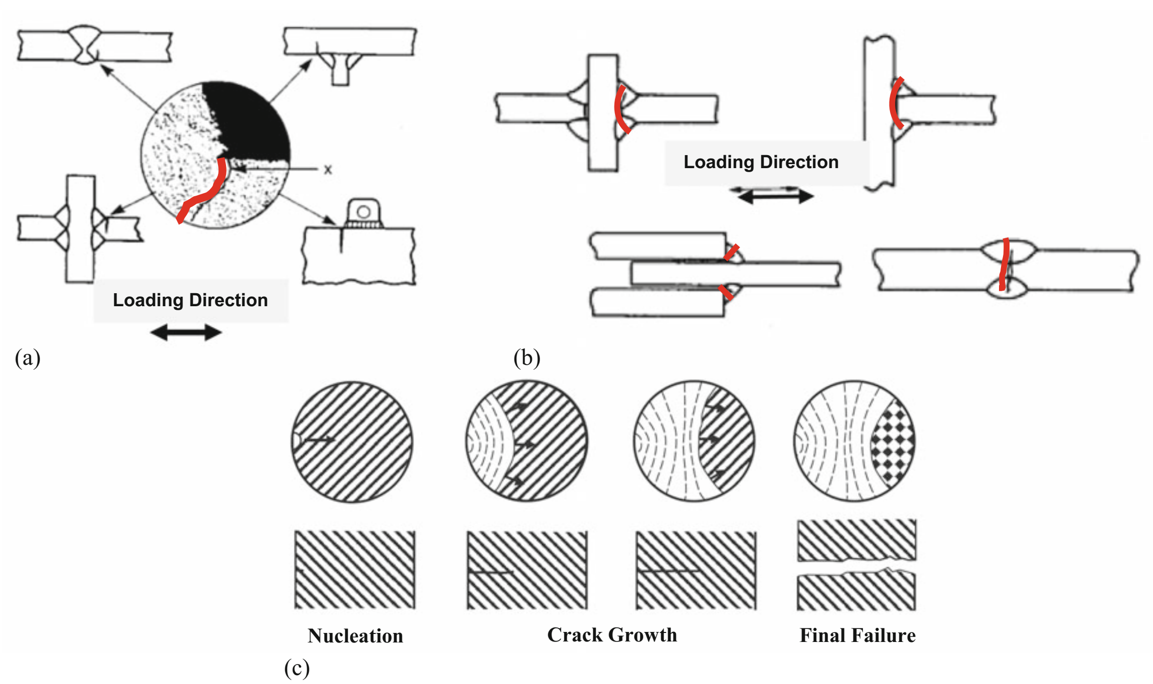


Figure 1.30 Typical comparison of failure modes between fatigue crack vs. stress concentrated crack. (**a**) Cracks by stress concentration. (**b**) Cracks by fatigue stress. (**c**) Typical propagation of fatigue crack. (Source: ASM Metal Handbook, Vol.11 modified)

The following analysis may be required:

- Fatigue analysis if needed – e.g., dynamic and thermal stress
- Strength calculation of vibration for tall towers, exchanger tubes/fatigue stress relaxation for boltings
- Strength calculation of expansion joints or thermal sleeves

See ASME STP-PT-007 (Comparison of Pressure Vessel Codes-ASME Sec. VIII and EN13445) for more detail technical, commercial, and usage comparison of design fatigue life.

Several factors have to be taken into account while using the empirical S-N curve for a real-life model.

The factors are corrosive environment (K_c), surface conditions (K_s), size factor (K_i), mode of loading (K_m), temperature factor (K_t), reliability factor (K_r), notch effects (K_f or K_g), and fretting conditions (K_{fret}).

Fatigue Strength Reduction Factor $= k_c * \times k_s * \times k_l * \times k_m * \times k_t * \times k_r * \times k_f * \times k_{fret}$

Typical load modes tensile-compressive, tensile-tensile, and compressive-compressive

If the local notch or effect of the weld is accounted for in the numerical model, then $k_g = 1.0$. However, if the local notch or effect of the weld is not accounted for in the numerical model, then a fatigue strength reduction factor, k_g (1.0 as no fatigue effect due to weld surface to 4.0 for the highest fatigue effect due to weld surface), shall be included.

Table 1.64 shows metal temperature differential factors for fatigue-screening criteria.

Table 1.65 and Table 1.66 show the weld surface fatigue-strength-reduction factors because the weld seam may become a very stress-concentrated zone per the joint details.

The elastic fatigue approach is used for the initial evaluation; however, the thermal stresses induced by the rapid transients result in the application of a significant fatigue penalty factor (K_e). Table 1.67 shows fatigue penalty factors (Ke) for fatigue assessment (elastic stress analysis and equivalent stresses)

The most typical case may be the fatigue life evaluation using transient thermal analysis for skirt/shell junction of code drums in refinery plant. Coke drums undergo severe thermal and pressure cycling on a daily basis when subject to alternative pre-heating, filling up with coke, quenching, and then decoking operation. This cyclic mode of operation results in significant thermal stresses at the support skirt attachment to the drum. Temperature gradients are developed along the skirt during steady-state and transient thermal conditions inside the coke drum. Higher thermal gradient will lead to higher thermal stresses and lower fatigue life. Transient temperature gradients developed during the cyclic quenching and heating process are reverse in nature and therefore cause reversal in bending stresses imposed on skirt.

In general, the magnitude of thermal stresses induced due to thermal condition of coke drum during quenching and preheating/switch to coking is much higher compared to steady-state thermal condition. Therefore, the fatigue evaluation of coke drum is governed by thermal transient analysis. It is determined that the weld between skirt and shell at the inner crotch is subjected to the highest bending stress reversal due to alternate cooling and heating.

Stress reversal effect is considered to determine the stress range and to evaluate fatigue life.

Finite element analysis is used to evaluate the thermal and stress profiles for the transient conditions. Thermal cycle includes transient cooling condition and transient heating condition.

Table 1.64 Temperature deferential factors for fatigue screening criteria (ASME Sec. VIII, Div.2, Table 5.8)

Metal temperature differential		Temperature factor for fatigue-screening criteria	Remark
°C	°F		
≤28	≤50	0	If the weld metal temperature differential is unknown or cannot be established, a value of 20 shall be used
29–56	51–100	1	
57–83	101–150	2	
84–139	151–250	4	
140–194	251–350	8	
195–250	351–450	12	
>250	>450	20	

General Note: As an example illustrating the use of this table, consider a component subject to metal temperature differentials for the following number of thermal cycles:

Temperature differential	Temperature factor based on temperature differential	Number of thermal cycles
28 °C (50 °F)	0	1000
50 °C (90 °F)	1	250
222 °C (400 °F)	12	5

Table 1.65 Weld surface fatigue strength reduction factors, *Kg* (ASME Sec. VIII, Div. 2, Table 5.11)

Weld condition	Surface condition	Quality levels (see ASME Sec. VIII, Div. 2, Table 5.12)						
		1	2	3	4	5	6	7
Full penetration	Machined	1.0	1.5	1.5	2.0	2.5	3.0	4.0
	As-welded	1.2	1.6	1.7	2.0	2.5	3.0	4.0
Partial penetration (a)	Final surface machined	NA	1.5	1.5	2.0	2.5	3.5	4.0
	Final surface as-welded	NA	1.6	1.7	2.0	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0
Fillet (b)	Toe machined	NA	NA	1.5	NA	2.5	3.0	4.0
	Toe as-welded	NA	NA	1.7	NA	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0

Commentary Notes:
(a) Application of partial penetration in Div. 2 may be greatly limited
(b) Fillet in Div. 2 may have to be full penetration type

Table 1.66 Weld surface fatigue strength reduction factors (ASME Sec. VIII, Div. 2, Table 5.12)

Fatigue-strength-reduction factor	Quality level	Definition
1.0	1	Machined or ground weld that receives a full volumetric examination and a surface that receives MT or PT examination and a VT examination
1.2	1	As-welded weld that receives a full volumetric examination and a surface that receives MT or PT and VT examination
1.5	2	Machined or ground weld that receives a partial volumetric examination and a surface that receives MT/PT examination and VT examination
1.6	2	As-welded weld that receives a partial volumetric examination and a surface that receives MT or PT and VT examination
1.5	3	Machined or ground weld surface that receives MT or PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
1.7	3	As-welded or ground weld surface that receives MT or PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
2.0	4	Weld has received a partial or full volumetric examination, and the surface has received VT examination, but no MT or PT examination
2.5	5	VT examination only of the surface; no volumetric examination nor MT or PT examination
3.0	6	Volumetric examination only
4.0	7	Weld backsides that are non-definable and/or receive no examination

Notes
1. Volumetric examination is RT or UT in accordance with ASME Sec. VIII, Div. 2, Part 7
2. MT or PT examination is performed in accordance with ASME Sec. VIII, Div. 2, Part 7
3. VT examination is visual examination in accordance with ASME Sec. VIII, Div. 2, Part 7
4. See WRC Bulletin 432 (fatigue strength reduction and stress concentration factors for welds in pressure vessels and piping) for more information

General Notes:
5. See ASME Sec. II, Part D, Figure E-100.16-1 through E-100.16-5, for design fatigue strain range, εt, in Cr-Mo steels, ASS, and Ni-alloys
6. See API TR934-G for coke drum design and fabrication with fatigue analysis

Table 1.67 Fatigue penalty factors, *Ke*, for fatigue analysis (ASME Sec. VIII, Div. 2, Table 5.13)

Material (typical metals)	$Ke^{(1)}$		$T_{max}^{(2)}$	
	m	n	°C	°F
LAS	2.0	0.2	371	700
MSS	2.0	0.2	371	700
CS	3.0	0.2	371	700
ASS	1.7	0.3	427	800
Ni-Cr-Fe (i.e., inconel, incoloy)	1.7	0.3	427	800
Ni-Cu (i.e., monel)	1.7	0.3	427	800

Notes: m, material constant used for the fatigue knockdown factor; n, material constant used for the fatigue knockdown factor
(1) Fatigue penalty factor (*Ke*), max. 5 for CS and LAS and max. 3.3 for ASS
(2) The fatigue penalty factor should only be used if all of the following are satisfied:
• The component is not subject to thermal ratcheting
• The maximum temperature in the cycle is within the value in the table for the material

The temperature gradients from thermal model is then exported to the stress model to determine thermal stresses. Three cases are considered in the stress model:

(i) The thermal case alone, for heat up and quench conditions
(ii) An internal pressure case acting with dead and live loads in the drum
(iii) The combined thermal, internal pressure plus dead and weight loads during the heat up and quench part of the coking cycle

Upon determination of the maximum stresses for both transient conditions, the stress reversal effect is considered to determine the full stress range and to evaluate fatigue life.

The allowable criteria for the evaluation of fatigue due to peak stress are twice the stress amplitude using fatigue curves from ASME Sec. VIII, Div. 2, Annex 5.

The results of this thermal/mechanical stress analysis are used to perform fatigue evaluation at critical locations.

For thermal/mechanical stress analysis, the following load cases are analyzed:

– Thermal gradient only
– Pressure + Weight
– Thermal Gradient + Pressure + Weight

See Figs. 1.31 and 1.32 for FEA plot by fatigue stress from a software. The red zone is the most stressed area, while the purple zone is the weakest stressed area. These red zones may have to be a major concern for maintenance and repair.

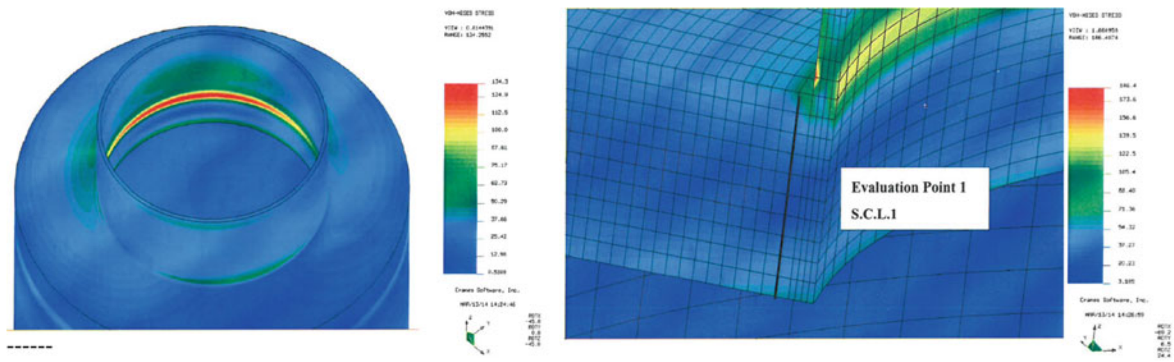
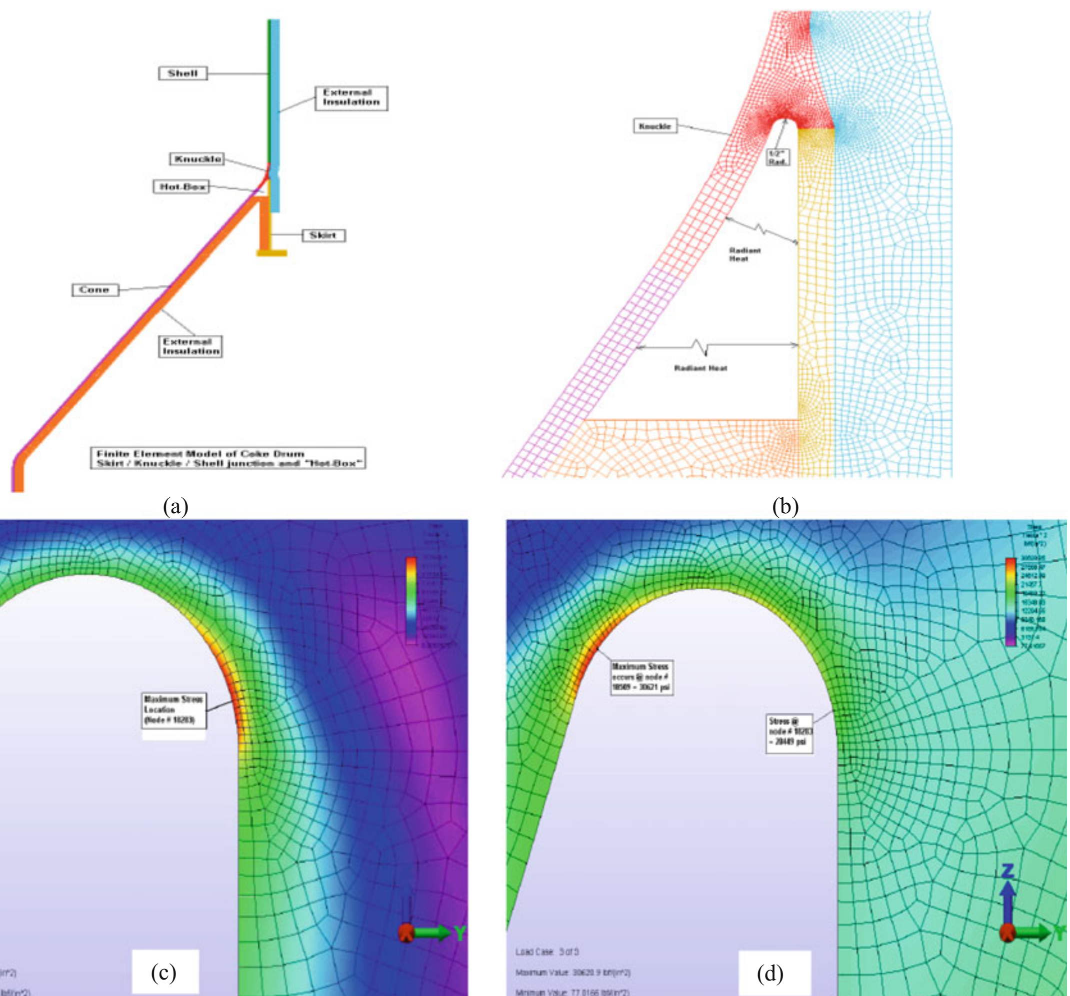


Figure 1.31 FEA analysis for nozzle on pressure vessel (Von-Mises stresses)



Local Case: Thermal + Weight + Pressure Time Step = 30 Time = 940 min, i.e. 40 min after "SWITCH" Maximum Transient Stress Plot (during Reheating + Switch Cycle)	Local Case: Thermal + Weight + Pressure Time Step = 64 Time = 144 min, i.e. 54 min into Quenching/ filling Maximum Transient Stress Reversal (Thermal + Pressure) during Quench Cycle

Figure 1.32 Fatigue life evaluation using transient thermal analysis for code drum skirt/shell junction

1.3.2.2 Fatigue Analysis for Piping, Pipelines, and Risers

The Stress range factor (reduction factor), f, by fatigue cycle should be considered the strength calculation. The allowable displacement stress range, S_A, which is compensated by the reduction factor, f, shall not be less than the computed displacement stress range, S_E, in a piping system in ASME B31.3. (See Fig. 1.33)

$$; S_A = f(1.25S_c + 0.25S_h) \quad \text{(Eq. 1.1)}$$

When S_h is greater than S_L, the difference between them may be added to the term $0.25Sh$ in Eq. 1.1. In that case, the allowable stress range is calculated by Eq. 1.2

$$; S_A = f[1.25(S_c + S_h) - S_L] \quad \text{(Eq. 1.2)}$$

f (see Fig. 1.23) $= 6.0\,(N)^{-0.2} \le f_m$
where:

f_m = maximum value of stress range factor; 1.2 for ferrous materials with specified minimum tensile strengths ≤517 MPa (75 ksi) and at metal temperatures ≤371 °C (700 °F); otherwise $f_m = 1.0$
N = equivalent number of full displacement cycles during the expected service life of the piping system
S_c = basic allowable stress at minimum metal temperature expected during the displacement cycle under analysis but maximum 138 MPa (20 ksi)
S_h = basic allowable stress at maximum metal temperature expected during the displacement cycle under analysis but maximum 138 MPa (20 ksi)
S_L = stress due to sustained loads; in systems where supports may be active in some conditions and inactive in others, the maximum value of sustained stress, considering all support conditions, shall be used

The pipelines and risers designed for the potential cyclic loading can cause fatigue damage include vortex-induced vibrations (VIV), wave-induced hydrodynamic loads, and cyclic pressure and thermal expansion loads.

Industrial Standards and References

ASME B31.1/B31.3/ B31.8/ B31.12, etc.
API RP1111/Standard 2RD, etc.
OTC Paper 6335, '90 Proc. V 2, pp 551–560, etc.

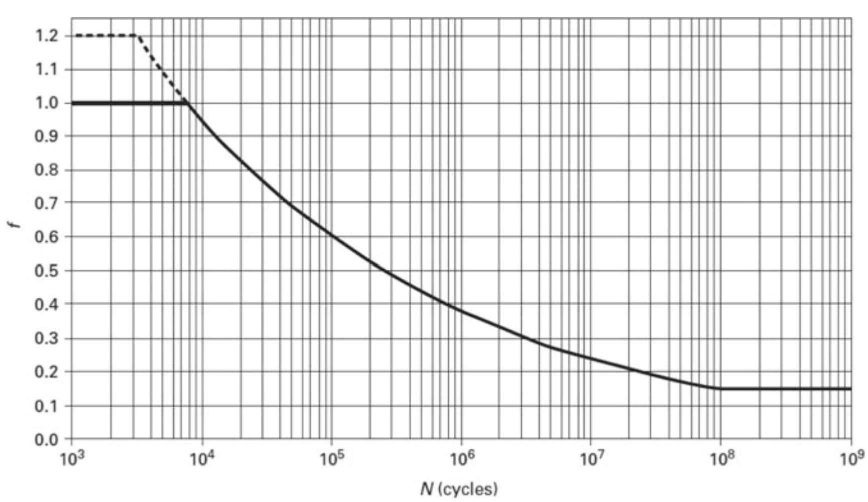


Figure 1.33 Stress range factor, f, by fatigue cycle (ASME B31.3 Fig. 302.3.5)

1.3.3 *Creep and Rupture Requirements Including Compressive Stress Rules*

1.3.3.1 Characteristics in High Temperature – Creep and Rupture (Fig. 1.34)

Figure 1.34 shows creep and rupture curve of metals as a function of long-term operation at elevated temperature.

Creep-stress rupture data for high temperature creep-resistant alloys are often plotted as log stress to rupture versus a combination of log time to rupture and temperature. One of the most common time-temperature parameters used to present this kind of data is the Larson-Miller parameter (LMP) or Hollomon-Jaffe parameter (HJP). The difference between the two parameters is that LMP is considered the holding time and temperature, while PJP is considered the heating and cooling rates as well as the holding time and temperature (Fig. 1.35).

The Larson-Miller parameter is a means of predicting the life time of material vs. time and temperature using a correlative approach based on the Arrhenius rate equation. The value of the LMP is usually expressed as

$$\text{LMP} = T(C + \log t);$$

where

C is a material-specific constant often approximated as 20 for ferrous materials and 15 for high alloy steel and nonferrous alloys,

t is the exposure (design) time in hours, and

T is the design (or PWHT with high temperature-longer holding time – see Figs. 2.128 and 2.129) temperature in Kelvin. T can be classified as minimum, average, and maximum temperature.

See API 530, WRC Bulletin 541 (Evaluation of Material Strength Data for Use in API Std 530), and API-579-1/ASME FFS-1 for more details. See API-579-1/ASME FFS-1 for Zener-Hollomon parameter which is for high temperature creep strain of the steel. Some standards recognize the Larson-Miller parameter is the same as Hollomon-Jaffe parameter because typically the factors of Kh (heating rate) and Kc (cooling rate) are not remarkable.

Per ASME Sec. II, Part D, A-220, the previous studies suggested that carbon steel produced to a coarse austenitic grain size melting practice exhibited superior creep properties compared to those produced to a fine austenitic grain size melting practice (aluminum treated). However, some studies have shown that the 100,000 h rupture strengths of steel made to either fine or coarse austenitic grain size melting practices are about the same at temperatures above 455 °C (851 °F). More recent studies have shown that the superiority of the "coarse grain" steels is associated with "free" nitrogen (N). Once the free nitrogen is removed from solid solution by precipitation, the differences in creep properties are negated. Precipitation of nitrogen may occur prior to service by heat treatment (tempering or PWHT) or by service at elevated temperatures. The amount of precipitation is dependent on both the temperature and the time at temperature. In addition to deoxidization practice and heat treatment, the creep and creep-rupture properties of CS are influenced by residual elements. For example, a small addition (0.10%) of molybdenum (Mo) can markedly increase the strength of carbon steel.

Because of the superior notch toughness of normalized steel made to a fine austenitic grain size melting practice, it is often desirable to forego any possible creep strength advantage of the steels made to "coarse grain" practice. However, when considering fine austenitic grain size materials, it should be recognized that aluminum (Al)-treated steels have been shown to be more prone to graphitization than silicon (Si)-killed steels not treated with aluminum.

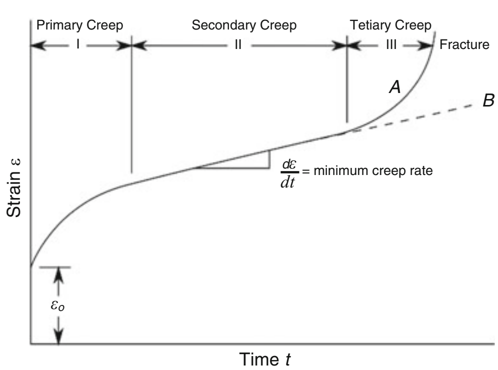


Figure 1.34 Creep and rupture curve of metals. Curve A: constant load test. Curve B: constant strain test

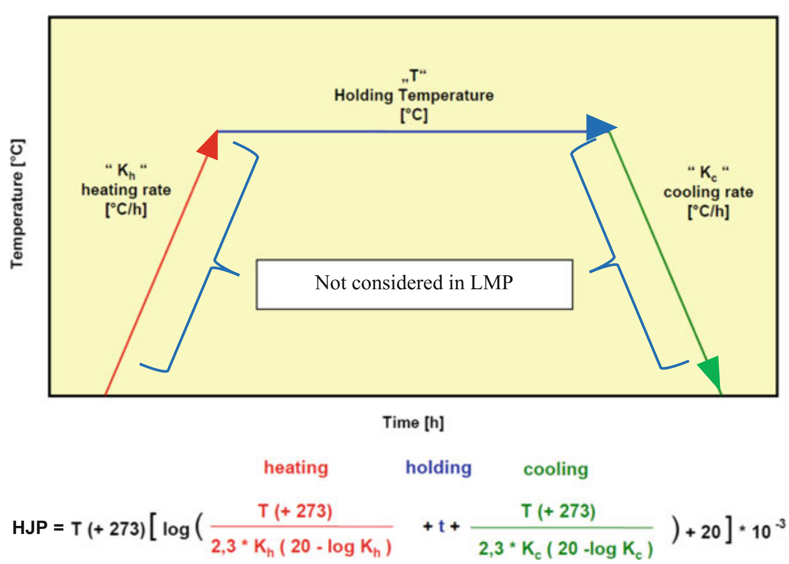


Figure 1.35 Schematization of Hollomon-Jaffe parameter calculation

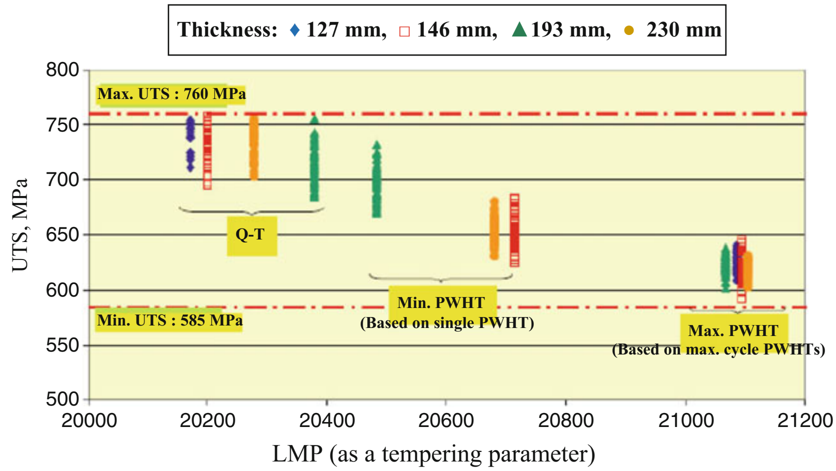


Figure 1.36 Influence of LMP and thickness on UTS for 2.25 Cr-1Mo-V steel. (Source: ArcelorMittal Industeel's presentation in NACE 2015 conference)

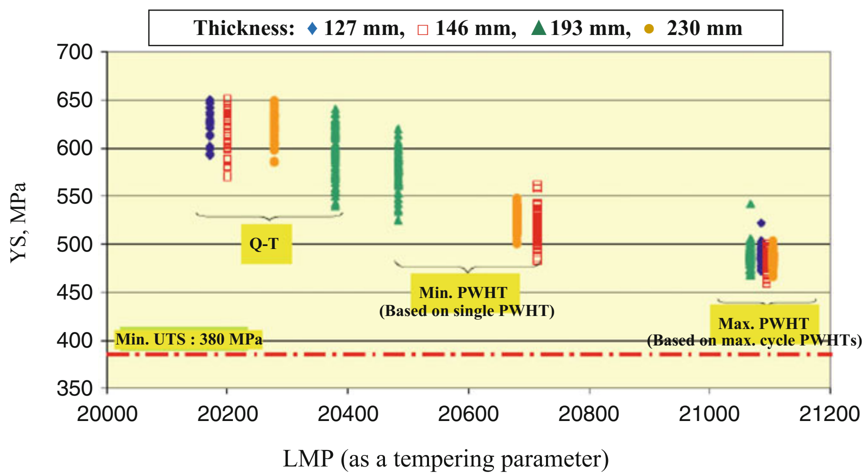


Figure 1.37 Influence of the thickness and LMP on yield strength for 2.25Cr-1Mo-V steel. (Source: ArcelorMittal Industeel's presentation in NACE 2015 conference)

The existing data base for CS does not permit a quantitative assessment of the various factors affecting the strength of these steels. To a large extent, the existing allowable stresses are based on service experiences rather than on individual test data.

Figure 1.36 shows that even for usual maximum PWHT (705 °C during 33 hrs), the UTS requirement is still met. One can also underline that the effect of thickness is more present for low LMP than the highest ones. It is interesting to notice the decrease as a function of the tempering parameter. In particular, this implies that the initial target in the Q&T state must be close to upper limit of UTS requirement.

Figure 1.37 describes the evolution of the yield strength (YS) as a function of the LMP. Even if the trend is obviously the same as for UTS, it appears that the margin is larger regarding the minimum requirement to be met. Anyway these two last figures clearly show the influence of multiple PWHT on the mechanical properties of the base metal. The chemical analysis optimization has given some extra margin, but the material is close to its metallurgical limit.

1.3.3.2 Creep-Rupture Stress

See API 530 Fired Heater Tubes Calculation (use the allowable stresses of Annex E)/API 579-1/ASME FFS-1 (Fitness for Service) Part 10, API RP571, and ASME B16.5. The creep-rupture design is required above the temperature limitation in Tables 1.68 and Table 1.69. Table 1.70 shows the limitation of design metal temperature for heater-tube alloys. The final required thickness will be the greater of the required thickness in elastic design or the required thickness in rupture design. See API 579-1/ASME FFS-1, Figure 10.3 through 10.26M for Level 1 Screening Curves with creep stress-tube skin temperature-exposure time-damage rate (1/hr) of Several Materials.

The API 530, Figure 4 to 6 show the sample calculation sheets for rupture design at constant temperature and at changing temperature, respectively. The definition of temperature limitation is not clear in API 579-1/ASME FFS-1 and ASME B16.5, but the maximum operating temperature (but not for short-term operating conditions) may be the most reasonable value. The corresponding rupture allowable stress should be developed from the Larson-Miller parameter curves for the minimum rupture strength.

Meanwhile ASME STP-PT-024 (Report for Development of Basic Time-Dependent Allowable Stresses for Creep Regime in ASME Section VIII, Division 1) provides the basic time-dependent allowable stresses at creep-rupture regime, while ASME Section VIII,

Table 1.68 Temperature limits used to define the creep range (API 579-1/ASME FFS-1 modified)

Material	Temperature and above-modified [3]	
	API 579-1/ASME FFS-1	API RP571
Carbon steel [UTS ≤ 414 MPa (60 ksi)]	343 °C (650 °F)	371 °C (700 °F)
Carbon steel [UTS > 414 MPa (60 ksi)]	371 °C (700 °F)	
Carbon steel-graphitized[1]	371 °C (700 °F)	–
C-0.5Mo	400 °C (750 °F)	400 °C (750 °F)
1.25Cr-0.5Mo, N-T or annealed	427 °C (800 °F)	427 °C (800 °F)
2.25Cr-1Mo, N-T or annealed	427 °C (800 °F)	427 °C (800 °F)
2.25Cr-1Mo, Q-T	427 °C (800 °F)	427 °C (800 °F)
2.25 to 3Cr-1Mo-V	441 °C (825 °F)	–
5 to 7Cr-0.5Mo	427 °C (800 °F)	427 °C (800 °F)
9Cr-1Mo	427 °C (800 °F)	427 °C (800 °F)
9Cr-1Mo-V	454 °C (850 °F)	–
12 to 13Cr	482 °C (900 °F)	–
304(H) SS[2]	510 °C (950 °F)	480 °C (900 °F)
316(H) SS[2]	538 °C (1000 °F)	–
321(H) SS	538 °C (1000 °F)	–
347(H) SS	538 °C (1000 °F)	538 °C (1000 °F)
Alloy 800/800H/800HT	565 °C (1050 °F)	–
HK-40	649 °C (1200 °F)	–

Commentary Notes: "-" No data
[1]See Sect. 2.3.1 and NACE Paper 05558 and 05559 for more details
[2]"L" grade should not be used in these temperature range
[3]The temperature is based on the maximum operating temperature in continuous operation. However, the cyclic or batch operation temperatures that run above and below these temperatures as a borderline may not be applicable

Table 1.69 Temperature limit used to define the creep range (ASME B16.5, A-2)

Materials	Temperature limitation [1]
Group 1 (carbon steels and low alloy steels)	370 °C (700 °F)
Group 2 (austenitic stainless steels)	510 °C (950 °F)
Group 3 (nickel alloys)	Depends on materials

Division 1, provides an allowable stress for design of pressure vessels that is independent of load duration (Fig. 1.38). ASME STP-PT-024 also provides recommendations for design rules for very short-term loads (creep rupture during earthquake loading and/or at design wind velocity) for which creep should not be a design consideration, termed Occasional Loads herein, and rules for loads for which creep is a design consideration, termed Time-Dependent Design Considering Creep. API TR942-B shows creep rate curves, creep tests, and creep threshold temperatures of several austenitic SS and alloys.

With respect to overload failure, the relevant material properties are yield and tensile properties, not creep properties. Considering, for example, the ratio of yield strength to the allowable stress for 304H SS at 650 °C (1200 °F) and 760 °C (1400 °F) are 2.3 and 5.0 (yield strength values per ASME Sec. III, Subsection NH),

Table 1.70 Limiting design metal temperature for heater-tube alloys (API 530, Table 5)

Materials	Type or grade	Limiting design metal temperature		LCPTT [1]	
		°C	°F	°C	°F
Carbon steel	Low & medium C	540	1000	720	1325
C-1/2Mo steel	T1 or P1	566	1050	720	1325
1 1/4Cr-1/2Mo steel	T11 or P11	650	1200	775	1430
2 1/4Cr-1Mo steel	T22 or P22	650	1200	805	1480
3Cr-1Mo steel	T21 or P21	650	1200	815	1500
5Cr-1/2Mo steel	T5 or P5	650	1200	820	1510
5Cr-1/2Mo-Si steel	T5b or P5b	650	1200	845	1550
7Cr-1/2Mo steel	T7 or P7	705	1300	825	1515
9Cr-1Mo steel	T9 or P9	705	1300	825	1515
9Cr-1Mo-V steel	T91 or P91	705	1300	830	1525
18Cr-8Ni steel	304 or 304H	815	1500	–	–
18Cr-8Ni steel	304L	677	1250		
16Cr-12Ni-2Mo steel	316 or 316H	815	1500	–	–
16Cr-12Ni-2/3Mo steel	316L/317L	704	1300	–	–
18Cr-10Ni-Ti steel	321 or 321H	815	1500	–	–
18Cr-10Ni-Nb steel	347 or 347H	815	1500	–	–
Ni-Fe-Cr	Alloy 800	815	1500		
Ni-Fe-Cr	Alloy 800H/800HT	900	1650	–	–
25Cr-20Ni	HK40	954	1750	–	–

Notes:
The above data in Table 1.70 for fired heater are a little bit different from those of Table 4.113 for power piping (ASME B31.3)
[1]The data for LCPTT (Lower critical phase transformation temperature) may be a little bit different with those in ASME B31.1, Table 129.3.2 (see Table 4.113 in this book)

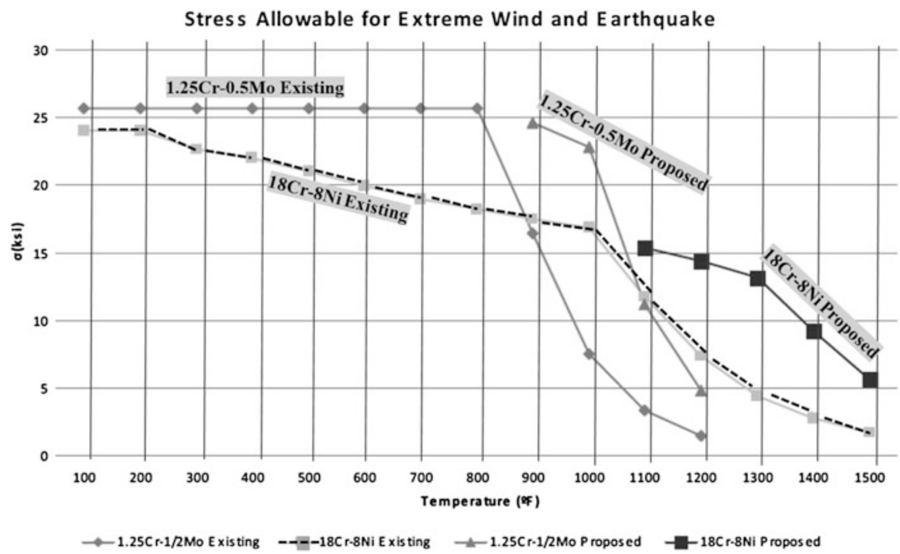


Figure 1.38 Comparison of existing allowable stresses and proposed allowable stresses in extreme wind and earthquake zone. (Source: ASME STP-PT-024)

respectively, provides an indication of the conservatism of using creep properties for earthquake design. Figure 1.35 shows a comparison of current allowable stresses and the proposed allowable stresses for two selected materials. For these two materials, at least, the proposed allowable stresses are significantly and reasonably higher than the current allowable stresses for loads of short duration, such as earthquakes. A creep damage calculation was made using the methodology of Time-Dependent Design Considering Creep provided in API 579-1/ASME FFS-1 for a case with 2.25Cr-1Mo material, to confirm the conservatism of the method. The ASME FFS-1 Level 1 damage assessment is provided in Section A.2 of ASME STP-PT-024, The proposed method in API 530, Appendix A (Estimation of Allowable Skin Temperature, Tube Retirement Thickness, and Remaining Life) is more conservative results than that provided in API 579-1/ASME FFS-1. The margin in the proposed method is consistent with the existing ASME Section VIII Code Criteria. The data in Table 1.70 for fired heater are a little bit different from those of Table 4.113 for power piping (ASME B31.3). In addition, API 579-1/ASME FFS-1, 10B.2.1 introduces the MPC Project Omega Method which is an assessment procedure documented in the public domain with a proven record and associated property relations covering a wide range of materials used in the refining and petrochemical industry. In this methodology, a strain-rate parameter and multi-axial damage parameter (Omega) are used to predict the rate of strain accumulation, creep damage accumulation, and remaining time to failure as a function of stress state and temperature. The creep-rupture curves (hours-temperature) by Omega Method typically indicates between LMP Curve$_{T=min}$ and LMP Curve$_{T=average}$.

1.3.3.3 Development History of Creep-Rupture Resistance Metals

Figure 1.39 shows a historic evolution of materials in terms of increasing creep rupture strength.

Figure 1.40 shows historic evolution of FSS and MSS.

Figure 1.41 shows development history of ASS.

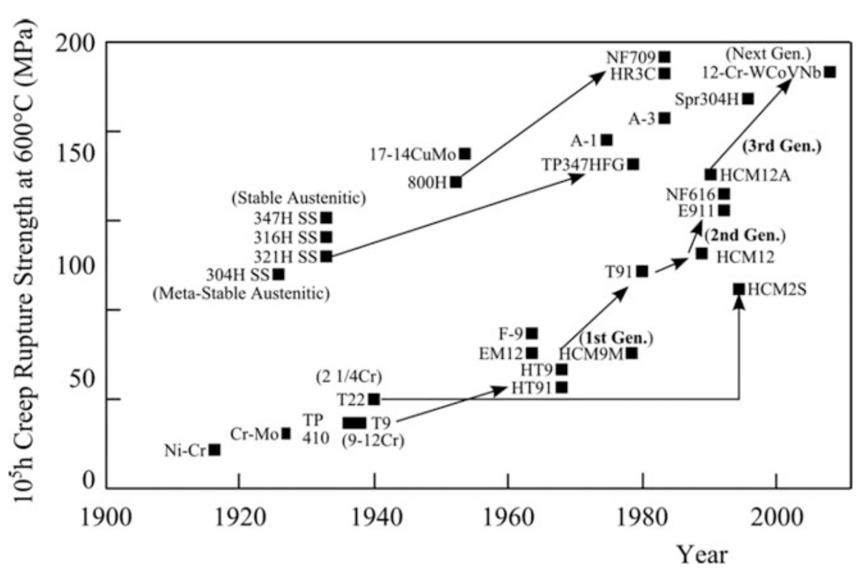


Figure 1.39 Historic evolution of materials in terms of increasing creep rupture strength. (Source: 2000 International Joint Power Generation Conference Data)

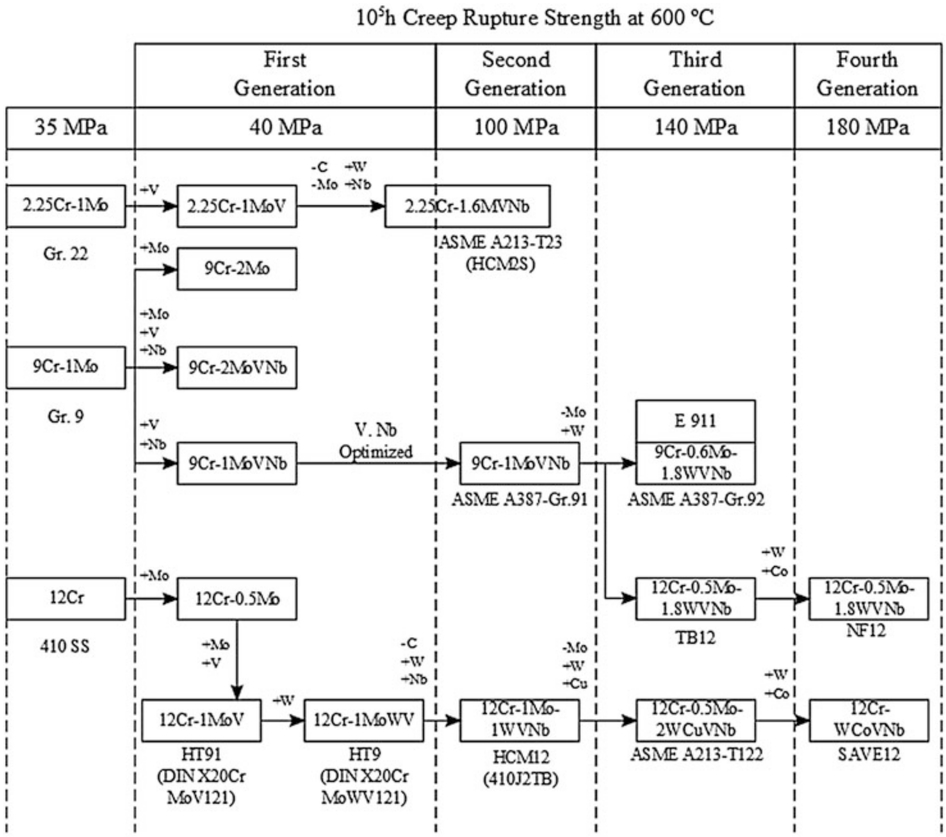


Figure 1.40 Historic evolution of ferritic and martensitic stainless steels (MSS) (Source: 2000 International Joint Power Generation Conference Data)

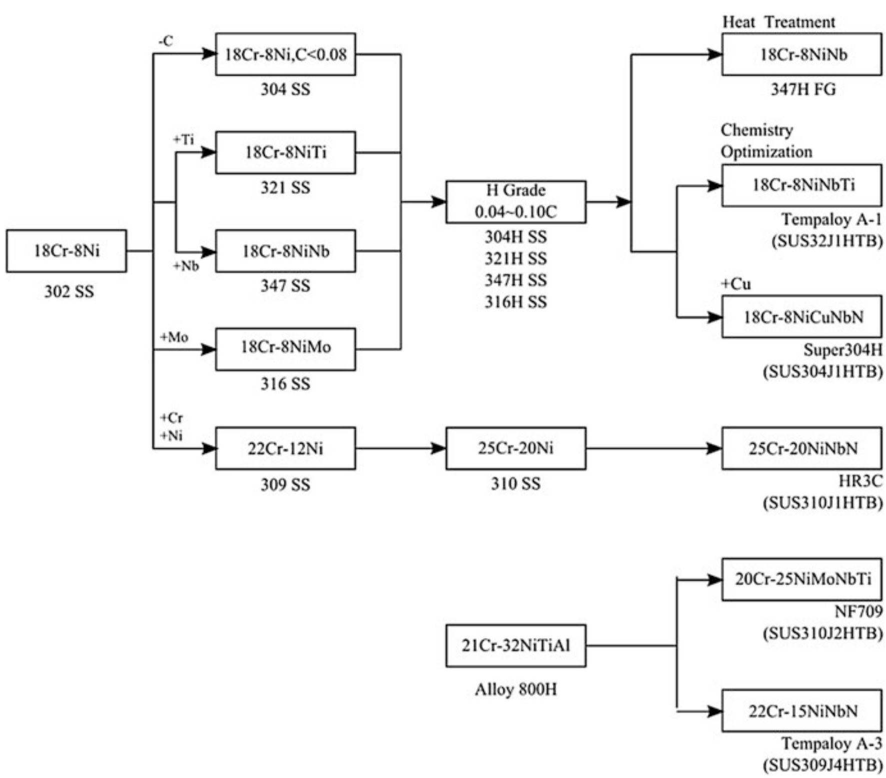


Figure 1.41 Development history of austenitic stainless steels (ASS). (Source: 2000 International Joint Power Generation Conference Data)

1.3.3.4 Weld Joint Strength Reduction at Elevated Temperature

Tables 1.71 and 1.72 show strength reduction requirements for weld joint at elevated temperature. Creep test data may be used to determine the weld joint strength reduction factor, *W*. However, the use of creep test data to increase the factor *W* above that shown in ASME B31.3 and B31.1 is not permitted for the Cr-Mo steel and creep strength-enhanced ferritic (CSEF) steel materials, as defined in ASME B31.3 and B31.1. Creep testing of weld joints to determine weld joint strength reduction factors, when permitted, should be full thickness cross-weld specimens with test durations of at least 1000 hours. Full thickness tests shall be used unless the designer otherwise considers effects such as stress redistribution across the weld.

With the end-user's approval, extensive successful experience may be used to justify the factor *W* above that shown in ASME B31.3 and B31.1. Successful experience must include same or like material, weld metal composition, and welding process under equivalent or more severe, sustained operating conditions.

Table 1.71 Weld joint strength reduction factor, *W* (ASME B31.3, Table 302.3.5 – modified)(9)

Metal Group	Weld strength reduction factors (*W*) per component temperature, *Ti*, °C (°F)														
	427 (800)	454 (850)	482 (900)	510 (950)	538 (1000)	566 (1050)	593 (1100)	621 (1150)	649 (1200)	677 (1250)	704 (1300)	732 (1350)	760 (1400)	788 (1450)	816 (1500)
Cr-Mo (1)(2)(3)	1	0.95	0.91	0.86	0.82	0.77	0.73	0.68	0.64	–	–	–	–	–	–
CSEF (N + T) (3)(4)(5)	–	–	–	1	0.95	0.91	0.86	0.82	0.77	–	–	–	–	–	–
CSEF (3)(4) subcritical PWHT	–	–	1	0.5	0.5	0.5	0.5	0.5	0.5	–	–	–	–	–	–
300 series ASS, alloy 800/800H/800HT/825 (7) (8)	–	–	–	1	0.95	0.91	0.86	0.82	0.77	0.73	0.68	0.64	0.59	0.55	0.5

General Notes (from B31.3 unless otherwise noted below):

(a) Weld joint strength reduction factors at temperatures above the upper temperature limit listed in Appendix A for the base metal or outside of the applicable range in ASME B31.1, Table 302.3.5, are the responsibility of the designer. At temperatures below those where weld joint strength reduction factors are tabulated, a value of 1.0 shall be used for the factor *W* where required; however, the additional rules of this Table and Notes do not apply

(b) *Tcr* = temperature 28 °C (50 °F) below the temperature identifying the start of time-dependent properties listed under "NOTES – TIME-DEPENDENT PROPERTIES" (Txx) in the Notes to Tables 1A and B of ASME Section II, Part D, for the base metals joined by welding. For materials not listed in ASME Section II, Part D, *Tcr* shall be the temperature where the creep rate or stress rupture criteria in ASME B31.1, paras. 302.3.2(d)(4), (5), and (6) governs the basic allowable stress value of the metals joined by welding. When the base metals differ, the lower value of *Tcr* shall be used for the weld joint

(c) *Ti* = temperature, °C (°F), of the component for the coincident operating pressure-temperature condition, *i*, under consideration

(d) The weld joint strength reduction factor, *W*, may be determined using linear interpolation for intermediate temperature values

(e) CAUTIONARY NOTE: There are many factors that may affect the life of a welded joint at elevated temperature, and all of those factors cannot be addressed in a table of weld strength reduction factors, *W*. For example, fabrication issues such as the deviation from a true circular form in pipe (e.g., "peaking" at longitudinal weld seams) or offset at the weld joint can cause an increase in stress that may result in reduced service life, and control of these deviations is recommended

(f) 1 for autogenous 300 series ASS, alloy 800/800H/800HT/825, and alloy 600/601/625/686 from 510 °C (950 °F) to 816 °C (1500 °F) – see note (6) below

Notes (with Commentary Notes) (from B31.3 unless otherwise noted below): *CSEF* creep strength-enhanced ferritic steel

(1)The Cr–Mo Steels include 0.5Cr–0.5Mo, 1Cr–0.5Mo, 1.25Cr–0.5Mo–Si, 2.25Cr–1Mo, 3Cr–1Mo, 5Cr–0.5Mo, 9Cr–1Mo (P No. 3, 4, 5A, and 5B). Longitudinal and spiral (helical seam) welds shall be normalized (N), normalized and tempered (N-T), or subjected to proper subcritical PWHT for the steels. Required examination is in accordance with ASME B31.1, 341.4.4 (VT, RT, UT, and PT for elevated fluid service) or ASME B31.1, 305.2.4 (RT for elevated fluid service)

(2)Longitudinal and spiral (helical seam) seam fusion welded construction is not permitted for C–0.5Mo steel above 454 °C (850 °F)

(3)The required carbon content of the weld filler metal shall be ≥0.05 wt% (C% is 0.05 wt% and above for ASME/ASTM standard base metal). See ASME B31.1, 341.4.4(b), for examination requirements. Basicity index of SAW flux ≥1.0. See Sect. 4.7.2.5(e) in this book for more details of basicity

(4)The CSEF steels include Grades 91, 92, 911, 122, and 23 [See Table 2.31, Sect. 2.1.4.3(b), and Sect. 2.6.2.2(1) in this book for more details]

(5)N + T: Normalizing + Tempering

(6)Autogenous welds without filler metal in 300 series ASS, alloy 800/800H/800HT/825, and alloy 600/601/625/686. A solution anneal after welding is required for use of the factors in the table. See ASME B31.1, 341.4.3(b), for examination requirements of severe cyclic conditions

(7)Alternatively, the 100,000 hr stress rupture factors listed in ASME Section III, Div. 1, Subsection NH, Tables I-14.10 A-xx, B-xx, and C-xx, may be used as the weld joint strength reduction factor, *W*, for the materials and welding consumables specified

(8)Certain heats of the ASS, particularly for those grades whose creep strength is enhanced by the precipitation of temper-resistant carbides and carbon nitrides, can suffer from an embrittlement condition in the weld HAZ that can lead to premature failure of welded components operating at elevated temperatures. A solution annealing or thermally stabilized heat treatment (TSHT) of the weld area mitigates this susceptibility. See Sect. 4.12.5 (TSHT-general theory), Table 4.140 (TSHT temperatures), Sect. 2.1.6.3 (for knife-line attack), and Sect. 2.1.6.8 (for PTASCC) in this book for more details

(9)For CS, *W* = 1.0 for all temperatures. For materials other than CS, Cr-Mo, CSEF, and the austenitic alloys listed in ASME B31.1, Table 302.3.5, *W* shall be as follows: For $Ti \le Tcr$, $W = 1.0$. For $Tcr < Ti \le 816$ °C (1500 °F), $W = 1–0.000909(Ti - Tcr)$. If *Ti* exceeds the upper temperature for which an allowable stress value is listed in Appendix A for the base metal, the value for *W* is the responsibility of the designer

Table 1.72 Weld strength reduction factors, *W*, to be applied when calculating the minimum wall thickness or allowable design pressure of components fabricated with a longitudinal seam fusion weld – ASME B31.1, Table 102.4.7-1

Metal group	Weld strength reduction factors (W) per component temperature, °C (°F) [(2)–(7)]										
	371 (700)	399 (750)	427 (800)	454 (850)	482 (900)	510 (950)	538 (1000)	566 (1050)	593 (1100)	621 (1150)	649 (1200)
Cr-Mo [(8)(9)(10)]	–	–	1	0.95	0.91	0.86	0.82	0.77	0.73	0.68	0.64
CSEF (N + T) [(8)(11)(12)]	–	–	–	–	–	1	0.95	0.91	0.86	0.82	0.77
CSEF [(8)(13)] subcritical PWHT	–	–	–	–	1	0.5	0.5	0.5	0.5	0.5	0.5
ASS (300 series SS), alloy 800/800H [(14)] [(15)]	–	–	–	–	–	1	0.95	0.91	0.86	0.82	0.77
Autogenous welds in ASS (300 series SS) [(16)]	–	–	–	–	–	1	1	1	1	1	1

(Commentary) Notes: CSEF, creep strength-enhanced ferritic; WSRF, weld joint strength reduction factor

[(1)]Based on ASME B31.1 unless otherwise noted below

[(2)]Longitudinal welds in pipe for materials not covered in this Table operating in the creep regime are not permitted. For the purposes of this Table, the start of the creep range is the highest temperature where the nonitalicized stress values end in ASME B31.1, Mandatory Appendix A for the base material involved

[(3)]All weld filler metal shall be a minimum of 0.05% C for Cr-Mo and CSEF materials, and 0.04% C for ASS in this Table

[(4)]Materials designed for temperatures below the creep range [see Note (2)] may be used without consideration of the WSRF or the rules of this Table. All other Code rules apply

[(5)]Longitudinal seam welds in Cr-Mo and CSEF materials shall be subjected to, and pass, a 100% volumetric examination (RT or UT). For materials other than Cr-Mo and CSEF, see ASME B31.1, para. 123.4(B)

[(6)]At temperatures below those where WSRFs are tabulated, a value of 1.0 shall be used for the factor *W* where required by the rules of this Section. However, the additional rules of this Table and Notes do not apply

[(7)]CS pipes and tubes are exempt from the requirements of ASME B31.1, para. 102.4.7, and ASME B31.1, Table 102.4.7

[(8)]Basicity index of SAW flux ≥1.0. See Sect. 4.7.2.5(e) in this book for more details of basicity

[(9)]The Cr-Mo steels include 0.5Cr–0.5Mo, 1Cr–0.5Mo, 1.25Cr–0.5Mo–Si, 2.25Cr–1Mo, 3Cr–1Mo, and 5Cr–0.5Mo (P No. 3, 4, 5A, and 5B). Longitudinal welds shall either be normalized (N), normalized and tempered (N-T), or subjected to proper subcritical PWHT for the alloy

[(10)]Longitudinal seam fusion welded construction is not permitted for C–1/2Mo steel for operation in the creep range [see Notes (2) and (4)]

[(11)]The CSEF steels include Grades 91, 92, 911, 122, and 23 (see Table 2.31, Sect. 2.1.4.2(h), and Sect. 2.6.2.1(1) in this book for more details)

[(12)]N + T = normalizing + tempering

[(13)]Sub Crit = subcritical PWHT is required. No exemptions from PWHT are permitted. The PWHT time and temperature shall meet the requirements of ASME B31.1, Table 132; the alternate PWHT requirements of ASME B31.1, Table 132.1, are not permitted

[(14)]WSRFs have been assigned for austenitic stainless (including 800H and 800HT) longitudinally welded pipe up to 816 °C (1500 °F) as follows:

Table 1.72a W factor of ASS (300 series SS) and alloy 800/800H at elevated temperature (ASME B31.1, Table 102.4.7-1)

Temperature, °C (°F)	Weld joint strength reduction factor (WSRF), *W*
677 (1250)	0.73
704 (1300)	0.68
732 (1350)	0.64
760 (1400)	0.59
788 (1450)	0.55
816 (1500)	0.50

[(15)]Certain heats of the ASS, particularly for those grades whose creep strength is enhanced by the precipitation of temper-resistant carbides and carbo-nitrides, can suffer from an embrittlement condition in the weld heat-affected zone that can lead to premature failure of welded components operating at elevated temperatures. A solution annealing heat treatment of the weld area mitigates this susceptibility. See Table 4.140, Sect. 4.12.5 (general theory), Sect. 2.1.6.3 (for knife-line attack), and Sect. 2.1.6.8 (for PTASCC) in this book for more details of stabilizing heat treatment

[(16)]Autogenous SS welded pipe (without weld filler metal) has been assigned a WSRF up to 816 °C (1500 °F) of 1.00, provided that the product is solution annealed after welding and receives nondestructive electric examination, in accordance with the material specification (Table 1.72a)

1.3.3.5 Maximum Metal Temperature for Compressive Stress Rules

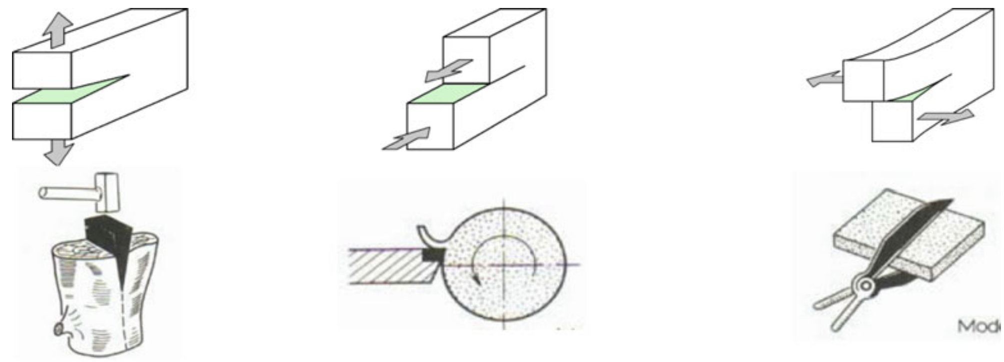
ASME Sec. VIII, Div. 2, requires the maximum metal temperature for compressive stress rules (Table 1.73).

1.3.4 Fracture Toughness

K_1c is a plane strain fracture toughness characterized by a stress intensity factor (K-factor) for crack growth evaluation in linear-elastic, plane-strain conditions with model-I crack (Fig. 1.42), while J_1c is a plane strain fracture toughness characterized by J-integral which a mathematical expression, a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack front.

Table 1.73 Maximum metal temperature for compressive stress rules in ASME Sec. VIII, Div. 2

Materials	Materials in the following tables in ASME Sec. VIII, Div. 1	Temperature limits	
		°C	°F
CS and LAS	Table 3-A.1	425	800
Q-T steels	Table 3-A.2	370	700
High alloy steels	Table 3-A.3	425	800
Al and Al alloys	Table 3-A.4	150	300
Cu and au alloys	Table 3-A.5	65	150
Ni and Ni alloys	Table 3-A.6	480	900
Ti and Ti alloys	Table 3-A.7	315	600



Mode I (Tension, Opening) Mode II (In-Plane Shear, Sliding) Mode III (Out-Of-Plane Shear, Tearing)

Figure 1.42 Three basic modes of crack tip deformation

The fracture toughness tests (K_{1C}, J_{1C}, CTOD, Charpy V-notch impact absorbing energy, etc.) have somewhat a relationship to each other in a given material and/or service even though the goals of each test are a little bit different.

1.3.4.1 Three Failure Modes

Stress and displacement fields *near* a crack tip of a linear elastic isotropic material are listed separately for all three modes: Mode I, Mode II, and Mode III as shown in Fig. 1.42.

Note that we use μ to denote the shear modulus, usually written as G, for fear that one might mistake it for the strain release rate, $\mathcal{G}$. Also, the small differences in formulas for plane stress and plane strain are handled by K, where ν = Poisson's ratio:

$$K = (3-\nu)/(1+\nu) \text{---Plane Stress,}$$
$$= 3 - 4\nu \qquad \text{---Plane Strain.}$$

For linear elastic materials, the principle of superposition applies. A mixed-mode problem can be treated as a summation of each mode.

$$\sigma_{ij}{}^{(\mathrm{Total})} = \sigma_{ij}{}^{(I)} + \sigma_{ij}{}^{(II)} + \sigma_{ij}{}^{(III)}$$

There are three basic modes of crack tip deformation, the opening (Mode I), the in-plane shear (Mode II), and the out-of-plane shear (Mode III):

1.3.4.2 Stress Intensity Factor (K) and Crack Tip Stresses

The stress intensity factor (K) is used as a single-parameter characterization in the field of fracture mechanics near the tip of a crack caused by a remote load or residual stresses. The magnitude of K depends on the material and the geometry, size and location of the crack, magnitude, and distribution of load.

The stress fields near a crack tip of an isotropic linear elastic material can be expressed as a product of $1/\sqrt{r}$ and a function of θ with a scaling factor K (Fig. 1.43), where the superscripts and subscripts I, II, and III denote the three different modes that different loadings may be applied to a crack. The factor K is called the *stress intensity factor*.

The detailed breakdown of stresses and displacements for each mode is summarized in this page.

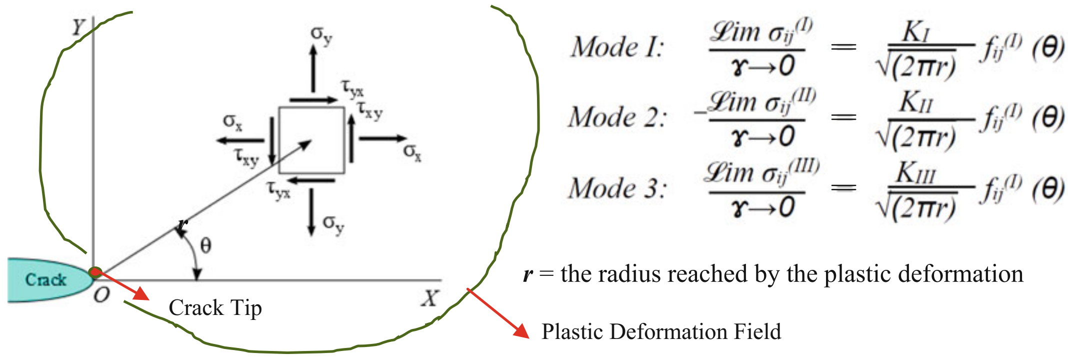


Figure 1.43 Stresses at crack tip

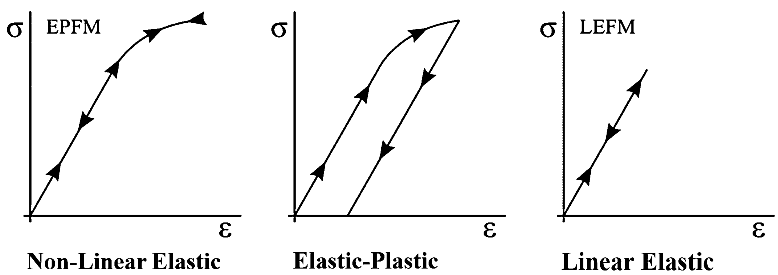


Figure 1.44 Several stress-strain modes

1.3.4.3 Linear Elastic Fracture Mechanics (LEFM) and Elastic Plastic Fracture Mechanics (EPFM)

Fracture mechanics models, such as linear elastic fracture mechanics (LEFM) or elastic-plastic fracture mechanics (EPFM), provide mathematical relationships for critical combinations of stress, crack size, and fracture toughness that lead to crack propagation.

(a) LEFM approaches apply to cases where crack propagation occurs during predominately elastic loading with negligible plasticity. LEFM applies when the nonlinear deformation of the material is confined to a small region near the crack tip. For brittle materials, it accurately establishes the criteria for catastrophic failure. However, severe limitations arise when large regions of the material are subject to plastic deformation before a crack propagates (Fig. 1.44).

(b) EPFM methods are suitable for materials that undergo significant plastic deformation during crack propagation. EPFM is normally proposed to analyze the relatively large plastic zones. EPFM assumes isotropic and elastic-plastic materials. Based on the assumption, the strain energy fields or opening displacement near the crack tips are calculated. When the energy or opening exceeds the critical value, the crack will grow (Fig. 1.44).

Note that although the term elastic-plastic is used in this approach, the material is merely nonlinear-elastic. In others words, the unloading curve of the so-called elastic-plastic material in EPFM follows the original loading curve, instead of a parallel line to the linear loading part which is normally the case for true plastic-plastic materials.

* **Fracture Analysis Using EPFM**

There are two major branches in EPFM: *Crack Tip Opening Displacement* (CTOD) suggested by Wells, popular in Europe, and the *J Integral* proposed by Rice, widely used in the USA. However, Shih provided evidence that a unique relationship between J and CTOD exists for a given material. Thus, these two parameters are both valid in characterizing crack tip toughness for elastic-plastic materials.

The basic EPFM analysis can be summarized as follows:

1	Calculate the J integral or crack tip opening displacement (CTOD), δ, as a function of the loading and the geometry
2	The critical J integral J_c or the critical CTOD, δc, can be determined empirically
3	The J integral J should NOT exceed J_c, or, the CTOD δ should not exceed the critical CTOD, δc

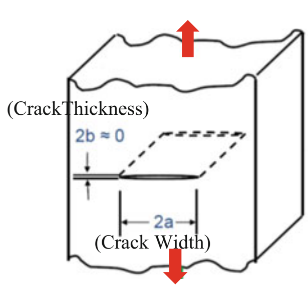


Figure 1.45 Stress intensity factor at crack

1.3.4.4 Stress Intensity Factor in Practice

Engineers are interested in the maximum stress near the crack tip and whether it exceeds the fracture toughness. Thus, the stress intensity factor K is commonly expressed in terms of the *applied stresses*, σ, at $r \to 0$ and $\theta = 0$.

For example, for a through crack in an infinite plate under uniform tension σ, the stress intensity factor is where a is one half of the width of the through crack. The dimension of K is $K_I = \sigma\sqrt{\pi\alpha}$. (Fig. 1.45). $I = mode\ I,\ c = critical.$

In the last few decades, many closed-form solutions of the stress intensity factor K for simple configurations were derived. Some of the common ones are listed in the following three categories: classic, specimen, and structure.

1.3.4.5 Stress Intensity Factor and Fracture Toughness

Based on the linear theory, the stresses at the crack tip are infinite, but in reality there is always a plastic zone at the values. It is very difficult to model and calculate the actual stresses in the plastic zone and compare them to the maximum allowable stresses of the material to determine whether a crack is going to grow or not.

(a) Plane Strain Fracture Toughness-Critical Stress Intensity Factor, K_{IC}/Critical J Value (J Integrity, J_{crit})
The fracture toughness (K_{1C}) of a material measures its ability to resist crack growth initiation and propagation. The critical J value (J Integrity, J_{crit}) characterizes energy release rate during a small crack extension, which may also be valid in the presence of significant crack tip plasticity. The subscript Ic denotes mode I crack opening under a normal tensile stress perpendicular to the crack, since the material can be made deep enough to stand shear (mode II) or tear (mode III) as shown in Fig. 1.42. Finally it is denoted K_{Ic} and has the units of Pa $(m)^{1/2}$ or psi $(inch)^{1/2}$.
An engineering approach is to perform a series of experiments and reach a critical stress intensity factor K_c for each material, called the *fracture toughness* of the material. One can then determine the crack stability by comparing K and K_c directly.
K_c's for a number of common engineering materials are listed in this page.

(b) Definition of J Integral – Fig. 1.46
To consider a nonlinear elastic body containing a crack, the J integral is defined as

$$J = \int_r wdy\text{-}T_i \frac{\partial Ui}{\partial x} ds$$

where $w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$ is the strain energy density, $Ti = \sigma_{ij} n_j$ is the traction vector, Γ is an arbitrary contour around the tip of the crack, n is the unit vector normal to Γ, and σ, ε, and u are the stress, strain, and displacement field, respectively.
Rice, J.R. showed that the J integral is a *path-independent* line integral and it represents the *strain energy release rate of nonlinear elastic materials*:

$$J \approx -dM/dA$$

where $M = U - W$ is the potential energy, the strain energy U stored in the body minus the work W done by external forces, and A is the crack area.

$$\text{The dimension of } J \text{ is } Dim[J] = F \cdot L/L^2 = \text{Energy/Area}$$

Plastic-elastic fracture toughness is denoted by J_{Ic}, with the unit of J/cm^2 or lbf-in/in^2, and is a measurement of the energy required to grow a thin crack (Fig. 1.46).

(c) Relationship Between $\mathcal{G}(j)$ and K
For *linear elastic* materials, the integral J is in fact the strain energy release rate, $\mathcal{G}$, and both are related to the stress intensity factor K in the following fashion:

$$\begin{aligned} \mathcal{G} &= K^2/E \quad \textit{(Plane Stress)} \\ &= K^2(1-\nu^2)/E \quad \textit{(Plane Stress)} \end{aligned}$$

The dimension of $\mathcal{G}$ is:

$$\begin{aligned} Dim[\mathcal{G}] &= [F\sqrt{L}/L^2]^2/[F/L^2] \\ &= [F{\cdot}L/L^2] = (Energy/Area) = F/L \end{aligned}$$

$K_{IC} = [J_{CRIT} * E/(1\text{-}\nu^2)]^{1/2}$ E = Young's modulus, MPa or ksi
K_{IC} = ksi $(in)^{1/2}$ or MPa $(m)^{1/2}$ ν = Poisson's ratio
J_{CRIT} = MPa-m or ksi-in $L = \pi\alpha$ [α = 1/2 of crack length]

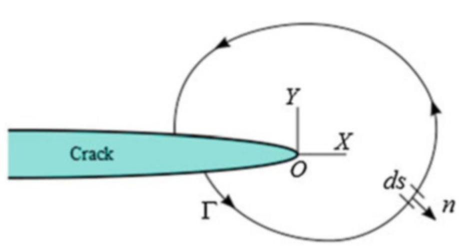


Figure 1.46 Mode of definition of J integral

1.3.4.6 Fracture Toughness Estimation from Charpy V-Notch Data

The V-notch Charpy test provides an indication of fracture toughness rather than a direct measurement. Many correlations between V-notch Charpy energy and fracture toughness have been published over decades. The majority of these correlations were developed with limited data and materials. In some cases, correlations developed in the 1970s, when fracture toughness testing was in its infancy, have been shown to be unreliable when applied to the large amount of toughness data that is available today.
See API 579-1/ASME FFS-1, 9F.3.4, for more details.

1.3.4.7 Test Methods for Failure Assessment and ASTM Standards

a. State-of-the-art facilities and software for performing:

- K_{1C}
- R-curve determinations
- Drop weight tear tests (DWTT)
- Nil ductility transition temperature
- J_{1C}
- CTOD
- Dynamic tear testing
- Notched bar impact (Charpy and Izod)

b. References

- ASTM E399 Linear Plastic Plane Strain Fracture Toughness (K_{1C}) of Metallic Materials
- NTIS AD-773 673 Plane Strain Fracture Toughness (K_{IC}) Data Handbook for Metals (1973)
- ASTM E813 JIC Testing – withdrawn. Now go to ASTM E1820 Measurement of Fracture Toughness
- ASTM E1820 Measurement of Fracture Toughness
- ASTM E561 K_R-Curve Determination
- ASTM E1290 Crack Tip Opening Displacement (CTOD) Fracture Toughness – withdrawn. Now go to ASTM E1820 Measurement of Fracture Toughness
- ASTM E208 Drop Weight Test to Determine Nil Ductility Transition Temperature
- ASTM E604 Dynamic Tear Testing of Metallic Materials
- ASTM E23 Notched Bar Impact Testing of Metallic Materials
- API 579-1/ASME FFS-1

See Sect. 5.2.3 for detailed information for several test methods of fracture toughness.

1.3.5 Minimum Allowable Temperature (MAT) and Lowest Metal Temperature (LMT)

1.3.5.1 Minimum Allowable Temperature (MAT)

The MAT is the lowest (coldest) permissible metal temperature for a given material and thickness based on its resistance to brittle fracture. It may be a single temperature or an envelope of allowable operating temperatures as a function of pressure. The MAT is derived from mechanical design information and material specification. See API 579-1/ASME FFS-1, 3.1.6, for more details. MAT at design pressure is MDMT. The permissible MAT during depressurization and blowdown may be able to be lower than MDMT.

1.3.5.2 Lowest Metal Temperature (LMT)

LMT defined and used in this book is the lowest metal skin temperature at the process side due to the operating condition (mostly during depressurization and blowdown) and minimum ambient temperature. The LMT may be a single temperature at an operating pressure or an envelope of temperatures and coincident pressures. In this case, the LMT is calculated by the inner wall skin temperature calculated due to the contained process fluid temperature and also the minimum ambient temperature. The LMTs of the vessels coincident with final pressures (after depressurization and blowdown) are shown in Fig. 1.47.

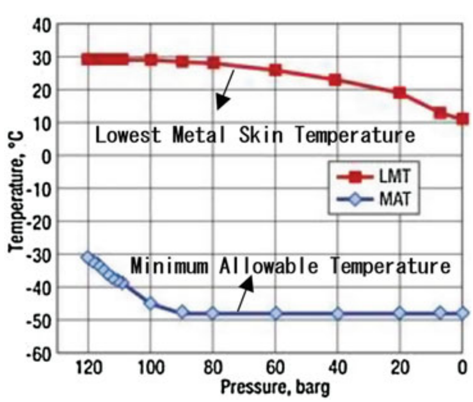


Figure 1.47 MAT and LMT (a sample calculation). (Source: Khazai, F. Avoid brittle fracture in pressure vessels, hydrocarbon processing, 2011 modified)

1.3.6 MPT (Minimum Pressurizing Temperature)

1.3.6.1 What Is MPT?

Normally pressure shows slow strain of the material. However, the pressurizing at low temperature may be able to be a root cause of brittle failure. Especially the precipitations of Cr-Mo steel during operation create temper embrittlement of the metal and then a gradual increase of the ductile-to-brittle transition temperature.

As a result, the vessel may be exposed to brittle failure on starting up and hydrostatic test unless the pressurizing is controlled by the certain temperature and pressuring rate.

Therefore, MPT is for the threshold minimum temperature before pressurizing to avoid the brittle failure. API RP934F committee has been developing the standard (MPT requirements for Cr-Mo reactors) to issue in the near future. Figure 1.48 shows a result of brittle failure during start-up.

Figure 1.48 Failure due to pressuring under limitation of low temperature during startup. (Source: CLG report 2011)

1.3.6.2 Key Considerations for MPT Decision

(a) Fast Brittle Fracture Considerations
  (a-1) Temper Embrittlement on Fast Brittle Fracture
  (a-2) Determining the Effect of Temper Embrittlement on Fast Fracture
  (a-3) Dissolved Hydrogen on Fast Brittle Fracture
(b) Slow Stable Crack Growth Considerations
  (b-1) Hydrogen-Assisted Crack Growth in Cr-Mo Steels
  (b-2) Laboratory K_{IH} (slow-rising-displacement threshold stress Intensity) Testing and MPT Estimation for Internal Hydrogen-Assisted Cracking (IHAC) of 2¼-1Mo
  (b-3) Modeling Stable Crack Growth in Cr-Mo Steels
  (b-4) Establishing Tcrit (Threshold Temperature) for Hydrogen-Assisted Crack Growth
  (b-5) Laboratory K_{IH} Testing and MPT Estimation for IHAC and HEAC (Hydrogen Environment-Assisted Cracking) of 2¼Cr-1Mo-V
(c) Hydrogen Embrittlement
  (c-1) Hydrogen Solubility, Diffusivity, and Trapping in V-modified Cr-Mo Steel
  (c-2) Hydrogen Embrittlement of Cr-Mo and Cr-Mo-V Steels in hydrogen containing service

1.3.6.3 Requirements of MPT Curve

MPT is not a material requirement, but a requirement for operation due to embrittlement at low temperature in Cr-Mo steel with heavy wall.

The heavy wall Cr-Mo vessels in hydrocracking units have MPT limits that must be adhered to during the startup process or field hydrotesting. These MPT limits require unit operations to achieve certain reactor wall temperature thresholds before the pressure can be raised. In addition, the recycle compressor has a minimum pressure at which it can safely operate outside the pressure surge ranges when liquid is added to the unit.

When required, the vessel fabricator shall define MPT requirement based on this document and in accordance with sound industry practice to avoid brittle fracture of the base material and welds during vessel operation including startup and shutdown.

The requirements of this document shall be included in the operating manual of the unit that specify startup and shutdown procedures.

All mechanical and metallurgical properties for new pressure vessel shall comply with this document, process requirements, and purchase requisition of the equipment.

1.3.6.4 Vendor Data Requirements

(a) Test Reports from Mill Manufacturer

The manufacturer shall prepare a report where the minimum requirement noted in this document, process specification, and purchase requisition are verified through calculation and testing. The reports shall be made of each heat-number of the shell and head materials. Following reports are required, as a minimum:

1. Report showing the details of "step cooling" heat treatment. The step cooling test is required for the base metals. The test procedure and acceptance criteria shall be in accordance with API RP934-A, if applicable.
2. Details of all heat treatments used to simulate and accelerate embrittlement of test specimens for the purpose of evaluating the potential of temper embrittlement of alloy steel in high temperature service.

(b) Additional Deliverables by Vendor

1. The vessel fabricator shall define MPT considering the requirements noted in this document and also taking into account the following, as a minimum:
   – The FATT (Fracture Appearance Transition Temperature-ASTM A370) of material and welds considering any possible embrittlement due to in-service metallurgical degradation
   – Effect of hydrogen absorbed to material during operation
   – A safety margin
2. The vendor shall provide the following additional reports:
   – All reports shall consider the effects of wall thickness (base metal and clad) and the material damage (due to high temperature creep and hydrogen embrittlement) on fracture toughness, in order to predict the minimum pressurization temperature.
   – Report showing the safe curve (pressure × temperature) to the reactor's operation, in startup and shutdown, to prevent brittle fracture and to permit sufficient time for hydrogen degassing (that were trapped in the matrix of the base metal). The maximum rate in temperature increasing or decreasing and in pressure increasing or decreasing shall be indicated.
   – Using "REACT" program or other acceptable technique, the vessel fabricator shall submit a report which shall include the curve with threshold hydrogen partial pressure (up to design pressure) vs. temperature (up to design temperature) to sustain the hydrogen levels at the cladding interface below 2.0 ppm.
   – If the dissolved hydrogen level in the clad bond layer is above 2 ppm, the vendor shall perform analysis to determine hydrogen levels after cool down and advise the results of an outgassing evaluation. Also, the vendor shall advise the impact on MPT and recommend controls to permit outgassing of the hydrogen to ensure dissolved hydrogen levels is less than 2 ppm to avoid hydrogen-assisted cracking.

1.3.6.5 General Guidelines for Application of MPT Curves in Operations

It is a normal practice during unit startup and shutdown of heavy wall alloy vessels to maintain pressure at a low level until vessel wall temperature exceeds the minimum pressurizing temperature (MPT).

The following general guidelines shall be incorporated in operating manual:

(a) The MPT curves which specify the temperature and pressure limit shall be applied for vessel operation during startup and shutdown.
(b) Typical guidelines for pressurizing vessel require the pressure during startup be limited to 25% of design pressure for temperature below MPT.
(c) Pressure vessel fabricator's recommendations for MPT and operating (P/T) transient/pressurizing rates, etc. shall be considered in finalizing the operating guidelines of heavy wall Cr-Mo pressure vessels.

References

(a) API TR934-F, Part 1 through 4 (Reports regarding MPT): see Table 2.37 in this book for more details.
(b) API RP934-A Materials and Fabrication of 2 1/4Cr-1Mo, 2 1/4Cr-1Mo-1/4V, 3Cr-1Mo, and 3Cr-1Mo-1/4V Steel Heavy Wall Pressure Vessels for High temperature and High Pressure Hydrogen Service
(c) API RP579/ ASME FFS-1 Fitness-For-Service
(d) WRC 562 Recommendations for Establishing the Minimum Pressurization Temperature (MPT) for Equipment
(d) J. Mclaughlin, Establishing MPT for Heavy Wall Reactors in Hydroprocessing Units, ASME PVP2006-ICPVT-11-93243
(e) A. Seijas and T. Munsterman, MPT and Pressure-Temperature Envelope of A 1 1/4Cr-1/2Mo Steel Heavy Wall Vessel, ASME PVP2006-ICPVT-11-93310
(f) Y. Wada et al., Hydrogen Embrittlement Testing of Aging Pressure Vessel Steels Using Large Thick Specimen, Processing ICPVT-10 (Jul. 7-10, Vienna, Austria)
(g) Y. Wada et al., Hydrogen Embrittlement Testing of 2.25Cr-1Mo Steel Using Large Thick Specimen, PVP2002
(h) T. Iwadata, MPT for Pressure Vessels made of Cr-Mo Steels, ASME PVP-Vol. 288 (1994)
(i) API 934 committee meeting minutes email (2008) prepared by J. Mclaughlin
(j) S. Pillot et al., Effect of Hydrogen of Mechanical Behavior for 2.25Cr-0.5Mo Steel Grades (Standard and Vanadium Added), NACE paper 08559
(k) Iwadate, T. and Tahara, T., "Minimum Pressurization Temperature of Pressure Vessels made of Cr-Mo Steels", Pressure Vessels and Piping Conference/ High Pressure Technology PVP vol. 297, ASME 1995

1.4 Standardization and Documentations

1.4.1 Principal Engineering Execution Documents (PEED) for Facilities in PDP, FEED, EPC, and Operation

Normally PEED may include the following documents at the initial stage of the project:

1. Basic Engineering Design Data (BEDD) (see Sect. 1.1.2.1 for more details)
2. HAZID and/or HAZOP Study Reports
3. Adequate Reports for Existing Facilities in Revamping Projects
4. DPDT (design pressure and design temperature-minimum and maximum) (see Sect. 1.1.2.2 for more details)
5. PFD, Heat and Materials Balance, UFD, P&ID, Datasheets for Facilities
6. Process Design Basis and Process Safety Design Basis
7. Scopes (service, materials, guarantee, etc.) and Schedule
8. List of Specifications and Design Manuals including Applicable Codes, Standards, and Regulations
9. List of Approved Vendors
10. List of Equipment
11. Organization Chart for Project Execution

1.4.2 Basic Documents for Materials and Corrosion

1.4.2.1 Design Stage

Normally the following documents are prepared at the beginning stage for project execution.

– Adequate report, list of MOC (materials of construction)
– CII (corrosion inhibition injection)
– CMR (corrosion monitoring report)
– MSD (materials selection diagrams)
– MSG (materials selection guideline)
– MSP (materials selection philosophy)

- CP DWG (cathodic protection drawing)
- CRAS (corrosion risk assessment study) report
- List of MOC (materials of construction)
- MCA (material-corrosion audit) report
- MSR (materials selection report)
- MST (materials selection table)
- TML (thickness measurement location) including CUI inspection window

1.4.2.2 Operation and Maintenance Stage

On-stream inspection reports (for remained thickness, internal local corrosion, cracks including NDE reports) should be prepared periodically. In addition, various documentations in Sect. 1.5 are also used for sound fitness-for-service system.

1.4.3 Piping Materials Classes

See Sect. 1.2.12 for continuous development and responsibility of piping materials classes.

The grouping of piping materials classes has the following key factors for the project execution:

1. Material (CS, LTCS, SS, Nickel Alloy, Copper Alloy, Aluminum Alloys, etc.)
2. Services (hydrocarbon (HC), HC + wet H_2S (sour), HC + amine, HC + HF, HC + hydrogen, hydrogen, caustic, water-untreated/treated/seawater/steam/condensate/air/etc.
3. Corrosion allowance (0 mm, 0.5 mm, 1 mm, 1.5 mm, 3 mm, 4.5 mm, 6 mm, etc.)
4. Pressure rating (normally using psi., e.g., #150, 300, 600, 900, 1500, 2500, etc.)
5. Heat treatment (PWHT, normalizing, Q-T, etc.)
6. Design temperature range
7. Valve trim material and hardfacing
8. Specific requirements (part's materials, design, fabrication, test and inspection, etc.)

1.4.4 Units of Dimension and Measurement

Table 1.74 shows the types of most common units in oil and gas industries. Table 1.75 indicates the conversion factors of several units. Tables 1.76, 1.77, 1.78, and 1.79 show the typical conversion standards used in ASME Section VIII for the convenience of users.

1.4.5 Description and Locations of Major Activities in ASME

Table 1.80 shows the standard description with templates in ASME.

Table 1.74 Principal units

Units	US customary	SI (ISO standard)	Metric
Length	Inch, foot	m	m
Weight (mass)	lb.	kg, g, ton	kg, g, ton
Weight, %	wt%, ppmw		
Pressure, gauge	psig	Pag	Kgf/cm^{2}g
Pressure, absolute	psia		Kgf/cm^{2}a
Stress	Psi or ksi	KPa or MPa	Kgf/cm^2, Kgf/mm^2
Temperature, T	°F	°C	°C
T conversion	°C = 5/9 (°F – 32), °F = 9/5(°C) + 32		
ΔT conversion	°C = 5/9 (°F), °F = 9/5(°C)		
Energy	Ft.lbs	J (joule)	Kgf·m
Volume	Inch^3, ft^3	m^3	m^3
Volume %	vol.%, mol%, ppmv, baume (caustic)		

Table 1.75 Conversion factors (ASME Section VIII)

From US Customary	To SI	Conversion Factor	Notes
in.	mm	25.4	–
ft	m	0.3048	–
in^2	mm^2	645.16	–
ft^2	m^2	0.09290304	–
in^3	mm^3	16,387.064	–
ft^3	m^3	0.02831685	–
US Gal.	m^3	0.003785412	–
psi	MPa	0.0068948	Used exclusively in equations
psi	kPa	6.894757	Used only in text and for nameplate
ft-lb	J	1.355818	–
°F	°C	5/9(°F–32)	Not for temperature difference
°F	°C	5/9(°F)	For temperature differences only
R	K	5/9	Absolute temperature
lbm	kg	0.4535924	–
lbf	N	4.448222	–
in.-lb	N · mm	112.98484	Use exclusively in equations
ft-lb	N · m	1.3558181	Use only in text
$ksi(in.)^{1/2}$	$MPa(m)^{1/2}$	1.0988434	–
Btu/hr	W	0.2930711	Use for boiler rating and heat transfer
lb/ft^3	kg/m^3	16.018463	–

Table 1.76 Typical conversion of length and thickness used in ASME Section VIII

US Customary, inch	to SI, mm	Difference (%)	US Customary, inch	to SI, mm	Difference (%)
1/32	0.8	–0.8	2 1/2	64	–0.8
3/64	1.2	–0.8	3	75	+1.6
1/16	1.5	+5.5	3–1/2	89	–0.1
3/32	2.5	–5.0	4	100	+1.6
1/8	3	+5.5	4–1/2	114	+0.3
5/32	4	–0.8	5	125	+1.6
3/16	5	–5.0	6	150	+1.6
7/32	5.5	+1.0	8	200	+1.6
1/4	6	+5.5	10	250	+1.6
5/16	8	–0.8	12	300	+1.6
3/8	10	–5.0	14	350	+1.6
7/16	11	+1.0	16	400	+1.6
1/2	13	–2.4	18	450	+1.6
9/16	14	+2.0	20	500	+1.6
5/8	16	–0.8	24	600	+1.6
11/16	17	+2.6	26	650	+1.6
3/4	19	+0.3	28	700	+1.6
7/8	22	+1.0	32	800	+1.6
1	25	+1.6	36	900	+1.6
1 1/8	29	–1.5	40	1000	+1.6
1 ¼	32	–0.8	54	1350	+1.6
1 ½	38	+0.2	60	1500	+1.6
2	50	+1.6	72	1800	+1.6
2 1/4	57	+0.3			

Table 1.77 Typical conversion of pressure used in ASME Section VIII

US Customary	SI	US Customary	SI	US Customary	SI	US Customary	SI
0.5 psi	3 kPa	30 psi	200 kPa	300 psi	2 MPa	1500 psi	10 MPa
2 psi	15 kPa	50 psi	350 kPa	350 psi	2.5 MPa	30,000 psi	205 MPa
3 psi	20 kPa	100 psi	700 kPa	400 psi	3 MPa	38,000 psi	260 MPa
10 psi	70 kPa	150 psi	1 MPa	500 psi	3.5 MPa	60,000 psi	415 MPa
14.7 psi	101 kPa	200 psi	1.5 MPa	600 psi	4 MPa	70,000 psi	480 MPa
15 psi	100 kPa	250 psi	1.7 MPa	1200 psi	8 MPa	95,000 psi	655 MPa

Table 1.78 Typical conversion of NPS and DN used in ASME Section VIII NPS (nominal pipe size) and DN (diameter nominal)

US Customary	SI	US Customary	SI	US Customary	SI	US Customary	SI
NPS 1/8	DN 6	NPS 3 1/2	DN 90	NPS 22	DN 550	NPS 44	DN 1100
NPS 1/4	DN 8	NPS 4	DN 100	NPS 24	DN 600	NPS 46	DN 1150
NPS 3/8	DN 10	NPS 5	DN 125	NPS 26	DN 650	NPS 48	DN 1200
NPS 1/2	DN 15	NPS 6	DN 150	NPS 28	DN 700	NPS 50	DN 1250
NPS 3/4	DN 20	NPS 8	DN 200	NPS 30	DN 750	NPS 52	DN 1300
NPS 1	DN 25	NPS 10	DN 250	NPS 32	DN 800	NPS 54	DN 1350
NPS 1 1/4	DN 32	NPS 12	DN 300	NPS 34	DN 850	NPS 56	DN 1400
NPS 1 1/2	DN 40	NPS 14	DN 350	NPS 36	DN 900	NPS 58	DN 1450
NPS 2	DN 50	NPS 16	DN 400	NPS 38	DN 950	NPS 60	DN 1500
NPS 2 1/2	DN 65	NPS 18	DN 450	NPS 40	DN 1000		
NPS 3	DN 80	NPS 20	DN 500	NPS 42	DN 1050		

Table 1.79 Typical temperature conversion used in ASME Section VIII (see Appendix A.1 in this book for detailed design)

Temperature, °F	Temperature, °C	Temperature, °F	Temperature, °C	Temperature, °F	Temperature, °C
−320	−196	350	175	950	510
−275	−171	400	205	1000	540
−155	−104	450	230	1050	565
−55	−48	500	260	1100	595
−50	−46	550	290	1150	620
−20	−29	600	315	1200	650
0	−18	650	345	1250	675
70	20	700	370	1800	980
100	38	750	400	1900	1040
120	50	800	425	2000	1095
150	65	850	455	2050	1120
200	95	900	480		
250	120	925	495		

1.5 Maintenance, Reliability, and Integrity

OSHA, MIL, NASA, ASME, API, and several companies have developed standards, regulations, certifications, programs, reports, guidance, and commercial software for practical application of effective maintenance, reliability, fitness-for-service, and integrity of the facilities. Here is a brief summary of the terms and characteristics of several tools and terms. The Omega & Alfa of scale reliability are not summarized in this book.

Commercial Programs (Prog), Software (S/W), Certification (Cert), Standards/Regulations (Reg), Guidance (Guide), and Organizations (Org)

CCDs (Corrosion Control Documents-Prog): CCDs are a valuable addition to an effective Mechanical Integrity Program that help identify the damage mechanism susceptibilities of pressure-containing equipment, their related corrosion-causing components, and recommended actions to be implemented to mitigate the risk of loss of containment or unplanned outages. They serve the basis for tracking their development, implementation, and maintenance in order to maintain consistency and to integrate the CCD work process with other plant integrity programs, such as MOC, PHA, HazOps, RCM, and RBI. See API RP970 for more details.

Table 1.80 Standard description with templates in ASME

Items	Parts	Paragraphs of Codes
User's design requirements	Single Chamber & Multi-chamber	Sec. VIII, Div. 1: Form U-DR-1&2 Sec. VIII, Div. 2: Table 2-A.1
Marking for ASME stamp	U, UM, PRT, etc.	Sec. VIII, Div. 1: Figure UG-116, 129.1&2, Sec. VIII, Div. 2: Figure 2-F.1
Marking for types of construction	W (arc or gas welded), P (pressure fusion welded), B (brazed), RES (resistance welded), G (graphite)	Sec. VIII, Div. 1: UG-116
Marking for service	L (lethal service), UB (unfired steam boiler), DF (direct firing)	Sec. VIII, Div. 1: UG-116
Nameplate (stamping form)	Stamping form	Sec. VIII, Div. 1: UG-119
Welding	Joint categories	Div. 1: UW-3
	Joints details	Div. 2: Table AF-241.1
Impregnated graphite vessel		Sec. VIII, Div. 1
WPS and PQR	Forms	ASME Sec. IX
Final data report for vessels and pressure relief valves	Data report forms & supplementary sheet, manufacturer's certificate of compliance forms	Sec. VIII, Div. 1, Form U-1, U-1A, U-1B, U-1P, U-2, U-2A, U-3, U-3A, U-3P, U-4, U-5, Fig. W-3.1 & 3.2, Table W-3.1, Form UV-1, UD-1 Sec. VIII, Div. 1, Table 2-B.1, Form A-1/ A-1P/ A-2/ A-3/ A-3L/ A-4/
Company certification	Certificate of authorization	Sec. VIII, Div. 1, Fig. DD-1 Sec. VIII, Div. 2, Fig. 2-H.1
Tube expansion procedure specification (TEPS)	H_EX tube bundles including tube-to-Tubesheet	Sec. VIII, Div. 1, Form QEXP-1&2, Table QEXP-1 Sec. VIII, Div. 2, Form TEXP-1&2
PMI report	Technical data sheet	Sec. VIII, Div. 2, Table 6-A, 9.2-1
Marking and reports	Forms and contents	Div. 1: UG-115 to 120

CMMS (Computerized Maintenance Management System-Prog): It is also known as computerized maintenance management information system (CMMIS). A CMMS software package maintains a computer database of information about an organization's maintenance operations, i.e., CMMIS. This information is intended to help maintenance workers do their jobs more effectively (e.g., determining which machines require maintenance and which storerooms contain the spare parts they need) and to help management make informed decisions (e.g., calculating the cost of machine breakdown repair versus preventive maintenance for each machine, possibly leading to better allocation of resources). CMMS data may also be used to verify regulatory compliance.

CMMS packages can produce status reports and documents giving details or summaries of maintenance activities. The more sophisticated the package, the more analysis facilities are available.

CMMS packages are closely related to computer-aided facility management packages (also called *facility management software*).

CMRP (Certified Maintenance & Reliability Professional-Prog & Cert): The leading credentialing program for certifying the knowledge, skills, and abilities of maintenance and reliability professionals. It is accredited by the American National Standards Institute (ANSI), which follows ISO standards for its accreditation and processes. Examining more than just textbook information, the CMRP is a thorough examination of a broader scope of expertise measured against a universal standard. It was developed to assess professionals' aptitude within the following five pillars:

– *Maintenance and Reliability Body of Knowledge*
– *Business Management*
– *Equipment Reliability*
– *Manufacturing Process Reliability*
– *Organization and Leadership and Work Management*

The CMRP Program has the following three components:

– Eligibility requirements that are a blend of education and healthcare-specific experience and profile of the individual who is likely to be successful on the Certification Examination.
– A 110-item multiple-choice Certification Examination that tests tasks that are performed regularly in practice and are considered important to competent practice. 100 items are scored; 10 are pretest items used to collect data.
– A renewal requirement. Certification is valid for 3 years at which time it must be renewed through retaking and passing the Certification Examination or documenting 45 contact hours of continuing professional education.

Meanwhile the CMRT is for Certified Maintenance and Reliability Technician (Prog).

CPI (Center for Public Integrity-Org): This is an American nonprofit investigative journalism organization whose stated mission is "to reveal abuses of power, corruption and dereliction of duty by powerful public and private institutions in order to cause them to operate with honesty, integrity, accountability and to put the public interest first."

FME(C)A (Failure Mode and Effects (Criticality) Analysis-Guide): FMEA is a design tool used to systematically analyze postulated component failures and identify the resultant effects on system operations. The analysis is sometimes characterized as consisting of two sub-analyses, the first being the failure modes and effects analysis (FMEA) of a system reliability study and the second the criticality analysis (CA). It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes and their causes and effects. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. There are numerous variations of such worksheets. An FMEA can be a qualitative analysis but may be put on a quantitative basis when mathematical failure rate models are combined with a statistical failure mode ratio database.

A successful FMEA activity helps to identify potential failure modes based on experience with similar products and processes or based on common physics of failure logic. It is widely used in development and manufacturing industries in various phases of the product life cycle. FMEA can be performed at the system, subsystem, assembly, subassembly, or part level.

IOW (Integrity Operating Windows): Program to avoid unexpected process facilities degradation that could lead to loss of containment. A vital component of corrosion management (materials degradation control) and inspection planning, including RBI. Other PSM systems may be affected by or involved with the IOW program, including Management of Change (MOC), Process Safety Information (PSI), and Training. See API RP584 for more details.

Meridium (Mechanical Integrity-S/W): Meridium provides tools with sufficient database for problem-solving related to recurring equipment failures, including unplanned downtime; the inability to maintain planned production rates; high costs of fixing problems that result from equipment failures, and threats to employee and environmental safety. After the data exists in Meridium, it can be analyzed to determine the state of the equipment and the reliability, trends, potential risks, and probability of failures associated with that equipment. Based on the gathered data and associated analyses, you can map out the impact of projected changes and then make recommendations and suggest strategies for future equipment maintenance.

MI (Mechanical Integrity-Reg): MI is just the 14 elements included in Process Safety Management (*PSM*), driven by the OSHA 1910.119 standard, but it is significant in terms of the asset coverage involved. For example, MI includes any and all equipment/assets used to produce products made from specific quantities of defined hazardous materials on the list covered by the PSM standard. System examples include fixed equipment such as pressure vessels and storage tanks, piping systems and associated hardware (valves, fittings, etc.), relief devices, vent hardware, and emergency shutdown/control systems. Rotating equipment/assets, such as pumps, blowers, fans, and compressors that may be used to move hazardous materials within these systems are also included. In many cases, this means that all equipment within the boundaries of a facility are subject to the PSM standard. MI encompasses the activities necessary to ensure that equipment/assets are designed, fabricated, installed, operated and maintained in such a way that they provide the desired performance in a safe, environmentally protected, and reliable fashion. In short, it is the Life Cycle Asset Management (*LCAM*) process, including the above plus procurement, testing, commissioning, and disposal of the assets. MI is a part of an effective reliability program and overall asset management, specific to equipment types, and more tactical in nature including the evaluation of condition requirements through regular monitoring and inspection of the condition of these assets.

The key phases of MI program development, shown in Table 1.81, include management responsibility, equipment selection, and implementation through inspection, testing, and application of proactive maintenance strategies. Properly trained and certified personnel conducting these activities are also a key part of an effective MI program.

MTBF (*Mean Ti*me Before Failure) or *MTTF* (Mean Time To Failure): The average time that the units in the population are expected to operate before failure. This metric is often referred to as MTBF or MTTF. The results show the comparison of the failure rate per the design condition with future, current, and past process conditions.

MTTR (Mean Time To Repair): MTBF consists of MTTF (Mean Time To Failure) and MTTR (Mean Time To Repair). MTTF is the difference of time between two consecutive failures, and MTTR is the time required to fix the failure. Reliability for good *software* is a number between 0 and 1.

Table 1.81 Key phases of work necessary for effective mechanical integrity (MI) requirements

Phase 1 (Management Responsibility)	Phase 2 (Equipment Selection)[1]	Phase 3 (Inspection, Testing and Proactive Maintenance)[1]
– Roles and responsibility for facility leadership and organization – Reporting – Auditing	– Selection criteria per priority and consequence – Level of detail to be addressed – Documentation required	For targeted task: – Planning – Selection – Scheduling – Execution and monitoring

Source: LCE report 2017

Note: [1]Personnel Qualification for MI Execution (Staff, Contractors, and 3rd parties)

– Shill/Knowledge for Assessment

– Training Required and the Verified Certifications and Documentation

– Continuous and Refresher Training

OEE (Overall Equipment Effectiveness):

Availability × Performance × Quality

Availability = Actual Run Time/Total Operative Mode Time [Time Losses deducted]

Performance = Actual Speed/Normal Speed [Speed Losses deducted]

Quality = Actual Good Product/Product Output [Rework/Defects/Waste deducted]

Pareto Diagram (Guide): A Pareto diagram (Fig. 1.49) (source: http://www.discover6sigma.org/post/2005/11/pareto-chart/) is a simple bar chart that ranks related measures in decreasing order of occurrence. The purpose of a Pareto diagram is to separate the significant aspects of a problem from the trivial ones. By graphically separating the aspects of a problem, a team will know where to direct its improvement efforts. Reducing the largest bars identified in the diagram will do more for overall improvement than reducing the smaller ones.

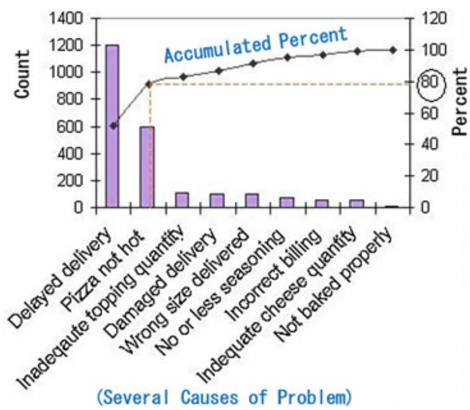


Figure 1.49 Typical Pareto diagram in (Sample in Pizza House)

There are two ways to analyze Pareto data depending on what the user wants to know:

– *Counts Pareto*: May use this type of Pareto analysis to learn which category occurs most often. The user will need to do a counts Pareto diagram. To create a counts Pareto, the user will need to know the categories and how often each occurred.
– *Cost Pareto*: May use this type of Pareto analysis if the user wants to know which category of problem is the most expensive in terms of some cost. A cost Pareto provides more details about the impact of a specific category than a count Pareto can. For example, suppose the user have 50 occurrences of one problem and 3 occurrences of another. Based on a counts Pareto, the user would be likely to tackle the problem that occurred 50 times first. However, suppose the problem that occurred 50 times costs only $0.5 per occurrence ($25 total) and the problem that occurred 3 times costs $50 each time ($150 total). Based on the cost Pareto, the user may want to tackle the more expensive problem first. To create a cost Pareto, the user will need to know the categories, how often each occurred, and the cost for each category.

Despite its simplicity, Pareto analysis is one of the most powerful problem-solving tools for system improvement. Getting the most from Pareto analysis includes making subdivisions, multi-perspective analyses, and repeat analyses.

PCMS® (Plant Condition Management Software-S/W): PCMS (by MISTRAS Group) is a utilized software in many different energy industries for the management of inspection information on piping, pressure vessels, safety relief devices, valves, tanks, and other process equipment. PCMS offers tremendous benefits to any facility to budget and plan long-term maintenance strategies to identify problems before failures actually occur, thus reducing unplanned shutdown. The program provides a host of tools to organize, link, and synchronize information enabling the thorough evaluation of the results.

PCMS is the only Mechanical Integrity software application on the market today that has 25+ plus years in asset, corrosion, and inspection data management. All program modules are seamlessly fed into the integrated RBI calculator, thus eliminating the need to manage multiple applications to perform total asset integrity analysis. PCMS is truly a "single-source" inspection management solution that provides an array of elements to achieve a company's Mechanical Integrity initiatives including:

- Complete Asset Tracking and Analysis
- Integrated RBI
- Comprehensive Inspection Tracking and Analysis
- Inspection and Turnaround Planning
- Corrosion Analysis and Trending
- Safety Relief Valve Management

PM (Preventive/Preventative Maintenance-Guide): PM is regularly performed on a piece of equipment to lessen the likelihood of its failing. Preventative maintenance is performed while the equipment is still working, so that it does not break down unexpectedly. Preventative maintenance is more complex to coordinate than run-to-failure maintenance because the maintenance schedule must be planned. Preventative maintenance is less complex to coordinate than predictive maintenance because monitoring strategies do not have to be planned nor the results interpreted.

PSM (Process Safety Management-Reg.): It is a regulation, promulgated by the US Occupational Safety and Health Administration (*OSHA*). A process is any activity or combination of activities including any use, storage, manufacturing, handling, or the on-site movement of highly hazardous chemicals (HHCs) as defined by OSHA and the Environmental Protection Agency (*EPA*).

The end-user should document that equipment complies with RAGAGEP. For existing equipment designed and constructed in accordance with codes, standards or practices that are no longer in general use, the end-user should determine and document that the equipment is designed, maintained, inspected, tested, and operated in a safe manner.

A process safety incident is the "Unexpected release of toxic, reactive, or flammable liquids and gases in processes involving highly hazardous chemicals." Incidents continue to occur in various industries that use highly hazardous chemicals which exhibit toxic, reactive, flammable, or even explosive properties or may exhibit a combination of these properties. Regardless of the industry that uses these highly hazardous chemicals, there is a potential for an accidental release any time they are not properly controlled. OSHA has issued the Process Safety Management of Highly Hazardous Chemicals regulation (Title 29 of CFR Section 1910.119) which contains requirements for the management of hazards associated with processes using highly hazardous chemicals.

RAGAGEP (Recognized and Generally Accepted Good Engineering Practices-Guide): The PSM standard does not define RAGAGEP. This RAGAGEP (memorandum) provides guidance on the enforcement of the PSM (Process Safety Management) Standard's recognized and generally accepted good engineering practices (RAGAGEP) requirements, including how to interpret "*shall*" and "*should*" language in published codes, standards, published technical reports, recommended practices (*RP*) or similar documents, and on the use of internal employer documents as RAGAGEP. Enforcement activity, including the Petroleum Refinery Process Safety Management National Emphasis Program, and requests for assistance from the field revealed the need for guidance on the PSM standard's RAGAGEP provisions.

RAM (Reliability, Availability, and Maintainability-Prog): An asset management program developed by PinnacleART for optimization of costs through a combination of increased asset availability and reliability and optimized maintenance strategies.

– *Reliability* is defined as the probability that an item will perform its intended function for a specified period of time.
– *Availability* refers to the total time a system is in an operative state.
– *Maintainability* describes the ability of an item to be retained or restored to specified conditions when maintenance is performed by qualified personnel.

RAT (Bundle Retube Analysis Tool-Company's Prog.): Developed by LyondellBasell.

Traditionally the top failure mechanisms of tubes of H/EXs in oil and gas industries, listed below, resulted in 90% of the failures:

- Corrosion by corrosive process fluids
- Under deposit corrosion of carbon steel tubes
- SCC of stainless steel tubes
- Steam/condensate corrosion
- Erosion by vibration of tubes
- Galvanic corrosion
- Crevice corrosion
- SRB corrosion of cooling water in carbon steel or copper alloy tubes

A Weibull analysis of cooling water exchanger failures was performed for each production unit in this plant. The range of MTTF (mean time to failure) was found to be between 7.2 and 13.2 years.

The team identified three main areas for improvement to minimize future in-service tube failures. These areas were:

1. Tube testing
2. Retubing strategy during turnarounds
3. Design improvements (tube material, velocity, no tubes in window (NTIW), tube arrangement, impingement plate, tube-to-tubesheet design, etc.)

Currently, the following four techniques are being used to test ferromagnetic tubes:

1. Remote field eddy current testing (RFEC)
2. Partial saturation eddy current testing (PSET)
3. Magnetic flux leakage (MFL)
4. Internal rotating inspection system (IRIS)

The retube-analysis matrix is based on a point system. The following four risk factors are used in the matrix:

1. Tube-age factor
2. Remaining life factor
3. Production-criticality factor
4. Service factor

[Background]

The tube age factor compares the current age of the tube bundle to the historic average age of the tube bundle. The remaining life factor is based on the current tube wall loss and the corrosion rate.

The production criticality factor takes into consideration the business and/or safety/environmental consequences of a tube leak. The service factor primarily covers the variables associated with reboilers, cooling water exchangers, and the mechanical design. A maximum of 4 points can be obtained for each factor.

The inspection and retube priorities are determined based on the total number of points. The following are the three risk categories:

1. Retube, 11–16 points
2. Priority inspection, 8–10 points
3. Normal inspection, 1–7 points

Retube-category exchangers are high-risk exchangers and are planned for retube during the turnaround. Exchangers in the "priority inspection" category are scheduled for testing early in the turnaround so that if required, there is sufficient time during the turnaround for retube.

The turnaround team must evaluate whether material is required or shop space must be reserved for these exchangers. "Normal inspection" category exchangers are not expected to have problems and are inspected after the priority exchangers. The retube-analysis matrix was validated and fine-tuned against past in-service tube failures (reliability hits) and past turnaround scopes. Of the exchangers that failed in service resulting in production loss of this plant, 77% would have been retubed during the turnaround if the retube-analysis matrix had been used. The remaining 23% of the exchangers fell in the "priority inspection" category.

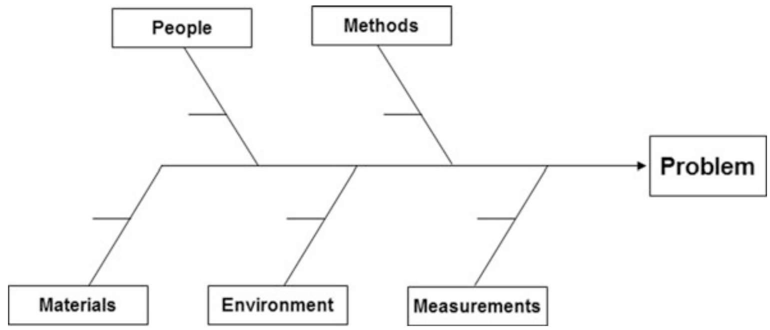


Figure 1.50 Fishbone cause mapping by Kaoru Ishikawa

RC(F)A (Root Cause (Failure) Analysis-Guide): Root cause analysis is an approach for identifying the underlying causes of why an incident occurred so that the most effective solutions can be identified and implemented. It is typically used when something goes badly but can also be used when something goes well. Within an organization, problem-solving, incident investigation, and root cause analysis are all fundamentally connected by three basic questions: What's the problem? Why did it happen? What should be done to prevent it? Figure 1.50 shows the fishbone diagram that builds from right to left. The Cause Mapping method actually uses Ishikawa's convention by asking why questions in the direction we read.

For the chronic failures, the following data should be collected and analyzed:

– Preserving Failure Data
– Ordering the Analysis
– Analyzing the Data
– Communicating Findings and Recommendations
– Tracking for Success

RCM (Reliability-Centered Maintenance-Prog): It is a process of determining the most effective maintenance approach. The final result of an RCM program is the implementation of a specific maintenance strategy on each of the assets of the facility. It is generally used to achieve improvements in fields such as the establishment of safe minimum levels of maintenance. Successful implementation philosophy of RCM employs Preventive Maintenance (*PM*), Predictive Maintenance (*PdM*), Real-Time Monitoring (*RTM*), Run-to-Failure (*RTF*), and Proactive Maintenance techniques in an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance. The goal of the philosophy is to provide the stated function of the facility, with the required reliability and availability at the lowest cost. RCM requires that maintenance decisions be based on maintenance requirements supported by sound technical and economic justification.

Currently RCM is defined in the standard SAE JA1011 (Evaluation Criteria for RCM Processes). This sets out the minimum criteria for what is, and for what is not, able to be defined as RCM.

There are several different methods for implementing reliability-centered maintenance that are recommended, summarized in the following seven steps:

– Step 1: Select an equipment for RCM analysis
– Step 2: Define the boundaries and function of the systems that contain the selected equipment
– Step 3: Define the ways that the system can fail (failure modes)
– Step 4: Identify the root causes of the failure modes
– Step 5: Assess the effects of failure
– Step 6: Select a maintenance tactic for each failure mode
– Step 7: Implement and then regularly review the maintenance tactic selected

RMP (Risk Management Plan): It is used for facilities which are under extremely hazardous substances. These plans provide valuable information to local fire, police, and emergency response personnel to prepare for and respond to chemical emergencies in their community. The following identifications are to be prepared for the Risk Management Plan:

– Identifies the potential effects of a chemical accident
– Identifies the steps the facility is taking to prevent an accident
– Spells out emergency response procedures should an accident occur

SagePlus® (FFS Assessment Software-S/W): SagePlus (by E2G) is a software for FFS (API 579/ASME FFS-1, Level 1 & 2), equipment design codes, materials tools, fluid and heat transfer, specialty in-service evaluation, safety, and stress analysis of equipment in oil and gas industries. It is based on the API/ASME 579, API 520, ASME B31.3, and other relevant code and standard committees. It is continuously updated in accordance with the updates of the based industrial standards.

SAP (Systems, Applications, and Productions for Process Industries-rog): It is an asset management program that manage physical assets sustainably, to maximize return on assets, manage risk, achieve superior asset performance, optimize assets and portfolios, solve issues quickly, and mitigate risk. It can be used for all industries, infrastructures, building, utilities, militaries, etc.

SMRP (Society for Maintenance & Reliability Professionals-Cert): SMRP Certification Programs such as the edited Certified Maintenance and Reliability Professional (CMRP), the Certified Maintenance and Reliability Technician (CMRT), and the Certified Asset Management Assessor (*CAMA*) are the No. 1 credentialing programs for validating the knowledge, skills, and abilities of M&R and asset management professionals and technicians.

SPC (Statistical Process Control-Guide): It is an application of the same 14 tools to control process *inputs* (independent variables).

SQC (Statistical Quality Control-Guide): It is an application of the 14 statistical and analytical tools (7-QC and 7-SUPP) to monitor process *outputs* (dependent variables).

7-QC	7-Supplemental
• Cause-and-effect analysis • Check sheets/tally sheets • Control charts • Histograms • Pareto analysis • Scatter analysis	• Data stratification • Defect maps • Events logs • Process flowcharts/maps • Progress centers • Randomization • Sample size determination

TPM (Total Productive Maintenance-Guide): It is a system of maintaining and improving the integrity of production and quality systems through the machines, equipment, processes, and employees that add business value to an organization.

TPM focuses on keeping all equipment in top working condition to avoid breakdowns and delays in manufacturing processes.

One of the main objectives of TPM is to increase the productivity of plant and equipment with a modest investment in maintenance. Total quality management (TQM) and total productive maintenance (TPM) are considered as the key operational activities of the quality management system.

The main objective of TPM is to increase the Overall Equipment Effectiveness (OEE) of plant equipment. TPM addresses the causes for accelerated deterioration while creating the correct environment between operators and equipment to create ownership.

OEE has three factors below which are multiplied to give one measure called OEE.

$$\text{Performance} \times \text{Availability} \times \text{Quality} = \text{OEE}$$

Each factor has two associated losses making six in total, these six losses are as follows:

Performance = (1) running at reduced speed – (2) minor stops
Availability = (3) breakdowns – (4) product changeover
Quality = (5) startup rejects – (6) running rejects

The objective finally is to identify then prioritize and eliminate the causes of the losses. This is done by self-managing teams that problem solve. Employing consultants to create this culture is common practice.

Weibull Analysis (Life Data Analysis-Guide): In Weibull analysis (life data analysis), the practitioner attempts to make predictions about the life of all products in the population by fitting a statistical distribution to life data from a representative sample of units. The parameterized distribution for the data set can then be used to estimate important life characteristics of the product such as reliability or probability of failure at a specific time, the mean life, and the failure rate. Life data analysis requires the practitioner to:

- Gather life data for the product
- Select a life time distribution that will fit the data and model the life of the product
- Estimate the parameters that will fit the distribution to the data
- Generate plots and results that estimate the life characteristics of product, such as the reliability or mean life

Once the user has calculated the parameters to fit a life distribution to a particular data set, the user can obtain a variety of plots and calculated results from the analysis, including:

- *Reliability Given Time*: The probability that a unit will operate successfully at a particular point in time. For example, there is an 88% chance that the product will operate successfully after 3 years of operation.
- *Probability of Failure Given Time*: The probability that a unit will fail at a particular point in time. Probability of failure is also known as "unreliability," and it is the reciprocal of reliability. For example, there is a 12% chance that the unit will fail after 3 years of operation (probability of failure or unreliability) and an 88% chance that it will operate successfully (reliability).
- *Mean Life*: The average time that the units in the population are expected to operate before failure. This metric is often referred to as "mean time to failure" (MTTF) or "mean time before failure" (MTBF).
- *Failure Rate*: The number of failures per unit time that can be expected to occur for the product.

- *Reliable Life* (warranty time). The estimated time when the reliability will be equal to a specified goal. For example, the estimated time of operation is 4 years for a reliability of 90%.
- *B(X) Life*: The estimated time when the probability of failure will reach a specified point (X%). For example, if 10% of the products are expected to fail by 4 years of operation, then the B(10) life is 4 years. (Note that this is equivalent to a reliable life of 4 years for a 90% reliability.)
- *Probability Plot*: A plot of the probability of failure over time. (Note that probability plots are based on the linearization of a specific distribution. Consequently, the form of a probability plot for one distribution will be different from the form of another. For example, an exponential distribution probability plot has different axes than those of a normal distribution probability plot.)
- *Reliability* vs. *Time Plot*: A plot of reliability over time.
- *pdf Plot:* A plot of probability density function (*pdf*).
- *Failure Rate* vs. *Time Plot*: A plot of the failure rate over time.
- *Contour Plot*: A graphical representation of the possible solutions to the likelihood ratio equation. This is employed to make comparisons between two different data sets.

References for Maintenance, Reliability, and Integrity
API 579/ASME FFS-1, API RP580/581/584, API STD 689/ISO 14224, API STD2610, API RP2D/1107/1111, API 500 series for Inspection Standards, ISO/TC 67, IPMC (international property maintenance code), TWI Report 13,237 for CRIS (corrosion reliability inspection scheduling), PIP REEE002, NACE Conference Paper 04184, NACE MP Sep.2004 (p38), NACE Corrosion, Vol.60, No.5, p429, etc.

1.6 Reiterative Engineering Mistakes

1.6.1 Pressure

psig: Internal Pressure (1 atm = 1.013 bar = 14.7 psig = 29.4 psia, 0 psig = 14.7 psia, 1 bar = 14.5 psi)
psia: Partial Pressure (H_2, CO_2, H_2S, etc.) = total absolute pressure x mole fraction
Half/Full Vacuum: Internal Vacuum
Ext. 15 psig (for design): Internal Vacuum
Torr: Internal Vacuum (760 torr = 14.7 psia = 0 psig)
*Differential Pressure: psi

1.6.2 Temperature

Conversion Formula

$°C = 5/9(°F - 32)$ *1
$°F = 9/5°C + 32$ *1

Several Mistakes of Conversion
A Certain Temperature – Same as Above Differential Pressure:

$\Delta\ °C = \Delta\ 5/9\ °F$ *2
$\Delta\ °F = \Delta\ 9/5\ °C$ *2

For example,

PWHT: 1150 °F*1 ± 50 °F*2 → 621 °C*1 ± 28 °C*2
621 ← (1150-32) × 5/9 and 28 ← 50 × 5/9

For 50 °F,

*1 (Absolute value): °C = 5/9 (50−32) = 10°F – False
*2 (Differential value): Δ °C = 5/9 (50) = Δ 28°F – True

1.6.3 Weight and Volume

1. Weight (liquid or solid): weight%, ppmw, ppbw, baume (caustic)
2. Volume (gas or vapor): sometimes used for partial pressure calculation
   : mole%, vol%, ppmv, ppbv

1.6.4 Minimum, Maximum, and Average: ( ) for Example

1. Minimum: TS (tensile strength), YS (yield strength), Impact Test Absorbing Energy Value/Lateral Expansion, Elongation, Tolerance (machined parts of H/EX), Minimum Thickness, Chemical Composition, Hardness (wear resistance, hardfacing), Preheat, Postheat, Heat Treatment Temperature, Interpass Temperature, Fluid Velocity (to avoid MIC)
2. Maximum: TS, Ratio of YS/TS, Tolerance (most cases), Deflection (tower, structures), Hardness (stress corrosion cracking, sulfide stress corrosion, weld crack), Chemical Composition (carbon equivalent and carbon content for weldability), Noise (max. dB), Vibration, Heat Treatment Temperature, Interpass Temperature, Fluid Velocity (to avoid severe corrosion), etc.
3. Average or Range: Chemical Composition, Impact Test Absorbing Energy Value, etc.

1.6.5 Shall, Should, May, and Can

"Shall" is "must be." "Should" is "strongly recommend." However, many project specifications may apply the "Should" in the applicable industrial codes/standards to "Shall" for the project execution for new construction and maintenance. These terminologies are the most important concern in RAGAGEP (Recognized and Generally Accepted Good Engineering Practices-Guide).

Meanwhile, "May" indicates a permission and "Can" indicates a possibility or a capability.

1.6.6 Applicable Standards and Reference Standards

Applicable Standards have the same authority with the code requirements.

Reference Standards in the project specification are only for reference information unless the specification indicates to alloy the reference as project requirements.

Chapter 2
Types and Requirements of Materials and Corrosion

2.1 Characteristics and Requirements of Raw Materials

2.1.1 Classes and Properties of Materials

2.1.1.1 Classes of Materials (Table 2.1)

2.1.1.2 Classes and Terminology of Metals

Metal has two classes, ferrous and nonferrous, as shown in Table 2.2. The borderline is the content of iron.

References

– See ASTM A941 for Terminology relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys.
– See ASTM E527 for Standard Practice for Numbering Metals and Alloys (UNS).

Table 2.3 shows the nominal elements compositions of the most common metals.

2.1.1.3 Ferrous Base Metal (ASME SAxxx or ASTM Axxx)

Table 2.4 shows the types and their characteristics of ferrous metals in energy and chemical industries.

2.1.1.4 Effects of each Chemical Component in Ferritic Steels

Steel is a combination of iron (Fe) and carbon (C). In its softened state, the base is a matrix composed of simple iron molecules (ferrite), in which are suspended molecules of iron carbide (cementite-Fe_3C). When steel is heated to prescribed temperatures, then cooled at a specific rate, it undergoes internal physical changes, which manifest themselves in the form of various microstructures such as pearlite, bainite, and martensite. These microstructures (and others) provide a wide range of mechanical properties, making steel an extremely versatile metal. Alloying elements are added to effect changes in the properties of steels.

Table 2.5 shows the characteristics of several elements in ferritic steels. Each element covers some of the different alloying elements added to the basic system of iron and carbon, and what they do to change the properties or effectiveness of steel.

Table 2.6 shows the effects of alloy elements on the heat treatment (hardenability and tempering) of Q-T alloy steels. The best application for use should consider the combinations of several elements.

Table 2.7 shows the effects of each element on welding of ferritic steels.

2.1.1.5 Commercial Metals

There are several types of commercial metals, such as code and standard materials, brand materials, and patent materials, as shown in Table 2.8. Most brand materials also have the code and standard numbers, but the names are used more often compared to code and standard numbers.

2.1.1.6 European Steel Names and Designations

Steel Names (See EN10027–1)
Group 1 Steels
S = Structural Steels
L = Steels for line pipework
P = Steels for pressure purposes
E = Engineering steels

All above are followed by the specified minimum yield stress for the smallest thickness,
e.g., S275 is a structural grade steel with a minimum specified yield stress of 275 N/mm^2

J. -C. Eun, *Handbook of Engineering Practice of Materials and Corrosion*,
https://doi.org/10.1007/978-3-030-36430-4_2

Table 2.1 Classes of materials (typical)

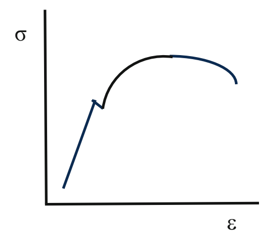
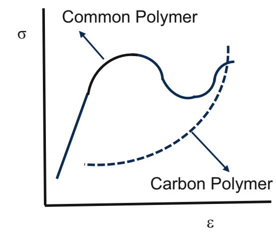
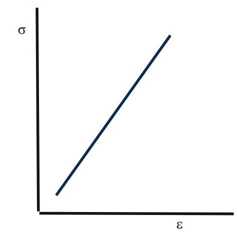
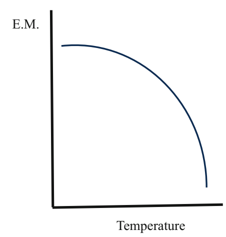
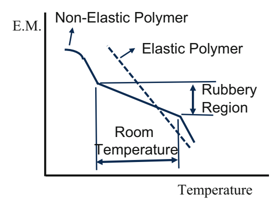
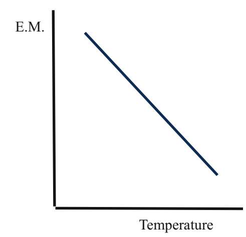
No	Items	Metal	Plastic	Ceramic
1	Main composition	Metal elements, C, H, O, S, etc.	C, H, O & Cl/S/N, etc.	Si, Al, O, etc.
2	Tensile strength	Good	Weak	Good (somewhat)
3	Compressive strength	Good	Better	Excellent
4	Hardness	Good	Weak	Excellent
5	Stress-strain (σ-ε) curve (typical)			
6	Toughness (ductility) at low temperature	Excellent	Thermo-plastic: excellent Thermo-setting: weak	Very weak
7	Thermal impact resist	Excellent	Good	Very weak
8	Thermal resist	Good	Very weak	Excellent
9	Fatigue resist	Good	Good	Very weak
10	Creep resist	Good	Weak	Good
11	Thermal conductivity	Very high	Very low	Low
12	Thermal expansion	Medium	High	Very low
13	Elastic Modulus-Temperature (E.M-T) curve			
14	Transparency	None	Semi or none	Complete, semi, or none
15	Bond	Metal bond	Common bond	Common & ion bond
16	Electric conductivity	High	None	None
17	Surface brightness	Good	Bad	Excellent
18	Corrosion resist.	Medium	Very good	Excellent
19	Castability	Good	Very good	Bad
20	Machinability	Very good	Bad	Good
21	Hardenability	High	None	None
22	Plasticity	High	A little	None
23	Weldability	Good	Restricted	Highly restricted
24	Specific gravity	High	Very low	Medium
25	Elasticity	High	Thermo-plastic: very low Thermo-setting: low	Very high
26	Elongation	Medium	Thermo-plastic: very high Thermo-setting: low	Very low

Table 2.2 Classes of metal

Metals	Fe content	Classes by ASTM
Ferrous materials (metals)	Fe >50%	A (e.g., *A*516–70: PV carbon steel)
Nonferrous materials (metals)	Fe ≤50%	B (e.g., *B*127-N04400: Monel 400)

Group 2 Steels

1. Non-alloy steels with an average manganese content less than 1% C followed by the average percentage carbon content × 100
2. Non-alloy steels with an average manganese content greater than 1%, with average percentage carbon content × 100
3. The chemical symbols that characterizes the steel: Cr, Mo, etc.
4. The percentage content of each alloy above multiplied by a factor

Table 2.3 Nominal compositions of most common metals (element, wt%)

Material	Fe	Cr	Ni	Mo	Cu	Zn	Other
Carbon steel and cast iron	Base	–	–	–	–	–	
Low alloy steel – See Tables 2.12, 2.31, 2.32, 2.33, 2.34, 2.35, 2.36, 2.37, 2.38, and 2.39 for more detail							
C-0.5Mo	Base	–	–	0.50	–	–	
1.25 Cr-0.5 Mo	Base	1.25	–	0.50	–	–	
2.25Cr-Mo	Base	2.25	–	1	–	–	
5 Cr-0.5Mo	Base	5	–	0.50	–	–	
9 Cr-1Mo	Base	9	–	1	–	–	
AISI 4140	Base	1	–	0.25	–	–	0.4C
AISI 4340	Base	1	2	0.25	–	–	0.4C
2.5 nickel	Base	–	2.5	–	–	–	Mn $\leq$ 0.78
3.5 nickel	Base	–	3.5	–	–	–	Mn $\leq$ 0.78
9 nickel	Base	–	9.0	–	–	–	Mn $\leq$ 0.98
Martensitic stainless steels (MSS) – See Table 2.51 for more detail							
Type 403	Base	13	–	–	–	–	0.08–0.15C
Type 410	Base	13	<0.75	–	–	–	0.08–0.15C
Ferritic stainless steels (FSS) and super FSS (SFSS) – See Table 2.50 for more detail							
Type 405	Base	13	<0.6	–	–	–	0.3 Al
Type 410S	Base	13	<0.6	–	–	–	C $\leq$ 0.08
Type 430	Base	17	<0.75				
Sea-cure (S44660)	Base	27	1.5	3.7			(Ti + Cb) 0.20–1.00,
Monit (S44635)	Base	25	4	3.9			(Ti + Cb) [0.20 + 4]
29–4-2	Base	29	2	4			(C + N) 0.025, cu 0.15
Austenitic stainless steels (ASS) and super ASS (SASS) – See Tables 2.47, 2.48, and 2.49 for more detail							
Type 304(L)	Base	18	10	–	–	–	C $\leq$ 0.03 for "(L)"
Type 316(L)	Base	17	10	2.5	–	–	C $\leq$ 0.03 for "(L)"
Type 321	Base	18	10	–	–	–	Ti 5xC min
Type 347	Base	18	10	–	–	–	0.8Cb
Type 904L	Base	20	25	4.3	–	–	0.15 N
254 SMO (SASS)	Base	20	18	6.3	–	–	0.2 N
AL-6XN (SASS)	Base	20	25	6	0.75	–	0.2 N
Alloy 28 (SASS)	Base	27	32	3.5	1	–	
Precipitation hardening stainless steels (PHSS) – See Tables 2.52 for more detail							
Type 17-4PH	Base	17	4	–	4	–	
Type 17-7PH	Base	17	7	–	–	–	1.0Al
Duplex stainless steels (DSS) and super DSS – See Tables 2.53, 2.54, 2.55, and 2.56 for more detail							
Type 2205	Base	22	5	3	–	–	
Type 2507	Base	22	7	3.25	–	–	
Nickel based alloys – See Tables 2.68 and 2.70, 2.71, 2.72, and 2.73 for more detail							
Alloy 20Cb3	36	21	35	3	4	–	1.0Cb
Alloy 800	46	21	33	–	–	–	
Alloy 825	30	22	42	3	2	–	1.0Ti
Alloy 600	8	16	76	–	–	–	
Alloy 625	3	22	62	9	–	–	4.0Cb
Alloy B	5	–	65	30	–	–	
Alloy C-276	5	16	59	16	–	–	4.0 W
Alloy 400	2	–	–	68	–	30	
Copper based alloys – See Tables 2.74, 2.76, and 2.77 for more detail							
Admiralty	–	–	–	–	70	29	1.0Sn
Aluminum brass	–	–	–	–	77	21	2.0Al
Naval brass	–	–	–	–	60	39	1.0Sn
Copper nickel 90/10	1	–	10	–	89	–	
70/30	1	–	30	–	69	–	
Aluminum bronze	2	–	–	–	91	–	7.0Al
Aluminum and its alloys	See Tables 2.81, 2.82, and 2.83 classes of aluminum alloys						
Titanium and its alloys	See Tables 2.84 and 2.85 classes of titanium alloys						
Zirconium and its alloys	See Table 2.87 classes of aluminum alloys						
Hardfacing alloys	See Table 2.89 classes of hardfacing alloys						

Table 2.4 Classification and characteristics of the most common ferrous (Fe > 50%) metals[(1),(2),(3)]

Materials	Definition and group	Sub-materials	Use/characteristics/typical material standards	Remark (e.g., ASTM and others)
Cast iron (CI)	Casted metal with 2.0 ~ 4.5%C *Compared to cast steel* Better castability, machinability, vibration damping, compressive strength, and cost (cheaper)	Gray		A48, A126, A278
		White		A667, A748, A942, A532
		Ductile (nodular, spheroidal)	Better toughness in low temperature than gray or white irons	A395, A536
		Malleable	Better toughness in low temperature than other nodular irons	A47, A220
		High Si	Better corrosion resistance in specific corrosion environment	A518, A861, BS1591
Cast steel	Casted metal with less than 2%C *Compared to cast iron* Better weldability, impact resistance	Cast	Improved toughness and weldability compared to cast iron. ASTM A488 for repair welding	A216
Carbon steel (CS)	– Ferrous steel with 0.01~2%C and min. 0.25%Mn – Including impurity elements, such as P, S and Si. If they have the materials other than above elements, they call as alloy steel.		Mostly weldable. Tensile strength, toughness, and corrosion resistance can be adjusted by heat treatment, chemical control, and others.	A516, A515, A106, A105 A36, A285. A537
Low alloy steel/cast (LAS)	– The total of Ni, Cr, V, W, and Cb (or Nb) are less than 10.5%, – High Mn steel (i.e., 11–14% Mn-Hadfield steel for wear resistance/24–27% Mn austenitic steel for cryogenic service and high strength) – Ni containing (0.5–9%) steel for low/cryogenic service.	Elevated temperature steel (or hydrogen service materials)	1. Including Cr & Mo 2. To be used up to 650 °C (1200 °F) 3. Mainly used for heater tubes and high temperature pressure vessels.	A387
		High strength tool materials	Tool materials per AISI/SAE standards	See Table 2.3
		Low temperature/ cryogenic steel	0.5–9% Ni steel	A203, A333, A334
		High manganese austenitic steel[(4)]	24–26% Mn. Fe > 50% For cryogenic service (LNG), alternative metal of 9Ni steel	POSCO 8C1V See Sect. 2.1.4.5 for more detail
		Ferritic steels (ASME Sec. VIII Div. 1, UHT)	Tensile properties enhanced by heat treatment (N, N-T, or Q-T)	A353, A517, A533, A487, A333–8, A508
		Special purpose steel	Welded boiler or pressure vessel	A302 (Mn-Mo)
Stainless steel/cast (SS or high alloy steel)	The steels more than 10.5% Cr. Fe >50%	Conventional stainless steel	MSS: 410 (12Cr) FSS: 405, 430 ASS: 304, 316, 321, 347, 310, High Mn ASS DSS: 2205 (22Cr) PHSS: 631 SSS: 6%Mo, 254 SMo	A240, A312, A213
		Super stainless steel	PRE (pitting resistance index): Cr + 3.3Mo + 16 N >40%	254 SMO (S31254) AL-6XN (N08367)

Notes
(1)Ferrous Metal: Metal with Fe >50 wt%. [ASTM & ASME: Axxx or SAxxx]
(2)Nonferrous Metal: Metal with Fe ≤50 wt% [ASTM & ASME: Bxxx or SBxxx]
(3)Ferritic Steel: Steel with fully ferrite structure
(4)Even though it has 100% austenitic structure, it is not called stainless steel because it does not contain sufficient Cr (Cr-oxide)

Alloy steels where at least one element exceeds 5%
The letter X is the chemical symbol that characterizes the steel: Cr, Mo, etc.
The percentage content of each alloy above multiplied by a factor

Factors used above	
Factor	Alloy
4	Cr, Co, Mn, Ni, Si, W
10	Al, Be, Cu, Mo, Nb, Pb, Ta, Ti, V, Zr
1000	B

Example: 13 CrMo 4–5

0.08 to 0.18 Average × 100 = 13
CrMo = Cr and Mo are the alloys used to specify the steel.
Cr = 0.7 to 1.15 average × 4 = 4
Mo = 0.4 to 0.6 average × 10 = 5

Table 2.5 (1/2) Characteristics of several elements in ferritic steels (wrought, cast, tools, etc.)[1],[2]

Elements	Characteristics (% = weight %)
Al[3],[4] (Aluminum)	Al is added to steel in very small amounts (up to 0.10%) as a deoxidizer [see Sect. 2.1.4.1(b) for more detail]. It also is a grain refiner for improved toughness of steels. It is the principal element for fine grain practice of steel. Usually used in combination with silicon to obtain a semi- or fully killed steel. Al is more susceptible to graphitization than Si at high temperature, so that Al-killed steel is not recommended for high-temperature services [see Sect. 2.4.3.5 for more detail].
B (boron)	Increases high temperature toughness. Significantly increases the hardenability of steel without loss of ductility. Its effectiveness is most noticeable at lower carbon levels.
C (carbon)	The basic metal, iron (Fe), is alloyed with carbon to make steel and has the effect of increasing the hardness (wear resistance) and strength by heat treatment but the addition of carbon enables a wide range of hardness and strength. Decreases corrosion resistance in stainless steel and weldability in carbon and low alloy steel. C is also used to increase the casting effect as well as abrasion resistance in casting materials. C is the most important element for the classification of CS, CI, and cast steel as seen in Table 2.4 as well as for weldability evaluation of ferritic steels.
Ca (calcium)	Deoxidizing element. The ratio of Ca/S should be controlled in a range of 1.5–5.0 for HIC-resistant steel (Ca treatment) in sour service.
Co (cobalt)	Cobalt improves strength at high temperatures and magnetic permeability. Increases hardness, also allows for higher quenching temperatures (during the heat treatment procedure). Intensifies the individual effects of other elements in more complex steels. Co is not a carbide former; however, adding cobalt to the alloy allows for higher attainable hardness and higher red hot hardness. Co becomes highly radioactive when exposed to the intense radiation of nuclear reactors, and as a result, any stainless steel that is in nuclear service will have a cobalt restriction, usually approximately 0.2% max. This problem is emphasized because there is residual cobalt content in the nickel used in producing these steels.
Cr (chromium)	Cr is added to the steel to increase resistance to oxidation, pitting, temper embrittlement, and hydrogen attack. Increases corrosion resistance (see Table 2.43 for PREN). SS has approximately 11% Cr and a very marked degree of general corrosion resistance when compared with steels with a lower percentage of Cr. Chromium, in combination with C, is a powerful hardening alloying element. In addition to its hardening properties (wear resistance). The critical quenching speed is reduced to the point that the steel becomes air hardening. Cr is a ferrite former in SS. Often used in combination with Ni, Mo, and Cu.
Cu	Copper (0.2–0.5%) contributes greatly to the corrosion resistance of CS by retarding the rate of rusting at room temperature (improves weathering resistance/atmospheric corrosion resistance – i.e., ASTM A242 & A588), but high levels of copper can cause welding difficulties. It should be noted that with respect to knife steels, Cu has a detrimental effect to surface quality and to hot-working behavior due to migration into the grain boundaries of the steel. However, decreases corrosion resistance in wet H_2S (sour) or HF environment, so Cu + Ni + Cr should be 0.20% or less even though Cu above 0.2–0.3% increases the HIC resistance in CS.
Mn[3] (Manganese)	Mn is added to steel to assist deoxidation in melting process, improve hot working properties, and increase strength, toughness, and hardenability. It is also able to decrease the critical cooling rate during hardening, thus increasing the steels hardenability much more efficient than any other alloying elements. Mn is capable to form MnS with S in the metal, which is beneficial to machining, but the flattened MnS in mill-rolling process can be a nucleation site of atomic hydrogen in wet H_2S (sour) or HF service. At the same time, it counters the brittleness from sulfur and is beneficial to the surface finish of CS. Increases strength (normally Mn $\leq$2% in carbon steel wire), toughness [per higher Mn/C, but normally Mn $\leq$1.5% in low carbon steel; see Sect. 2.2.1.3], and 14–16% Mn (Hadfield) steel has excellent wear resistance. 24–27% Mn austenitic steel has excellent toughness in cryogenic temperature. Mn in carbon steel should be 1.0–1.1% or less in wet H_2S (sour) service. Mn is a necessity for the process of hot rolling of steel by its combination with oxygen (O_2) and sulfur (S).
Mo (molybdenum)	Increases the hardness, slows down the critical quenching speed, and increases high temperature tensile strength and corrosion resistance (high temperature attack). It is quite often used in combination with Cr to improve the strength of the steel at high temperatures. Mo is a strong carbide former and is usually added at an amount of less than 1% in alloy steels. When Mo is added to Cr steels, it greatly diminishes the tendency of steels to decay in service or in heat treatment. Also, it used in structural steels in varying amounts, e.g., ASTM A514 (0.15–0.65%Ni) and ASTM A588 (0.08–0.25% Ni).
Nb or Cb[4] (Niobium) or (Columbium)	Nb lowers the transition temperature and aids in a fine grain structure. Nb retards tempering and can decrease the hardenability of steel because it forms very stable carbides. Nb is added to steel in order to stabilize carbon, and as such performs in the same way as described for titanium. Nb is a strength-enhancing element, and is one of the important components in some of the HSLA steels (e.g., type 1 and 3 in ASTM A572). Nb also has the effect of strengthening steels and alloys for high-temperature service. Decreases corrosion resistance in HIC or HF environment, so that V + Cb shall be 0.03% or 0.1% and less, respectively.
Ni (nickel)	Ni improves resistance to oxidation and corrosion. Also, increases toughness at low temperatures and cryogenic service when added in smaller amounts (up to 9%Ni) to alloy steels [see 2.1.4(3) for Ni-alloyed steel for low temperature]. Ni is added in large amounts, over about 8%, to high Cr stainless steel to form the most important class of corrosion- and heat-resistant steels. Improves toughness and high strength at both high and low temperatures. Also, used in structural steels in varying amounts; e.g., ASTM A514 (0.30–1.5% Ni) and ASTM A588 (0.25–1.25%Ni).
P (phosphorus)	P is usually added with S to improve machinability in low alloy free-cutting steels. P, in small amounts (up to 0.15%), aids strength in low-alloy, high-strength steel. P prevents the sticking of light-gauge sheets when it is used as an alloy in steel. P additions are known to increase the tendency to crack during welding or on operation in HIC environment of hydrocarbon processing. Max 0.05% for common requirement. Max 0.010~0.015% for HIC-resistant steels.
S (sulfur)	When added in small amounts, S (0.10–0.30%) improves machinability of a steel, called free machining, but does not cause hot shortness. Hot shortness is reduced by the addition of Mn because it combines with the S to form manganese sulfide (MnS) so that the Mn content increased to counter any detrimental effects since sulfur is beneficial to machining. As MnS has a higher melting point than iron sulfide (FeS), which would form if Mn was not present, the weak spots at the grain boundaries are greatly reduced during hot working. S addition is known to increase the tendency to cracking during welding or on operation in HIC environment of hydrocarbon processing. To be controlled max 0.002~0.008% for HIC-resistant or HF-resistant steel.

Table 2.5 (2/2) Characteristics of several elements in ferritic steels (wrought, cast, tools, etc.)[(1),(2)]

Elements	Characteristics (% = weight %)
Se (selenium)	Se is added to improve machinability.
Si[(3)] (Silicon)	Si is usually contained in the melting of steel as a deoxidizer (killing agent), as a result, most steels contain a small percentage of silicon. Si contributes to hardening of the ferritic phase in steels and for this reason Si-killed steels are somewhat harder and stiffer than Al-killed steels. Si content in CS shall be minimum 1.0% (1.2% preferable) in high-temperature sulfidation environments [see Sect. 2.1.4.1(b) for more detail.]. Si, as a coarse grain former, has oxidation and sulfidation resistance at high temperatures, and so it is used to substitute Al for deoxidizing in steel melting processes. Increases strength and elastic modulus and decreases the toughness. Si is also used to increase the casting effect (Si < 3%) as well as abrasion resistance (14–16% Si) of casting materials. For galvanizing purposes, steels containing more than 0.04% Si can greatly affect the thickness and appearance of the galvanized coating. This will result in thick coatings consisting mainly Zn-Fe alloys, and the surface has a dark and dull finish. Nevertheless, it provides as much corrosion protection as a shiny galvanized coating where the outer layer is pure zinc.
Ta[(4)] (Tantalum)	Chemically similar to Nb (Cb) and has similar effects, such as having a similar effect on the alloy – Forms very hard, very small, simple carbides. Improves ductility, hardness, wear, and corrosion resistance. It is also a fine grain former that improves toughness.
Ti[(3),(4)] (Titanium)	Deoxidizing element. Ti when used in conjunction with boron (B) increases the effectiveness of the B in the hardenability of steel. Fine grain former which improves toughness. Also transforms sulfide inclusions form elongated to globular, improving strength and corrosion resistance as well as toughness and ductility.
V (vanadium)[(4)]	The addition (up to 0.05%) of vanadium (as an enhanced element) will result in an increase in the hardenability and/or strength of a low alloy steel. At greater than 0.05%, there may be a tendency of the steel to become embrittled during thermal stress relief treatments. V helps keep steel in the desirable fine grain condition after heat treatment. It also helps increase the depth of hardening and resists softening of the steel during tempering treatments, and induces secondary hardness on high speed steels. V is used in nitriding, heat resisting, tool and spring steels together with other alloying elements. It is also being utilized in ferrite/pearlite microalloy steels to increase hardness through carbonitride precipitation strengthening of the matrix. V decreases corrosion resistance in HIC or HF environment, and so V + Cb should be 0.03 or 0.1% and less, respectively. But the toughness and weldability will be decreased.
W[(4)] (tungsten)	W combines with the free carbides in steel during heat treatment, to produce high wear resistance with little or no loss of toughness due to promotion of fine grains. High amounts combined with Cr gives steel a property known as red hardness. This means that the steel will not lose its working hardness at high temperatures. An example of this would be tools designed to cut hard materials at high speeds, where the friction between the tool and the material would generate high temperatures.
Zr[(3)] Zirconium	Zr is added to steel to modify the shape of inclusions. Typically added to low alloy, low carbon steels. Deoxidizing element. The result is that toughness and ductility are improved when transforms shape from elongated to globular, improving toughness and ductility.

Notes: Source; ASM Metal Handbooks
(1)See Table 2.7 for characteristics of elements in welding of carbon and low alloy steel (CS and LAS)
(2)See Table 2.44 for characteristics of elements in welding of stainless steel (SS)
(3)Si, Al, Mn, Ti, Zr: Deoxidizer. See Sect. 2.1.4.1(b)
(4)Al, Ti, Ta, Nb (Cb), W, V: Fine grain former. See Sect. 2.1.4.1(b)

Table 2.6 (1/2) Effects of alloy elements on the heat treatment of Q-T alloy steels

	Effect of alloy on hardenability during quenching	Effect of alloy on tempering
B (boron)	B can considerably improve hardenability, the effect varying notably with C content of the steel. The full effect of B on hardenability is obtained only in fully deoxidized (Al-killed) steels.	B has no effect on the tempering characteristics of martensite, but a detrimental effect on toughness can result from the transformation to nonmartensitic products.
Cr (chromium)	Cr behaves much like Mo and has its greatest effect in medium-CS. In low-CS and carburized steel, the effect is less than in medium-CS, but is still significant. As a result of the stability of Cr carbide at lower austenitizing temperatures, Cr becomes less effective.	Cr, like molybdenum, is a strong carbide-forming element that can be expected to retard the softening of martensite at all temperatures. Also, by substituting Cr for some of Fe in cementite, the coalescence of carbides is retarded.
Cu (copper)	Cu is usually added to alloy steels for its contribution to atmospheric corrosion resistance and at higher levels for precipitation hardening. The effect of Cu on hardenability is similar to that of Ni, and in hardenability calculations it has been suggested that the sum of Cu plus Ni be used with the appropriate multiplying factor of Ni.	Copper is precipitated out when steel is heated to about 425–650 °C (800–1200 °F) and thus can provide a degree of precipitation hardening.
Mn (manganese)	Mn contributes markedly to hardenability, especially in amounts greater than 0.8%. The effect of Mn up to 1.0% is stronger in low- and high-CS than in medium-CS steels.	Mn increases the hardness of tempered martensite by retarding the coalescence of carbides, which prevent grain growth in the ferrite matrix. These effects cause a substantial increase in the hardness of tempered martensite as the percentage of Mn in the steel increases.
Mo (molybdenum)	Mo is most effective in improving hardenability. Mo has a much greater effect in high-CS than in medium-CS. The presence of Cr decreases the multiplying factor, whereas the presence of Ni enhances the hardenability effect of Mo.	Mo retards the softening of martensite at all tempering temperatures. Above 540 °C (1000 °F), Mo partitions to the carbide phase and thus keeps the carbide particles small and numerous. In addition, Mo reduces susceptibility to tempering embrittlement.
Ni (nickel)	Ni is similar to Mn at low alloy additions, but is less potent at the high alloy levels. Ni is also affected by C content, the medium-CS having the greatest effect. There is an alloy interaction between Mn and Ni that must be taken into account at lower austenitizing temperatures.	Ni has a relatively small effect on the hardness of tempered martensite, which is essentially the same at all tempering temperatures. Because Ni is not a carbide former, its influence is considered to be due to a weak solid solution strengthening.

Table 2.6 (2/2) Effects of alloy elements on the heat treatment of Q-T alloy steels

	Effect of alloy on hardenability during quenching	Effect of alloy on tempering
Si (silicon)	Si is more effective than Mn at low alloy levels and has a strengthening effect on LAS. However, at levels greater than 1% this element is much less effective than Mn. The effect of Si also varies considerably with C content and other alloys present. Si is relatively ineffective in low-CS but is very effective in high-CS.	Si increases the hardness of tempered martensite at all tempering temperatures. Si also has a substantial retarding effect on softening at 316 °C (600 °F), and has been attributed to the inhibiting effect of Si on the conversion of carbide to cementite.
V (vanadium)	V is usually not added for hardenability in Q-T structural steels (such as ASTM A678- D) but is added to provide secondary hardening during tempering. V is a strong carbide former, and the steel must be austenitized at a sufficiently high temperature and for a sufficient length of time to ensure that V is in solution and thus able to contribute to hardenability. Moreover, solution is possible only if small amounts of V are added.	V is a stronger carbide former than Mo and Cr and can therefore be expected to have a much more potent effect at equivalent alloy levels. The strong effect of V is probably due to the formation of an alloy carbide that replaces cementite-type carbides at high tempering temperatures and persists as a fine dispersion up to the *A*1 transformation temperature.
W (tungsten)	W has been found to be more effective in high-CS steel than in steels of low C content (<0.5%). Alloy interaction is important in W-containing steels, with Mn-Mo-Cr having a greater effect on the multiplying factors than Si or Ni additions.	W is also a carbide former and behaves like Mo in simple steels. W has been proposed as a substitute for Mo in reduced-activation ferritic steels for nuclear applications.
Others	Ti, Nb, and Zr are all strong carbide formers and are usually not added to enhance hardenability for the same reasons given for V. in addition, Ti and Zr are strong nitride formers, a characteristic that affects their solubility in austenite and hence their contribution to hardenability.	Ti, Nb, and Zr should behave like V because they are strong carbide formers.

Note: Source; ASM Metal Handbooks

Table 2.7 (1/2) Characteristics of elements in welding of carbon and low-alloy steel[(1),(2),(3)]

Elements	Characteristics (% = weight%)
Al (aluminum)	Deoxidizing element. Fine grain former. See Sect. 2.1.4.1(b) for more details of killing effects and Sect. 2.4.3.5 for more details of high temperature sulfidation environment. Normally the trace Al for deoxidizing in steel does not impact the weldability if the welding is controlled under deoxidizing condition.
B (boron)	Significantly increases the hardenability of steel without loss of ductility. Its effectiveness is most noticeable at lower carbon levels. The addition of B is usually in very small amounts ranging up to 0.003%. B has typically 5 times hardenability of carbon (C) on welds.
C (carbon)	Increases strength and hardness. Decreases corrosion resistance in cracking environment as well as weldability, so a C content of max.0.22~0.28% and/or C equivalent of max.0.42~0.45% is recommended. C also accelerates the solidification (hot) cracking during welding (see Sect. 4.2.7 for more detail). The term for carbon equivalent (Ceq and Pcm) in Sect. 4.4.1 is initiated from the C content.
Ca (calcium)	The ratio of Ca/S should be controlled in a range of 1.5–5.0 for HIC-resistant steel (Ca treatment) in sour service and the welding. Trace Ca does not impact the weldability.
Cr (chromium)	Cr is added to steel to increase resistance to oxidation and hydrogen attack. This corrosion resistance increases as more Cr is added. When added to low-alloy steels, Cr can increase the response to heat treatment, thus improving hardenability and strength. The hardenability of Cr is about 20% that of carbon. So, higher Cr in ferritic steels can be susceptible to weld crack unless higher preheating temperature is applied.
Cu (copper)	The hardenability of Cu is about 7% that of carbon. So, higher Cu in ferritic steels may be susceptible to weld crack due to somewhat increased Ceq.
Mn (manganese)	The hardenability of Mn is about 17% that of carbon (Sect. 4.4.1 for Ceq.). The ratio of Mn/S should be at least 10. Mn content of less than 0.30% may promote internal porosity and cracking in the weld bead, cracking can also result if the content is over 0.80%. Steel with low Mn/S ratio may contain S in the form of FeS, which can cause cracking (a "hot-short" condition) in the weld. So, higher Mn (up to 1.5% in weldable CS) in ferritic steels may be susceptible to weld crack unless higher preheating temperature is applied. Mn may contribute to retard the solidification (hot) cracking during welding (see Sect. 4.2.7 for more detail).
Mo (molybdenum)	Increases the hardness, slows the critical quenching speed, and increases high temperature tensile strength and corrosion resistance (high temperature attack). The hardenability of Mo is about 20% that of carbon (Sect. 4.4.1 for Ceq.). So, higher Mo in ferritic steels (i.e., Cr-Mo steels) may be susceptible to weld crack unless higher preheating temperature is applied.
Nb (niobium) or Cb (columbium)	Trace Nb does not impact weldability; however, it may increase the solidification (hot) cracking during welding (see Sect. 4.2.7 for more detail).
Ni (nickel)	Electrodes with high nickel content are used to weld cast iron materials. The hardenability of Ni is about 7% that of carbon. So, higher Ni in ferritic steels may be susceptible to weld crack due to somewhat increased Ceq.
P (phosphorous)	P additions (>0.04%) are known to increase the tendency to cracking during welding. The surface tension of the molten weld metal is lowered, making it difficult to control (hot cracking. See Sect. 4.2.7 for more detail). Max 0.05% for common requirement. Max 0.010~0.015% for HIC resistant steels.
S (sulfur)	Hot shortness is reduced by the addition of Mn, which combines with the S to form manganese sulfide (MnS). As MnS has a higher melting point than iron sulfide (FeS), which would form if Mn was not present, the weak spots at the grain boundaries are greatly reduced during hot working. S additions are known to increase the tendency of cracking during welding or on operation in HIC environment. To be controlled, the max amount is 0.002~0.008% for HIC-resistant or HF-resistant steels. Normally, every effort is made to reduce the S to the lowest possible level because it can create welding difficulties.

Table 2.7 (2/2) Characteristics of elements in welding of carbon and low-alloy steel(1),(2),(3)

Elements	Characteristics (% = weight%)
Si (silicon)	Increases the strength and elastic modulus while decreasing the toughness in 0.2–0.6%. Si is used as a deoxidizing (killing) agent in the melting of steel. Si contributes to hardening of the ferritic phase in steels and for this reason Si-killed steels are somewhat harder and stiffer than Al-killed steels. Coarse grain former. Can be substituted for aluminum for deoxidizing in hydrogen and sour service. Additional amounts of silicon are sometimes added to welding electrodes to increase the fluid flow of weld metal. Si is detrimental to surface quality on welds, especially in the low carbon, resulfurized grades. It aggravates cracking tendencies when the C content is fairly high. For best welding condition, Si content should not exceed 0.10%. However, amounts up to 0.30% are not as serious as high S or P content. The hardenability of Si is about 17% that of carbon (Sect. 4.4.1 for Ceq.). So, higher Si in ferritic steels may be susceptible to weld crack unless higher preheating temperature is applied. However, Si contributes to retard the solidification (hot) cracking during welding (see Sect. 4.2.7 for more detail).
Ti (titanium)	Ti, when used in conjunction with boron, increases the effectiveness of the B in the hardenability of steel. Trace Ti does not impact weldability in ferritic steels.
V (vanadium)	Increases strength (advanced Cr-Mo steels) and decreases toughness. V decreases corrosion resistance in HIC or HF environment, and so V + Cb should be 0.03% or 0.1% or less, respectively. The hardenability of V is about 20% that of carbon (Sect. 4.4.1 for Ceq.). So, higher V in ferritic steels (i.e., Cr-Mo steels) may be susceptible to weld crack unless higher preheating temperature is applied.

Notes: source; ASM Metal Handbooks, vol.1
(1)See Table 2.5 for general characteristics of elements in ferritic steels (wrought, cast, tools, etc.)
(2)The additional elements through the welding electrode, filler, and flux to a base metal may influence the crystalline form of the resultant alloy. The alloying element may also effect the crystalline changes by either suppressing the appearance of certain crystalline forms or even by creating entirely new forms. All these transformations induced by alloying elements are dependent on heat input and cooling rates. These factors are closely controlled at the steel mill, but since the welding operation involves a nonuniform heating and cooling of metal, special care is often needed in the welding of low- and high-alloy steel
(3)References of element effects for other alloys and crack susceptibility
See Sect. 4.4.1 for carbon equivalent
See Sect. 4.2.8 for solidification cracking of ASS
See Sect. 4.2.6 for lamellar tearing
See Table 2.75 for Copper-Based Alloys
See Sect. 4.2.7 for solidification cracking of CS
See Table 2.115, Figs. 2.112, 2.113, 2.114, 2.115, 2.116, 2.117, and 2.118 for low temperature toughness
See Sect. 4.11.3 for crack susceptibility of Cr-Mo LAS

Table 2.8 Types of commercial metals

Types	Examples	Characteristics
Code & standard materials(a)	ASTM, ASME, AISI, SAE, EN (BS, DIN, AFNOR), CSA, UNS, JIS & KS, etc.	Internationally certified and selected as per contraction spec.
Brand materials	Monel, Inconel, Incoloy, Hastelloy, Nimonic, Corten, etc.	1. Internationally certified with code materials or 2. Required UNS number (or others)
Pilot or patent materials	SX, ZeCor®, Saramet® (for H_2SO_4 service) or Safurex® (for ammonia service) by Edmeston and Sandvik, Dupont, Chemetics, and Sandvik respectively	To be used under the agreement between user and supplier

Note: (a)See ASTM DS67B Handbook, CASTI Metals Data Book Series, EPRI-Carbon Steel Handbook, and Stahlschlüssel, Verlag Stahlschlüssel Wegst GmbH for Conversion of World Steel Standards

Steel Numbers

As defined in EN10027–2, provide a numerical identification of steel composition, but not product form. They are based on the German "Werkstoff" numbering system.

1. X X Y Y

The number 1 denotes steel.

The next two numbers (**XX**) denote the principal characteristics of the steel. Examples are shown below:

XX	Characteristics
00	Base steel
01	General structural steels with Rm $\leq$ 500 N/mm^2
03	Steels with average carbon, C $\leq$ 0.12% or Rm $\leq$ 400 N/mm^2
04	Steels with average carbon, 0.12% < C $\leq$ 0.25% or 400 N/mm^2 < Rm $\leq$ 500 N/mm^2
05	Steels with average carbon, 0.25% < C $\leq$ 0.55% or 500 N/mm^2 < Rm $\leq$ 700 N/mm^2
43	Stainless steel Ni > 2.5%
44	Stainless steel Ni > 2.5% + Mo
48	Heat resistant stainless steel Ni > 2.5%

YY Denotes sequential number assigned by the standards committee.

Example: 1.4401 and 1.4404

The first two digits (44): Both materials are 316 SS.

The last two digits (01 or 04): Whilst both steels are similar, their alloy content is different, but does not define what the difference is. "01" is for regular carbon content (316 SS, C $\leq$ 0.08%) while "04" is for low carbon content (316L SS, C $\leq$ 0.03%).

2.1.1.7 UNS and AISI/SAE Numbering System

(a) UNS (United Numbering System) Numbers.

UNS consisting of a prefix letter (Table 2.9) and five digits designating is based on the chemical composition of the material. For example, a prefix of S indicates stainless steel alloys, C indicates copper, brass, or bronze alloys, T indicates tool steels, and so on. The first 3 digits often match older 3-digit numbering systems, while the last 2 digits indicate more modern variations. For example, 304 SS (austenitic stainless steel) in the original 3-digit system became C30400 in the UNS System. The UNS is managed jointly by ASTM International and SAE International. A UNS number alone does not constitute a full material specification because it establishes no requirements for material properties, heat treatment, form, or quality. See ASTM E527 Numbering Metals and Alloys (UNS) for a more detailed description (Table 2.10 below).

See Tables 2.47, 2.48, 2.49, 2.50, 2.51, 2.52, 2.53, 2.54, 2.55 and 2.56 for the UNS numbers of Stainless Steels.
See Tables 2.68, 2.70, 2.71, 2.72, and 2.73 for the UNS numbers of Nickel and Nickel-based alloys.
See Tables 2.74, 2.75, 2.76, and 2.77 for the UNS numbers of Copper and Copper-based alloys.
See Table 2.84 for the UNS numbers of Titanium and Titanium-based alloys.
See Table 2.87 for the UNS numbers of Zirconium and Zirconium-based alloys.
See Table 2.88 for the UNS numbers of Tantalum and Tantalum-based alloys.

(b) AISI/SAE Numbers

An "H" suffix can be added to any designation to denote hardenability is a major requirement. The chemical requirements are loosened but hardness values are defined for various distances on a Jominy test.

Table 2.11 shows the major classes of AISI/SAE steels. Table 2.12 shows the grades of carbon and alloy steel of AISI/SAE.

Reference Codes (ASTM) for Classes of AISI/SAE

ASTM A29 Standard Specification for Steel Bars, Carbon and Alloy, Hot-Wrought, General Requirements
ASTM A304 Standard Specification for Carbon and Alloy Steel Bars Subject to End-Quench Hardenability Requirements
ASTM A311 Standard Specification for Cold-Drawn, Stress-Relieved Carbon Steel Bars Subject to Mechanical Property Requirements
ASTM A322 Specification for Steel Bars, Alloy, Standard Grades

Table 2.9 Alphabet prefixes used in UNS

Prefix	Alloy series	Remark
A	Aluminum and aluminum-based alloys	Nonferrous metals and alloys
C	Copper and copper-based alloys	Nonferrous metals and alloys
D	Steels with specified mechanical properties (not used)	Ferrous metals and alloys
E	Rare earth and similar metals and alloys	Nonferrous metals and alloys
F	Cast irons	Ferrous metals and alloys
G	AISI and SAE carbon and alloy steels	Ferrous metals and alloys
H	AISI and SAE H-steels	Ferrous metals and alloys
J	Cast steels (except tool steels)	Ferrous metals and alloys
K	Miscellaneous steels and ferrous alloys	Ferrous metals and alloys
L	Low melting metals and alloys	Nonferrous metals and alloys
M	Miscellaneous nonferrous metals and alloys	Nonferrous metals and alloys
N	Nickel and nickel-based alloys	Nonferrous metals and alloys
P	Precious metals and alloys	Nonferrous metals and alloys
R	Reactive and refractory metals and alloys R03xxx- molybdenum-based alloys R04xxx- niobium (columbium)-based alloys R05xxx- tantalum-based alloys R3xxxx- cobalt-based alloys R5xxxx- titanium-based alloys R6xxxx- zirconium-based alloys	Nonferrous metals and alloys
S	Heat and corrosion resist steels (including stainless), valve steels, and iron-based "Superalloys"	Ferrous metals and alloys
T	Tool steels, wrought, and cast	Ferrous metals and alloys
W	Welding filler metals	Specialized metals and alloys
Z	Zinc and zinc-based alloys	Nonferrous metals and alloys

Table 2.10 Secondary divisions of some series of UNS numbers

UNS numbers	Metals and alloys	UNS numbers	Metals and alloys
E00001–E99999 rare earth and rare earth-like metals and alloys		**L00001–L99999 low-melting metals and alloys**	
E00000–E00999	Actinium (Ac)	L00001–L00999	Bismuth (Bi)
E01000–E20999	Cerium (Ce)	L01001–L01999	Cadmium (Cd)
E21000–E45999	Mixed rare earths[A]	L02001–L02999	Cesium (Cs)
E46000–E47999	Dysprosium (Dy)	L03001–L03999	Gallium (Ga)
E48000–E49999	Erbium (Er)	L04001–L04999	Indium (In)
E50000–E51999	Europium (Eu)	L05001–L05999	Lead (Pb)
E52000–E55999	Gadolinium (Gd)	L06001–L06999	Lithium (Li)
E56000–E57999	Holmium (Ho)	L07001–L07999	Mercury (Hg)
E58000–E67999	Lanthanum (La)	L08001–L08999	Potassium (K)
E68000–E68999	Lutetium (Lu)	L09001–L09999	Rubidium (Rb)
E69000–E73999	Neodymium (Nd)	L10001–L10999	Selenium (Se)
E74000–E77999	Praseodymium (Pr)	L11001–L11999	Sodium (Na)
E78000–E78999	Promethium (Pm)	L12001–L12999	Thallium (Tl)
E79000–E82999	Samarium (Sm)	L13001–L13999	Tin (Sn)
E83000–E84999	Scandium (Sc)	**M00001–M99999 miscellaneous nonferrous metals and alloys**	
E85000–E86999	Terbium (Tb)	M00001–M00999	Antimony (Sb)
E87000–E87999	Thulium (Tm)	M01001–M01999	Arsenic (As)
E88000–E89999	Ytterbium (Yb)	M02001–M02999	Barium (Ba)
E90000–E99999	Yttrium (Y)	M03001–M03999	Calcium (Ca)
R00001–R99999 reactive and refractory metals and alloys		M04001–M04999	Germanium (Ge)
R01001–R01999	Boron (B)	M05001–M05999	Plutonium (Pu)
R02001–R02999	Hafnium (Hf)	M06001–M06999	Strontium (Sr)
R03001–R03999	Molybdenum (Mo)	M07001–M07999	Tellurium (Te)
R04001–R04999	Niobium (Columbium)	M08001–M08999	Uranium (U)
R05001–R05999	Tantalum (Ta)	M10001–M19999	Magnesium (Mg)
R06001–R06999	Thorium (Th)	M20001–M29999	Manganese (Mn)
R07001–R07999	Tungsten (W)	M30001–M39999	Silicon (Si)
R08001–R08999	Vanadium (V)	**P00001–P99999 precious metals and alloys**	
R10001–R19999	Beryllium (Be)	P00001–P00999	Gold (Au)
R20001–R29999	Chromium (Cr)	P01001–P01999	Iridium (Ir)
R30001–R39999	Cobalt (Co)	P02001–P02999	Osmium (Os)
R40001–R49999	Rhenium (Re)	P03001–P03999	Palladium (Pd)
R50001–R59999	Titanium (Ti)	P04001–P04999	Platinum (Pt)
R60001–R69999	Zirconium (Zr)	P05001–P05999	Rhodium (Rh)
		P06001–P06999	Ruthenium (Ru)
		P07001–P07999	Silver (Ag)

UNS numbers	Metals and alloys
W00001–W99999 welding filler metals classified by weld deposit composition	
W00001–W09999	Carbon steel with no significant alloying elements
W10000–W19999	Manganese-molybdenum low alloy steels
W20000–W29999	Nickel low alloy steels
W30000–W39999	Austenitic stainless steels
W40000–W49999	Ferritic stainless steels
W50000–W59999	Chromium low-alloy steels
W60000–W69999	Copper-based alloys
W70000–W79999	Surfacing alloys
W80000–W89999	Nickel-based alloys

Source: UNS
[A]Alloys in which the rare earths are used in the ratio of their natural occurrence (i.e., unseparated rare earths). In this mixture, cerium is the most abundant of the rare earth elements

Table 2.11 Major classifications of AISI/SAE steels

AISI/SAE designation	Material group
1xxx	Carbon steels
2xxx	Nickel steels
3xxx	Nickel-chromium steels
4xxx	Molybdenum steels
5xxx	Chromium steels
6xxx	Chromium-vanadium steels
7xxx	Tungsten steels
8xxx	Nickel-chromium-molybdenum steels
9xxx	Silicon-manganese steels

Source: AISI/SAE

ASTM A400 Practice for Steel Bars, Selection Guide, Composition, and Mechanical Properties

ASTM A434 Specification for Steel Bars, Alloy, Hot-Wrought or Cold-Finished, Quenched and Tempered

ASTM A575 Specification for Steel Bars, Carbon, Merchant Quality, M (Merchant)-Grades

ASTM A576 Specification for Steel Bars, Carbon, Hot-Wrought, Special Quality

2.1.1.8 Locations of Materials Data in ASME Sec. VIII, Div. 1 and Sec. II (Table 2.13)

2.1.1.9 Temperature Limitation of Metal for Pressure Component (Typical)

Table 2.14 shows a general guideline for temperature limits of pressure boundary materials in hydrocarbon handling service (noncorrosive condition). All notes should be also applied carefully.

2.1.1.10 Temperature Limitation in Use of Metals in Several Codes and Standards

Table 2.15 shows the temperature limitation in ASME Section VIII and B31.3.

In addition, Table 2.16 shows the limits in service temperatures of nickel-based alloys as nonmandatory appendix-ASME Sec. II, Part D. Nickel combines with sulfur at elevated temperatures to form a brittle sulfide (Sulfur Embrittlement). This phenomenon takes place preferentially at the grain boundaries, and results in embrittlement that exhibits itself as a network of cracks when the material is stressed or bent. Nickel is affected most, Ni-Cu somewhat less, and Ni-Cr-Fe still less. Table 4.95 lists the limiting service temperatures of nickel based welding electrodes in sulfur and nonsulfur environments. The more sulfur present or the higher the temperature, the more rapid and deep will be the attack. When the material has been sulfur embrittled, it cannot be salvaged, and then be scrapped.

API 618 (Reciprocating Compressors) states the following requirements and cautions for materials. Some commentary notes are included.

Table 2.12 Grades of carbon and alloy steel (AISI/SAE)

Material group	AISI/SAE designation	Material type
Carbon steels	10xx	Plain carbon (Mn 1.00% max.)
	11xx	Resulfurized
	12xx	Resulfurized and rephosphorized
	15xx	Plain carbon (Mn 1.00–1.65%)
Mn steels	13xx	Mn 1.75%
Ni steels	23xx	Ni 3.50%
	25xx	Ni 5.00%
Ni-Cr steels	31xx	Ni 1.25%; Cr 0.65% or 0.80%
	32xx	Ni 1.25%; Cr 1.07%
	33xx	Ni 3.50%; Cr 1.50% or 1.57%
	34xx	Ni 3.00%; Cr 0.77%
Mo steels	40xx	Mo 0.20%, 0.25%, or Mo 0.25% and S 0.042%
	44xx	Mo 0.40%, or 0.52%
Cr-Mo steel	41xx	Cr 0.50%, 0.80%, or 0.95%; Mo 0.12%, 0.20%, 0.25%, or 0.30%
Ni-Cr-Mo steels	43xx	Ni 1.82%; Cr 0.50–0.80%; Mo 0.25%
	43BVxx	Ni 1.82%; Cr 0.50%; Mo 0.12%, or 0.35%; V 0.03% min
	47xx	Ni 1.05%; Cr 0.45%; Mo 0.20%, or 0.35%
	81xx	Ni 0.30%; Cr 0.40%; Mo 0.12%
	81Bxx	Ni 0.30%; Cr 0.45%; Mo 0.12%; and added boron
	86xx	Ni 0.55%; Cr 0.50%; Mo 0.20%
	87xx	Ni 0.55%; Cr 0.50%; Mo 0.25%
	88xx	Ni 0.55%; Cr 0.50%; Mo 0.35%
	93xx	Ni 3.25%; Cr 1.20%; Mo 0.12%
	94xx	Ni 0.45%; Cr 0.40%; Mo 0.12%
	97xx	Ni 0.55%; Cr 0.20%; Mo 0.20%
	98xx	Ni 1.00%; Cr 0.80%; Mo 0.25%
Ni-Mo steels	46xx	Ni 0.85%, or 1.82%; Mo 0.20%, or 0.25%
	48xx	Ni 3.50%; Mo 0.25%
Cr steels	50xx	Cr 0.27%, 0.40%, 0.50%, or 0.65%
	50xxx	Cr 0.50%; C 1.00% min
	50Bxx	Cr 0.28%, or 0.50%; and added boron
	51xx	Cr 0.80%, 0.87%, 0.92%, 1.00%, or 1.05%
	51xxx	Cr 1.02%; C 1.00% min.
	51Bxx	Cr 0.80%; and added boron
Cr-V steel	61xx	Cr 0.60%, 0.80%, 0.95%; V 0.10%, or 0.15% min.
W-Cr steels	72xx	W 1.75%; Cr 0.75%
Si-Mn steels	92xx	Si 1.40%, or 2.00%; Mn 0.65%, 0.82%, or 0.85%; Cr 0.00%, or 0.65%
High strength low alloy steels	9xx	Various SAE grades
	xxBxx	Boron steels
	xxLxx	Leaded steels

Source: AISI/SAE

Table 2.13 Locations of materials data in ASME Sec. VIII, Div. 1 and Sec. II

Material	Covering code part	Applicable stress value location	Remarks
Carbon and low-alloy steels	UCS	Sec. II, Part D, Table 1A	• Basis for establishing stress values – Appendix P, UG-23 • Low-temperature service requires use of notch-tough materials; UCS-65, UCS-66, UCS-67, UCS-68, UG-84, Figure UCS-66 & UCS-66.1 • Corrosion allowance; UCS-25 • In high-temperature operation, creep strength is essential • Design temperature; UG-20 • Design pressure; UG-21, footnote. 8 • Temperature above 427 °C (800 °F) may cause carbide phase of carbon steel to convert to graphite • Pipe and tubes – UG-8, UG-10, UG-16, UG-31, UCS-9, UCS-27 • Creep and rupture properties – UCS-151, sec.II part D-appendix A-200
Nonferrous metals	UNF	Sec. II, Part D, Table 1B	• Basis for establishing values – Appendix P, UG-23 • Metal characteristics – UNF, appendix NF, NF-1 to NF-14 • Low-temperature operation – UNF-65 • Nonferrous castings – UNF-8
High-alloy steels	UHA	Sec. II, Part D, Table 1A	• Selection and treatment of ASS – UHA-11, UHA appendix HA, UHA-100 to UHA-109 • Inspection and tests – UHA-34, UHA-50, UHA-51, UHA-52 • Liquid penetration test required if shell thickness > ¾" – All 36% nickel steel welds – UHA-34 • Low temperature service – UHA-51, UG-84
Castings	UG, CS, UHA	UCI-23	• High alloy castings – UHA-8, UG-7, UG-11, UG-24, UCS-8, appendix 7
Cast iron	UCI, UG	UCI-23	• Vessel not permitted to contain lethal or flammable substance – UCI-2 • Selection materials – UCI-1/3/5/12, UG-10/11, UCS 10/11 • Inspection and tests – UCI-90, UCI-99, UCI-101, UCI-3 • Repairs in cast iron materials – UCI-78
Dual cast iron	UCI	UCI-23	• Repairs in cast iron materials – UCI-1, UCI-23, UCI-29
Integrally clad plate, weld metal overlay, or applied linings	UCL	UCL-11, UCL-23	• Suggest careful study of entire metal UCL section • Selection of materials – UCL-1, UCL-3, UCL-10, UCS-5, UF-5, ULW-5, UCL-11, UCL-12, UG-10 • Qualification of welding procedure – UCL-40 to 46 • PWHT – UCL-34, UCS-56 (including footnote) • Inspection and test – UCL-50 to 52 • Spot RT required if cladding is included in calculated required thickness – UCL-23(c) • Use of linings – UG-26 and Appendix F
Welded and seamless pipe and tubes (CS and LAS)	UCS	Sec. II, Part D, Table 1A	• Thickness under internal pressure – UG-27 • Thickness under external pressure – UG-28 • Provide additional thickness when tubes are threaded and when corrosion, erosion, or wear caused by cleaning is expected – UG-31. • For calculating thickness required, minimum pipe wall thickness is 87.5% of nominal wall thickness • 30 inch maximum on welded pipe made by pen-hearth, basic oxygen, or electric furnace process – USC-27
Welded and seamless pipe (HAS)	UHA	Sec. II, Part D, Table 1A	• See the frailties of stainless steels – Sect. 2.1.5
Forgings		Sec. II, Part D, Table 1A	• Materials – UG-6, UG-7, UG-11, UF-6, UCS-7 and Sec. II, Part D, Table 1A • Welding – UF-32, and Sec. IX, QW-250 and variables. QW-404.12, QW-406.3, • QW-407.2, QW-409.1 when welding forgings
Low temperature materials	ULT	Table ULT-23	• Operation at very low temperatures, requires use of notch-tough materials • Table ULT-82: Min. T.S requirements for WPQ
Layered construction	ULW		• Vessels having a shell/heads made up of two or more separate layers – ULW-2
Ferrite steels with tensile properties enhanced by heat treatment	UHT		• Scope – UHT-1 • Marking on plate or stamping, use "low temperature" stamps – UHT-86

Table 2.14 Temperature limits of pressure boundary materials (noncorrosive)[a]

	Plates			Pipes/tubes		Forgings		Wrought pipe fittings		Castings	
Design temp., T °C (°F)	Thickness including corr. allow. mm	ASTM spec no.	Grade	ASTM spec no.	Grade	ASTM spec no.	Grade	ASTM spec no.	Grade	ASTM spec no.	Grade
−254 (−425) ≤ T < −196 (−320)	All	A240	304(L)	A312	TP304(L)	A182	F304(L)	A403	WP304 (L)	A351 A744[u]	All
−196 (−320) ≤ T < −101 (−150)[z]	All	A240	304(L) 316(L)	A312	TP304(L), 316(L)	A182	F304(L), 316(L)	A403	WP304 (L), 316(L)	A351 A744[u]	All
−196 (−320) ≤ T < −101 (−150)	Over 13–50	A353[k] A553[L]	(9Ni) I (9Ni)	A333	8 (9Ni)	A522	I (9Ni)	A420	WPL8 (9Ni)	A352	LC9 (9Ni)
−101 (−150) ≤ T < −46 (−50)[w]	All	A203[q]	D, E (3.5Ni)	A333	3 (3.5Ni)	A350 A765	LF3 (3.5Ni) III (3.5Ni)[t]	A420[t]	WPL3 (3.5Ni)	A352	LC3 (3.5Ni), LC4 (4.5Ni)[P]
−46 (−50) ≤ T < −29 (−20)[x]	All	A516[d]	55, 60 65, 70	A333[r] A334	1, 6 1, 6	A350 A765	LF2-cl.1 II	A420	WPL6	A352	LCB[b], LCC[b], LC1[P], LC2 (2.25Ni)[P], CA6NM (4Ni-13Cr)
−29 (−20) ≤ T < 18 (65)				A106[e] A53[e]	B B	A105[e, g] A266[e, g]	Gr. 1 to 4[n]	A234[c, e]	WPB	A352 A216[f, j]	LCA[V] WCB, WCC
18 (65) ≤ T	19 & under	A285[d, i]	C			A765	I & IV				
≤ 427 (800)[y]	All	A516[d, e]	55, 60 65, 70								
427 (800) < T ≤ 482 (900)[y]	All	A204 A302[h]	A, B[aa] A, B	A335[h]	P1[aa]	A182/ A336[h]	F1[aa]	A234[h]	WP1[aa]	A217[h]	WC1[aa]
427 (800) < T ≤ 649 (1200)[y]	All	A387 Normal-Temp.[h]	11, 12° 22	A335[h]	P11, P12° P22	A182 A336[h]	F11, 12° F22	A234[h]	WP11, WP12[O] WP22	A217[h]	WC6° WC9
649 (1200) < T ≤ 816 (1500)[y]	All	A-240[h]	304H, 321(H), 347(H)	A312[m] A358[h]	TP304H, 321(H), 347(H)	A182 A336[h]	F304H 321(H), 347(H)	A403[h]	WP304H, 321(H), 347(H)	A351 A744[h]	8, CF8C, CF8M, CF8

Notes (All temperatures in these notes indicate design temperature and/or MDMT/DMT)

[a](1) All recommended steel materials are based on the safety, economic cost, and commonly used industrial practice only for material selection. If the material is welded by inadequate welding process or cold/hot formed without following adequate heat treatment, the final products may show premature failure in the recommended temperature range

(2) All recommended materials are not considered under the specific service condition, such as corrosion, erosion, fatigue, weldability, physical properties (magnetic, thermal conductivity, electric conductivity, permeability, specific gravity, specific heat, etc.), mechanical/metallurgical properties (strength, elongation, thermal expansion coeff., hardenability, malleability, etc.)

(3) Alternative materials, such as EN, BS/ISO, DIN, JIS, etc., or unspecified materials above may be used by approval of a responsible metallurgist

(4) All materials in low temperature shall meet the requirements (e.g., impact test for base metal/welds) in the applicable codes

(5) See Sect. 2.6.2 for Nickel-based alloys in elevated temperature [>427 °C (800 °F)]

(6) See Appendix A for Low Temperature Requirements, including Impact Tests in ASME

(7) See ASTM A20, Table A1.15 and A2.15 for Generally Available Grade-Thickness-Minimum Test Temperature Combinations Meeting CVN Impact Test Requirements Indicated (Normalized or Quenched and Tempered Condition)

(8) See the following paragraphs of tables for the temperature limitations per metal shape/products/equipment

- Section 2.6.2.1 for several ASTM materials of plates and strips
- Section 2.6.2.2(1) for several ASTM materials of pipes and tubes
- Section 2.6.2.2(2) for several ASTM materials of heat exchanger tubes
- Section 2.6.2.3 for several ASTM materials of fired heaters/boiler tubes
- Section 2.6.2.4 for several ASTM materials of forged and wrought
- Section 2.6.2.5 for several ASTM materials of castings
- Section 2.6.2.6 for several ASTM materials of bolting materials
- Section 2.6.2.6 Note 7 for bolting materials in low/cryogenic service
- Section 2.6.2.7 for insulation/refractory materials
- Table 2.17 Temperature Limitation of API 617 (Centrifugal Compressors)

[b]Use of ASTM A352-LCB/LCC is preferred at −20 °C (−4 °F) and warmer as a good engineering practice

[c]Carbon steel fittings made from plate shall be made with ASTM A516 material

[d]If carbon steel is specified for small diameter pressure vessels and heat exchanger shell, ASTM A106 Gr. B or A333–6 [at 300 °C (573 °F) and colder] seamless pipes may be used

[e]The materials should not be used at 399 °C (750 °F) and warmer unless approved by a responsible metallurgist

[f]ASTM A278-WCB, Cl. 40–60 (gray iron casting) may be used at 343 °C (650 °F) and colder

[g]The impact test of these metals at −20 °C (−4 °F) and colder may not be readily passed when the thickness is 2″ and above. LTCS (low temperature CS, e.g., ASTM A350-LF2-Cl.1) may be a better choice in this case if the supplier does not have successful experience
[h]Nickel or Cobalt alloys may be also considered as an alternative
[i]To be used at 343 °C (650 °F) and colder. It may be used at −16 °C (3 °F) and warmer if the impact test is passed
[j]Ductile iron (D.I., such as ASTM A395/A536) may be also used at 343 °C (650 °F) and colder
[k]Double Normalized-Tempered and max. 50 mm (2 inch) thickness
[l]Quenched-Tempered and max. 50 mm (2 inch) thickness
[m]ASTM A358 instead of ASTM A312-welded is preferable for a thickness of 1/2 inch and above because of limited commercial market
[n]When selecting Gr.3 (SMTS = 75-100ksi), consult with a responsible metallurgist
[o]Grades 11 and 12, WP6 (1.0–1.25Cr steel) should be used at 593 °C (1100 °F) and colder unless approved by a responsible metallurgist
[p]LC1 (0.5Mo): at −59 °C (−74 °F) and warmer, LC2 (2.5 Ni): at −73 °C (−99 °F) and warmer, LC4 (4.5Ni): at −115 °C (−175 °F) and warmer if the impact test is passed
[q]ASTM A537-Cl.1 (N) & 2 (Q-T) may be used at −62 °C (−80 °F) and warmer and − 68 °C (−90 °F) and warmer respectively per class, thickness, and impact test results of applicable code or standard
[r]ASTM A671 (ERW Pipe) may be used when the mother plate material meets the impact test requirements per codes
[s]ASTM A420-Gr.WPL9 (2.0Ni steel) may be used at −75 °C (−100 °F) and warmer if the impact test is passed
[t]ASTM A765-Gr.V (1.5 Ni steel) may be used at −60 °C (−75 °F) and warmer if the impact test is passed
[u]ASTM A743-Gr.CF3, CF8, CF8M may be also used
[v]ASTM A352-Gr.LCA shall be used at −32 °C (−25 °F) and warmer
[w]Use of 3.5 Ni steel may not be recommended. See Table 3, Note 4 for a more detailed background
[x]Pressure vessel code (ASME Sec.VIII) allows to use at −48 °C (−55 °F) and warmer per thickness and material quality for carbon steel at low temperature. See Table 2.14 (a), Note (4) for MDMT/DMT limits of LTCS (low temperature carbon steel)
[y]The high temperature creep-rupture strength calculation should be considered for the design life if the maximum operating temperature is above the threshold temperature of each material in Table 1.68, 1.69, and 1.70
[z]–196 °C (−320 °F) ≤ T < −46 °C (−50 °F) is recommended due to good weldability, constructability, and maintainability
[aa]C-0.5Mo steel shall not be used for high-temperature hydrogen attack (HTHA) environments. See API RP941 & TR941 for more details

Table 2.15 (1/3) Temperature limitation of ASME materials (*noncorrosive service*)

※ *Only for quick access as design temperature Please refer ASME Sec.II Part D code for a more detailed application*

Materials	Oxidizing scaling temperature in air (37)		Temperature limitation of materials in ASME code, up to add. 2010 "–": not listed						Remark (note)
			Sec. VIII, Div. 1		Sec. VIII, Div.2 (24)		ASME B 31.3		
	°C	°F	°C	°F	°C	°F	°C	°F	
C.I	400	752	−29~343	−20~650	Not listed	Not listed	−29~343	−20~650	(1)
C.S	400	752	−46~538	−50~1000	−46~371	−50~700	−46~538	−50~1100	(1)(2)(3)(4)(23)
1 Cr-0.5Mo (27)	566	1050	−46~649	−50~1200	−46~371	−50~700	−29~649	−20~1200	(2)(6)
1.25Cr-0.5Mo (27)	566	1050	−46~649	−50~1200	−46~482	−50~900	−29~649	−20~1200	(2)(6)(26)
2.25Cr-1Mo (27)	580	1075	−46~649	−50~1200	−46~482	−50~900	−29~649	−20~1200	(2)
3Cr-1Mo (27)	621	1150	−46~649	−50~1200	−46~454	−50~850	−29~649	−20~1200	(2)
5Cr-0.5Mo (27)	621	1150	−46~649	−50~1200	−46~454	−50~850	−29~649	−20~1200	(2)
9Cr-1Mo	650	1200	−46~649	−50~1200	−46~371	−50~700	−29~649	−20~1200	(2)
2.25 Ni	538	1000	−73~550 (28)	−100~1022 (28)	−73~550 (29)	−100~1022 (29)	−73~593	−100~1100	
3.5 Ni	538	1000	−101~375 (30)	−150~707 (30)	−101~375 (31)	−150~707 (31)	−101~593	−150~1100	(7)
9 Ni	538	1000	−196~121	−320~250	−196~121	−320~250	−196~93	−320~200	
12Cr (410 SS)	760	1400	−29~649	−20~1200	−29~649	−20~1200	–	–	(8)
12Cr (410S SS)	760	1400	−29~649	−20~1200	−29~649	−20~1200	–	–	(8)
13Cr (405 SS)	760	1400	−29~649	−20~1200	−29~649	−20~1200	–	–	(8)
12Cr/ CA15 (J91150)	760	1400	−29~649	−20~1200	−29~371	−20~700	−29~649	−20~1200	(8)
13Cr-4Ni (CA6NM)	830	1525	−29~427	−20~800	−29~371	−20~700	−29~371	−20~700	(8)
17Cr (430 SS)	845	1550	−29~649	−20~1200	−29~649	−20~1200	−29~649	−20~1200	(8)
17–4 PHSS(S17400)	845	1550	−29~93	−20~200	–	–	–	–	(5)
17–7 PHSS(S17700)	845	1550	−29~ − 38	−20~100	–	–	–	–	(5)
304 SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−254~816	−425~1500	
304L SS	899	1650	−196~427	−320~800	−196~427	−320~800	−254~816	−425~1500	
304H SS (15)	899	1650	−196~816	−320~1500	−196~816	−320~1500	−198~816	−325~1500	(11)
309(S) SS (15)	1093	2000	−196~816	−320~1500	−196~816	−320~1500	−198~816	−325~1500	(12)(13)(17)
309H(Cb) SS (15)	1093	2000	−196~816	−320~1500	−196~816	−320~1500	–	–	
310 SS (15)	1150	2100	−196~816	−320~1500	−196~816	−320~1500	−198~816	−325~1500	(14)

Table 2.15 (2/3) Temperature limitation of ASME materials (*noncorrosive service*)

※ *Only for quick access as design temperature Please refer ASME Sec.II Part D code for a more detailed application*

Materials	Oxidizing scaling temperature in air (37)		Temperature limitation of materials in ASME code, up to add. 2010 "–": not listed						Remark (note)
			Sec. VIII, Div. 1		Sec. VIII, Div.2 (24)		ASME B 31.3		
	°C	°F	°C	°F	°C	°F	°C	°F	
316SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−254~427	−425~800	
316L SS	899	1650	−196~454	−320~850	−196~427	−320~800	−254~816	−425~1500	
316H SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−198~816	−325~1500	
316Ti SS (15)	899	1650	−196~816	−320~1500	–	–	Not listed	–	
317 SS (15)	899	1650	−196~816	−320~1500	−196~816	−320~1500	−198~816	−325~1500	
317L SS	899	1650	−196~454	−320~850	−196~454	−320~850	−198~454	−325~850	
321 SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−198~816	−325~1500	
321H SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−198~816	−325~1500	
347 SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−254~816	−425~1500	
347H SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−198~816	−325~1500	18Cr-10Ni, high C
348 SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−198~816	−325~1500	18Cr-10Ni, Cb
348H SS (15)	899	1650	−196~816	−320~1500	−196~427	−320~800	−198~816	−325~1500	18Cr-10Ni, high C
2205 DSS	1038	1900	−29~316	−20~600	Not listed	Not listed	−51~316	−60~600	22Cr-5Ni-3Mo-N (38)
2507 DSS	1038	1900	−29~316	−20~600	Not listed	Not listed	−51~316	−60~600	25Cr-7Ni-4Mo-N (38)
254 SMO	982	1800	−196~399	−320~750	Not listed	Not listed	Not listed	Not listed	20Cr-18Ni-6Mo
654 SMO (16)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	24Cr-22Ni-7.3Mo-3Mn
Alloy 20-mod	982	1800	−198~427	−325~800	Not listed	Not listed	−198~427	−325~800	22Cr-26Ni-5Mo
Alloy 20 Cb-3	982	1800	−198~427	−325~800	Not listed	Not listed	−198~427	−325~800	20Cr-35Ni-2.5Mo
Alloy AL-6XN	982	1800	−198~427	−325~800	Not listed	Not listed	−198~427	−325~800	21Cr-24Ni-6Mo
Alloy 904L	982	1800	−198~371	−325~700	Not listed	Not listed	Not listed	Not listed	21Cr-25Ni-5Mo
Alloy 200	982	1800	−198~316	−325~600	−198~316	−325~600	−198~316	−325~600	99Ni
Alloy 201	982	1800	−198~649	−325~1200	−198~427	−325~800	−198~649	−325~1200	99Ni, low carbon
Alloy 400	538	1000	−198~482	−325~900	−198~427	−325~800	−198~482	−325~900	67Ni-30Cu
Alloy R405	538	1000	−198~482	−325~900	−198~427	−325~800 (33)	–	–	63Ni-30Cu-2Fe
Alloy K-500 (N05500)	538	1000	−198~260	−325~500	–	–	–	–	67Ni-28Cu-3Al (32)
Alloy 800	1038	1900	−198~816	−325~1500	−198~816	−325~1500	−198~816	−325~1500	21Cr-33Ni-42Fe, Al, Ti, Cu
Alloy 800H/HT	1038	1900	−198~899	−325~1650	−198~899	−325~1650	−198~899	−325~1650	21Cr-33Ni-42Fe, Al, Ti, Cu
Alloy 825	1038	1900	−198~538	−325~1000	−198~427	−325~800	–	–	22Cr-42Ni-3Mo, Ti
Alloy X	1205	2200	−198~899	−325~1650	−198~427	−325~800	−198~816	−325~1500	22Cr-47Ni-9Mo
Alloy C-22	1038	1900	−198~427	−325~800	–	–	−198~427	−325~800	22Cr-58Ni-13Mo-3W
Alloy C-4	1038	1900	−198~427	−325~800	−198~427	−325~800	−198~427	−325~800	16Cr-61Ni-16Mo
Alloy C-276	1150	2100	−198~677	−325~1250	−198~427	−325~800	−198~677	−325~1250	15Cr-54Ni-16Mo-4W
Alloy G-30	>1093	>2000	−198~427	−325~800	–	–	–	–	29Cr-40Ni-15Fe-5Mo
Alloy B-2	760	1400	−198~427	−325~800	−198~427	−325~800	−198~427	−325~800	65Ni-28Mo-Fe
Alloy 686 (N06686)	1150	2100	−198~427	−325~800	–	–	–	–	58Ni-21Cr-16Mo-4W
Alloy 600	1038	1900	−198~649	−325~1200	−198~427	−325~800	−198~649	−325~1200	15Cr-72Ni-8Fe
Alloy 601 (N06601)	1038	1900	−198~899	−325~1650	–	–	–	–	60Ni-23Cr-12Fe
Alloy 625 (N06625)	1038	1900	−198~649	−325~1200	–	–	−198~649	−325~1200	22Cr-60Ni-9Mo-4Cb, $C < 0.10$
Alloy 625LCF (N06626)	1038	1900	–	–	–	–	–	–	22Cr-60Ni-9Mo-4Cb, $C < 0.03$
Alloy G-3 (N06985)	982	1800	−198~427	−325~800	–	–	–	–	22Cr-47Ni-20-7Mo-2Cu, Co < 5
Alloy 718 (N07718)	982	1800	−198~621 (9)	−325~1150 (9)	−198~427 (9)	−325~800 (9)	–	–	19Cr-52Ni-5(Cb + Ta)-3Mo-1Ti (10)
Inhibited admiralty brass	705	1300	−198~232	−325~450	−198~260	−325~500	–	–	71Cu-28Zn-1Sn

Table 2.15 (3/3) Temperature limitation of ASME materials (*noncorrosive service*)

※ *Only for quick access as design temperature Please refer ASME Sec.II Part D code for a more detailed application*

Materials	Oxidizing scaling temperature in air (37)		Temperature limitation of materials in ASME code, up to add. 2010 "–": not listed						Remark (note)
			Sec. VIII, Div. 1		Sec. VIII, Div.2 (24)		ASME B 31.3		
	°C	°F	°C	°F	°C	°F	°C	°F	
Naval brass	705	1300	−198~204	−325~400	−198~38	−325~100	−269~204	−452~400	60Cu-40Zn
Al bronze			−198~316	−325~600	−198~260	−325~500	−269~316	−452~600	90Cu-5Al(-3Fe),Sn
Ni-Al bronze			−198~371	−325~700	–	–	−269~260	−452~500	81Cu-10Al-3Fe-5Ni
90/10 Cu/Ni			−198~316	−325~600	−198~232	−325~450	−269~316	−452~600	
70/30 Cu/Ni			−198~371	−325~700	−198~343	−325~650	−269~371	−452~700	
Aluminum			−269~204(22)	−452~400(22)	−269~149	−452~300	−269~204	−452~400	(33)
Ni-resist D-2	760	1400	–	–	–	–	–	–	20Ni-2Cr (18)(19)
Tantalum	260	500	–	–	–	–	–	–	(20)(36)
Titanium	427/649	800/1200	−59~316	−75~600	−59~316	−75~600	−59~316	−75~600	(21)(34)
Zirconium	538	1000	−269~371	−452~700	–	–	−59~371	−75~700	(35)

General Notes:

(a) *This table is for noncorrosive service*

(b) See Sect. 2.6.2 for more details. The specific materials and/or conditions reduce the permitted temperature ranges

(c) See Sect. 2.6.2.6 for bolts/nuts materials

(d) Refer to the applicable Code for specific impact testing requirements or exemption conditions for the lowest temperature limits

(e) The maximum temperatures may be somewhat increased for nonpressure parts and/or removable components

(f) See API 530 for creep-rupture limits at elevated temperature

(g) Most company/project specifications have some safety margin. Therefore, more narrow temperature ranges may be applicable

(h) The oxidation temperatures of scale initiation are only for reference information. The actual temperature depends on the contamination, metal surface condition, and alloy elements (e.g., Cr, Mo, Si, etc.)

Notes:

(1) Cast Iron & Carbon Steels: The prolonged exposure to temperatures exceeding 427 °C (800 °F) can result in several kinds of microstructural deterioration; e.g., creep cavitation, carbide coarsening, spheroidization, and, graphitization. See para. A-240 in ASME Sec. II-Part D and ASME B31.3, para. F323.4(b)(2). Therefore, the maximum operating temperature should be 427 °C (800 °F) and below for these materials. They weaken by carbide spheroidization as well as graphitization of carbides from prolonged exposure to temperatures above 455 °C (850 °F). Carbon steels are susceptible to creep for long-term exposure above 400 °C (750 °F). See Sect. 2.3.1 for graphitization

(2) Most pipes, tubes, forgings, fittings, and plates with thin wall [≤12.7 mm (1/2 in.)] may be used without impact test at −29 °C (−20 °F) and above

(3) Coarse grain CS (e.g., ASTM A515) is preferred for long-term exposure above 400 °C (750 °F)

(4) The impact tested CS (e.g., ASTM A516) may be used at −48 °C (−55 °F) and warmer. ASME Sec. VIII allows that the following materials are exempt from impact testing at MDMT not more than 3 °C (5 °F) colder than the impact-tested temperature required by the material specimen. For instance, A333–6 impact tested at −45.6 °C (−50 °F) [or − 46 °C] can be used at −48.3 °C (−55 °F) [or − 49 °C] and warmer without additional impact test

Sec. VIII, Div.1	Sec. VIII, Div.2
SA-320, SA-333, SA-334, SA-350, SA-352, SA-420, impact-tested SA/AS 1548 (*L* impact designations), SA-437, SA-540 (except for materials produced under Table 2, Note 4 in SA-540), and SA-765.	SA-320, SA-333, SA-334, SA-350, SA-352, SA-420, SA-437, SA-508 grade 5 class 2, SA-540 except for materials produced under Table 2, note 4 in this specification, SA-723

However, ASME B31.3 does not address the mitigation of 3 °C (5 °F) as above. So LTCS pipe/tube (A333/A334), forging (A350), and fitting (A420) materials which are tested at −46 °C (−50 °F) in process piping are designed at −46 °C (−50 °F) and warmer unless satisfied with the ASME B31.3, Fig. 3.23.2.2A with the strength calculation. Practically the lowest temperature of LTCS for pressure vessels is recognized to −48 °C (−55 °F), but that of LTCS for piping materials is recognized to −46 °C (−50 °F) in the same plant/project. Therefore, currently MTI technical committee for impact test requirement of LTCS (impact tested per ASTM) suggested to ASTM LTCS (pipe, flange, fitting, casting, etc.) committees to change −46 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME BPVC requirements

(5) Once the impact test has passed at the lower temperature, the threshold temperature can decrease accordingly

(6) These materials are often used instead of carbon steel above 400 °C (750 °F)

(7) 3½ Ni steels have an intermittent history of welding problems. Austenitic stainless steel may be a better choice when welding is an issue. ASTM A707 Gr L7 qualified up to −73 °C (−100 °F) at low temperature

(8) Castings: 475 °C (885 °F) embrittlement is usually mild in the straight 12–13% Cr grades but can become severe in grades having a Cr content of 15% or more. It has become industry practice to avoid the use of any of the straight Cr stainless steels for pressure containment at temperatures exceeding 343 °C (650 °F). ASTM A352 Gr CA-6NM is qualified at −73 °C (−100 °F). The impact test is required for its use below −29 °C (−20 °F)

(9) Only for bolting

(10) Reference: API 6A718 Ni Based Alloy 718 for Oil and Gas Drilling and Production Equipment

(11) 304H SS are beneficial above 540 °C (1000 °F), since they have a maximum code-allowable stress advantage over the conventional grades. The H grades should be used with cautions in the services subject to carburization

(12) Type 309 SS containing carbon in excess of 0.1 wt% is not permitted in ASME Sec VIII, Div. 1 at temperatures less than −46 °C (−50 °F), or in Div.2 at temperatures less than −29 °C (−20 °F), without impact testing

(13) Castings; ASTM A351 Gr CH-8; the lower temperature limit, without impact testing, may be −29 °C (−20 °F)

(14) Type 310 SS containing carbon in excess of 0.1 wt% is not permitted in ASME Sec VIII, Div. 1 at temperatures less than −46 °C (−50 °F), or in Div.2 at temperatures less than −29 °C (−20 °F), without impact testing. 310 SS has better spalling resistance than 309 SS

(15) For $T > 538$ °C (1000 °F), the allowable stress valves in each code are used if the carbon content is 0.04% and above

(16) The temperature limits are similar with those of 254 SMO
(17) Above 1038 °C (1900 °F), oxidation performance of 309S becomes unsatisfactory
(18) These materials are castings, having several different composition; they typically contain 13–35% Ni and may contain other additions such as Si, Mn, Cu, and Cr
(19) It is for spheroidal graphite type, e.g., ASTM A571 Type D-2 M, class 1 and 2 (austenitic ductile iron) for compressors, expanders, pumps, valves, and other pressure-containing parts intended primarily for low-temperature service up to −196 °C (−320 °F). Ni-resist materials have two different graphite types, such as flake and spheroidal. See Sect. 2.6.2.5 for more details
(20) This material is typically used either as tubing or as a liner, with some other material servicing as pressure containment
(21) Oxidation Scaling Threshold Temperature; 427 °C (800 °F) long term, 649 °C (1200 °F) short term
(22) Cast aluminum alloys: min. −198 °C (−325 °F) in ASME, Sec. VIII, Div.1, UNF-65
(23) Maximum Temperature

	Sec. I	Sec. VIII-1	B31.3
SA675–50/55/65/70	454 °C (850 °F)	482 °C (900 °F)	
SA516–55/60/65/70	454 °C (850 °F)	538 °C (1000 °F)	538 °C (1000 °F)
SA36	343 °C (650 °F)	482 °C (900 °F)	371 °C (700 °F)
SA333–6	371 °C (700 °F)	538 °C (1000 °F)	593 °C (1100 °F)
SA/EN10028–2-P295GH	454 °C (850 °F)	538 °C (1000 °F)	–

(24) ASME Sec. VIII, Div.2, Annex 3-F: The welded joint design fatigue curves can be used to evaluate welded joints for the following materials and associated temperature limits
(a) Carbon, Low Alloy, Series 4xx, and High Tensile Strength Steels for temperatures not exceeding 371 °C (700 °F)
(b) 3xx Stainless Steels, Ni-Cr-Fe Alloy, Ni-Fe-Cr Alloy, and Ni-Cu Alloy for temperatures not exceeding 427 °C (800 °F)
(c) Wrought 70Cu-30Ni for temperatures not exceeding 232 °C (450 °F)
(d) Ni-Cr-Mo-Fe, Alloys X, G, C-4, and C-276 for temperatures not exceeding 427 °C (800 °F)
(e) Al Alloys
(25) For API 5L, Gr. A25/X42/X46/X52/X56/X60/X65/X70/X80, max. 400 °F in B31.3, Table A-1 (US Customary)/max. 225 °C in B31.3, Table A-1 M (Metric)
For API 5L, Gr. A/B, max. 593 °C (1100 °F) in B31.3, Table A-1 (US Customary)/max. 600 °C in B31.3, Table A-1M (Metric)
For API 5L, Gr. B, max. 371 °C (700 °F) in B31.3, Table K-1 (US Customary)
For API 5L, Gr. X42/X46/X52/X56/X60/X65/X70/X80, max. 100 °F in B31.3, Table K-1 (US Customary)
(26) See API TR934-D for toughness problem in heavy wall (>2–4 inch)
(27) Prohibited or very lower temperature limits for forging (for thin wall pressure vessel, e.g., A372) and for welded pipe or cast pipe
(28) Max. 550 °C (1022 °F) for plates, and 350 °C (662 °F) for pipes, tubes, and castings. See ASME Sec. II-D for more details
(29) Max. 550 °C (1022 °F) for plates, and 350 °C (662 °F) for castings. See ASME Sec. II-D for more details
(30) Max. 375 °C (707 °F) for forgings, max. 200 °C (392 °F) for plates, 40 °C (104 °F) for castings. See ASME Sec. II-D for more details
(31) Max. 375 °C (707 °F) for forgings, max. 250 °C (482 °F) for plates, 40 °C (104 °F) for castings. See ASME Sec. II-D for more details
(32) Monel 500 should not be used as an alternative of Monel 400 for bolting materials in HF service unless approved by end-user
(33) See Sect. 2.1.7.3 for various grades
(34) See Sect. 2.1.7.4 for various grades
(35) See Sect. 2.1.7.5 for various grades
(36) See Sect. 2.1.7.6 for various grades
(37) Oxide scales at high temperature (without free water) may be created within a few minutes or hours. The oxidation scaling temperature is not for the maximum use temperature or second phase/intermetallic precipitation of the metal. See Sect. 2.4.3.1 for more detail of high temperature oxidation
(38) Up to 343 °C (650 °F) for S32003 and 260 °C (500 °F) for S32550 & S32707. See API TR938-C for other DSS materials

Table 2.16 Limits of service temperature, °C (°F) – reference (ASME Sec. II, Part D Table A–452 – 2011 Edition)

		Sulfur-free atmospheres			Sulfurous atmospheres		
Material	ASME spec no.	Oxidizing	Reducing H_2	Reducing CO	Steam	Oxidizing	Reducing
Nickel	SB-160, 161, 162, and163	1038 (1900)	1260 (2300)	1260 (2300)	427 (800)	316 (600)	260 (500)
Low-C & Nickel	SB-160, 161, 162, and163	1038 (1900)	1260 (2300)	1260 (2300)	127 (800)	316 (600)	260 (500)
Nickel-copper	SB-127, 161, 163, 164, and 165	538 (1000)	538 (1000)	816 (1500)	371 (700)	316 (600)	216 (500)
Ni-Cr-Fe	SB-163, 167, 168	1093 (2000)	1149 (2100)	1149 (2100)	816 (1500)	816 (1500)	538 (1000)
Ni-Fe-Cr	SB-163, 407, 408, 409	1093 (2000)	1260 (2300)	1149 (2100)	982 (1800)	816 (1500)	538(1000)

[General]

Note 1: Copper and copper-based alloys shall not be used for parts of compressors or auxiliaries in contact with corrosive gas or with gases capable of forming explosive copper compounds. Certain corrosive fluids in contact with copper-based alloys have been known to form explosive compounds.

Note 2: Nickel-copper alloys (UNS N04400 Monel or its equivalent), Babbitt bearings, and precipitation-hardened stainless steels (PHSS) are excluded from this requirement.

Note 3: Where mutually agreed between the vendor and purchaser, copper-containing materials may be used for packing on lubricated compressors or other specific purposes.

Note 4: Typical agents of concern are hydrogen sulfide (H_2S -See Note 6 below), amines, chlorides, cyanide, fluoride, naphthenic acid, and polythionic acid.

Note 5: If chlorides are present in the process gas stream to any extent, extreme care must be taken with the selection of materials in contact with the process gas. Caution should be given to components of aluminum and austenitic stainless steel (ASS).

Note 6: All materials exposed to H_2S gas service as defined by ANSI/NACE MR0175/ISO 15156 shall be in accordance with the requirements of that standard. Ferrous materials not covered by ANSI/NACE MR0175/ISO 15156 shall not have a yield strength (*actual YS in MTR, not for SMYS*) exceeding 90 ksi (620 N/mm^2) nor a hardness exceeding Rockwell C22. Components fabricated by welding shall be postweld heat treated, if required, so that both the welds and the HAZ meet the yield strength and hardness requirements. *All PWHT requirements in EAC (environmental assisted cracking) service shall comply with the applicable standards and specifications. Normally the minimum PWHT temperature is higher than that in ASME Section VIII, Div.1.*

Note 7: The corrosion allowance (CA) for separate CS knockout pots shall be a minimum of 3 mm (1/8 in.). The purchaser and the vendor shall agree upon the CA for H/EXs and alloy parts required for special services.

[Low Temperature Materials or Impact Test Required Materials] *at < −29 °C (−20 °F) for Wrought CS & LAS and < −10 °C (14 °F) for Castings Unless Otherwise Noted in API 618 and the Applicable Specifications*

Note 8: Low-carbon steels can be notch sensitive and susceptible to brittle fracture at ambient or lower temperatures. Therefore, only fully killed, normalized steels made to fine-grain practice are acceptable. The use of steel made to a coarse austenitic grain size practice (such as ASTM A515) shall be avoided for use at ambient or lower temperatures.

Note 9: Minimum temperature can be caused by operating and/or environmental conditions including auto-refrigeration, and low ambient temperatures during shipping, installation, operation, or shutdown. All CS and LAS pressure-containing components, including nozzles, flanges, and weldments, shall be impact tested in accordance with the requirements of ASME Section VIII, Division 1, UCS-65 through 68, or the specified pressure design code. High-alloy steels shall be tested in accordance with ASME Section VIII, Division l, UHA-51, or the specified pressure design code. For materials and thickness' not covered by ASME Section VIII, Division l or the specified pressure design code, testing requirements shall be as specified by the purchaser. The vendor should exercise caution in the selection of required materials for the impact test intended for services between −30 °C (−20 °F) and 40 °C (100 °F). ASME Section VIII, Div.1 shall be complied unless otherwise noted.

[Boltings]

Note 10: The minimum quality bolting material for pressure joints shall be CS such as ASTM A307, Gr. B for cast iron components, and high temperature alloy steel such as ASTM A193, Grade B7 for steel or ductile iron components. CS nuts such as ASTM A194, Gr. 2H shall be used. For minimum allowable temperatures equal to or lower than −30 °C (−20 °F), low-temperature bolting material such as ASTM A320 shall be used.

[Cast Irons]

Note 11: Unless otherwise specified, pressure-retaining castings of gray iron shall be produced in accordance with ASTM A278, and pressure-retaining castings of steel shall be produced in accordance with ASTM A216.

[Nodular (*Ductile*) Iron Castings]

Note 12: Nodular iron castings shall be produced in accordance with an internationally recognized standard such as ASTM A395. A minimum of one set (three samples) of CVN impact specimens at one-third the thickness of the test block shall be made from the material adjacent to the tensile specimen on each keel or Y-block. All three specimens shall have an impact value not less than 12 J (9 ft-lb) and the mean of the three specimens shall not be less than 14 J (10 ft-lb) at room temperature.

[Cylinders and Cylinder Heads]

Note 13: After preparation for welding, plate edges shall be inspected by magnetic particle or liquid penetrant examination as required by the specified pressure vessel code or internationally recognized standard such as ASME Section VIII, Division 1, UG-93 (d)(3).

Note 14: Accessible surfaces of welds shall be inspected by MT or PT after chipping or back-gouging and again after PWHT.

Note 15: Unless approved by the purchaser prior to the start of fabrication, pressure-containing welds, including welds to horizontal- and vertical-joint flanges, shall be full-penetration (complete-joint) welds.

Note 16: All fabricated cylinders and cylinder heads shall be post-weld heat treated, regardless of thickness.

Note 17: All butt welds on the inner barrel of welded cylinders shall be 100% RT. Other welds to the inner barrel shall be inspected radiographically where possible. If radiography is not possible, other methods such as UT shall be used.

[Repair, Welding, and Others] See API 618.

Table 2.17 shows the temperature limits of metal components for centrifugal compressors. Some commentary notes for API 617 (Centrifugal Compressors), Table 1.E-1 are added.

Table 2.17 (1/3) Temperature limitation of API 617 (centrifugal compressors) (*noncorrosive service*) – modified

Part	Materials[a]	Specification[b,e]	Form	Temperature Limits[c], °C (°F)	
				Minimum	Minimum
Casings cast	Cast irons	ASTM A278 Cl.30	Cast	−45 (−50)[(1)]	230 (450)
		ASTM A278 Cl.40	Cast	−28 (−20)	260 (500)
	Austenitic cast irons	ASTM A436 Type 2	Cast	−45 (−50)	260 (500)
		ASTM A571 Type D-2 M Cl.1 &2	Cast	−195 (−320)	260 (500)
	Ductile iron	ASTM A395	Cast	−28 (−20)	260 (500)
	Cast steels	ASTM A216-WCB[d]	Cast	−28 (−20)	400 (750)
		ASTM A352-LCB	Cast	−45 (−50)	345 (650)
		ASTM A352-LC2	Cast	−75 (−100)	345 (650)
		ASTM A352-LC3	Cast	−100 (−150)	345 (650)
		ASTM A352-LC4	Cast	−115 (−175)	345 (650)
		ASTM A352-LC9	Cast	−195 (−320)	205 (400)
		ASTM A352-LCC	Cast	−45 (−50)	345 (650)
		ASTM A217	Cast	−28 (−20)	345 (650)
	Cast stainless steels	ASTM A743/744/351-CF3, CF3M, CF8, CF8M	Cast	−195 (−320)	345 (650)
		ASTM A351 Gr.CF3MA, CF8MA	Cast	−195 (−320)	345 (650)
		ASTM A487 Gr.CA6NM Cl.A & B	Cast	−45 (−50)	345 (650)
		ASTM A757 Gr.E3N	Cast	−75 (−100)	345 (650)
		ASTM A757 Gr.D1Q1	Cast	−28 (−20)	345 (650)
	Cast aluminum	AISI A356 (UNS A13560) or A357	Cast	−195 (−320)	150 (300)
	Cast titanium	ASTM A367 Gr.C3 or C4	Cast	−45 (−50)	150 (300)
Casings fabricated	Steels	ASTM A285-C	Plate	*−45 (−50)*[(1)]	345 (650)
		ASTM A516–55,60,65,70	Plate	−45 (−50)	345 (650)
		ASTM A203-A/B	Plate	−60 (−75)	345 (650)
		ASTM A203-D/E	Plate	−105 (−160)	345 (650)
		ASTM A537 Cl.1 & 2	Plate	−60 (−75)	345 (650)
		ASTM A353	Plate	−195 (−320)	345 (650)
		ASTM A553 Type I	Plate	−195 (−320)	345 (650)
		ASTM A553 Type II	Plate	−170 (−275)	345 (650)
		ASTM A266 Cl.1 & 4	Forged	−28 (−20)	345 (650)
		ASTM A366 Cl.F1	Forged	−28 (−20)	345 (650)
		ASTM A414	Sheet	−28 (−20)	345 (650)
		ASTM A508 Gr.5-Cl.2	Forged	−28 (−20)	345 (650)
		ASTM A350 Gr. LF2	Forged	−45 (−50)	345 (650)
		ASTM A350 Gr. LF3	Forged	−100 (−150)	345 (650)
		ASTM A266 Cl.1	Forged	−28 (−20)	345 (650)
		ASTM A662 Gr.B	Plate	−45 (−50)	345 (650)
		ASTM A765 Gr.IV	Forged	−30 (−20)	345 (650)
		ASTM A350 Gr. LF6-Cl.1	Forged	−50 (−60)	345 (650)
	Stainless steels	ASTM A240-Type 304, 304L, 316, 316L, 321	Plate	−195 (−320)	345 (650)
		ASTM A182-F304, F304L, F316, F321	Forged	−195 (−320)	345 (650)
		ASTM A182 Gr.F 6NM	Forged	−45 (−50)	345 (650)
	Aluminum alloys	ASTM B209-Alloy 6061/7075	Plate	−195 (−320)	150 (300)
		ASTM B211-Alloy 6061/7075	Bar	−195 (−320)	150 (300)
		ASTM B246-Alloy 6061/7075	Forged	−195 (−320)	150 (300)
		AMS 4108-Alloy 7050	Forged	−195 (−320)	150 (300)

Table 2.17 (2/3) Temperature limitation of API 617 (centrifugal compressors) (*noncorrosive service*) – modified

Part	Materials[a]	Specification[b,e]	Form	Temperature Limits[c], °C (°F)[(7)] Minimum	Maximum
Diaphragms guide vanes and inner casings	Cast iron	ASTM A48/278-Cl.30	Cast	*−195 (−320)[(1)]*	345 (650)
	Ductile iron	ASTM A536	Cast	*−195 (−320)[(1)]*	345 (650)
	Cast steel	ASTM A216-WCB	Cast	*−195 (−320)[(1)]*	345 (650)
	Steel	ASTM A283/284/285/516/543 & A36	Plate	*−195 (−320)[(1)]*	345 (650)
	Stainless steel	ASTM A743/744/351-CA15,CF3,CF3M,CF8,CF8M	Cast	−195 (−320)	345 (650)
		ASTM A240 Type 410	Plate	*−195 (−320)[(2)]*	345 (650)
		ASTM A276 Type 410	Bar	*−195 (−320)[(2)]*	345 (650)
		AISI 304, 304L	Plate	−195 (−320)	345 (650)
		ASTM A182 Gr. F321, F316Ti	Forged	−195 (−320)	345 (650)
		ASTM A662 Gr.B	Plate	−195 (−320)	345 (650)
		ASTM A350 Gr.LF6-Cl.1/ A487 Gr.CA6NM-Cl.A & B	Forged	−195 (−320)	345 (650)
		ASTM A757 Gr.E3N	Cast	−195 (−320)	345 (650)
	Aluminum	ASTM B26-alloy 355, C355	Cast	−195 (−320)	145 (300)
Shaft	Steels	ASTM A470 Cl. 8	Forged	−28 (−20)	345 (650)
		ASTM A470 Cl. 7	Forged	−115 (−175)	400 (750)
		AISI Type 4340	Forged	−115 (−175)[(4)]	345 (650)
		AISI Type 4140	Forged	−28 (−20)	400 (750)
		AISI Type 1040-1050[c]	Bar or forged	−28 (−20)	345 (650)
		AISI Type 4140-4150[c]		−28 (−20)	400 (750)
		AISI Type 2320[c], Type 2330		−110 (−170)[(4)]	345 (650)
		ASTM A522 type I (9Ni)	Forged	−195 (−320)	345 (650)
		AISI 4340–4345	Forged	−115 (−175)[(4)]	345 (650)
	Stainless steel	ASTM A336-F6, A473 type 410, ASTM A1021 Gr.D-Cl.2 (422), A182 Gr.F-6NM	Forged	−60 (−75)	345 (650)
	PHSS	ASTM A705 type 630, XM-12	Forged	−75 (−100)	345 (650)
		ASTM A564 type 630, XM-12	Bar	−270 (−454)[(6)]	345 (650)
Through bolt (axial rotor)	Stainless steel	UNS S45000	Bar	−60 (−75)	345 (650)
		UNS S42200	Bar	−60 (−75)	345 (650)
Impellers cast	Steels	ASTM A148	Cast	−28 (−20)	345 (650)
		ASTM A487-Gr.4Q	Cast	−45 (−50)	345 (650)
	PHSS	ASTM A747 type CB7CU-1 & 2	Cast	−75 (−100)	345 (650)
	Stainless steels	ASTM A743/744/351-CA15, CA6NM	Cast	−45 (−50)	345 (650)
		ASTM A743/744/351-CF3, CF3M, CF8, CF8M	Cast	−195 (−320)	345 (650)
	Aluminum	AISI A356 (UNS A13560), B26-alloy C355	Cast	−195 (−320)	150 (300)
	Titanium	ASTM B367-C3 or C4	Cast	−45 (−50)	345 (650)
		ASTM B367-C5	Cast	−195 (−320)[(5)]	345 (650)
Impellers fabricated (covers, hubs, blades)	Steels	AISI 4130-4140[c]	Plates or forged	−28 (−20)	400 (750)
		AISI 4320-4345[c]		−115 (−175)[(4)]	400 (750)
		ASTM A470 Cl. 8	Forged	−45 (−50)	400 (750)
		AISI 3140[c]	Forged	−45 (−50)	400 (750)
		ASTM A543	Plate	−115 (−175)[(4)]	400 (750)
		ASTM A522 type I (9Ni)	Forged	*−145 (−230)[(3)]*	345 (650)
		ASTM A522 type II (8Ni)	Forged	−170 (−275)[(4)]	345 (650)
		ASTM A353	Plate	−195 (−320)	345 (650)
		AISI type 403 [c], ASTM A473 & AISI type 410	Forged	−60 (−75)	345 (650)
		ASTM A240 type 304, 304L, 316, 316L	Plate	−195 (−320)	345 (650)
		ASTM A473 type 304, 304L, 316, 316L	Forged	−195 (−320)	345 (650)
		UNS S42400	Forged	−101 (−150)[(4)]	345 (650)
	PHSS	ASTM A705 type 630/XM-12, AISI S17400	Forged	−75 (−100)	345 (650)
		ASTM A693 type 630/XM-12	Plate	−75 (−100)	345 (650)
	Ni-based	AMS 5662-Alloy 718		−110 (−170)	345 (650)
	Aluminum	ASTM B209-Alloy 6061, 7075	Plate	−195 (−320)	150 (300)
		ASTM B211-Alloy 6061, 7075	Bar	−195 (−320)	150 (300)
		ASTM B221-Alloy 6061, 7075	Extruded	−195 (−320)	150 (300)
		ASTM B247-Alloy 2618, 6061, 7075	Forged	−195 (−320)	150 (300)
		AMS 4108-Alloy 7050	Forged	−195 (−320)	150 (300)
	Ni-Cu	SAE AMS 4646	Forged	−115 (−175)[(4)]	345 (650)
		ASTM B127, QQ-N-286, ASTM B865-N05500	Plate	−115 (−175)[(4)]	345 (650)

Table 2.17 (3/3) Temperature limitation of API 617 (centrifugal compressors) (*noncorrosive service*) – modified

Part	Materials[a]	Specification[b,e]	Form	Temperature Limits[c], °C (°F)	
				Minimum	Minimum
Balance piston	Steels	*ASTM A470 Cl.8*	*Forged*	*−28 (−20)*	*345 (650)*
		ASTM A470 Cl.7	Forged	−115 (−175)	400 (750)
		AISI Type 1040-1050[c]	Forged	−28 (−20)	345 (650)
		AISI Type 4130-4145[c]	Forged	−28 (−20)	400 (750)
		AISI Type 4330, 4340, 4345[c]	Forged	−115 (−175)	455 (850)
		AISI Type 2320[c]	Forged	−112 (−170)	345 (650)
		ASTM A522 type I (9Ni)	Forged	−195 (−320)	345 (650)
	Stainless steel	ASTM A336-F6	Forged	−60 (−75)	345 (650)
		ASTM A473 type 410	Forged	−60 (−75)	345 (650)
		AISI type 403, 410[c]	Forged	−28 (−20)	345 (650)
	PHSS	ASTM A705 type 630, XM-12	Forged	−75 (−100)	345 (650)
		ASTM A470 Cl.8	*Forged*	*−45 (−50)*	*400 (750)*
		UNS S42400	Forged	−101 (−150)	345 (650)
		ASTM A638 Gr.660 type 2 (A286)	Forged	−115 (−175)	345 (650)
	Ni-Cu alloys	SAE AMS 4676, ASTM B865-N05500	Forged	−115 (−175)	345 (650)
Rotor blades	Stainless steels	UNS S45000, S42200	Forged or Bar	−60 (−75)	345 (650)
	Titanium	AMS 4928 Ti-6Al-4 V	Forged or Bar	−60 (−75)	345 (650)
Labyrinths impeller interstage shaft seal and balance piston	Stainless steels (SS)	AISI type 403, 410, 416, 420	Wrought	−195 (−320)[(2)]	345 (650)
	Stainless steels (SS)	AISI type 303, 304, 316	Wrought	−195 (−320)	345 (650)
	Cr-Ni-Fe-Mo-Cu-Cb	ASTM B462	Wrought	−195 (−320)	345 (650)
	SS honeycomb	ASTM A240 type 304, 304L, 316, 316L	Fabricated	−195 (−320)	345 (650)
	Aluminum	ASTM B26-alloy 443, 335, 850, AA-A850, B850	Cast	−195 (−320)	315 (600)
		ASTM B209-Alloy 6061-T6, 1100, Gr.5083	Plate	−195 (−320)	315 (600)
	Babbitt	ASTM B23	Cast	−195 (−320)	175 (350)
	Brass	ASTM B16/B21	Rod, bar	−195 (−320)	150 (300)
		ASTM B36	Plate, bar	−195 (−320)	150 (300)
		ASTM B171	Plate	−195 (−320)	150 (300)
	Ni-Cu alloy	ASTM B564-N04400, B164	Forging	−115 (−175)	345 (650)
	Nonmetallic TFE[f]		Molded	−195 (−320)	260 (500)
	Nonmetallic TFE[f]	Carbon-filled	Molded	−28 (−20)	260 (500)
	Nonmetallic TFE[f]	Mica-filled	Molded	−54 (−65)	260 (500)
	Polyamide-imide	PAI	Molded	−100 (−150)	300 (570)
	Polyaryletherketone	PEEK	Molded	−100 (−150)	160 (320)
	Polyaryletherketone	PEK	Molded	−100 (−150)	195 (380)
	Lead	ASTM B29	Cast	−101 (−150)[(4)]	205 (400)
	Nickel graphite		Coating	−101 (−150)	482 (900)
	Phenolic resin	Micarta, NEMA, Gr. LE	Sheet	−195 (−320)	65 (130)
	Impregnated	Micarta, NEMA, Gr. G10, G9	Sheet	−195 (−320)	110 (230)
Shaft sleeves	Steels	AISI Type 4130-4150[c]	Forged	−45 (−50)	345 (650)
		AISI Type 4320-4345[c], 4330[c]	Forged	−115 (−175)[(5)]	400 (750)
		ASTM A470 Cl.7	Forged	−115 (−175)	400 (750)
		ASTM A522 type I	Forged	−195 (−320)	345 (650)
		ASTM A106	Pipe	−28 (−20)	345 (650)
		ASTM A350 LF2, Cl.1	Forged	−45 (−50)	345 (650)
		ASTM A350 LF3	Forged	−100 (−150)	345 (650)
	Stainless steels	AISI type 403, 410[c]	Forged	−75 (−100)[(2)]	400 (750)
	Ni-Cu alloy	ASTM B164 & SAE AMS 4676	Forged	−115 (−175)	345 (650)
	Ni-Mo-Cr	ASTM B574-alloy N10276	Wrought	−115 (−175)	345 (650)
		ASTM A494 CW-12 M-1	Cast	−115 (−175)	345 (650)
	PHSS	ASTM A705 type 630, XM-12	Forged	−75 (−100)	345 (650)

Notes:

[a]The materials shown in this table are those commonly used by compressor manufacturers, but the list is not all inclusive. Other suitable materials may exist and may be used as indicated by specific design considerations

[b]Descriptions of AISI Types can be found in ASTM DS 56D. See Note "e"

[c]The temperature limits shown in this table are those commonly observed by compressor manufacturers and are not necessarily the same as any temperature limits specified in the applicable material specifications
[d]Normalized or normalized and tempered
[e]AISI designations are only a description of chemical analyses of types of steel; they are not procurement specifications. All materials should be purchased to a specification that adequately defines the required properties and controls
[f]TFE = tetrafluoroethylene
[g]See nomenclature in cross sections of either the centrifugal or axial compressor for part names in API 617, Annex C
Commentary Notes on API 617, Table 1.E-1:
[(1)]It may have to be −28 °C (−20 °F) unless it is impact tested or thin wall
[(2)]It may have to be −60 °C (−75 °F) unless it is impact tested or thin wall
[(3)]It may have to be −196 °C (−320 °F)
[(4)]It should be observed by compressor manufacturers and purchaser's engineers
[(5)]It may have to be −45 °C (−50 °F) unless it is impact tested or thin wall
[(6)]It may have to be −75 °C (−100 °F) unless it is impact tested or thin wall
[(7)]The temperatures ranges for use may be narrowed in corrosive and/or fatigue environments

2.1.1.11 Permitted Variations of Chemical Requirements

See Sect. 2.5.2 in this book.

2.1.1.12 Grain Size in the Microstructure of Metal

(a) Characteristics and measurement of grain size

The grain size of a metal is an important material characteristic for strength (*per low, moderate, and elevated temperature*), toughness, formability, directionality, corrosion resistance, texture and surface appearance. As the average grain size becomes smaller, the metal is to be stronger (more resistant against plastic flow) and as the grain size becomes larger, *the strength may be decreased at moderate temperature and below*. In general, for a given alloy and thickness, ductility increases with grain size *and/or* strength decreases *at moderate temperature and below*. This occurs because the smaller the grains, the shorter the distance dislocations can move, and then can be economically fabricated into the desired part.

The measurement of grain size, whether by the chart comparison method or by manual or automated measurement methods, may be complicated due to the different types of grain structures encountered *and/or* the etched appearance of the grains. (Fig. 2.1)

Standard Test Methods for Determining Grain Size in ASTM

- ASTM E112 Test Method for Determining Average Grain Size
- ASTM E930 Test Methods for Estimating the Largest Grain Observed in a Metallographic Section, (ALA Grain Size) [to handle the measurement of occasional, very large grains present in an otherwise uniform, fine grain size dispersion.]
- ASTM E1181 Standard Test Methods for Characterizing Duplex Grain Sizes [or for rating the grain size when the size distribution is not normal; e.g., bimodal or duplex steels.]
- ASTM E1382 Test Method for Determining Average Grain Size Using Semiautomatic and Automatic Image Analysis

Table 2.18 shows the comparison for ASTM No. vs. # of grain.
Table 2.19 shows the grain size calculation formula.
Fig. 2.2 shows the standard for grain size – ASTM.
Fig. 2.3 shows the average intercept counts on 500 mm test pattern (ASTM E112, Fig. 6).
See Sect. 2.2.1.5 for grain size effects for low temperature toughness.
Figures 2.4 and 2.5 show that the grain is growing in accordance with higher temperature and longer exposure time.

(b) Grain Size Requirements
1. Code Survey – each specified paragraph below is directly extracted from the code.
   (a) ASME Sec. VIII, Div.1:
   – UW-11(d) UT shall be done following the grain refining heat treatment of PWHT.
   – UW-27(f) & UW-UCS-56(a) When a single pass of electroslag welds is greater than 38 mm (1.5 in.) in ferritic materials, the joint shall be given a grain refining (austenitizing) heat treatment.
   – UW-UCS-56(a) Electroslag welds in ferritic materials over 38 mm (1.5 in.) in thickness at the joint shall be given a grain refining (austenitizing) heat treatment.
   – Fig. UCS-66(M) Impact Test Exemption Curves (Lower curves to use for grain refined steel)
   (b) ASME Sec. VIII, Div.2:
   – Figures 3.7(M) & 3.8(M) Impact Test Exemption Curves (Lower curves to use for grain refined steel)
   – Section 6.4.2.8 Electroslag welds in ferritic materials over 38 mm (1.5 in.) in thickness at the joint shall be given a grain refining (austenitizing) heat treatment.
   – Section 7.4.3.4 UT shall be done following the grain refining heat treatment of PWHT.

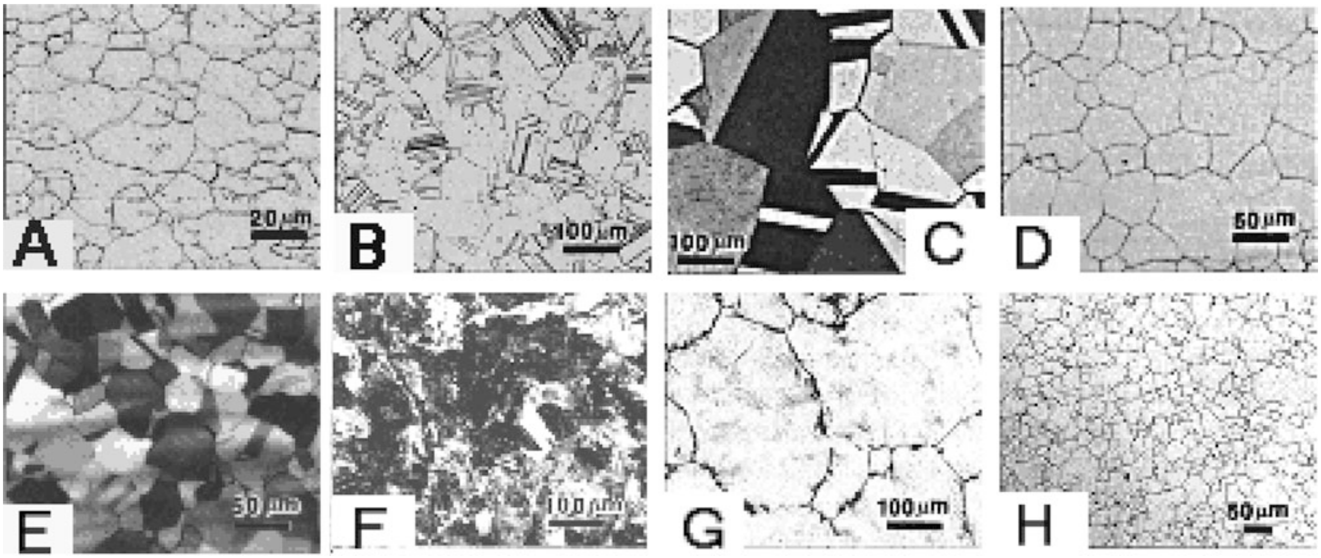


Figure 2.1 Types of micrographs (Source: http://metallography.com/types.htm). (**A**) It has typically for ferrite grains in a non-heat-treated or non-hardenable body-centered cubic (bcc) metal. These do not contain annealing twins, but could contain deformation twins, and second-phase constituents may be present. The example shown is ferrite in a low-carbon steel; carbides are present. This specimen was etched with nital and not all of the grain boundaries are visible; those that are visible in darkness and width. These factors are a minor nuisance for manual rating, but a significant problem for automatic rating. (**B**) It shows typically for a single phase austenitic alloy that contains annealing twins. Like Figure **A**, it shows the boundaries as dark lines, a so-called "flat etch." The austenitic alloy, Stellite 25 (UNS R30605, Haynes 25/L605: 20Cr-10Ni-15 W-Mn-Fe-bal.Co: See Table 2.89), illustrates a common problem with such alloys, they are very difficult to etch so that all of the grain boundaries are visible. Therefore, it is very difficult to measure the grain size with a high degree of precision. In addition, when rating grain size, the twin boundaries must be ignored, which is not easy, especially by image analysis. However, some austenitic alloys, such as aluminum alloys, rarely are twinned. Austenitic alloys may also be etched with reagents that produce grain contrast or color variations as a function of their crystallographic orientation. (**C**) It shows the twinned austenitic grain structure of cartridge brass that was etched producing grains with different contrast in black and white. Unlike the flat etched Stellite 25 specimen in **B**, all of the grains are readily revealed. This structure is easy to rate by the comparison method if the grain size chart depicts grains etched in the same manner. This condition is virtually impossible to measure by automatic image analysis, however. Again, twins are present but the coloration or contrast varies within the grains. To measure twinned austenitic grain structures by image analysis, it needs to either suppress the etching of twins or be able to identify and ignore them. At the same time, all of the grain boundaries must be revealed and be identifiable. The best solution is to use an etchant that reveals only the grain boundaries like Figure **D**. (**D**) It shows 316L SS electrolytically etched with 60% nitric acid in water (Pt cathode, 0.8 V dc, 45 s) to illustrate the grain boundary as a next micrograph of **C**. The grain boundaries are almost completely revealed but no twins are visible. (**E**) It shows a tint etched view of this specimen in **D** at the same magnification where the twins are visible. In dealing with CS and LAS, the steelmaker generally performs a test known as the McQuaid-Ehn test, to determine if the steel is inherently fine grained. A specimen is carburized at 927 °C (1700 °F) for 8 hours and furnace-cooled slowly. The excess carbon in the carburized case precipitates during cooling as cementite in the austenite grain boundaries present at the end of the carburizing cycle. The specimen is cut, polished, and etched so that the grains will clearly be seen under a microscope. Generally, nital is used as the etchant and a comparison chart rating is made where the Test Methods ASTM E 112 chart exhibits the same contrast. (**F**) It is not a very good micrograph if actual measurements are made, especially if image analysis is employed. The alternative is to darken the grain boundary cementite films. A number of etchants will darken cementite. (**G**) This was Beraha's sodium molybdate tint etch but the familiar alkaline sodium picrate etch works well also. Etched in this way, the grain structure shows up much more clearly and image analysis could be used. Once an alloy steel part is heat treated, only etching can be used to try to reveal the prior-austenite grain boundaries, i.e., the austenite boundaries present when the part was soaked at the austenitizing temperature. One of the most successful prior-austenite grain boundary etchants is a saturated aqueous solution of picric acid containing a wetting agent, several of which have been used. This etch is sensitive to phosphorus segregated to the prior-austenite grain boundaries and will not work otherwise. (**H**) It illustrates a fairly successful effort with a Q-T alloy steel. This type of etch rarely, if ever, yields an etch quality adequate for image analysis and is usually accompanied by substantial pitting

Table 2.18 ASTM grain size no. vs. # of grain – ASTM E112

ASTM grain size no.	# of grain/in^2 at ×100	# of grain/mm^2 at ×1
0	0.5	8
1	1	16
2	2	31
3	4	62
4	8	124
5	16	248
6	32	496
7	64	992
8	128	1980
9	256	3970
10	512	7940
11	1024	15,870
12	2048	31,700

Table 2.19 Grain size calculation formula

Imperial unit	SI/Metric unit
N (# of grain/in^2) $= 2^{(n-1)}$	N (# of grain/mm^2) $= 2^{(n+3)}$
n = ASTM grain no.	n = ASTM grain no.

(c) ASME B31.3
  – Note (29) for Tables A-1, A-1 M, A-1A, A-1B, A-2, AND A-2 M. The stress values above 538 °C (1000 °F) listed here shall be used only when the steel's austenitic micrograin size, as defined in ASTM E112, is No. 6 or less (coarser grain). Otherwise, the lower stress values listed for the same material, specification, and grade shall be used.

2. End-Users' specification: Austenitic Grain No. 6 or 7 and finer for low temperature or sour service (Table 2.20)

2.1.2 *Forging Materials – Source: FIA (Forging Industry Association) and ASTM STG 903*

1. Process
   The process is normally (but not always) performed hot by preheating the metal to a desired temperature before it is worked. It is important to note that the forging process is entirely different from the casting (or foundry) process, as metal used to make forged parts is never melted and poured (as in the casting process). As a result, the forging process can create parts that are stronger than those manufactured by any other metalworking process.
2. Applicable Metals
   Just about any metal can be forged. However, some of the most common metals include (a) carbon, alloy, and stainless steels; (b) very hard tool steels, aluminum, and titanium; (c) brass and copper; and (d) high-temperature alloys which contain cobalt, nickel, or molybdenum. Each metal has distinct strength or weight characteristics that best apply to specific parts as determined by the customer.
3. Mechanical Properties
   Mechanical properties for forging alloys, like physical properties, are listed in standard reference sources. In some cases, they are not

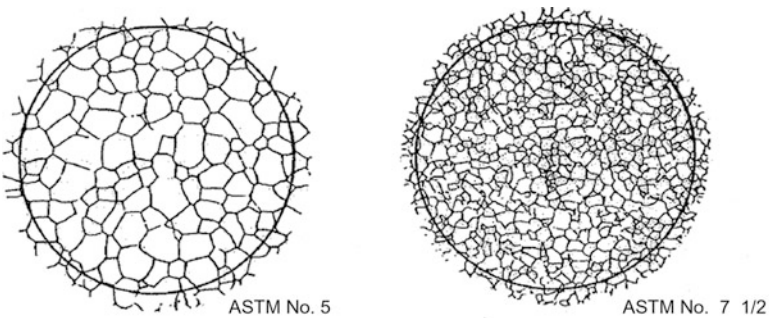


Figure 2.2 Standard for grain size – ASTM E112

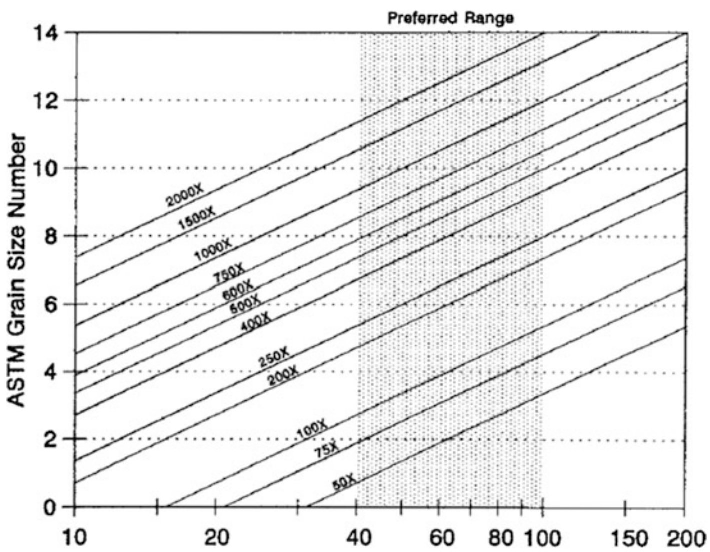
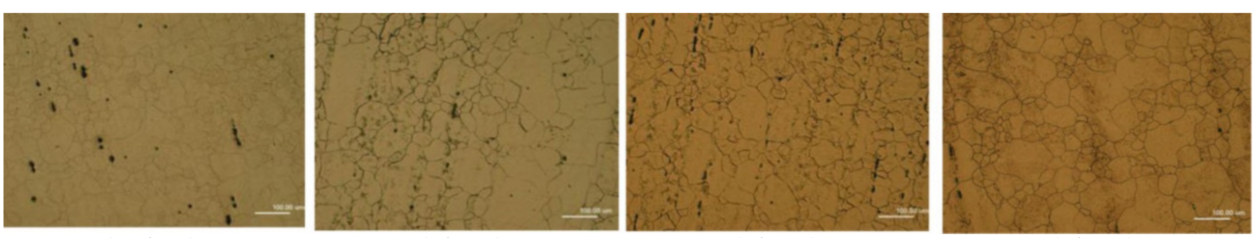
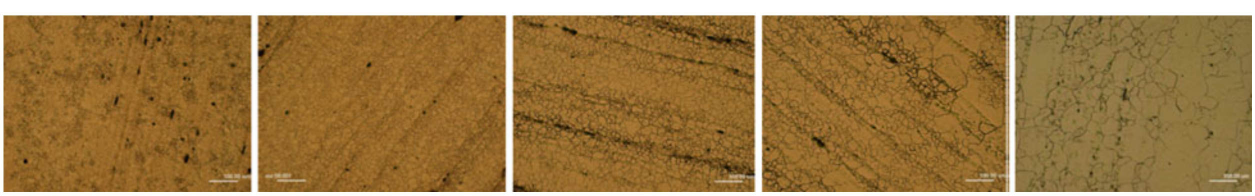


Figure 2.3 Average intercept counts on 500 mm test pattern (ASTM E112, Fig. 6)



(0.5 hour) (2 hours) (4 hours) (9 hours)

Figure 2.4 Variation in grain size of AISI 4140 with time at 1050 °C. (Source: Erik Khzouz, Grain Growth Kinetics in Steels, WTI graduate article 4/28/2011)



(850°C) (900°C) (950°C) (1000°C) (1050°C)

Figure 2.5 Variation of grain size of AISI 4140 with temperature at 2 hours. (Source: Erik Khzouz, Grain Growth Kinetics in Steels, WTI graduate article 4/28/2011)

Table 2.20 Grain size control of carbon steel and low alloy steels (reference)[1]

	Fine grain practice	Coarse grain practice
Effective application	1. Improvement of toughness (lower DBTT) – e.g., SA-516 2. Improvement of corrosion (SSC, HIC, HF, caustic, etc.) resistance	1. Improvement of creep strength at high temperature – e.g., SA-515
Evaluation methods	Austenite grain no. (austenite no.) ≥5	Austenite grain no. (austenite no.) < 5
Treatment method at mill	1. Chemical composition control – Al, Ti, Zr (killing element, Si to be reduced.) 2. Heat treatment – just above temperature from austenitic temperature and/or rapid cooling (e.g., N-T or Q-T steels) 3. TMCP steels	1. Chemical composition control – Si 2. Heat treatment – higher temperature from austenitic temperature and/or slow cooling

Note: [1] See ASTM E112 for Test Method for Determining Average Grain Size

Table 2.21 Effects of processing on mechanical properties

Property	Hot forged without heat treatment	Hot, warm or cold forged and heat treated	Warm or cold forged without heat treatment
Tensile strength	Subject to variations due to variations in cooling rates	Varies within the forging with section size, heat treatment and material hardenability	Warm forging, varies due to variations in cooling rate
Yield strength			
Hardness			
Elongation	No variation	No variation	No variation
Reduction in area	Will vary with variations in cooling rate and forging temperature. Can be enhanced by control of grain flow	Affected by grain flow and controlled by heat treatment	Cold forging, will vary with amount of grain flow Warm forging, will vary with variations in cooling rate
Modulus of elasticity			
Poisson's ratio			
Impact toughness			
Fracture toughness			

affected by subsequent manufacturing operations, and can be used with reasonable confidence to predict real-world performance. In other cases, mechanical properties are altered by subsequent processes, in varying amounts and with varying degrees of predictability in the end product. Variations are caused by factors such as:

- Forging temperature
- Forging reduction (deformation) which, in turn, affects grain size
- Heat treatment

In some cases, an experienced forging engineer can predict properties, such as yield strength, in critical areas of the forging with reasonable accuracy. Predictability is enhanced by two characteristics of forgings.

(a) Forgings are fully dense and not subjected to discontinuities, such as porosity in castings.
(b) Forging alloys are homogeneous, and not subject to variations in composition, such as orientation of reinforcing fibers in composites.
(c) ASTM A105 (CS forgings for piping applications) material has several premature failure histories for low temperature service industries even though ASME codes allow use at −29 °C (−20 °F) and above. See Sect. 2.6.2.4 for a more detailed application guideline.
(d) The essential mechanical properties of forging alloys and the effect of processing are summarized in Table 2.21.

4. Directional Strength

Directional strength is a direct result of the forging process. In the forging process, controlled deformation (usually at elevated temperatures) results in greater metallurgical soundness and improved mechanical properties of other materials. In most cases, forging stock has been pre-worked to remove porosity resulting from the solidification process. This produces directional alignment (or "grain flow") for important directional properties in strength, ductility, and resistance to impact and fatigue. These properties are deliberately oriented in directions requiring maximum strength. Working the material achieves recrystallization and grain refinement that yields the maximum strength potential of the material with the minimum property variation.

Properly developed grain flow in forgings closely follows the outline of the component. In contrast, bar stock and plate have unidirectional grain flow; any changes in contour will cut flow lines, exposing grain ends, and render the material more liable to fatigue and more sensitive to stress corrosion.

The resulting higher strength-to-weight ratio can be used to reduce section thickness in part designs without jeopardizing performance characteristics of safety. Weight reduction, even in parts produced from less expensive materials, can amount to a considerable cost savings over the life of a product run.

The consistency of material from one forging to the next, and between separate quantities of forgings is extremely high. Forged parts are made through a controlled sequence of production steps rather than random flow of material into the desired shape.

Uniformity of composition and structure piece-to-piece, lot-to-lot, assure reproducible response to heat treatment, minimum variation in machinability, and consistent property levels of finished parts.

Dimensional characteristics are remarkably stable. Successive forgings are produced from the same die impression, and because die impressions exert control over all contours of the forged part, the possibility of transfer distortion is eliminated.

For cryogenic applications, forgings have the necessary toughness, high strength-to-weight ratios, and freedom from ductile-brittle transition problems.

Forgings are produced economically in an extremely broad range of sizes. With the increased use of special punching, piercing, shearing, trimming, and coining operations, there have been substantial increases in the range of economical forging shapes and the feasibility of improved precision. However, parts with small holes, internal passages, re-entrant pockets, and severe draft limitations usually require more elaborate forging tooling and more complex processing, and are therefore usually more economical in larger sizes.

Forgings are superior to metal parts produced by other methods in their compatibility with other manufacturing processes (Table 2.22)

- The characteristically uniform refinement of crystalline structure in forged components assures superior response to all forms of heat treatment, maximum possible development of desired properties, and unequaled uniformity.
- Because forged components of weldable materials have a near absence of structural defects, material at welding surfaces offers the best possible opportunity for strong, efficient welds by any welding technique.
- Again, the near absence of internal discontinuities or surface inclusions in forgings provides a dependable machining base for metal-cutting processes such as turning, milling, drilling, boring, broaching, and shear spinning; and shaping processes such as electrochemical machining, chemical milling, electrical-discharge machining, and plasma jet techniques.
- Forged parts are readily fabricated by assembling processes such as welding, bolting, or riveting. More importantly, single-piece forging may be designed to eliminate the need for assemblies.
- In many applications, forgings are ready for use without surface conditioning or machining. Forged surfaces are suited to plating, polishing, painting, or treatment with decorative or protective coatings.

5. Application Guideline for Commercial Materials – See Sect. 2.6.2.4 and the notes for forging materials.

Table 2.22 Advantages of forging materials when using a similar alloy

Forging versus	Forging advantages when using a similar alloy
Casting	• Stronger • Preworking refines defects • More reliable, lower cost over component life • Better response to heat treatment • Adaptable to demand
Welding/ fabricating	• Material savings, production economies • Stronger • Cost-effective design/inspection • More consistent and better metallurgical properties • Simplified production
Machining	• Broader size range of desired material grades • Grain flow provides higher strength • More economical use of material • Yields lower scrap • Requires fewer secondary operations
Powder metal	• Stronger • Higher integrity • Requires fewer secondary operations • Greater design flexibility • Less costly materials
Composites/ plastics	• Less costly materials • Greater productivity • Established documentation • Broader service temperature range • More reliable service performance

2.1.3 Cast Iron, Ductile Iron, and Hot Isostatic Processing (HIP) Castings

2.1.3.1 Comparison of Cast Iron and Cast Steel

Table 2.23 shows the comparison between cast steel and cast iron.

2.1.3.2 Types of Cast Irons

Cast irons are conveniently classified per their structure that influences their mechanical properties and weldability.

(a) Gray cast irons – ASTM A48, A126, and A278.

Gray cast irons contain 2.0–4.5%C and 1–3%Si. With proper control of C and Si contents and the cooling rate, the formation of iron carbide during solidification entirely, and graphite precipitates directly from the melt as irregular, generally elongated and curved flakes in an iron matrix saturated with carbon. Their structure consists of branched and interconnected graphite flakes in a matrix that is pearlite, ferrite or a mixture of the two.

Table 2.23 Cast steel vs. cast iron

	Cast iron	Cast steel
Elongation	≈ 0%	≈10–30%
Toughness (DBTT)	Above 0 to −10 °C (32 to −14 °F)	Above −10 to −46 °C (−14 to −50 °F)
Being wrought	Impossible due to highly brittle	Possible, i.e., bending, drawing
Weldability	Very difficult because of high Content of carbon (around 1.7%C and over)	Possible because of low content of carbon (around less than 0.4%C)
Impurity or pore	Much	Little

The graphite flakes form planes of weakness and so strength and toughness are inferior to those of structural steels (Fig. 2.6). When a gray iron casting fractures, the crack path follows these graphite flakes and the fracture surface appears gray because of the presence of exposed graphite. The strength of gray cast iron depends almost entirely on the matrix in which these graphite flakes are embedded. Slow cooling rates and high carbon and silicon contents promote full graphitization, and the majority of the carbon dissolved in the iron at high temperatures is deposited as graphite on the existing flakes during cooling. The structure then consists of graphite flakes in a ferrite matrix, referred to as ferritic gray cast iron.

If graphitization of the carbon dissolved in the iron at high temperatures is prevented during cooling, iron carbide precipitates out and the matrix is pearlitic (referred to as pearlitic gray cast iron). Ferritic gray cast iron is normally soft and weak.

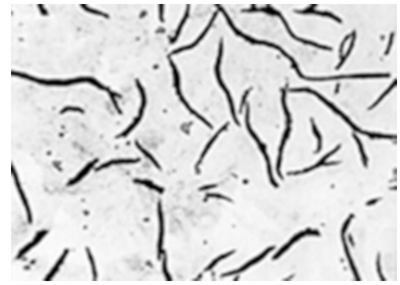


Figure 2.6 Flake type gray CI. (Source: ASM Metal Handbook, Vol.1)

(b) Nodular (or Ductile or Spheroidal) cast irons – ASTM A395, A536

The mechanical properties of gray irons may be greatly improved if the graphite shape is modified to eliminate planes of weakness. Such modification is possible if molten iron, having a composition in the range 3.2–4.5%C and 1.8–2.8%Si, is treated with magnesium or cerium additions before casting. This produces castings with graphite in spheroidal form instead of flakes, known as nodular, spherical graphite or ductile irons. Nodular irons are available with pearlite, ferrite, or pearlite-ferrite matrices, which offer a combination of greater ductility and higher tensile strength than gray cast irons. Ductile cast iron, also known as nodular iron or spheroidal graphite (SG) iron, is very similar in composition to gray cast iron, but the free graphite in these alloys precipitates from the melt as spherical particles rather than flakes. This is accomplished through the addition of small amounts of magnesium or cerium to the ladle just before casting. The spherical graphite particles do not disrupt the continuity of the matrix to the same extent as graphite flakes, resulting in higher strength and toughness compared with gray cast iron of similar composition (Fig. 2.7).

Typical applications are

- Agricultural (tractor and implement parts)
- Automotive and diesel (crankshafts, pistons and cylinder heads)
- Electrical fittings, switch boxes, motor frames and circuit breaker parts
- Mining (hoist drums, drive pulleys, flywheels and elevator buckets)
- Steel mill (work rolls, furnace doors, table rolls and bearings)
- Tool and die (wrenches, levers, clamp frames, chuck bodies and dies for shaping steel, aluminum, brass, bronze and titanium)

Meanwhile, ASTM A439 (Austenitic Ductile Iron, 18-37Ni) is used for corrosion resistance.

(c) White cast irons (CI) -ASTM A667, A748, A942 and Abrasion-Resistant Cast Iron-ASTM A532

By reducing C and Si content and cooling rapidly, much of C is retained in the form of iron carbide without graphite flakes. However, iron carbide, or cementite, is extremely hard and brittle and these castings are used where high hardness and wear resistance is needed.

White cast iron derives its name from the white, crystalline crack surface observed when a casting fractures. Most white cast irons contain <4.3% C, with low silicon contents to inhibit the precipitation of carbon as graphite. It is used in applications where abrasion resistance is important and ductility not required, such as liners for cement mixers, ball mills, certain types of drawing dies and extrusion nozzles.

White cast iron is generally considered unweldable. The absence of any ductility that can accommodate welding-induced stresses in the base metal and HAZ adjacent to the weld results in cracking during cooling after welding (Fig. 2.8)

White cast irons are widely used in abrasive wear applications involved in the crushing, grinding, milling, and handling of abrasive materials such as minerals and ores, both dry and as slurries.

Three types of irons are commonly used:

1. *White Iron* is unalloyed cast iron with low carbon and silicon content such that the structure is hard brittle iron carbide with no free graphite. These irons are limited in application because of the lack of impact resistance and the difficulty in maintaining the structure in thicker sections. In some cases, the castings are designed and produced to have a white structure in certain areas and a gray or flake structure elsewhere to improve toughness.

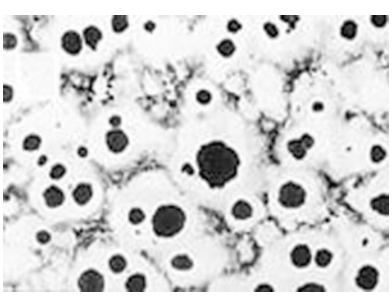


Figure 2.7 Nodular CI. (Source: ASM Metal Handbook, Vol.1)

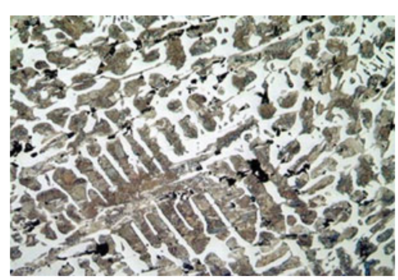


Figure 2.8 White CI. (Source: ASM Metal Handbook, Vol.1)

2. *Martensitic white cast irons containing nickel and chromium* are commonly known as Ni-Hards. There are two general types containing 4%Ni-2%Cr and 8%Cr-6%Ni. Both have a structure of iron and chromium carbides in a matrix of martensite and bainite, but the higher alloy content materials have a type of carbide which is discontinuous and confers greater impact and corrosion resistance.
3. *High-chromium cast irons* have typical compositions of 15%Cr-3%Mo and 23–28%Cr and a superior combination of abrasion resistance and toughness. In some cases, they may be used as cast, but are normally air-hardened to develop the optimum properties. Table 2.24 shows types and chemical compositions of ASTM A532 abrasion-resistant cast irons.

(d) *Malleable cast irons*-ASTM A47, A220

These are produced by heat treatment of closely controlled compositions of white irons which are decomposed to give carbon aggregates dispersed in a ferrite or pearlitic matrix. This reaction is favored by high temperatures, slow cooling rates, and high C and Si contents. As the compact shape of C does not reduce the matrix ductility to the same extent as graphite flakes, a useful level of ductility is obtained. Malleable iron exhibits better fracture toughness properties in low temperature environments than other nodular irons, due to its lower silicon content. The ductile to brittle transition temperature is lower than many other ductile iron alloys.

Malleable iron may be divided into the following classes; ferritic cast iron and pearlitic irons.

1. Ferritic Malleable Cast Iron -ASTM A47

   At room temperature, the microstructure therefore consists of temper carbon nodules in a ferrite matrix, generally known as ferritic malleable cast iron. The compact nodules of temper carbon do not break up the continuity of the tough ferritic matrix, resulting in high strength and improved ductility. The graphite nodules also serve to lubricate cutting tools, which accounts for the very high machinability of malleable cast iron (Fig. 2.9)

2. Pearlitic Malleable Irons – ASTM A220

   If full graphitization is prevented and a controlled amount of carbon remains in the iron during cooling, finely distributed iron carbide plates nucleate in the iron at lower temperatures. This can be achieved by alloying with manganese, or by replacing the second stage anneal by a quench (usually in air or oil). Due to the presence of iron carbide in the microstructure, the strength and hardness of these castings are increased over those of ferritic malleable cast iron (Fig. 2.10)

(e) High-silicon irons – ASTM A518, A861, BS 1591

High-silicon cast iron or acid-resistant iron contains up to 14–18% Si. This type of iron shows good corrosion resistance for acid environment exploitation, mainly for centrifugal pumps, equipment for sulfuric acids (blades, mixer, and other), reaction apparatus, compressors, etc.

Table 2.24 Types of ASTM A532 abrasion-resistant cast irons

												Hardness, HRC		
Class	Type	Description	C	Mn	Si	Ni	Cr	Mo	Cu	P	S		Hardened+SR	
												As Cast & SR	Level 1	Level 2
I	A	Ni-Cr-Hc	2.8–3.6	≤2.0	≤0.8	3.3–5.0	1.4–4.0	≤1.0	–	≤0.3	≤1.5	53	56	59
I	B	Ni-Cr-Lc	2.4–3.0	≤2.0	≤0.8	3.3–5.0	1.4–4.0	≤1.0	–	≤0.3	≤1.5	53	56	59
I	C	Ni-Cr-GB	2.5–3.7	≤2.0	≤0.8	≤4.0	1.0–2.5	≤1.0	–	≤0.3	≤1.5	53	56	59
I	D	Ni-high Cr	2.5–3.6	≤2.0	≤2.0	4.5–7.0	7.0–11.0	≤1.5	–	≤1.0	≤1.5	50	56	59
II	A	12%Cr	2.0–3.3	≤2.0	≤1.5	≤2.5	11.0–14.0	≤3.0	≤1.2	≤1.0	≤0.06	53	56	59
II	B	15%Cr-Mo	2.0–3.3	≤2.0	≤1.5	≤2.5	14.0–18.0	≤3.0	≤1.2	≤1.0	≤0.06	46	56	59
II	D	20%Cr-Mo	2.0–3.3	≤2.0	1/0–2.2	≤2.5	18.0–23.0	≤3.0	≤1.2	≤1.0	≤0.06	46	56	59
III	A	25%Cr	2.0–3.3	≤2.0	≤1.5	≤2.5	23.0–30.0	≤3.0	≤1.2	≤1.0	≤0.06	46	56	59

Source: ASTM A532

Notes:

SR stress relieved

[A]90% of the minimum surface hardness level shall be maintained to a depth of 40% of the casting section, with any softer material being at the thermal center of the casting. A sampling procedure should be established by agreement between the supplier and the purchaser

[B]Nonchilled areas of casting shall meet minimum hardness or sand cast requirements

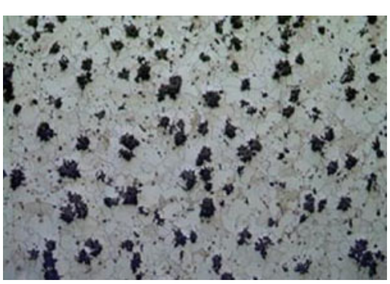


Figure 2.9 Ferritic Malleable CI. (Source: ASM Metal Handbook, Vol.1)

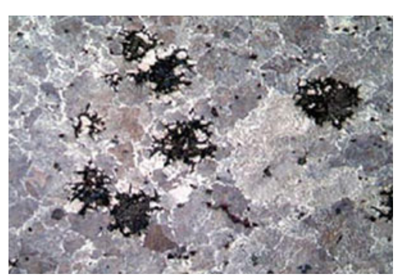


Figure 2.10 Pearlitic malleable cast iron (×200). (Source: ASM Metal Handbook, Vol.1)

Ferrum with strong energy with Si makes a solid solution, lowering meting point of Fe. Temperature interval between liquidus and solidus is so small that it's difficult to form Si segregation. Si is an element which makes smaller y area of ferrum. Because of that, modification points are on higher temperatures, so 17% Si moves these for 50 °C (90 °F). It's reason for forming of rough gain during annealing, recrystallization, and quenching.

Carbon provides an influence on Fe/Si system diagram so that doesn't change present phases configuration, but makes smaller solidification interval of system and also Si content at the eutecticum. Carbon present in high Si cast microstructure exists like lamellar graphite in the form of fine lamellas, rough lamellas, and in small bars. Sometimes in the microstructure carbide is present, especially in case of rapid cooling, immediately after solidification. See Table 2.25 for some limitations in industrial codes and standards.

Table 2.25 Casting materials requirements in ASME Sec. VIII, Div. 1 and B31.3

Material	Sec. VIII, Div. 1, pressure vessels	B31.3, process piping	Remarks
Castings	Conditionally acceptable in UG, UCS, and UHA	Para. 302.3.1 & 302.3.3 Para. 344.3 Para, K302.3.3D Table A-1A	• High alloy castings – UHA-8, UG-7, UG-11, UG-24, UCS-8, Appendix 7
Cast iron (CI)	[Part UCI] CI, DI, cast dual metals **UCI-2**: Not permitted for the following services: (a) Lethal, flammable – liquid or gaseous (b) Unfired steam boilers (c) Direct firing **UCI-3(a)**: Not permitted for the following: 1. DP > 1.1 MPag (160 psig) at DT ≤ 230 °C (450 °F) in gases, steam, and vapors services 2. DP > 1.1 MPag (160 psig) at DT ≤ 190 °C (375 °F) in liquids services 3. DP > 1.7 MPag (250 psig) at < boiling point at DT, or in case of DT > 50 °C (120 °F) in liquids. 4. >2.1 MPag (300 psig) at DT ≤ 230 °C (450 °F) for bolted heads, covers, or closures that are not major components of pressure vessels. **UCI-3(b)(c)(d):** Permitted for the following: • SA-278 cl. 40–60: DP ≤ 1.7 MPag (250 psig) at DT ≤ 343 °C (650 °F) • SA-476 cl. 40–60: DP ≤ 1.7 MPag (250 psig) at DT ≤ 232 °C (450 °F) • ASME B16.1 CI flanges & fittings: Cl.#125 & #250: DT ≤ 232 °C (450 °F) **Table UCI-23:** Max. Allowable stress values in tension for CI	**Para. 323.4.2** • Shall not be used above ground in hydrocarbon process units or other flammable fluid at >149 °C (300 °F) nor >1 MPag (150 psig) • In other locations the pressure limit shall be 2.8 MPag (400 psig)	• Vessel not permitted to contain lethal or flammable substance – UCI-2 • Selection materials – UCI-5, UCI-12, UG-11, UCS-10, UCS-11, UCI-3, UCI-1, UG-10 • Inspection and tests – UCI-90, UCI-99, UCI-101, UCI-3 • Repairs in cast iron materials – UCI-78
Ductile cast iron (DI)	**UCD-2**: Not permitted for the following services: (a) Lethal, flammable – liquid or gaseous (b) Unfired steam boilers (c) Direct firing **UCD-3(a)**: Not permitted for all following: 1. DT > 345 °C (650 °F) and MDMT<−29 °C (−20 °F) 2. DP > 7 MPag (1000 psig) unless casting quality factor per UG-24 is >90% and contains liquids only **UCD-3(b)**: Permitted the flanges and fittings which meet ASME B16.43 except that NPS 3–1/2 and smaller screwed and tapped flanges conforming in dimensions to the class 125 ASME B16.1 for CI flanged fittings shall have identical ratings specified in ASME B16.1. **UCD-3(c)**: Permitted the flanges and fittings which are Cl. ≥ #400 and meet ASME B16.5 at DT > 345 °C (650 °F) and MDMT<−29 °C (−20 °F), and DP > 7 MPag (1000 psig).	Para. 323.4.2 • Shall not be used at < −29 °C (−20 °F) (except ADI) or > 343 °C (650 °F) • Welding is not permitted	• Repairs in cast iron materials – UCI-1, UCI-23, UCI-29
Malleable iron (MI)	–	Para. 323.4.2 • Shall not be used at < −29 °C (−20 °F) or >343 °C (650 °F) • Shall not be used in flammable fluid at >149 °C (300 °F) nor >2.8MPag (400psig)	–
High (14–15%) Si iron (HSI)	–	Para. 323.4.2 • Shall not be used in flammable fluid	–

Notes: *ADI* austenitic ductile iron

2.1.3.3 Cast Steels – ASTM A148, A216, A352, A356, A660-Cast Steels), A957-Investment Castings

Cast steel was developed for better toughness, weldability, and machinability by lower carbon (<0.35%). As a result, typically it takes the higher elongation (>20%) and higher reduction of area (>30%). See Sect. 2.6.2.5 for more details on cast steels and cast alloys.

2.1.3.4 Materials Requirements for Casting Components

Table 2.25 shows the comparison of the requirements for casting in pressure vessels (ASME Sec. VIII, Div. 1) and process piping (ASME B31.3).

See some other standards with casting material requirements (other than ASTM, ASME Bxx.xx, ANSI, etc.).

- API Spec 20A – CS, LAS, SS, Ni Alloy Castings for Use in the Petroleum and Natural Gas Industry
- API Spec 5CT – Casing and Tubing
- API Spec 2SC – Manufacture of Structural Steel Castings for Primary Offshore Applications
- BS EN 1011–8 – Welding of Cast Irons
- BS EN10213 – Technical Delivery Conditions for Steel Castings for Pressure Purposes
- BS 1560–3.2 Specification for Cast Iron Flanges
- BSI PD ISO/TR 10809–1 – Cast irons Part 1: Materials and properties for design
- BSI PD ISO/TR 10809–2 – Cast irons: Welding
- BSI PD ISO/TS 10719
- BSI PD ISO/TR 945 – Microstructure of cast irons
- BS ISO 1083 – Spheroidal graphite cast irons — Classification
- BS ISO 19960 – Cast steels and alloys with special physical properties
- AWS D11.2 – Guide for Welding Iron Castings
- MSS SP-53 – Steel Castings for Valves, Flanges, Fittings, and Other Piping Components – MT Method
- MSS SP-55 – Steel Castings for Valves, Flanges, Fittings, and Other Piping Components – Visual Method

2.1.3.5 Typical Mechanical Properties of Cast Irons (Table 2.26)

Table 2.26 Typical mechanical properties of a range of cast irons

Cast iron	T.S (MPa)	Compressive strength (MPa)	Hardness (BHN)	Elongation (%)	Toughness-absorbing energy (J)
White	200–410	Not available	321–500	Very low	Very low
Malleable	276–724	1350–3600 (pearlitic and martensitic)	100–156 (ferritic), 149–321 (pearlitic and martensitic)	1–10	4–12 @ 20 °C
Gray	152–431	572–1293	156–302	<0.6	Very low
Ductile	345–827	359–920	143–302	1–20	16–27 @ 20 °C

Source: ASM Metal Handbook, Vol.1

2.1.3.6 Hot Isostatic Processing (HIP) Castings

HIP is a solid state process which applies heat and pressure simultaneously to objects in an autoclave via an inert gas (e.g., 99.99% Ar with max. 200 ppm impurity) in such a way as to eliminate internal voids and obtain desired properties, such as improved fatigue strength, toughness, ductility, and wear resistance as well as 100% theoretical density and no porosity in casting. It is also applied for diffusion bonding (cladding) of dissimilar metals (see Table 2.91(3/3)). The time, temperature, pressure, and other parameter for hot isostatic processing are normally decided by producer unless otherwise specified by the producer.

See ASTM A1080 (HIP of steel, stainless steel, and related alloy castings) for more details.

2.1.4 Carbon and Low-Alloy Steels

2.1.4.1 Carbon Steels

(a) Grade, Type, Group, and Class

Table 2.27 shows the primary role of several classifications in the *Metals Handbook*. However, the roles include use with more combined characteristics and properties. See Table 2.4 for definition of carbon steel.

(b) Classes by Deoxidation Treatment-Rimmed, Semi Killed, Killed, and Capped Steels (see Table 2.28, Figs. 2.11 and 2.119)

During steel-manufacturing processes, if the oxygen is not removed before or during casting (by adding Si, Al or other deoxidizer) the gaseous products continue to evolve during ingot solidification.

The following elements have characteristics of *deoxidation* in steelmaking.

Table 2.27 Grade, type, group, and class of standard materials

Classification	Role
Grade	Chemical composition
Type	Deoxidization
Group/class	Mechanical properties and others

Source: ASM Metal Handbook Vol.1

Table 2.28 Grades of oxidation in carbon steels (production base)

Item	Killed steel	Semikilled steel	Rimmed steel
O%	<0.003	<0.012	<0.025
C%	<1.5	<1.0	<0.3
Si% and/or Al%	>0.10	0.03–0.16	<0.03
Shrinkage	Large	None	None
Porosity	None (vacuum degassing)	Medium	Much
Segregation	Little	Medium	Much

Source: ASM Metal Handbook Vol.3

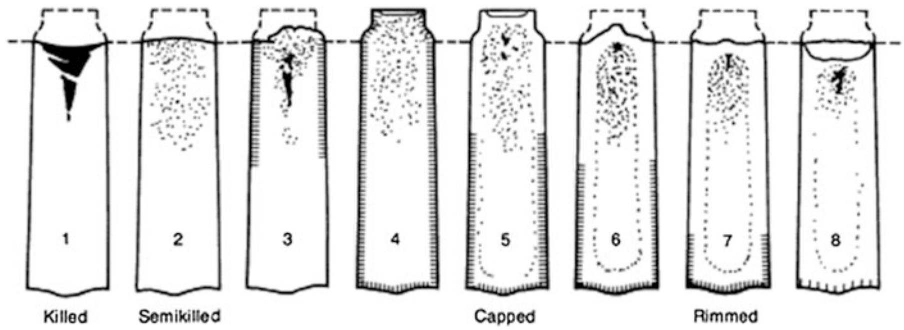


Figure 2.11 Grade of oxidation in carbon steels by Ingot casting. (Source: ASM Metal Handbook Vol.3)

- *Silicon (Si)* is one of the principal deoxidizers; therefore, the amount of Si present is related to the type of steel. Rimmed and capped steels contain no significant amounts of silicon. Semikilled steels may contain moderate amounts of Si, although there is a definite maximum amount that can be tolerated in such steels. When silicon-killed steel is used, it may contain a range of 0.10–0.45% (0.15–0.30% preferable) Si. If the material standard indicates Si $\leq$ 0.40% (or 0.45%) like ASTM A36, it may not be killed steel. If killing for A36 is required, "Killed" shall be specified on the material purchasing requisition. Si is somewhat less effective than manganese in increasing as-rolled strength and hardness. Si has only a slight tendency to segregate. In low-carbon steels, Si is usually detrimental to surface quality, and this condition is more pronounced in low-carbon resulfurized grades. Meanwhile, Si tends to have a coarse grain which is more resistant to degradation at high temperature, such as creep, graphitization, etc. Also, Si-killed steels are preferably used in H_2/H_2S (high temperature sulfidation corrosion) because they have better corrosion resistance than that of Al-killed steels. ASTM A53 pipe, A179 tube, and A285 plate which have no Si limitation should not be used in this service. See Sect. 2.4.3.5 in this book and API RP 939-C, Annex C.
- *Aluminum (Al)* is widely used as a deoxidizer. It is usually used in combination with Si to obtain a semi- or fully killed steel per other goals, such as grain size (Al is a fine grain former and Si a coarse grain former) and corrosion resistance. Even though ASTM standards for steel product do not specify the required Al content, Al killed steel may have 0.02–0.05% Al after killing treatment.
- *Titanium (Ti), Zirconium (Zr), and Vanadium (V)* are also effective grain growth inhibitors. However, for structural grades that are heat treated (quenched and tempered), these three elements may have adverse effects on hardenability because their carbides are quite stable and difficult to dissolve in austenite prior to quenching. The effects of Ti are similar to those of V and niobium (Nb), but it is only useful in fully killed (aluminum-deoxidized) steels because of its strong deoxidizing effects. Zr can also be added to killed high-strength low-alloy steels to obtain improvements in inclusion characteristics, particularly sulfide inclusions where changes in inclusion shape improve ductility in transverse bending.
- *Manganese (Mn), Calcium (Ca), and Cerium (Ce)* are also used as deoxidizers.

The following elements have characteristics of *grain refinement* in steelmaking.

- *Aluminum (Al)* restricts austenite grain growth in reheated steels, so that it is commonly used for "fine grain practice" which has good toughness as well as higher strength. Also, the grain refinement produces better corrosion resistance in cracking environments. Of all the alloying elements, Al is the most effective in controlling grain growth prior to quenching.
- *Niobium [Nb (Cb)] or Vanadium (V)* or both can be substituted for Al in fine grain practice.
- *Titanium (Ti), Tantalum (Ta), and Tungsten (W)* are also used as fine grain former.

The type of steel produced is determined by the control of the amount of gas evolved during ingot solidification. If no gas is evolved, the steel is called "killed" because it lies quietly in molds. The term of "fully killed steel" means perfectly deoxidized steel. The increasing degree of gas evolution results in semikilled, capped, or rimmed steels. The excess oxygen can also form oxide particles in conjunction with Fe and Mn, which reduce notch toughness and impact resistance of the steel.

Most alloy, stainless, and heat-resistant steels are normally manufactured as killed steel.

Vacuum-degassed steel is to subject the molten metal to vacuum to remove out hydrogen, CO_2, and other gases. This process ensures steel is free from hydrogen traps and flakes and can also produce low carbon quality depending on the type of degassing procedure.

Carbon steels used in sour service normally require cleanliness, such as freedom from hydrogen, oxygen, any other contamination.

1. *Killed Steel* – During the steel making process, the molten metal as it comes from the furnace contains more or less oxygen in the form of dissolved oxides, the amount varying with the composition desired and with certain conditions of steel making. If certain elements such as Mn, Si, and Al are added in sufficient amounts to molten steel in the ladle, the metal will solidify quietly without evolution of gases, and is characterized by high composition and property uniformity. When processing rimmed steel and semikilled steel, killed steel is one of the methods of deoxidizing. Killed steel is deoxidized with strong deoxidizing agent(s) to reduce the oxygen content to a minimum so that no reaction occurs between carbon and oxygen during solidification. Usually, killed steel has the best internal cleanliness condition because these types of steels are free from blow holes and segregation. The cost of killing steel is evidently higher than rimmed or capped steel. However, the cost gap was greatly reduced by continuous casting process.
2. *Semikilled Steel* is a type of steel wherein there is a greater degree of gas evolution than in killed steel but less than in capped or rimmed steel. The amount of deoxidizer used (customarily Si or Al) will determine the amount of gas evolved. Semikilled steels generally have 0.15–0.30% C; they are used for a wide range of structural shape applications. The aim of semikilled steel is to produce metal free from surface blowhole in metal. Semikilled steels are characterized by variable degrees of uniformity in composition, which are intermediate between those of killed and rimmed steels. Semikilled steel has a pronounced tendency for positive chemical segregation at the top-center of the ingot. They are used for general applications of structural or non/low-pressure parts.
3. *Capped Steel* has characteristics similar to those of rimmed steels but to a degree intermediate between those of rimmed and semikilled steels. A deoxidizer may be added to effect a controlled rimming action when the ingot is cast. The gas entrapped during ingot solidification is in excess of that needed to counteract normal shrinkage, resulting in a tendency for the steel to rise in the mold. The capping operation limits the time of gas evolution and prevents the formation of an excessive number of gas voids within the ingot. The capping is accomplished by adding Al or ferrosilicon to the top of the ingot, causing the steel at the top surface to solidify rapidly. The top portion of the ingot is discarded. The capped ingot practice is usually applied to steel with carbon contents greater than 0.15% that is used for sheet, strip, wire, and bars.
4. *Rimmed Steel* – Low-carbon steel containing sufficient iron oxide to produce continuous evolution of CO_2 during ingot solidification of outer rim, resulting in a case or rim of metal virtually free of voids. The rim is of somewhat purer composition than the original metal poured. If the rimming action stopped shortly after pouring of the ingot is completed, the metal may be known as capped steel. They exhibit greatest difference in chemical composition across sections and from top to bottom of the ingot. They have an outer rim that is lower in carbon, phosphorus, and sulfur than the average composition of the whole ingot and an inner portion or core that is higher than the average in those elements. Rimmed steel is softer than killed steel with the same C and Mn content. Rimmed steel is also known as drawing-quality steel, and used for general structural applications.

The effect of deoxidation practice on CVN impact energy varies with temperature as shown in Fig. 2.119.

(c) Characteristics of Elements: See Table 2.5 for general characteristics in ferritic steels, Table 2.6 for Q-T steels, Table 2.7 for weldability in CS and LAS, and Table 2.44 for stainless steels.

(d) Tempering Colors of Steel

Different tempering temperatures produce different characteristic colors on clean steel surfaces such as machined parts (i.e., pump shafts). Temper colors will not develop on painted steel or rusty surfaces. The temper colors commonly observed on steel as a function of temperature are shown in Table 2.29.

Table 2.29 Tempering colors of steel

Temper color	Approximate temperature	
	°C	°F
Pale yellow	190	380
Straw yellow	215–225	420–440
Yellowish brown	240–250	460–480
Bluish purple	260–280	500–540
Violet	280–295	540–560
Pale blue	295–305	560–580
Blue	315–340	600–640

Source: API 579–1/ASME FFS-1

2.1.4.2 Low-Alloy Steels (Max. 3%Cr-Mo Steels)

Cr-Mo low-alloy steels have superior properties than CS in strength and erosion and corrosion resistance. Normally, deoxidization treatment (killing) of Cr-Mo steel is similar to that of CS. So, most low-alloy steels for high pressure containing parts require deoxidization treatment in the material standards. Figure 2.12 shows the Cr-Mo heavy wall reactors with 150–300 mm (6–12 in.) thickness for refinery plants.

See Table 2.4 for definition of low alloy steel.

(a) Advantage (Strength) and Disadvantage (Embrittlement) compared to carbon steels

1. Advantage
   – High strength at moderate temperature
   – High creep-rupture strength
   – Higher oxidation temperature
   – Good corrosion resistance in hydrocarbon processes
   – Good corrosion resistance in hydrogen attack at high temperatures
   – Good erosion resistance
2. Disadvantage

   These materials are subject to the following risks during fabrication (including welding and heat treatment) and operation:
   – Reheat/stress relaxation (SR) crack
   – Temper embrittlement – heavy wall and 2–3%Cr steel is more susceptible than 1.25%Cr steel.

Figure 2.12 Cr-Mo steel reactors with 150–300 mm (6–12 in.) thickness. (Source: Doosan and JSW brochures, 2005)

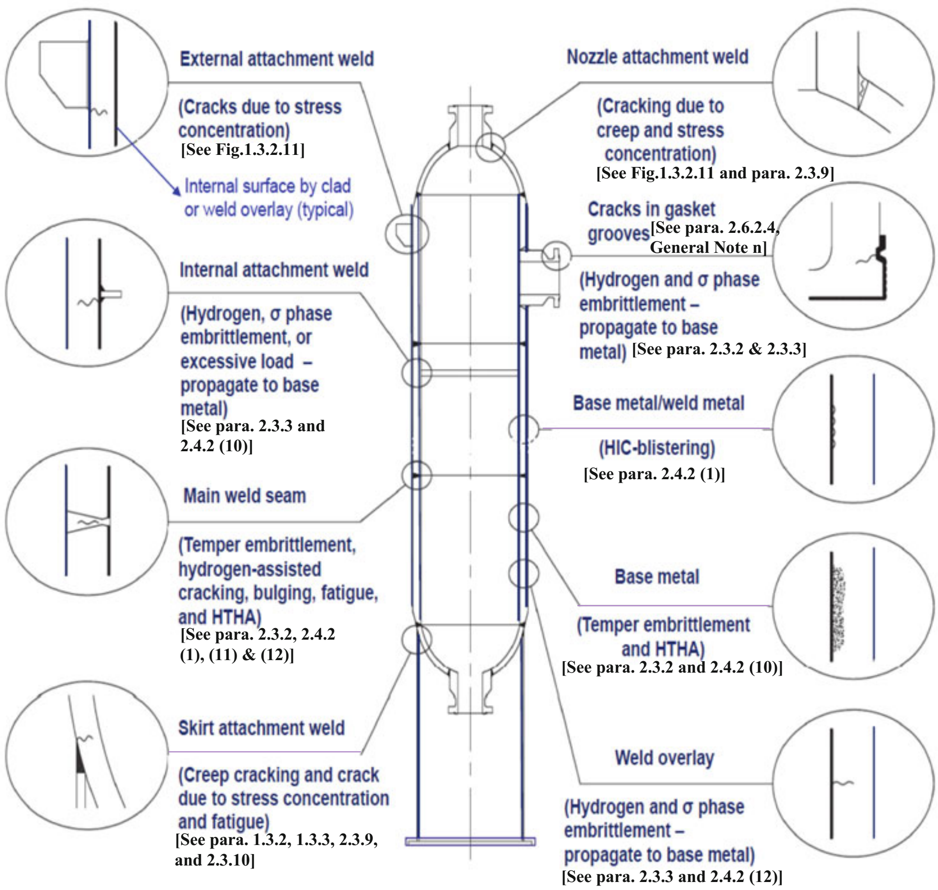


Figure 2.13 Common failures of equipment made by Cr-Mo steels in refining service. (Source: ASME PCC-2, 2015 modified)

– Brittle/low toughness (MDMT is higher than CS)
– Bad weldability compared to low carbon steels
– Higher material cost and delivery impact compared to CS
– More susceptible to hydrogen embrittlement compared to CS

See Fig. 2.13 for typical failure of Cr-Mo vessels.

Table 2.30 shows the characteristics of Cr-Mo-V steels.

(b) Classes of Cr-Mo Steels in Oil and Gas Industries – See Table 2.31.

Table 2.32 shows ASTM Specifications (API TR934-D, Table 5a modified) for Cr-Mo steels. The Allowable Stresses for ASME Sec. VIII, Div.1 (API TR934-D, Table 6 modified) for Cr-Mo steel are shown in Table 2.33. Table 2.34 shows the typical properties of Cr-Mo-V steels in Hydrocarbon Process and Power Plants.

Figures 2.14 and 2.15 show V effect for creep rupture strength of several Cr-Mo-V steels and ISR effects for toughness of 2.25Cr-1Mo-V steels, respectively. They indicate that V is the most effective in 2.25Cr steel for creep-rupture resistance, 660 °C (1220 °F) of

Table 2.30 Characteristics of Cr-Mo-V steels(1)

Advantage	Trend	Cautions	Challenge for future
– Higher design stress intensity values – Improved resistance to hydrogen attack – Improved susceptibility to temper embrittlement – Thinner lighter reactors	– Designers will take advantage of designing for 482 °C (900 °F) of DT. – Designers will take advantage of designing for higher H_2 partial pressures. – Designers will take advantage of thinner walls & lower weights of reactors. – Reactor alloy of the future is expected to be 2.25Cr-1Mo-0.25 V.	– Preheat and method of application – PWHT – Weld metal hardness – Need for ISR in lieu of DHT for restrained joints – Consideration of low "as-deposited" weld metal toughness – Some reduction in low temperature toughness	– Improvement in as-welded weld toughness – Further development of fabrication and welding technology and improved fabrication methods – More experienced fabricators – Ability of plate suppliers to supply thicker, wider & heavier plates with these considerations we see an increasing degree of utilization of 2.25Cr-1Mo-0.25 V alloy plate for reactor & other vessel fabrication.

Note: (1)See API TR 934-B for more detail

Table 2.31 Materials group in Cr-Mo steel products in hydrocarbon processes and power plants(1)

Materials group	State	P No./ Gr. No.	Plate	Forgings	Pipe/Tube	Pipe (forged or bored)	Fitting
1 Cr-0.5Mo	C	4/1	A387 Gr. 12, Cl.*	A182 Gr. F12, Cl.* A336 Gr. F12	A335 Gr. P12 (s) A213 T12 (s) A691 Gr. 1CR (w)	A369 Gr. FP12	A234 Gr. WP12, Cl*
1.25Cr-0.5Mo(2)	C	4/1	A387 Gr. 11, Cl.*	A182 Gr. F11, Cl.** A336 Gr. F11, Cl.** A541 Gr. 11, Cl.4	A335 Gr. P11 (s) A213 T11 (s) A691 Gr. 1 ¼CR (w)	A369 Gr. FP11	A234 Gr. WP11, Cl.1, 2, 3 A217-WC6 (cast)
2.25Cr-1Mo	C	5A/1	A387 Gr. 22, Cl.*	A182 Gr. 22, Cl.1,3 A336 Gr.F22, Cl.1,3	A335 Gr. P22 (s) A213 T22 (s) A691 Gr. 2 ¼CR (w)	A369 Gr. FP22	A234 Gr. WP22, Cl.1, 3 A217-WC9 (cast)
2.25Cr-1Mo enhanced	A	5A/1	A542 type B, ***	A508 Gr. 22, Cl.3 A541 Gr. 22, Cl.3,4,5			
2.25Cr-1Mo-0.25 V	A	5C/1	A542 type D, *** A832 Gr. 22V	A182 Gr. F22V A336-Gr. F22V A541 Gr. 22V			
3 Cr-1Mo	C	5A/1	A387 Gr. 21, Cl.*	A182 Gr. 21 A336 Gr. F21, Cl.3	A335 Gr.P21 (s) A213 T21 (s) A691 Gr.3CR (w)	A369 Gr. FP21	
3 Cr-1Mo-0.25V-Ti-B	A	5C/1	A542 type C, *** A832 Gr. 21V	A182 Gr. F3V A336 Gr. F3V A508 Gr. 3V A541 Gr. 3V			
3 Cr-1Mo-0.25V-Cb-Ca	A	5C/1	A542 type E, *** A832 Gr. 23V	A182 Gr. F3VCb A336 Gr. F3VCb A508 Gr. 3VCb A541 Gr. 3VCb			
5Cr-0.5Mo	C	5B/1	A387 Gr. 5, Cl*	A182 Gr. F5 A336 CI. F5	A335 Gr. P5 (s) A213 T5/T5b/T5c(s) A691 Gr. 5CR (w)	A369 Gr. FP5	A234 Gr.WP5, Cl.1,3 A217 Gr. C5 (cast)
9Cr-1Mo	C	5B/1	A387 Gr. 9, Cl*	A182 Gr. F9 A336 CI. F9	A335 Gr. P9 (s) A213 T9 (s) A691 Gr. 9CR (w)	A369 Gr. FP9	A234 Gr. WP9, Cl.1, 3 A217 Gr. C12 (cast)
9Cr-1Mo-V-Cb(3)	M	15E/1	A387 Gr. 91, Cl.2	A182 Gr. F91 A336 CI. F91	A335 Gr. P91 A213 T91 A691 Gr.91CR (w)	A369 Gr. FP91	A234 Gr. WP91 A217 Gr. C1.12A (cast)
9Cr-1Mo-V-W	M	15E/1	A387 Gr. 911, Cl.2	A336 CI. F911	A335 Gr. P92 (s) A213 T92 (s)		

Abbreviation: *C* conventional, *A* advanced, *M* modified, *(s)* seamless, *(w)* welded, * 1 and 2, ** 1, 2, and 3, *** 1, 2, 3, 4, and 4a

Notes

(1)Most Cr-Mo steels which are subjected to the increased toughness requirements are now produced to fine grain practice (as defined in ASTM A941), vacuum degassed, with lower phosphorus (P) and sulfur (S) contents, and with particular emphasis on the reduction of the residual elements, as monitored by the X-bar factor (see Sect. 2.1.4.2(c))

(2)The allowable design stresses of Class 1 for ASME Sec. VIII at high temperatures (creep range) are the same with Class 2 properties for plates (and Class 3 properties for forgings and fittings), therefore, there is no need to use the higher tensile strength grades in the creep range. The use of the Class 1 properties for these vessels also permits somewhat higher PWHT temperatures than the higher strength grades (Class 2 or 3). Consequently, there is less risk of brittle fracture of the API 934-E vessels because of the lower strength of the Class 1 materials and the lower operating stresses and, therefore, less need for the higher energy values in API 934-C. However, all vessels must have adequate notch toughness for vessel fabrication and particularly for hydro-testing. In no

case that should be 7less than ASME Code requirements, preferably not less than 27 J (20 ft-lb) minimum average values in the direction transverse to the major direction of work of plates or forgings. Class 2 and Class 3 materials are generally produced in the quenched and tempered (Q-T) condition, particularly in thicknesses over about 50 mm (2 inches) to be able to meet the notch toughness and tensile strength requirements with PWHT temperatures at 690 °C ± 14 °C (1275 °F ± 25 °F) and multiple PWHT cycles, particularly in thicknesses over 50 mm (2 inches). Class 1 plates produced in normalized and tempered (N-T) condition can be stress relieved at higher PWHT temperatures than Class 2 plates or Class 2 or Class 3 forgings. However, the higher PWHT temperatures for Class 1 materials (which typically have lower carbon contents) may reduce their toughness. The steel producers cannot use the low carbon steel (which is desirable for improved toughness in Cr-Mo steels) for high PWHT temperatures. Such Class 1 plates may need to be Q-T to meet the toughness requirements (See API TR934-D).
(3)Table 2.31a

Table 2.31a Europe Standards for Grade 91 materials

Material specification and grade	Country	Description/Title
DIN 17175, VdTUV511/2, X10CrMoVNb9–1	Germany	Seamless tubes made from heat-resistant steels
BS 3604–2, Grade 91 (now withdrawn)	UK	Steel pipe and tubes for pressure purpose, ferritic alloy steel with specified elevated temperature properties
BS 3059–2, Grade 91 (now withdrawn)	UK	Steel boiler and superheater tubes; Part 2 specification for carbon alloy and austenitic stainless steel tubes with specified elevated temperature properties
EN 10216–2, X10CrMoVNb9–1 Steel No 1.4903	Europe	Seamless steel tubes for pressure purposes technical conditions of delivery; Part 2 ferritic and martensitic steels with specified elevated temperature properties
EN 10222–1:1998, X10CrMoVNb9–1 Steel No 1.4903	Europe	Steel forgings for pressure purposes – Part 1: General requirements for open die forgings
EN 10222–2:2000, X10CrMoVNb9–1 Steel No 1.4903	Europe	Steel forgings for pressure purposes – Part 2: Ferritic and martensitic steels with specified elevated temperature properties

Table 2.32 ASTM specifications (API TR934-D, Table 5a modified)

Products	Material spec	Grade	Class	Grain size control	Heat treatment	TS MPa (ksi)	SMYS, min MPa (ksi)
Plate	A387	11	1		Annealed or N-T	415–585 (60–85)	240 (35)
			2		N-T or Q-T	515–690 (75–100)	310 (45)
		12	1		Annealed or N-T	380–550 (55–80)	230 (33)
			2		N-T or Q-T	450–585 (65–85)	275 (40)
Forged	A182	F11	1		Annealed or N-T	≥415 (60)	205 (30)
Fittings			2		Annealed or N-T	≥485 (70)	275 (40)
			3		Annealed or N-T	≥515 (75)	310 (45)
		F12	1		Annealed or N-T	≥415 (60)	220 (32)
			2		Annealed or N-T	≥485 (70)	275 (40)
Forgings	A336	F11	1		Annealed or N-T or Q-T	415–585 (60–85)	205 (30)
			2		Annealed or N-T or Q-T	485–655 (70–95)	275 (40)
			3		Annealed or N-T or Q-T	515–655 (75–95)	310 (45)
		F12			Annealed or N-T or Q-T	485–655 (70–95)	275 (40)
Piping	A234	WP11	1	CGP or FGP	Annealed or N-T or Q-T	415–585 (60–85)	205 (30)
Fittings			2	CGP or FGP	Annealed or N-T or Q-T	485–655 (70–95)	275 (40)
			3	CGP or FGP	Annealed or N-T or Q-T	515–655 (75–95)	310 (45)
		WP12	2	CGP or FGP	Annealed or N-T or Q-T	485–655 (70–95)	275 (40)
Pipe	A335	P11		CGP		≥415 (60)	205 (30)
		P12				≥415 (60)	220 (32)
Tubes	A213	T11			Annealed or N-T	≥415 (60)	205 (30)
		T12			Annealed or N-T	≥415 (60)	220 (32)

Legend
CGP coarse grain practice, *FGP* fine grain practice, *N-T* normalized and tempered, *Q-T* quenched and tempered, *Blank.* not specified

Table 2.33 Allowable stresses for 1–1.25Cr steels in ASME Sec VIII, Div.1 (API TR934-D, Table 6 modified), Unit: MPa (ksi)

	At Temperature, °C (°F)									
Material Spec.	−18 to 38 (−20 to 100)	93 (200)	371 (700)	399 (750)	427 (800)	454 (850)	482 (900)	510 (950)	538 (1000)	566 (1050)
A387-Gr.11, Cl.1	118 (17.1)	118 (17.1)	118 (17.1)	118 (17.1)	116 (16.8)	113 (16.4)	94 (13.7)	64 (9.3)	43 (6.3)	29 (4.2)
A387-Gr.11, Cl.2	148 (21.4)	148 (21.4)	148 (21.4)	148 (21.4)	148 (21.4)	139 (20.2)	94 (13.7)	64 (9.3)	43 (6.3)	29 (4.2)
A387-Gr.12, Cl.1	108 (15.7)	106 (15.4)	104 (15.1)	104 (15.1)	104 (15.1)	104 (15.1)	101 (14.7)	78 (11.3)	50 (7.2)	31 (4.5)
A387-Gr.12, Cl.2	128 (18.6)	126 (18.2)	123 (17.9)	123 (17.9)	123 (17.9)	123 (17.9)	120 (17.4)	78 (11.3)	50 (7.2)	31 (4.5)

Table 2.34 Typical properties of Cr-Mo-V steels in hydrocarbon process and power plants[1] (API TR934-B)-modified

ASME/API-Item	2.25Cr-1Mo	Enhanced 2.25Cr-1Mo[a]	2.25Cr-1Mo-V	3Cr-1Mo	3Cr-1Mo-0.25 V-Ti-B	3Cr-1Mo-0.25 V-Cb-Ca
ASME Mat'l spec or code case	SA-336-F22,Cl.3 (F) SA-387-22,Cl.2 (P)	SA-508–22,Cl.3 (F) SA-542-B,Cl.4 (P) Formerly code case 1960	SA-336,Gr.F22V (F) SA-541,Gr.22V(F) SA-542-D,Cl.4a(P) SA-832-22V(P) Formerly code case 2098	SA-336-F21,Cl.3 (F) SA-387-Gr.21,Cl.2 (P)	SA-336-F3V (F) SA-542-C, Cl.4a (P) Formerly code case 1961	SA-336-F3VCb (F) SA-542-E, Cl.4a (P) Code case 2151–1
P no./Gr.no.	5A/1	5C/1	5C/1	5A/1	5C/1	5C/1
Sec.VIII, div.1, max. Allowable temp.	649 °C (1200 °F)	454 °C (850 °F)	482 °C (900 °F)	649 °C (1200 °F)	482 °C (900 °F)	482 °C (900 °F)
Sec.VIII, Div.2, max. Allowable temp.	649 °C (1200 °F)	454 °C (850 °F)	482 °C (900 °F)	649 °C (1200 °F)	454 °C (850 °F)	454 °C (850 °F)[b]
T.S @ room temp.	515–690 MPa (75–100 ksi)	585–760 MPa (85–110 ksi)	585–760 MPa (85–110 ksi)	515–690 MPa (75–100 ksi)	585–760 MPa (85–110 ksi)	585–760 MPa (85–110 ksi)
Y.S @ room temp.	310 MPa (45 ksi)	380 MPa (55 ksi)	415 MPa (60 ksi)	310 MPa (45 ksi)	415 MPa (60 ksi)	415 MPa (60 ksi)
Sec.VIII, Div.2, design stress intensity value[2]	151 MPa @ 454 °C (21.9 ksi @ 850 °F) 117 MPa @ 482 °C (17.0 ksi @ 900 °F)	151 MPa @ 454 °C (21.9 ksi @ 850 °F) N/A @ 482 °C (N/A @ 900 °F)	199 MPa @ 454 °C (28.9 ksi @ 850 °F) 164 MPa @ 482 °C (23.8 ksi @ 900 °F)	131 MPa @ 454 °C (19.0 ksi @ 850 °F) 90 MPa @ 482 °C (13.1 @ 900 °F)	178 MPa @ 454 °C (25.8 ksi @ 850 °F) 145 @ 482 °C (21.0 @ 900 °F)	164 MPa @454 °C[b] (23.8 ksi @850 °F)[b] N/A@482 °C (900 °F)
API RP941, Fig. 1 temp. Limit for >13.8 MPa HTHA service	454 °C (850 °F)	454 °C (850 °F)[c]	510 °C (950 °F)[c]	510 °C (950 °F)[c]	510 °C (950 °F)[c]	510 °C (950 °F)[c]

Notes:
[1](F) Forgings, (P) Plates, See Tables 2.31a and 2.38 for Applicable Codes/Standards and Code Cases of 9Cr-Mo/W-(V) steels
[2]Depending on the design temperature, use of these allowables may require extra design analysis and weld procedure qualifications with stress rupture tests per ASME Sec. VIII, Div. 2, Chap. 3 and 4, and Code Case 2605
Commentary Notes:
[a]Q-T Steel without Vanadium
[b]Not Specified in Sec. II, Part D (2017) even though Code Case 2151–1 (approved Mar.10, 1997, effective Mar.11, 2005) was issued as shown
[c]At least 14 °C (25 °F) should be lower than the maximum temperature limits in the applicable codes (e.g., Sec. VIII, Div.1 or 2) for effective industrial practice

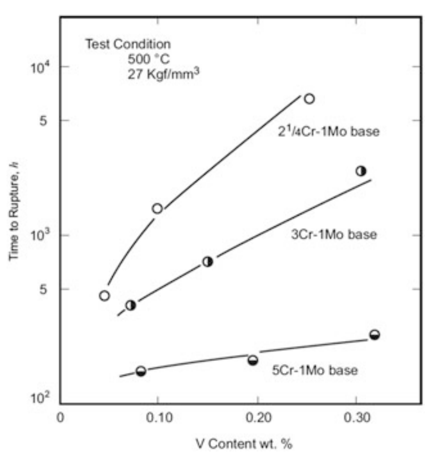


Figure 2.14 V Effect for Creep Rupture Strength of Cr-Mo-V Steels (API TR934-B)

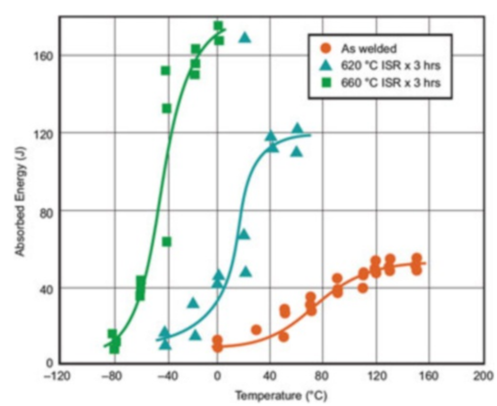


Figure 2.15 ISR effects for toughness of 2.25Cr-1Mo-V steels deposited weld metal after ISR using a second alternative wire flux combination (API TR934-B)

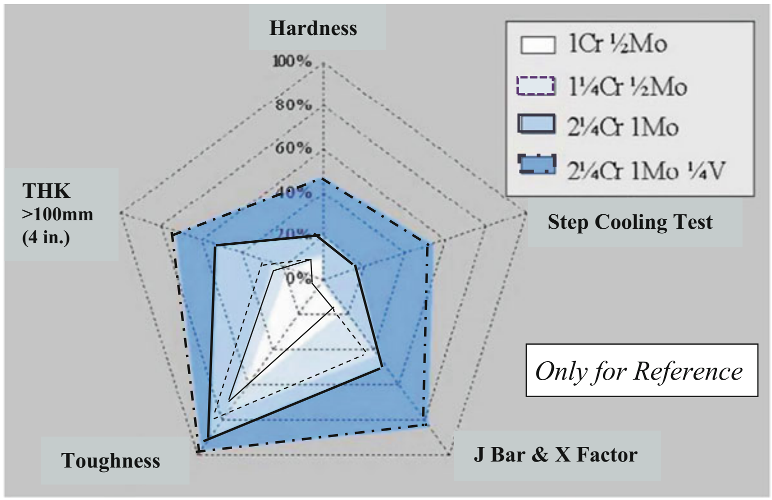


Figure 2.16 Comparison of additional requirements of several Cr-Mo-(V) steels. (Source: Drillinger Hütte GTS, 2010)

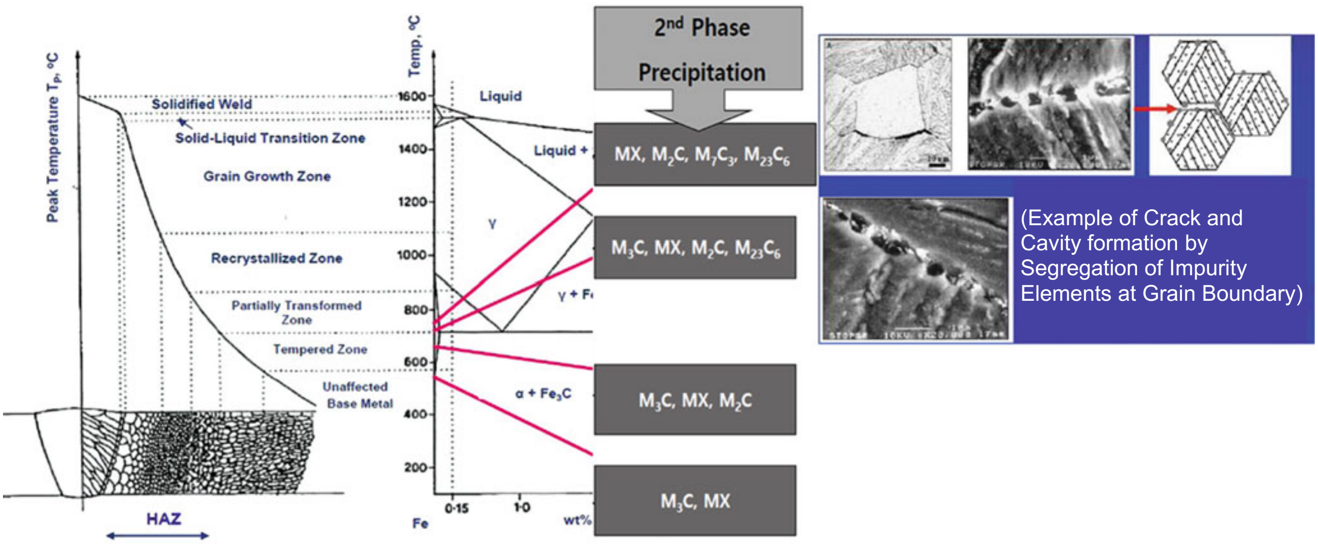


Figure 2.17 2nd phase precipitations in heavy wall Cr-Mo steels during welding/PWHT/long-term service

ISR is the most effective to improve the toughness in 2.25Cr-1Mo-V steel. Figure 2.16 shows the comparison of additional requirements of several Cr-Mo-(V) steels from a mill supplier's point of view. V-enhanced steel needs more requirements compared to conventional Cr-Mo steels.

(c) Temper Embrittlement

1. Temper embrittlement is a problem associated with tempered alloys and steels (Cr-Mo, Ni-Cr, and Ni-Cr-Mo) that are heated within, or slowly cooled through, a critical temperature range, generally 343–577 °C (650–1070 °F) or a prolonged time in that temperature range for Cr-Mo steels (Fig. 2.17a). The rate of temper embrittlement is a function of temperature, increasing as the temperature increases. Temper embrittlement is manifested by a large increase in the ductile-to-brittle transition temperature and fracture along prior austenite grain boundaries. The upper shelf energy value generally is not affected.

   Eventually this embrittlement causes a decrease in toughness (low impact absorbing energy).

   Temper embrittlement is reversible. Severely embrittled material may be de-embrittled by heating for a short time above the embrittling temperature range, followed by quenching. This is not a permanent solution and re-embrittlement with additional time in the temper embrittling range will occur.

   Particularly it occurs in heavy section components for pressure vessels or turbine rotors, which slowly cool down through the embrittlement range after tempering and in operating service at temperatures within the critical range (see Table 1.71 and 4.113). Normally, temper embrittlement does not occur in plain carbon steels. Table 2.35 and Fig. 2.17 indicate the characteristics of several embrittlement of heavy wall 1 to 3Cr-0.5 to 1.0Mo Steels exposed to high temperature.

Table 2.35 Several embrittlements due to high temperature in heavy wall 1 to 3Cr-0.5 to 1.0Mo steels (API 934 series)

Item	Temper embrittlement	Stress relaxation cracking	Low creep ductility (LCD)/Cracking
Susceptible materials & THK	2–3Cr >1–1.5Cr THK: ≥50 mm (2″) typically, but sometimes ≥25 mm (1″)	1–1.5Cr >2–3Cr THK: ≥50 mm (2″) typically, but sometimes ≥25 mm (1″)	1–1.5Cr >2–3Cr
Susceptible temperature & exposure time	After long-term service at 343–577 °C (650–1070 °F) At >440 °C (825 °F), creep/LCD embrittlement will be governed for 1–1.5Cr	Excessive heat treatments/welding (SAW) and/or after long-term service at >454 °C (850 °F). At >440 °C (825 °F), creep/LCD embrittlement will be governed for 1–1.5Cr	At HAZ has low ductility and creep strain tolerance after long-term service at >440 °C (825 °F)
Mechanisms	Segregation[(1)]	Carbide precipitation[(3)] (see Fig. 2.17) and/or segregation[(1)]	Segregation[(1)] and/or carbide agglomeration at grain boundaries.
Degradation	Toughness, low creep ductility	Toughness, creep strength, creep crack propagation-increased (after long term service)	Creep ductility and strength
Susceptible locations and equipment[(2)]	Welds and HAZ, e.g., brittle fracture occurs during start-up, shutdown, or hydrotest after weld repair in refinery plants	HAZ (mainly) or base metal, e.g., FCC and catalytic reforming reactors-refinery More susceptible in heavier THK and higher residual stressed	HAZ or base metal (intergranular fracture) e.g., FCC reactors & regenerators, catalytic reforming reactors, several heater tubes-refinery
Prevention, measurement, or tests	[Base metal/WPS-PQR] chemical composition[(4)], normalizing/vacuum degassing, welding (Sect. 4.11.3), additional heat treatment & impact test – Fig. 2.21 (2-3Cr) [production] DHT/(2-3Cr) ISR, step cooling test – Figs. 2.18 and 2.19	[Base metal/WPS-PQR] higher Mn (up to 1.5%), increase weld metal ductility. Larson-miller parameter (LMP) –Sect. 1.3.3.1 RCS index – Sect. 2.1.4.2(d) [production] NDE per ASME Sec.VIII-Div.2.	[Base metal/WPS-PQR] chemical composition[(4)] Larson-miller parameter (LMP) – Sect. 1.3.3.1 [production]

Notes:
[(1)]Segregation elements to grain boundary: As, Cu, P, B, Sb, Sn, Nb, V, Ti, etc.
[(2)]Embrittlement at Weld & HAZ depends on the thickness. Heavier thickness, more susceptible
[(3)]Precipitate carbides of Mo, Nb, V, Ti in grain boundary
[(4)]Chemical composition of steel: J factor & X-bar, including P control (max. 0.007% or 0.010%). See Table 2.36 for more details

Eventually this embrittlement causes a decrease in toughness (low impact absorbing energy).

Temper embrittlement is reversible. Severely embrittled material may be de-embrittled by heating for a short time above the embrittling temperature range, followed by quenching. This is not a permanent solution and re-embrittlement with additional time in the temper embrittling range will occur.

Particularly it occurs in heavy section components for pressure vessels or turbine rotors, which slowly cool down through the embrittlement range after tempering and in operating service at temperatures within the critical range (see Table 1.68 and 4.113). Normally temper embrittlement does not occur in plain CS.

2. API RP934-A/C/E, WRC Bulletin 275, ASTM STP-407 & 755, and ASME Sec.II-part D, A-203 for temper embrittlement of Cr-Mo steels

The usual method of reducing or avoiding temper embrittlement is to restrict the amounts of trace elements that may be present in the steel, such as C, P, S, Cu, Ni, as shown in Table 2.36.

The screening test with step cooling heat treatment (see below) may be followed by the following chemical composition control (parameter J factor and X bar factor below) to prevent temper embrittlement in Cr-Mo ($2\% < Cr < 3\%$) steels. The screening test may take more than 15 days (10 days for net holding time).

Step Cooling Heat Treatment

See Fig. 2.18 for each heat of plate and/or forging, and for weldments consisting of each batch or heat of weld consumables, covered electrodes, and wire-flux combinations for each weld process.

Acceptance

vTr40 + 2.5 (ΔvTr40) ≤0 °C (32 °F) for base metal and HAZ (heat affected zone),
vTr40 + 2.5 (ΔvTr40) ≤10 °C (50 °F) for weld metal,
vTr40; 55 J (40 ft-lbs) transition temperature (by CVN impact test @ −29 °C (−20 °F)) of the materials subjected to the min. PWHT,
ΔvTr40; the shift of 55 J (40 ft-lbs) transition temperature [by CVN impact test @ −29 °C (−20 °F)] of the materials subjected to the max. PWHT (min. PWHT plus step cooling).
Note: Specified heat treatment used to simulate and accelerate embrittlement of test specimens for the purpose of evaluating the potential for temper embrittlement of alloy steels in high-temperature service.

API RP934-A says the step cooling tests (Figs. 2.18 and 2.19) of the base metals are not mandatory. If the purchaser decides to impose the step cooling test, the test procedure and the acceptance criteria should be in accordance with para. 6.2.3 of API RP934-A. The purchaser may

Table 2.36 Requirements to prevent high temperature embrittlement and segregation in heavy wall Cr-Mo steels

Item	1.25%Cr Steel (≤ 440 °C (825 °F)		1.25%Cr Steel (>440 °C (825 °F)		2–3%Cr Steel (>345 °C (650 °F)	
	Base metal[1]	Welding consumable	Base metal[2]	Welding consumable	Base metal[2]	Welding consumable
$J = (Si + Mn) (P + Sn) \times 10^4$ [elements: Wt %]	N/A	N/A	N/A	N/A	100 max.	N/A
X = (10P + 5Sb + 4Sn + as)/100 [elements: Ppm]	15 max.	15 max.	15 max.	15 max.	N/A	15 max.
Additional requirements	Fine grain, vacuum degas. C ≤ 0.15%, P ≤ 0.010%[3], S ≤ 0.007%[3], Cu ≤ 0.20%, Ni ≤ 0.30%,	C ≤ 0.15%, Cu ≤ 0.20%, Ni ≤ 0.30%	Requirements for ≤ 440 °C (825 °F) in 1.25Cr plus; Nb ≤ 0.006%, V ≤ 0.025%, Ti ≤ 0.02%	C ≤ 0.15%, Cu ≤ 0.20%, Ni ≤ 0.30%	Fine grain, Vacuum degas. Cu ≤ 0.20%, Ni ≤ 0.30%, Ni ≤ 0.25% only For advanced steel	Cu ≤ 0.20%, Ni ≤ 0.30%,
Remark (recommendation for forging reactor)	Sb ≤ 0.0025%, as≤0.010%,		Sb ≤ 0.0025%, As≤0.010%,			

Source: API 934 RP/TR series

Notes:

[1]for plate or forging unless otherwise specified

[2]For plate, pipe, or forging unless otherwise specified

[3]*P ≤ 0.012% and S ≤ 0.012%* for piping, pipe flanges/fittings

Commentary Note: [a] Some company/project specifications may require more stringent acceptant limitations

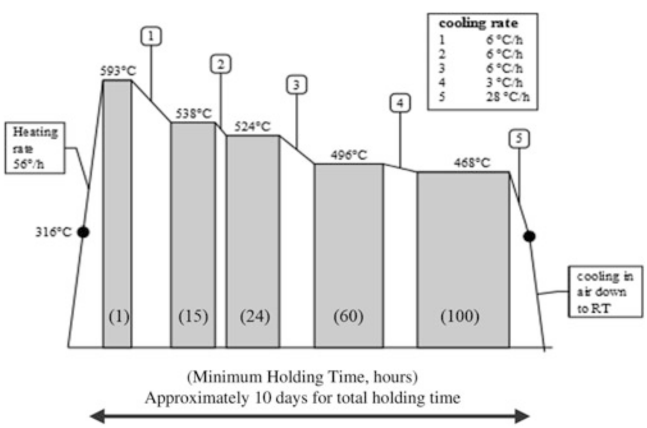


Figure 2.18 Step cooling heat treatment (API RP934-A)

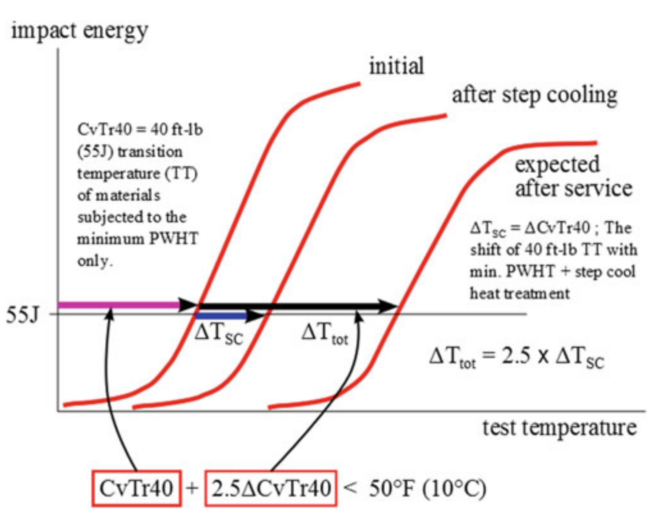


Figure 2.19 Change of impact energy after step cooling heat treatment (API RP934-A)

opt to require that the step cooling tests be performed only on the heat with the highest J-factor. API RP934-A also says in lieu of the step cooling tests, the purchaser may require impact testing at −62 °C (−80 °F) with results 55 J (40 ft-lbs) average minimum and no single value below 47 J (35 ft-lbs). The percent ductile fracture and lateral expansion in mils should also be reported.

3. Hot tensile tests
   Hot tensile tests (ASTM E21) shall be performed at the equipment design temperature (DT). Test specimen shall be in the maximum PWHT condition. Some companies suggest the acceptance criteria for hot tensile test values shall be min. 90%* of values listed in ASME Sec. II, Part D, Table U for hot tensile test required in API RP934A/C [no less than 2.73 times* the design stress intensity value at DT from Table 2A (for Div. 2 Vessel) of ASME Sec.II, Part D]. * only recommendation.

(d) Reheat Cracking and Low Creep Ductility (LCD as Creep Embrittlement) Cracking.

1. Reheat Cracking – Unlike temper embrittlement, reheat cracking in Cr-Mo steels which is recognized as a failure during fabrication (welding – mostly SAW and/or heat treatment) may occur during SAW process for 2.25Cr-1Mo-V heavy wall equipment unless flux/wire screening tests and/or Gleeble test are successfully performed. See Table 2.35 for more details.

   Figure 2.20 shows schematic phenomena of reheat cracking after SAW process of 2.25Cr-1Mo-V steel.

   The susceptibility of reheat cracking in Cr-Mo steel has been proposed by H. Nakamura et al.

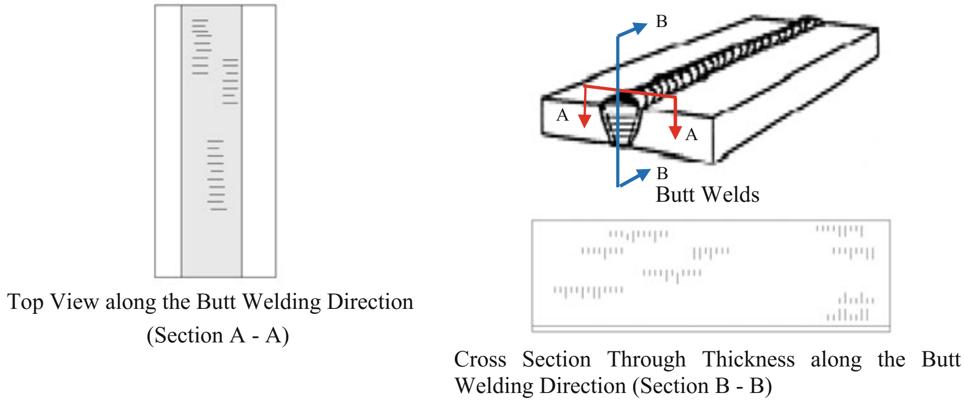


Figure 2.20 Schematic of reheat cracking of 2.25Cr-1Mo-V SAW welds. (Source: API RP934-A)

(International Institute of Welding Commission Document No. 9–648-69) in 1969 as below.

; RCS (reheat cracking susceptibility) = %Cr + 3.3 × (%Mo) + 8.1 × (%V) – 2

When the value of RCS is equal to or greater than zero, the steel may be susceptible to reheat cracking.

In the 2010s, several researchers have proposed "K factor" (Key factor) which is a good indicator to avoid reheat cracking of 2.25Cr-1Mo-V reactors (for welding consumables).

; K factor (Kf) = Pb + Bi +0.03Sb ≤1.5 ppm (element: ppm) [API TR934-B].

When Kf is higher than 1.5 ppm, it can have detrimental effects on weld metal and reduce the ductility at high temperatures [>620 °C (1150 °F)]. API RP934-A does not adopt this formula yet because of the weak accuracy in a few ppm (or ppb) of elements.

[UT Inspection]

See API RP934-A, Annex A for Guideline for Inspection for Transverse Reheat Cracking and ASME Sec. VIII, Div.2, 7.5.4.1 (e) for UT requirements in SAW welds in 2.25Cr–1Mo–0.25 V vessels.

See Tables 5.15, 5.16, and 5.23, part UT-TOFD and PAUT in lieu of RT.

2. Low Creep Ductility (LCD as Creep Embrittlement) Cracking: See Tables 2.35 and 2.36 for more detail.

(e) Additional Heat Treatment for 2.25 to 3Cr-1Mo steel pressure vessels (ASME Sec. VIII, Division 1, Mandatory Appendix Fig. 31.1/ ASME Sec. VIII, Div. 2, Fig. 3.1).

This Appendix covers special fabrication and testing rules for 2.25 to 3Cr-1Mo steels for which tightly controlled welding and heat treatment procedures are of particular importance (by end-users' decision). The materials and appropriate specifications covered by the ASME Sec. VIII-Division 1, Fig. 31–1 and ASME Sec. VIII-Div. 2, Fig. 3.1. Figure 2.21 shows the supplemental tension & CVN impact test specimen after final heat treatment. See Sect. 4.11.3 for requirements of the WPS in these materials.

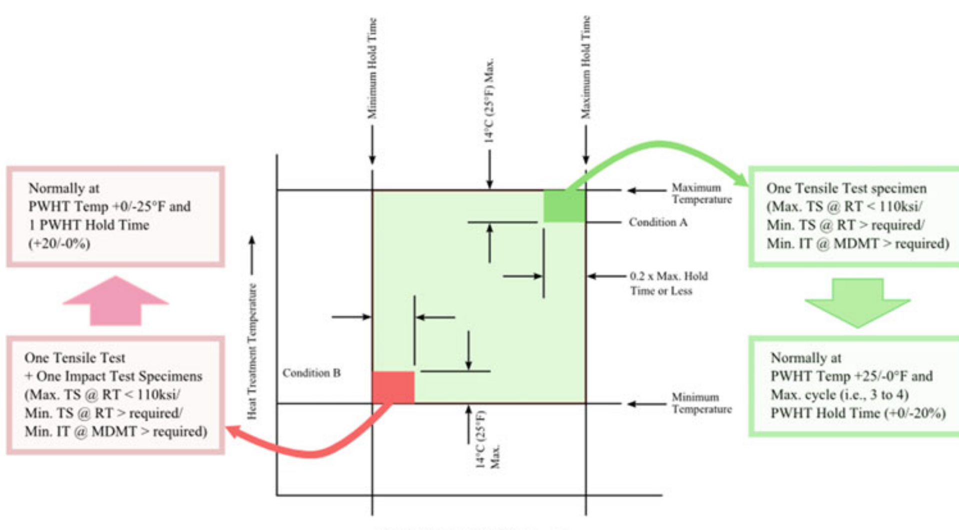


Figure 2.21 Supplemental tension-CVN impact test specimen after final heat treatment of 2.25 to 3Cr – 1Mo-(V, Ti, B, Cb, Ca) steels in ASME Sec. VIII-Div.1, Fig. 31–1/ASME Sec. VIII-Div.2, Fig. 3.1

Condition A (one set each of the tension specimens): Temperature shall be no lower than the actual maximum vessel-portion temperature, less 15 °C (25 °F) Time at temperature shall be no less than 80% of the actual hold time of the vessel-portion exposed to the maximum vessel-portion temperature.

Condition B (second set each of the tension specimens and one set each of CVN impact specimens): Temperature shall be no higher than the actual minimum vessel-portion temperature, plus 15 °C (25 °F). Time at temperature shall be no more than 120% of the actual hold time of the vessel-portion exposed to the minimum vessel-portion temperature.

The minimum toughness requirements (minimum absorbing energy values for full size CVN, transverse direction-preferable at the MDMT) for base metal, weld metal, and HAZ, after exposure to the simulated postweld heat treatment Condition B, should be 40 ft-lb and 35 ft-lb for average of three specimens and only one in set respectively.

(f) Toughness and Thickness Limitation of 1.25 Cr-0.5Mo Steel

Whereas most problems due to toughness loss in the refining and petrochemical industries were related to pressure vessels, the electric power industry experienced cracking in longitudinal weld seams of high temperature steam lines, which operated primarily at or above approximately 454 °C (850 °F). Most cracking was predominantly in heat-affected zones (HAZ) and was intergranular. In some cases (heavy wall) where CVN toughness measurements could be made low toughness values were also reported. Low toughness values in the range of 5–10 ft-lb (at room temperature) were reported for both plate material and forgings.

Therefore, the maximum thickness of 1.25Cr-0.5Mo plates is limited because of this alloy's hardenability properties, which leads to lower toughness than the 2.25Cr-1Mo plates. The addition of Cr and Mo aids in increasing the hardenability of the material by forming carbides. These carbides reduce the growth rate of the austenite/ferrite interface by allowing for slower cooling rates to produce a completely homogeneous bainitic microstructure through the thickness of the plate up to a critical cooling rate. Cr has a strong influence on this effect. As a general rule, the steel's hardenability increases as the Cr content increases. Therefore, there is a lesser potential for retaining a completely homogeneous bainitic microstructure with 1–1.25Cr-0.5Mo steels than with the higher Cr-Mo steels such as 2.25Cr-1Mo steel at higher thickness levels. Some steel producers indicate that this is indirectly affected by rolling reduction ratio. This nonuniform microstructure can be directly correlated with variations in mechanical properties, especially tensile strength and toughness, through the thickness of the plate.

1.25Cr-0.5Mo and 1Cr-0.5Mo steels. API RP934-C recommends 20 ft-lb (27 J) minimum single value because of the large scatter in the transition region of the CVN impact test transition curve, instead of the 35 ft-lb (47 J) minimum single value in API RP934-A for 2.25Cr-1Mo steels.

Nozzles for heavy wall should be manufactured from forgings. For thicker nozzles (thickness > 3~4 inch), 2.25Cr-1 Mo may be used to ensure that toughness requirements are met. When using 2.25Cr-1Mo, appropriate weld procedures with higher preheat, PWHT temperatures, etc., should be used.

References (Loss of Toughness): other than temper embrittlement

- API RP934-C & E and TR934-D/ WRC 275/ ASTM STP 755/ IIW Doc. XII-E-6-81.
- A.K. Singh et al., Remaining life assessment of a 37 year old catalytic reforming reactor, NACE Paper 94520
- D.L. Bagnoli et al., Embrittlement of 1Cr-0.5Mo and 1.25Cr-0.5Mo alloys after long time service, NACE 88160
- M. Haga et al., Perspective for 1.25Cr forgings, API round table, fabrication issues with 1.25Cr steels in refining, Atlanta 2004

(g) ISR (Intermediate Stress Relieving) and DHT (Dehydration Heat Treatment): See Table 4.110 and Sect. 4.12.3.7.

(h) MPT (Minimum Pressurizing Temperature)

MPT control is a requirement for operation to avoid fracture at lower temperature and lower pressure during startup and field hydrostatic test due to embrittlement related to brittle, temper, and hydrogen, especially in Cr-Mo steel with heavy wall. See Sect. 1.3.6 for more details.

(i) Codes/Standards for Cr-Mo Steels

Table 2.37 shows the applicable Codes and Standards for Cr-Mo Steels in oil and gas industries and power plants.

References

- R.A. Swift, Temper Embrittlement in Low Alloy Ferritic Steels, NACE Paper 76,125, 1976.
- J. Grosse-Wördemann et al., *Prevention of Temper Embrittlement in 2.25Cr-1Mo Weld Metal by Metallurgical Actions*. Welding Research Supplement (1983) p 123–128 s.
- R.A. Swift et al., *Temper Embrittlement of Pressure Vessel Steels.* Welding Research Supplement (1973) p 57–68 s.
- T. Takamatsu et al., Temper embrittlement characteristics of 2.25Cr-1Mo steels. Transactions. ISIJ. **22**, 434–441 (1982).
- A Sato et al., Temper embrittlement of Cr-Mo pressure vessel steels. K Steel Tech Report, No.2, (1981).
- Meeting minutes of EFC WP15 Corrosion in Refinery Industry, temper embrittlement of Cr-Mo Steels, Sep.9, (2009).
- H. Arabi et al., Temper Embrittlement Sensitivities of 3Cr-1Mo and 2.25Cr-1Mo Low Alloy Steel. ISIJ Int. **47**(9), 1363–1367 (2007).

Table 2.37 Codes and standards for Cr-Mo steels in oil and gas industries and power plants[(1)]

Items	Requirements
API RP/TR 941	Steels in hydrogen services at elevated temperatures and pressures in petroleum refineries and petrochemical plants
API RP934-A	Materials and fabrication of 2.25Cr-1Mo, 2.25Cr-1Mo-0.25 V, 3Cr-1Mo, and 3Cr-1Mo-0.25 V steel heavy wall pressure vessels for high-temperature, high-pressure hydrogen service
API TR934-B	Fabrication considerations for vanadium-modified Cr-Mo steel heavy wall pressure vessels
API RP934-C	Materials and fabrication requirements for 1.25Cr −0.5Mo steel heavy wall (2 inch ≤ thickness ≤ 4 inch) pressure vessels for high-pressure hydrogen service operating at or below 441 °C (825 °F)
API TR934-D	Technical report on the materials and fabrication issues of 1.25Cr-0.5Mo and 1Cr-0.5Mo steel pressure vessels
API RP934-E	Recommended practice for materials and fabrication of 1.25Cr-0.5Mo steel pressure vessels for service above 440 °C (825 °F)]
API TR934-F, part 1	Impact of hydrogen embrittlement on minimum pressurization temperature (MPT) for thick-wall Cr-Mo steel reactors in high-pressure H_2 service-initial technical basis for RP 934-F
API TR934-F, part 2	Literature review of fracture mechanics-based experimental data for internal hydrogen-assisted cracking of vanadium-modified 2.25Cr-Mo steel
API TR934-F, part 3	Subcritical cracking of modern 2.25Cr-1Mo 0.25 V steel due to dissolved internal hydrogen and H_2 environment, research report
API TR934-F, part 4	The effects of hydrogen for establishing a minimum pressurization temperature (MPT) for heavy wall steel reactor vessels
API TR934-G	Design, fabrication, operational effects, inspection, assessment and repair of coke drums and peripheral components in delayed coking units
API RP934-H (not issued yet)	Inspection and maintenance of heavy wall reactor vessels in high-temperature, high-pressure hydrogen service
API RP934-I (not issued yet)	Periodic inspection of 2.25Cr-0.5Mo and 2.25Cr-0.5Mo-V steel pressure vessels in high-pressure, high-temperature hydrogen-containing service
API TR938-B	Use of 9Cr-1Mo-V (gr 91) steel in the oil refinery industry
API Publ. 959	Characterization study of temper embrittlement of Cr-Mo steels
API RP920	Prevention of Brittle Fracture of pressure vessels, 1990 (withdrawn)
API RP571	Damage mechanism affecting fixed equipment in the refinery industry
API 579–1/ASME FFS-1	Fitness for service
API RP582	Welding guideline
API RP581	RBI technology
WRC-275	The use of quenched and tempered 2.25Cr-1Mo steel for thick wall reactor vessels in petroleum refinery process: an interpretative review of 25 years of research and application, February 2005
WRC-390	Failure of welds at elevated temperatures by G.R. Stevick, March 1994
WRC-405	Effect of heat treatment on the elevated temperature properties of a 2.25Cr-1Mo submerged arc weldment, by C.D. Lundin and K.K. Khan. September 1995
WRC-407	Reports on heat treatment of steels used in boiler and pressure vessel applications: (1) Carbon migration in Cr-Mo Weldments effect on metallurgical structure and mechanical properties, by C.D. Lundin, K.K. Khan and D. Yang and, (2) ASME post-weld heat treating practices: an interpretive report, by C.E. Spaeder, Jr. and W.D. Doty, December 1995
WRC-409	Fundamental studies of the metallurgical causes and mitigation of reheat cracking in 1.25Cr-0.5Mo and 2.25Cr-1Mo Steels, by C.D. Lundin and K.K. Khan, February 1996
WRC-411/ API Publ. 938	Cracking of 1.25Cr-0.5Mo steel equipment, 1996
WRC-412	Challenges and solutions in repair welding for power and processing plants, Proceedings of a workshop, June 1996
WRC-416	Creep crack growth behavior in weld metal/base metal/fusion zone regions in chromium molybdenum steels, by R.H. Norris and A. Saxena, November 1996
WRC-418	The effect of crack depth (a) and crack-depth to width ratio (a/W) on the fracture toughness of A533-B steel
WRC-439	Use of low carbon 1.25Cr-Mo weld metal for fabrication of Cr-Mo components, by C.D. Lundin, P. Liu, G. Zhou and K. Kahn – February 1999
WRC-454	A literature review on characteristics of high temperature ferritic Cr-Mo steels and weldments by Carl D. Lundin, Peng Liu, Yan Cui – August 2000.
WRC-499	Wang, Y., Lundin et al. Repair of Cr-Mo steels, 2005
WRC-506	Literature survey-half-bead temper-bead of Cr-Mo steels
WRC-524	Modern vanadium steels for high-temperature petroleum reactors
WRC 525	Fabrication and repair of low-alloy steel pressure equipment
Code Case 2235–10	Use of UT in lieu of RT, 2012
Code Case 2355–4	Use of UT, 3D size of defects, 2004
ASTM STP- 407	Temper embrittleness: an interpretive review in temper embrittlement in steel, p127–167, 1968
ASTM STP- 755	2.25%Cr-1%Mo pressure vessel steels with improved creep rupture strength; proceedings of the symposium on applications of 2.25%Cr-1%Mo steel for thick-wall pressure vessels, p129–147, 1980
ASTM G146	Disbonding test
ASTM E21	Hot tensile test
ANSI/AWS D10.8	Recommended practices for welding of Cr-Mo steel piping and tubing
ASME, sec. VIII, div. 1, mandatory appendix 31	Rules for Cr-Mo steels with additional requirements for welding and heat treatment
ASME, sec. VIII, div.2, mandatory appendix 26	Rules for Cr-Mo steels with additional requirements for welding and heat treatment
ASME PCC-2	Repair of pressure equipment and piping
ASME PCC-2S	Supplement to ASME PCC-2 repair of pressure equipment and piping
IIW doc. XII-E-6-81	Temper embrittlement of Cr-Mo weld metals, 1981

Notes:
[(1)]See Table 2.34 for some more Code Cases of 2-3Cr Steels and Table 2.38 for Code Cases of 9Cr Steels

2.1.4.3 Low-Alloy Steels (5–9%Cr-Mo Steels)

(a) 5–7Cr-Mo Steels

Traditionally 5–7%Cr-Mo steels have been used as an intermediate role of between 2% and 3%Cr-Mo steel and 9%Cr-Mo steel. However, 9Cr-1Mo steel has been recently using instead of 5–7Cr-Mo steels because of similar cost and higher strength.

(b) 9Cr-Mo-(V) Steels

1. Conventional 9Cr-1Mo steel

   The ferritic steels with 9% Cr for elevated-temperature service (e.g., creep-rupture, HTHA, graphitization, sulfidation, oxidation, etc.) have been used for pipe & tube materials in oil refinery and petrochemical plants as well as nuclear and power plants applications over the past several years.

2. Advanced (Enhanced) 9Cr-1Mo-V steel (Gr.91 steel)

   In May 1981, applications for inclusion of the modified 9Cr-lMo alloy (Gr.91- enhanced strength by vanadium-V, columbium/niobium-Cb/Nb, and nitrogen-N) in ASTM were initiated as a replacement for 300 series ASS. The P91 steels have several advantages (excellent high temperature strength) compared to austenitic alloys, as shown in Figs. 2.22 and 2.23). The thermal expansion coefficient of P91 is lower than those of ASS and its thermal conductivity is higher. These properties improve the resistance of P91 against thermally induced stresses and provide a better match of properties with the lower alloy steels used throughout other components of the boilers. The higher thermal conductivity also improves heat transfer through tubing walls. Also, P91 steels have relatively good oxidation resistance at intermediate temperatures and can exhibit high strengths up to about 600 °C (1112 °F).

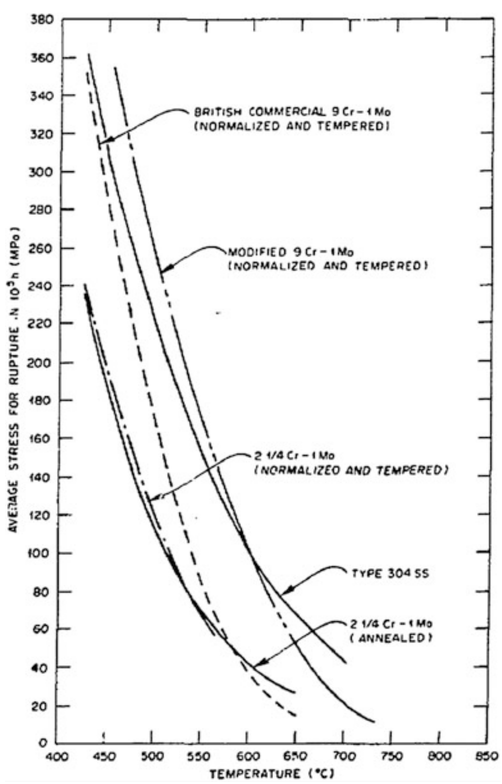


Figure 2.22 Variation of 105-h creep rupture strength with temperature for several materials. (Source: V.K. Sikka, ORNL technical report, 1994)

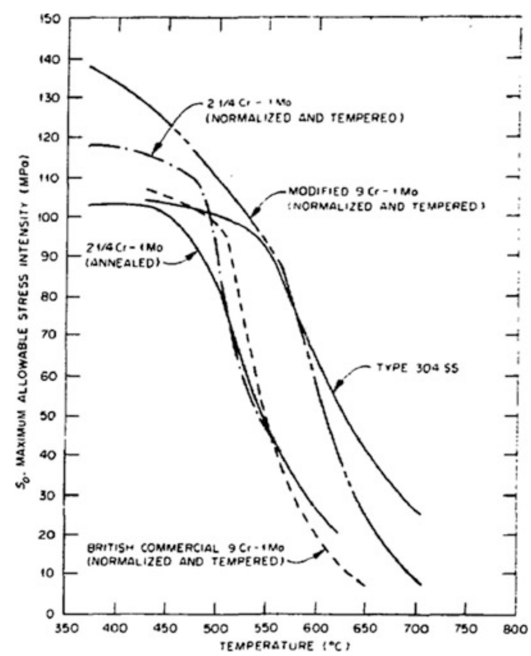


Figure 2.23 Estimated design allowable stresses as a function of temperature for modified 9Cr-1Mo-V steel (P91) Design allowable stress values for standard 9 Cr-1 Mo (P9) and 2.25Cr-1Mo steel are also included for comparison. (Source: V.K. Sikka, ORNL technical report, 1994)

Lastly, for any given product form, P91 steel will generally cost less than ASS. Although 9Cr-1Mo-V steel has been applied as boiler tube material in power generation for a few decades, it was reported that embrittlement occurred after long-term aging around 600 °C (1112 °F) which is an accelerated condition for pressure vessel operation. Since pressure vessels are more sensitive in stress-concentration around crack tip than boiler tube because of its large wall thickness, fracture toughness is an important property of concern when 9Cr-1Mo-V steel may be applied to piping, heater tubes, and pressure vessels. ASTM A-213 T91 was the first to receive approval and was extended to other products, such as A-387 Grade 91, A-182 F91, A-234 WP91, A-200, A-336 F91, A-369 P91, and A-335 P91. In July 1983, the material was accepted for use in the ASME Section I (Power Boilers) by virtue of approval of Code Case 1943.

In June 1984, the material received all necessary Subcommittee approvals for inclusion in the ASME Section VIII and was approved for use in February 1985 as Code Case 1973.

In December 1983, an initial data package was submitted to the appropriate Section III Subcommittee for consideration, and a revised data package was submitted in December 1984. In February 1985, Code Case 1973 received approval for inclusion of modified 9Cr-lMo Steel in the ASME Section VIII.

Figure 2.24 shows the advantage of modified 9Cr-1Mo (-V) compared to Gr. 9 (9Cr-1Mo steel) or Gr. 22 (2.25Cr1Mo steel) materials so that the project coat (material and construction) can be greatly saved.

However, the weldability is worse than that of Gr. 9 (9Cr-1Mo steel) or Gr.22 (2.25Cr-1Mo steels). So careful application is required for welding.

Table 2.38 shows the specifications and ASME Code Cases (CC) for 9Cr-1Mo-V Steels.

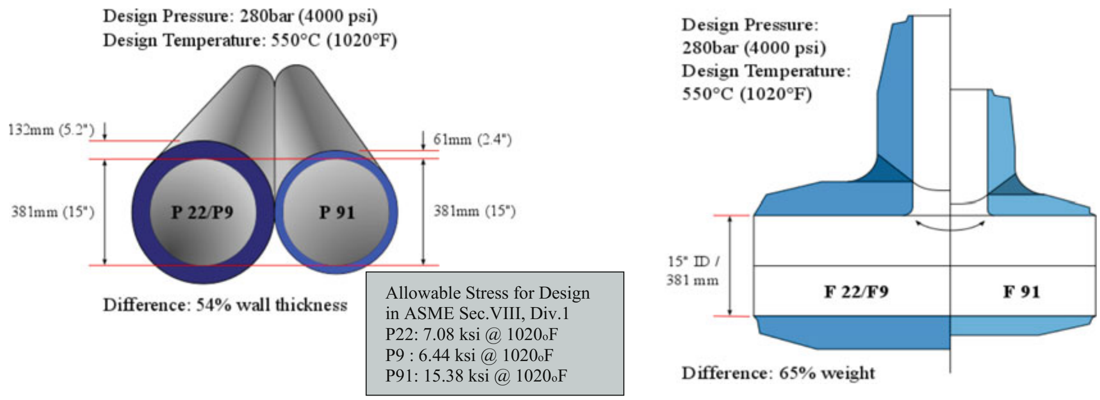


Figure 2.24 Advantage of modified 9Cr-1Mo steel (A Sample-heater tubes and B31.3 piping)

Table 2.38 Specifications and ASME code cases (CC) for 9Cr-1Mo-V steels

Specification or code case number for 9Cr-1Mo-V steel grade[(1)-(9)]	Title (for High Temperature Service)
SA-182 (Gr. F91)	Forged or rolled alloy-steel pipe flanges, forged fittings, and valves and parts for high-temperature service
SA-213 (Gr. 91 & 92)	Seamless ferritic and austenitic alloy-steel boilers, Superheaters, and H/EX tubes
SA-217 (Gr. C12A)	Steel Castings, Martensitic Stainless and Alloy, for Pressure-Containing Parts, Suitable
SA-234 (Gr. WP91)	Piping fittings of wrought CS and LAS for moderate and elevated temperature service
SA-335 (Gr. 91 & 92)	Seamless ferritic alloy-steel pipe for high-temperature service
SA-336 (Gr. F91)	Alloy steel forgings for pressure and high-temperature parts
SA-369 (Gr. FP91)	Carbon and ferritic alloy steel forged and bored pipe for high-temperature service
SA-387 (Gr. 91)	Specification for pressure vessel plates, alloy steel, chromium molybdenum
SA-426 (Gr. CP9)	Centrifugally Cast Ferritic Alloy Steel Pipe for High-Temperature Service
SA-691 (Gr. 9Cr)	Carbon and Alloy Steel Pipe, Electric-Fusion-Welded for High-Pressure Service at High Temperatures
CC 1876-5 (incl. Gr. 91)	Design of Safety Valve Connections –Section I (approved on Apr. 26, 2013)
Code case 1943 (Gr. 91)	Seamless modified 9Cr-1Mo, ASME Sec. I –allowable stress (approved on July 20, 1983; not active; requirement incorporated)
Code case 1973-2 (Gr. 91)	Modified 9Cr-1Mo-V material, ASME sec. VIII, Div. 2 (approved on august 12, 1996; annulled on January 1, 2005; requirements incorporated)
Code case 2179-8 (Gr. 92)	Seamless 9Cr-2 W material (UNS K92460 material), ASME Sec. I and Sec. VIII, Div. 1 (approved Jun. 28, 2012)
Code case 2192-9 (Gr. 91)	Modified 9Cr-1Mo-V, J94090 Cast Material, ASME Sec. I (approved Oct. 16, 2015)
Code case 2297 (Gr. 91)	Modified 9Cr-1Mo-V FCAW consumable, ASME Sec. IX (approved on Nov. 30, 1999)
Code case 2327-2 (Gr. 911)	Normalized-tempered 9Cr-1Mo-W-Cb materials, ASME Sec. I (approved on Jan. 29, 2009)
CC 2822-2 (Gr. 91)	Fatigue Evaluation (Omega Method) for Cl.2, 9Cr–1Mo–V (approved on Dec. 11, 2017)
CC 2843-2 (incl. Gr. 91)	Fatigue Analysis of Class 2 Components in the Time-Dependent Regime-ASME Sec. VIII-Div.2 (approved on Dec. 11, 2017)
CC 2864 (Gr. 91)	9Cr–1Mo–V Material-Section I (approved on Sep. 21, 2016)

Source; API TR938-B modified

Code Cases will remain available for use until annulled by the applicable Standards Committee unless otherwise noted

General Notes

(1)Gr.91 (0.20–0.50Si, 0.85–1.05Mo), Gr.911 (0.10–0.50Si, 0.9–1.1Mo), Gr.92 (max.0.50Si, 0.3–0.6Mo)

(2)Reference: EPRI 2015 Technical Report for Guidelines and Specifications for High-Reliability Fossil Power Plants, second Edition- Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components. See Table 2.31a for European Standards

(3)ABSA AB-536 (2019) Requirements for the Integrity Management of Grade 91 Steel Used Above Currently-Permitted Allowable Stresses

(4)DIN 17 175, VdTUV511/2, X10CrMoVNb9-1, Seamless tubes made from heat-resistant steels

(5)BS 3604-2, Grade 91 (now withdrawn), Steel pipe and tubes for pressure purpose, ferritic alloy steel with specified elevated temperature properties

(6)BS 3059-2, Grade 91 (now withdrawn), Steel boiler and superheater tubes; Part 2 specification for carbon alloy and austenitic stainless steel tubes with specified elevated temperature properties

(7)EN 10 216-2, X10CrMoVNb9-1 Steel No 1.4903, Seamless steel tubes for pressure purposes technical conditions of delivery; Part 2 ferritic and martensitic steels with specified elevated temperature properties

(8)EN 10 222-1, X10CrMoVNb9-1 Steel No 1.4903, Steel forgings for pressure purposes—Part 1: general requirements for open die forgings

(9)EN 10 222-2, X10CrMoVNb9-1 Steel No 1.4903, Steel forgings for pressure purposes—Part 2: ferritic and martensitic steels with specified elevated temperature properties

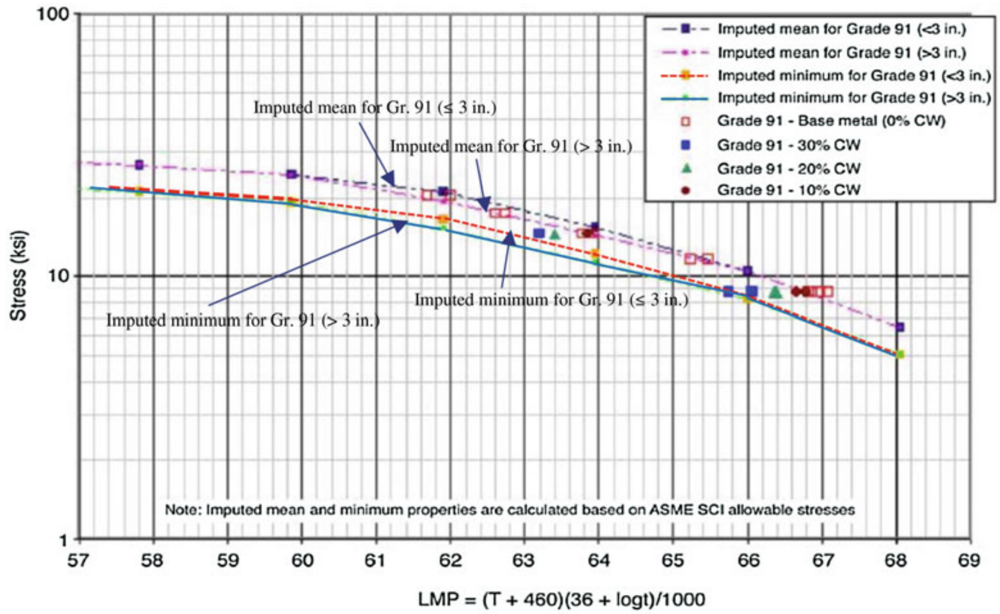


Figure 2.25 Effect of cold work on creep rupture behavior of Grade 91 material in comparison with the behavior of the unstrained base metal. (Source: EPRI 2015 Report, Fig. E-1)

EPRI in 2015 reports that cold work induced during all cold-forming processes of 9Cr-1Mo-V steels does have an adverse effect on the creep rupture strength, as shown in Fig. 2.25. Results indicate that there is no obvious threshold value below which the effect is absent but that the magnitude of the effect increases with the level of cold strain induced.

As mentioned above, the most critical factor before selection of this material is to consider the weldability because 9Cr-1Mo-V steel is susceptible to Type IV cracking during welding (Fig. 2.26).

Steels with properties enhanced by heat treatment commonly develop a drop in hardness in the outer extremity of the HAZ due to over-tempering at temperatures below the lower critical phase transformation temperature (LCPTT as Ac1-see Table 1.70 and 4.113 in this book) and/or microstructural changes in the intercritical temperature range. The temperature gap between Ac1 and PWHT is smaller, the susceptibility of Type IV cracking is higher. This purported "soft zone" exhibits stress rupture strength below that of the unaffected base metal in cross-weld tests resulting in reduction in the creep life of the welded joint.

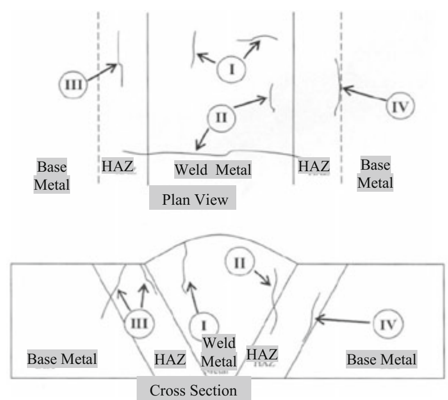


Figure 2.26 Typical types of embrittlement cracking during welding

At high stress levels, the 9Cr-1Mo-V steel may suffer Type IV cracking due to presence of such soft zone of reduced creep rupture strength. The most important goal for the successful use of this material is to minimize Type IV crack on welds.

So, a minimum of 2–3 hrs in the range of 750–760 °C (1382–1418 °F) is recommended, or longer for thicker sections to provide sufficient tempering. Also, the welding rod should have a Ni + Mn content of <1.5% to keep enough temperature gap between PWHT and A_{C1}. Type IV cracking is the generic name assigned to this phenomenon.

This will ensure that the Ac1 (LCPTT- see Table 4.113 in this book) will be high enough so that the PWHT temperature will not exceed it.

The mechanism of enhanced creep strength for Gr. 91 is the precipitation of V/Cb-rich carbonitrides and carbonnitrides (C-N) in the matrix. Al, deoxidizer, is commonly added to remove oxygen during the melting process. However, Al also has a stronger tendency to combine with N than do V and Cb, so that high levels of Al will reduce the amount of free nitrogen available to form the carbonitrides that contribute the long-term creep strength of this metal. As a solution of this problem, another deoxidizers, such as Zr and Ti, are added instead of the reduced Al, so that the free N can readily form adequate amounts of carbonnitrides (C-N) in the matrix. EPRI in 2015 report suggested that the target ratio of N/Al should be 4 or greater, and under no circumstances should a ratio of less than 2.0 be accepted. This guideline may be collaborated with API 938-B in the near future.

Figure 2.27 shows that when the Ni + Mn of weld metal = 1.5% the A_{C1} temperature is 780 °C (1436 °F). This is extremely close to the PWHT of 760 °C (1400 °F), and exceeding the 780 °C (1436 °F) temperature would not be uncommon, it is very possible that the A_{C1} could or would be exceeded. If the A_{C1} temperature were exceeded, some austenite would form, which in turn transforms to fresh untempered martensite on cooling, so that the toughness will be reduced. Even though the overall guideline to avoid premature failure is still under investigation, the best practical guidelines, at this time, are introduced below.

For base metal, the following requirements are to be selected partially or entirely.

In order to obtain a proper balance between fracture toughness, creep-rupture strength and resistance to long-term embrittlement, the following Ceq control for base metal is suggested by API TR938-B.

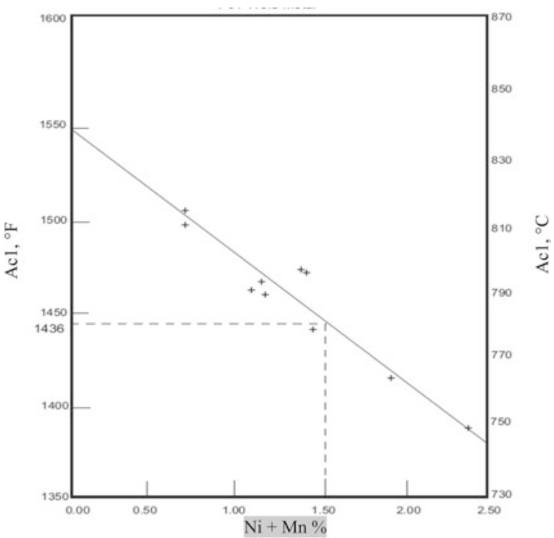


Figure 2.27 Effect of (Ni + Mn) on Ac1 temperature of Gr.91 steel welding material. (Source: API TR938-B)

Creq = Cr + 6Si + 4Mo + 1.5 W + 11 V + 5Nb + 9Ti + 12Al–40C–30 N–4Ni–2Mn–1Cu. < 10 (element: wt%).

Even materials with *Creq* between 10 and 12 exhibited adequate toughness when the delta ferrite <5%.

Also, in order to avoid reheat crack, P: $\leq$ 0.02 wt%, Ni + Mn: $\leq$1.0 wt%, N/Al ratio $\geq$ 4.0, and S: $\leq$0.01 wt% for base metal are recommended.

For welding, preheat, interpass temperature, heat input, and Type IV cracking, see Sect. 4.11.3.2.

3. Welding of 9Cr-1Mo-(V) steels: see Sect. 4.11.3.2 for more detail.

2.1.4.4 Low-Alloy Steels – Ni Steels for Low-Temperature Service – See Div. 1 ULT and Table 2.120 in this book

Table 2.39 shows approximate minimum service temperatures and applications in low temperature and cryogenic service.

See Sect. 4.4.2 for preheat, Sect. 4.4.3 for post-heating, Sect. 4.12.3 for PWHT, and Sect. 4.11.4 for welding of low-temperature/cryogenic steels.

2.1.4.5 High-Manganese (24–27%Mn) Austenitic Steels for Low/Cryogenic Temperature Service

Even though these metals have 100% austenitic microstructure, they are not called stainless steel because they do not contain Cr (Cr-oxide). High Mn steels have several benefits, such as wear resistance, high strength, nonmagnetic, good damping, low-temperature toughness, etc. Their

Table 2.39 Approximate minimum service temperatures of cryogenic/low temperature metals ($\leq$ −50 °C)

Metal group	Steel type	Specification (e.g., plate)	Minimum(1) temperature °C (°F)	Typical storage/processing application in atmosphere(2)
LTCS	Fine grained and killed C/Mn steel	ASTM A516-60N EN10028–3 P460NL2	−50 (−58)	Ammonia, propane (LPG)
LTCS	Normalized C-Mn-Si steel	ASTM A537-Cl.1	−60 (−76)	Ammonia, propane (LPG), propylene,
LTCS	Q-T C-Mn-Si steel	ASTM A537-Cl.2	−60 (−76)	Ammonia, propane (LPG), propylene
LTCS	Fine grained and killed TMCP steel	DNV HS NV F32/36/40 DNV HS NV F420/460/500/550/620/690(3)	−60 (−76)	Offshore structures in deep water
LAS	1.5% Ni steel	EN10028–4 15NiMn6	−60 (−76)	Ammonia, propane, carbon disulfide
LAS	2.5% Ni steel	ASTM A203 gr. B	−60 (−76)	Ammonia, propane, carbon disulfide
LAS	3.0%Ni Q-T steel	ASTM A543-type B	−101 (−150)	Carbon dioxide, acetylene, ethane
LAS	3.25%Ni Q-T steel	ASTM A543-type C	−101 (−150)	Carbon dioxide, acetylene, ethane
LAS	3.5% Ni steel	ASTM A203 gr. E EN10028–4 12Ni14	−101 (−150)	Carbon dioxide, acetylene, ethane(4)
LAS	5% Ni steel	ASTM A645 gr. A EN10028–4 X12Ni5	−130 (−202)	Ethylene (LEG)
LAS	8% Ni steel	ASTM A353/A553-type II	−170 (−274)	Methane (LNG), oxygen, argon
LAS	9% Ni steel (5)	ASTM A353/A553-type 1 EN10028–4 X8Ni9 or X7Ni9 (6)	−196 (−320)	Methane (LNG), oxygen, argon(5)
ASS	Manganese steel	22–26%Mn(7)	−163 (−261)	Methane (LNG), oxygen, argon,
ASS	Austenitic stainless steel (ASS)	Type 304(L)/316(L) SS EN10088–1 1.4305	−196 (−320) or −254 (−425)	Methane (LNG), nitrogen, hydrogen, helium
AL	Aluminum alloy	5083, 3003, 6061, etc.	−196 (−320) or −269 (−452)	Methane (LNG), nitrogen, hydrogen, helium

LTCS low temperature carbon steel, *LAS* low alloy steel, *ASS* austenitic stainless steel, *AL* aluminum alloys

Notes:

(1) The minimum use temperature may be increased as thicker wall (as plate). The minimum use temperature of pipes, fittings, and flanges may be different from those of plates

(2) The colder liquids can allow to use upper metal in pressurizing system because the boiling temperature of the liquids will be continuously raised in the pressurizing service

(3) HS = high strength steel/EHS = extra high strength/NV = Designation of a steel grade according to DNV offshore standards

(4) Some reports indicate field welding problems with 3.5% Ni steel on columns in the Texas Gulf coast along with failure of heavy plate (about 50 mm and above) thickness in a 9% Ni vessel, which occurred some months after start-up and this was similarly attributed to "hot cracking" during welding. The latter was an overhead drum from a column with the intent to provide liquid draw-off for hydrocarbons which condensed in the vessel. One of cases reported other European history within a 1997 AIChE symposium involving a German ethylene plant wherein a 3.5% Ni vessel ruptured. Further, this company also reported experiences at other user/operator companies which suggested fatality involvement with similar 3.5Ni vessels ruptures; and many of these were

reported to be believed, or may have involved "hydrogen in combination with coarse grained HAZ" along with some modified weld materials. Therefore, the caution of fabrications involving 3.5% Ni is that there is potentially a significantly greater risk to any project which chooses to apply these materials rather than austenitic stainless steels. Presuming that MDMTs cannot be increased to allow impact-tested carbon steels, e.g., and designers or owner/operators are considering 3.5% Ni, then the foregoing should be carefully reviewed. While material costs may suggest lower initial capital expenditures (although overall fabrication costs or material deliveries may or may not be equal), where the fabrication experience is similar to the foregoing, then the risk to plant startup as well as the additional cost in replacement may significantly outweigh the application of stainless steels. Due to this risk, many metallurgists do not consider the fabrication choice of 3.5% Nickel involving forgings to be appropriate

(5)The fracture toughness may be improved by DQT (direct quenching and tempering), QLT (quenching, lamelarizing treatment, and/or tempering), phosphorus control, $P \leq 0.005\%$), etc.

(6)X8Ni9: CVN at −196 °C (−320 °F) > 70 J/X7Ni9: CVN at −196 °C (−320 °F) > 100 J

(7)Currently developed material. C 0.2~0.6, Mn 20~28, P < 0.1, S < 0.01, N < 0.1 with Ni, Cr, Mo, Cu, Al, Si, Ti, Nb, and B if necessary, TS > 760 MPa (110 ksi), YS > 360 MPa (52 ksi), CVN Impact Energy >27 J @ −196 °C (−320 °F)

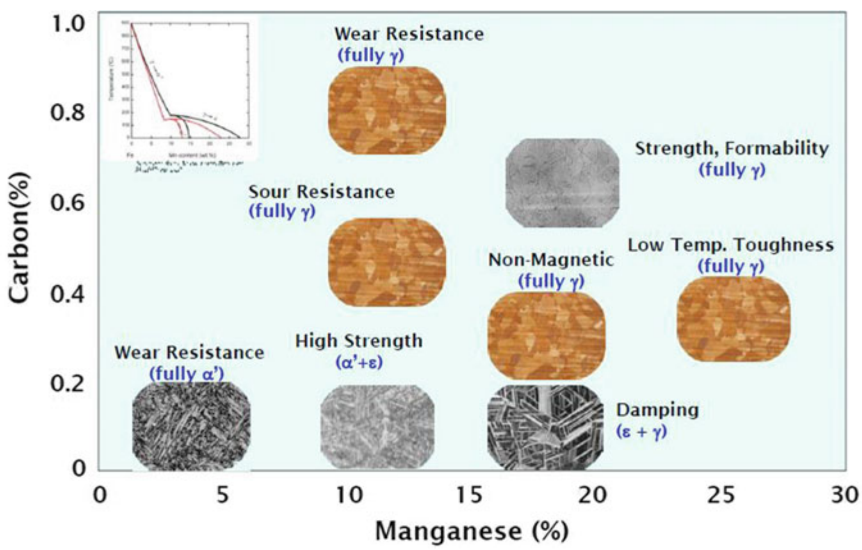


Figure 2.28 The application zone per C-Mn contents. (Source: POSCO technical report, 2010)

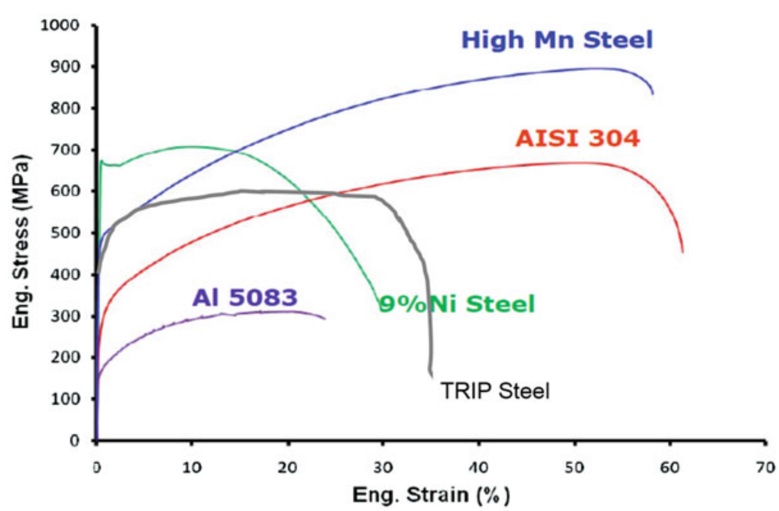


Figure 2.29 Comparison of tensile properties at 25 °C for several low-temperature materials. (Source: POSCO report, 2010)

corrosion resistance is very similar to 9%Ni steel. Figure 2.28 shows a typical application zone per the C-Mn contents of CS. The 24–27% Mn and 0.23–0.43%C steel has good toughness in cryogenic temperature (@ − 196 °C). This material has the same low-temperature toughness (impact test and drop weight test @ − 196 °C, CTOD @ − 163 °C) and corrosion resistance (at 3.5% NaCl solution per ASTM G31), greatly better weldability and lower cost of material itself (about 60%) and welding electrode (about 30%) compared to 9Ni steel even though the tensile strength (TS) of high Mn steel is about 80% of TS for 9Ni steel at low stain zone as shown in Fig. 2.29. The total construction cost of high Mn steel is remarkably lower than that of 9Ni steel. It can be another candidate material for cryogenic service (e.g., LNG storage tanks, etc.).

2.1.4.6 Ferritic Steels with Tensile Properties Enhanced by Heat Treatment

See ASME Sec. VIII, Div. 1, UHT.

This part is not intended to apply to those steels approved for use under the rules of Part UCS but which are furnished in such thickness that heat treatment involving the use of accelerated cooling, including liquid quenching, is used to attain structures comparable to those attained by normalizing thinner sections. Integrally forged vessels, quenched and tempered (Q-T), which do not contain welded seams, are not intended to be covered by the rule of this Part, UHT. See Table 4.125 for heat treatment requirements and applicable materials.

2.1.4.7 Thermo-Mechanical Controlled Process (TMCP) Steel

The aim of TMCP is to achieve superior toughness and higher strength because of a fine (ASTM grain size 10–11 after accelerated cooling from above the Ar_3 temperature) and uniform acicular ferrite microstructure (ferrite/pearlite/bainite) by mechanical control process above Ar_1 point (Fig. 2.30) instead of a ferrite/pearlite-banded structure of conventional normalized steels (ASTM grain size 8–9). The initial hot rolling (roughing) is carried out about 1200 °C (2192 °F), but the final hot rolling is continuously carried out at a lower temperature below Ar_3 transformation temperature. AC (Accelerated Cooling), in which steels meeting the specified requirements are produced by promoting grain refinement and increasing the pearlite and/or bainite volume fraction through controlled cooling (accelerated cooling and air cooling) immediately after the final controlled rolling (CR) or thermos mechanical rolling (TMR) operation.

See ASTM A841, A1066 or API Spec 2 W for Steel Plates for Pressure Vessels or Offshore Structural Plates, Produced by TMCP.

The carbon equivalent of TMCP is very low, so that the weldability is very good and the PWHT may not be required per the condition.

Figures 2.31 and 2.32 show the relationship between tensile strength and Ceq (Carbon Equivalent). At the same Ceq level, the strength of TMCP steels is higher than those of conventional steels. As shown in Fig. 2.33, TMCP steel has finer grain size than normalized steel. Therefore, it can be summarized that TMCP steels have better toughness than conventional materials. The PWHT of TMCP can reduce the tensile strength as well as impact toughness. Therefore, the PWHT on TMCP steels should be restricted. Where PWHT cannot be avoided, testing should be performed on the specific material to clearly define the magnitude of any deterioration in properties at the proposed PWHT temperature and thermal cycle.

TMCP steels have been successfully used in many applications such as offshore structures, ships, Tension Leg Platform (TLP) tendons, and most pipelines.

Traditionally, TMCP has not been used much in HIC environments because the MnS inclusions during controlled rolling are more flattened than in conventional rolling, and the HIC (hydrogen induced cracking-sour service) sites are more extended. However, NACE standards do not have the limitation for use of TMCP in HIC environment because not only S & P control, Ca treatment, and rolling temperature control can greatly reduce the cracks (HIC) but also HIC test per NACE TM0284/TM0177 can successfully prove its susceptibility. Therefore, many oil and gas end-users allow to use the TMCP steel in wet H_2S service if the HIC test is successfully performed.

At the same yield strength level TMPC-steels provide the lowest carbon equivalent.

The interrupted accelerated cooling is controlled between 800 °C and 500 °C (1472 °F and 932 °F) while the direct quenching is cont5rolled between 900 °C and 200 °C (1652 °F and 392 °F). Figure 2.34 shows the time-temperature profile in core and surface in accordance with various cooling treatment of plate.

Figure 2.35 shows a typical trend of TS and YS of normalized steel, TMCP steel, and direct quenched steel.

See ASTM A841 (Steel plates for pressure vessels by TMCP), A1066 (High-strength low-alloy structural steel plate by TMCP), EN 10338 (Hot-rolled and cold-rolled noncoated products of multiphase steels for cold forming), etc., for more details.

Meanwhile, TRIP (Transformation induced plasticity) aided steels which have significant volume fractions of retained austenite with some bainite and martensite in the ferrite matrix by higher Si are an advanced material group for outstanding combination of strength and ductility (Fig. 2.36). The most common TRIP range of steels which are typically used in automobile industry comprise two cold-rolled grades in both uncoated and coated formats (TRIP 690 and TRIP 780) and one hot-rolled grade (TRIP 780), identified by their SMTS expressed in MPa. The process of hot-rolled grade is very similar with TMCP process (except rapid cooling). See ASTM A1088 [Steel, Sheet, Cold-Rolled, Complex Phase (CP), Dual Phase (DP) and TRIP] for more details. See Fig. 2.29 for stress-strain curve of TRIP steel.

2.1.4.8 Normalizing-Accelerated Cooling and Tempering (NACT) Steel

The purpose of NACT is to get on a thick plate the same microstructure as on a thin plate. The fine grain size has a good influence on toughness. The accelerated cooling from normalizing [above austenitizing zone: A_3 TT + 30–50 °C (54–90 °F)] is controlled from the normalizing temperature to 500 °C (932 °F) followed by accelerated air cooling [maximum cooling rate for accelerated cooling: from 80 °C/s (144 °F/s) for 10 mm (0.4 in.) thickness to about 1 °C/s (1.8 °F/s) for 80 mm (3.15 in.) thickness] while the direct quenching is controlled between 900 °C and 200 °C (1652 °F and 392 °F) under cooling rate from 5 to 60 °C/s (9–108 °F/s). As a result, the grain size of NACT will be refined from ASTM #7–9 for N (normalized) to ASTM #10–11 and the final microstructure of NACT steel has 100% fine pearlite or a uniform mixture of fine pearlite and ferrite-bainite while the Q-T steel has 100% tempered martensitic structure (Fig. 2.37).

ASME Sec. VIII, Div.1, UHT allows to use the accelerated cooling including liquid quenching for the fabrication. Normally two (2) times NACT + three-four (3–4) times PWHT may be applied to purchase the heavy wall base metal.

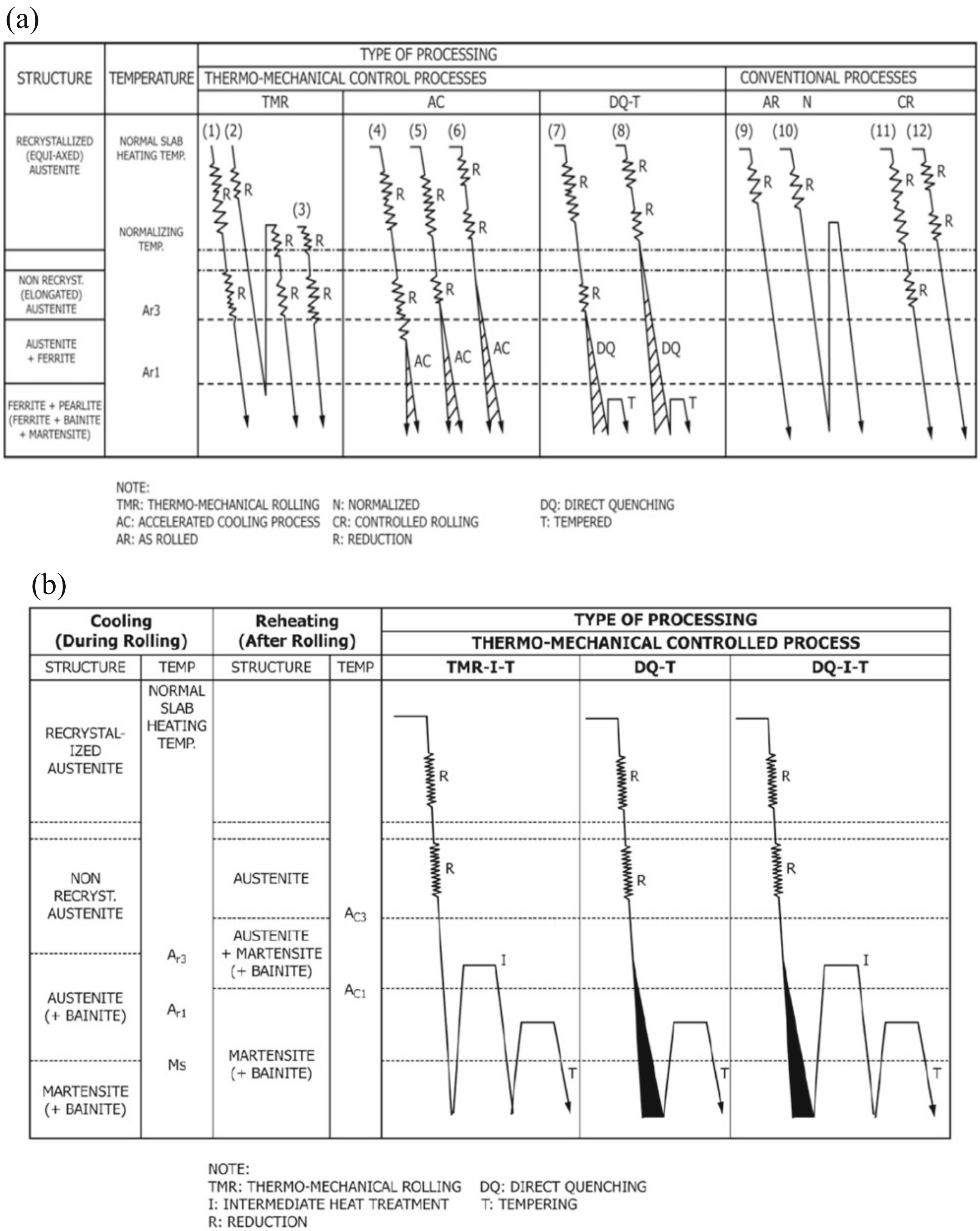


Figure 2.30 Comparison of conventional and TMCP routes "Zig-zag" part of line indicates rolling. (Source: ASTM A841). (**a**) ASTM A841, Grade A Through F. (**b**) ASTM A841, Grade G. Ac_1 – The temperature at which austenite begins to form during heating, with the c being derived from the French *chauffant*. Ac_3 – The temperature at which transformation of ferrite to austenite is completed during heating. Ms. – Martensite starting temperature. Ar_1 – The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling. Ar_3 – The temperature at which austenite begins to transform to ferrite during cooling. Note: TMR thermo-mechanical rolling, AC accelerated cooling process, AR AS rolled, N normalized, CR controlled rolling, R reduction, DR direct quenching, T tempered

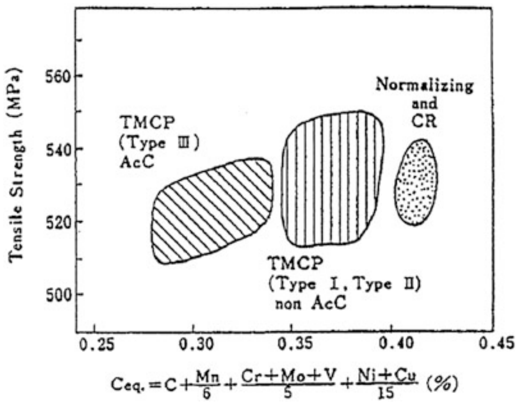


Figure 2.31 Ceq ranges of TMCP types. (Source: voestalpine report, 2010)

2.1.4.9 Quenched-Tempered (Q-T) and Quenched-Self Tempered (QST) Steels

(a) Quenched-Tempered (Q-T) Steel.

The quenching process consists of cooling it rapidly from a temperature [austenizing zone: 840–860 °C (1544–1580 °F) except 760–780 °C (1400–1436 °F) carbon steel tools – high carbon contained] just above the transformation temperature (A_3). The microstructure after will be typically needle/acicular type martensite under microscope due to its fine lamellar structure (Fig. 2.37). The properties of high hardness and internal stresses (very brittle fracture) obtained after quenching should be eliminated by tempering, which accompanies loss of acicular martensite pattern and the precipitation of tiny carbide particles referred to as tempered martensite. As a result, there's improved toughness and slightly reduced the hardness. The success of Q-T treatment, which is to obtain both strength and ductility, depends on the ability of the steel to transform to martensite during the quenching process; the formation of pearlite or

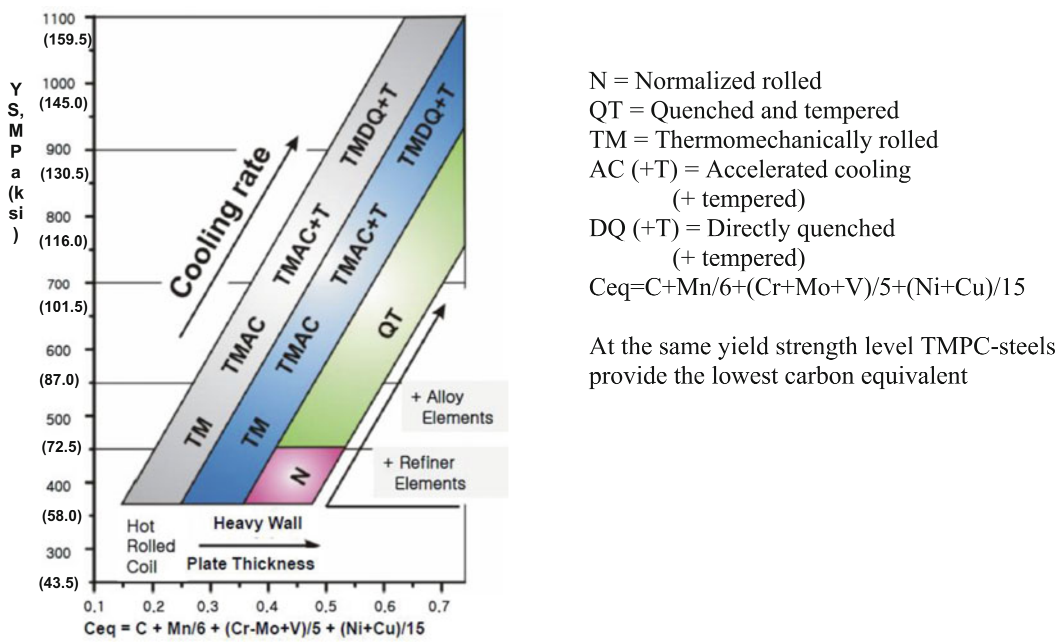


Figure 2.32 Relationship between yield strength (YS) and Ceq among TMCP and Normalized steels. (Source: voestalpine report, 2010). N Normalized rolled, Q-T Quenched and tempered, TM Thermomechanically rolled, AC (+T) Accelerated cooling (+ tempered), DQ (+T) Directly quenched (+ tempered), Ceq C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

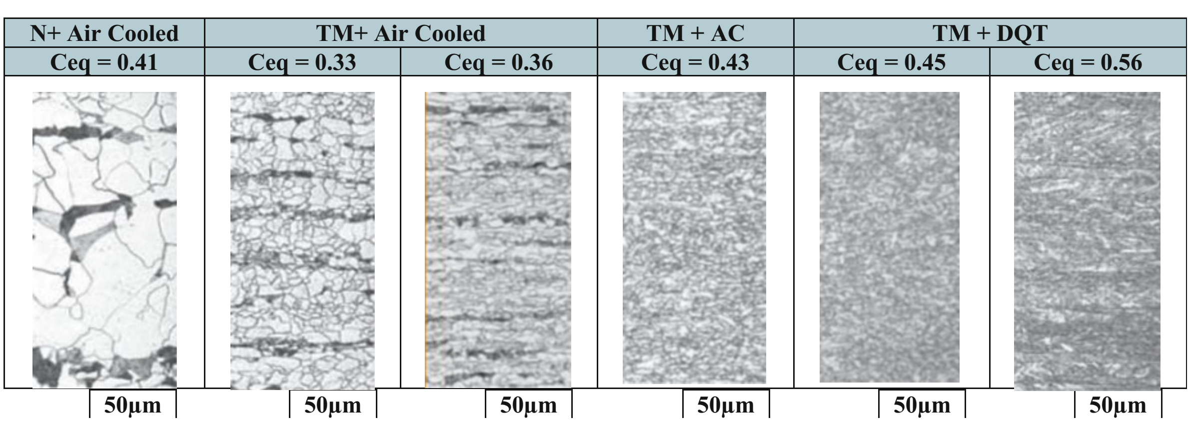


Figure 2.33 Comparison of grain size among several TMCP and normalized steels. (Source: voestalpine report, 2010)

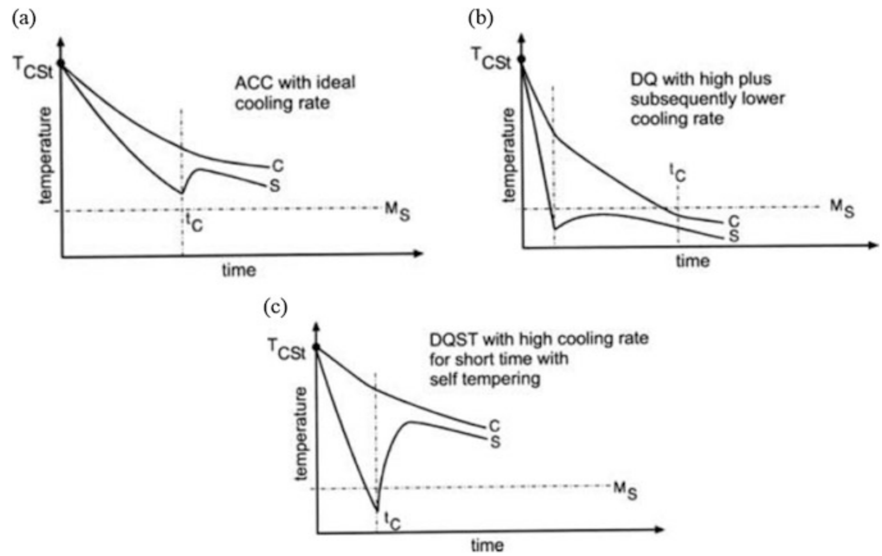


Figure 2.34 Various cooling treatment of plate. (Source: ASTM Journal, Vol.5, No.8, Paper JAI101777). (**a**) Interrupted accelerated cooling (AC). (**b**) Direct quenching (DQ). (**c**) Direct quenching + self tempering (DQ-ST). C temperature in the core, S temperature at the surface, Ms martensite starting temperature, T_{CSt} cooling starting temperature, tc elapsed time of cooling from T_{CSt}

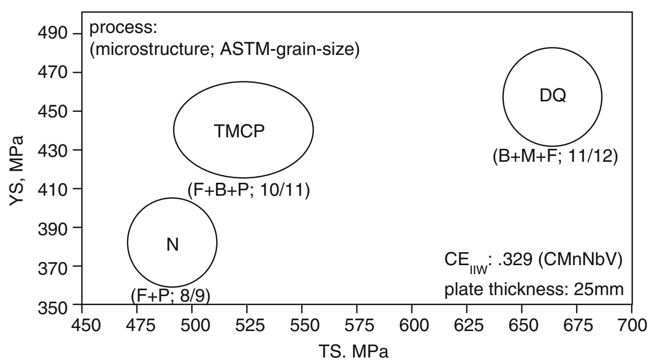


Figure 2.35 Trend of TS and YS per the N, TMCP, and DQ. (Source: ASTM Journal, Vol.5, No.8, Paper JAI101777). N normalized, TMCP thermo-mechanical interrupted accelerated cooling process [from 800 °C (1472 °F) to 500 °C (932 °F) under maximum cooling rate from 80 °C/s (144 °F/s) for 10 mm (0.4 in.) thickness to about 1 °C/s (1.8 °F/s) for 80 mm (3.15 in.) thickness], DQ direct quenching (from the holding temperature to 200 °C (392 °F) under cooling rate from 5 to 60 °C/s (9–108 °F/s), F ferrite, P pearlite, B bainite, CE IIW carbon Eq. per IIW formula

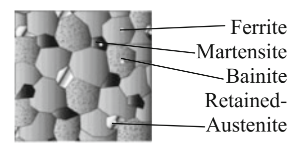
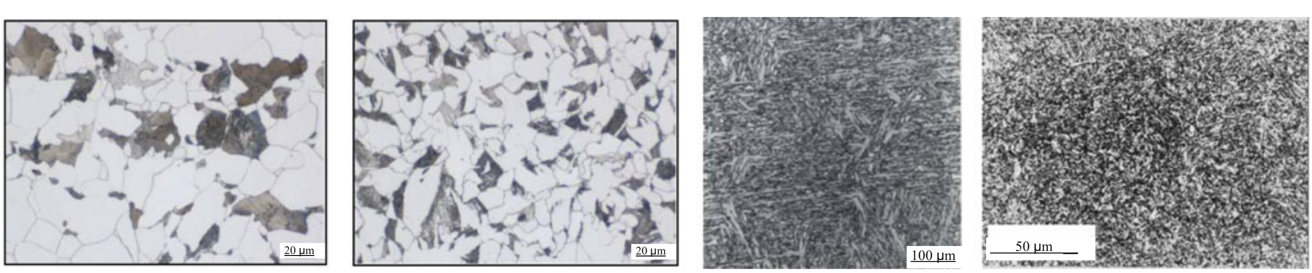


Figure 2.36 Microstructure of TRIP steel. (Source: www.worldautosteel.org)



N – Grain Size = 8-9, F=75%, P=25%, t=180 mm

NACT – Grain Size = 9-11, F=75%, P=25%, t=180 mm

Acicular Martensite of LAS (after quenched-Q)

Tempered Martensite of LAS (after guenched and tempered, Q-T)

Figure 2.37 Microstructures after N, NACT, Q, and Q-T. (Source: voestalpine report, 2010). N normalized, NACT normalizing-accelerated cooling and tempering bainite during rapid cooling will limit martensite formation and hence lower the optimum strength. During the quenching treatment, it is impossible to cool at a uniform rate over the whole specimen. The surface will always cool more rapidly than the interior regions. Hence, the austenite will transform over a range of cooling rates being highest at the surface and at lower cooling rates at the interior regions. The result is a variation in microstructure and properties as a function of cooling rates and position within the specimen. The heat treatment of steels to produce martensitic microstructure throughout the specimen depends on three factors: (1) the hardenability of the metal (metallurgy effect), (2) the quenching medium (to control cooling rate), and (3) the size and shape (for effective mass effect with homogeneous cooling rate of each part) of the Q-T steel. If we reheat martensite at 250–450 °C (482–842 °F) for 1 hour, we get tempered martensite. The tempering reaction in martensite occurs by the decomposition of martensite into ferrite and cementite: *martensite(BCT, single phase) → tempered martensite (α (ferrite) +* Fe_3C *(cementite)).*

The tempered martensite structure provides the best combination of strength and ductility available in steel microstructures. Figure 2.38 shows the variation in hardness for tempered AISI 4340 Q-T steel (1.85%Ni-0.80%Cr) as a function of tempering temperature conducted for 1 hour tempering treatment. As the tempering temperature is increased, the drop in strength and the gain in ductility (toughness) increase.

See Table 2.6 for the effects of alloy elements on the heat treatment of Q-T alloy steels.

(b) Quenched-Self Tempered (QST) Steels

The goal of QST is to achieve high ductility and good thickness properties as well as high strength with outstanding welding properties with reduced carbon equivalent (Ceq), so that it is commonly used for structural steels with heavy wall/section. QST has evolved from the TMCP (thermo-mechanical control processes) that have been known and used for a number of years. QST, which is a variation of TMCP, produces fine-grained steel by a combination of chemical composition and integrated controls of manufacturing processes from ingot or bloom reheating to in-line interrupted QST, thereby achieving the specified mechanical properties in the required product thicknesses.

QST steels of fine grain size are manufactured by producing tempered martensite and varying the pearlite or bainite, or both. This is accomplished through interrupted water quenching in which the duration of the quench is controlled after the final reduction pass while still in the temperature region above the Ar_3 transformation temperature. Rapid quenching is continued until the maximum surface temperature of the steel is below the Ms. (martensitic starting point). Tempering occurs as the core temperature causes the surface temperature to gradually rebound to a proper temperature, defined as the self-tempering temperature (STT), to achieve the desired properties (Fig. 2.39)

Figure 2.40 shows a typical application of QST for structural steel (H-Beam).

2.1.5 High-Alloy (Stainless) Steels

High-Alloy Steels are normally called stainless steel as well.

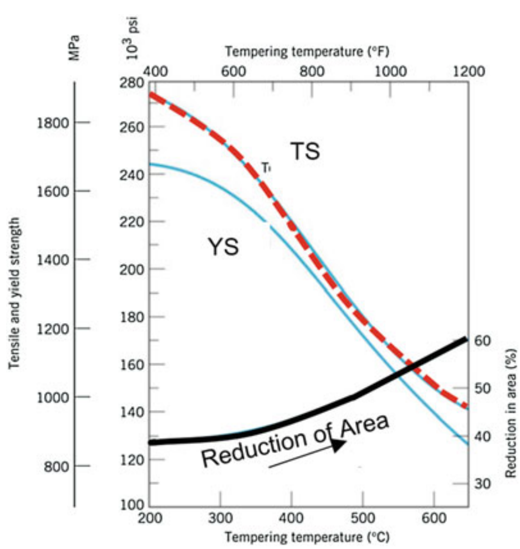


Figure 2.38 Mechanical properties after tempering at several temperatures of AISI 4340 Q-T steel. (Source: Republic Steel Corp., brochure, 2014)

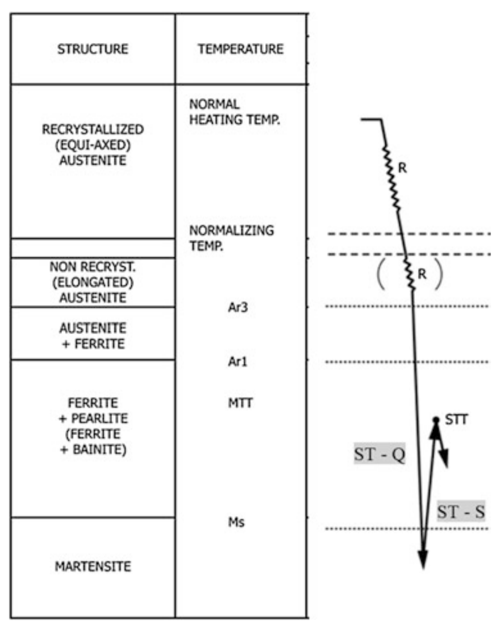


Figure 2.39 Schematic diagram of manufacturing process of QST steels. (Source: ASTM A913). R reduction, STT self tempering temperature, ST-Q & S surface temperature during quenching & self-tempering

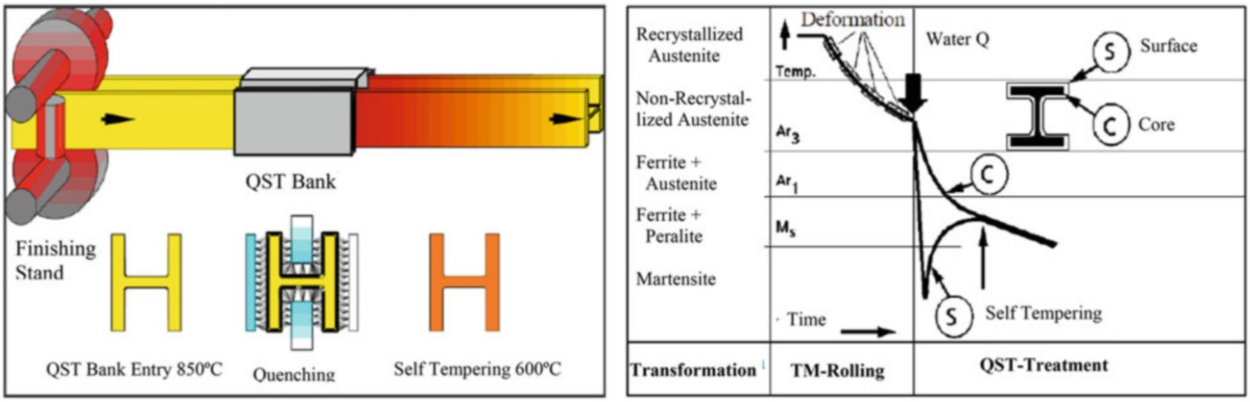


Figure 2.40 Manufacturing process of QST steels. (Source: Arcelor technical report, 2010)

Table 2.40 Major demands of stainless steels

Services	Facilities	Materials (e.g.)	Remark
Corrosive service	1. Chemical/food/semiconductor facilities 2. Facilities for decoration, architecture 3. Medical device, kitchen appliance, aircraft	304 SS, 316 SS, 2205 DSS	Cladding or lining (carbon or low-alloy steel + stainless steel) may be substituted for solid stainless steel.
Cold service	1. Liquid gas facilities 2. Cold service, below −50 °C (−58 °F)	300 series with $C < 0.08\%$	
Hot service	Heater tubes for >20Cr & 20Ni, Mo steels	310 SS, H grade ($C > 0.04\%$)	

2.1.5.1 Major Demands of Stainless Steels

Stainless steels are typically used for corrosion environments, cold service, and hot service, as shown in Table 2.40.

Stainless steels of various kinds are used in thousands of applications. The following gives a flavor of the full range:

Domestic – Appliances, cutlery, sinks, saucepans, washing machine drums, microwave oven liners, razor blades

Architectural/Civil – Cladding, handrails, door and window fittings, street furniture, structural sections, reinforcement bar, lighting columns, lintels, masonry supports

Transport – Exhaust systems, car trim/grilles, road tankers, ship containers, ships chemical tankers, refuse vehicles

Chemical/Pharmaceutical – Pressure vessels, process piping, instruments

Oil and Gas – Platform accommodation, cable trays, subsea pipelines

Medical – Surgical instruments, surgical implants, MRI scanners

Food and Drink – Dishes, catering equipment, brewing, distilling, food processing

Water – Water and sewage treatment, water tubing, hot water tanks, potable water facilities

General – Springs, fasteners (bolts, nuts, and washers), wire

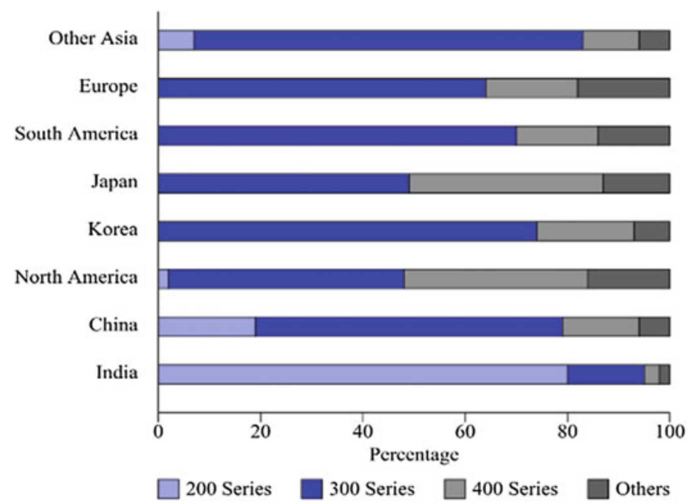


Figure 2.41 Stainless steel grade split by consuming region (2006). (Source: third new Caledonian nickel conference report, 2007)

Figure 2.41 shows the use of several types of stainless steel in the industrialized world. 300 series SS are use more than 60% of all types of stainless steels in the world.

2.1.5.2 Definition of Stainless Steel

Stainless (high-alloy) steel is a special type of steel with a low carbon content, at least 10.5% chromium, and amounts of molybdenum, nickel, nitrogen, and the balance Fe, more than 50%. When the metal is exposed to air, the chromium forms an oxide (Cr_2O_3) on the surface and will do so again if the original coating is damaged. This protective layer makes the metal resistant to rust and other corrosion, hence its name.

Stainless steel is a high grade of steel, and retains its strength and appearance at high temperatures. It resists scaling in fire and extreme heat, and remains shiny over time and with repeated exposure to water. Stainless steels are recognized as high-alloy steels. Typically, the fine-dense (passivated) film shows 80–100 Å thickness and active film has 30–100 Å thickness while the oxide layer on CS has 100–1000 Å with coarse-crystal per the growth of oxide crystal as shown in Fig. 2.42.

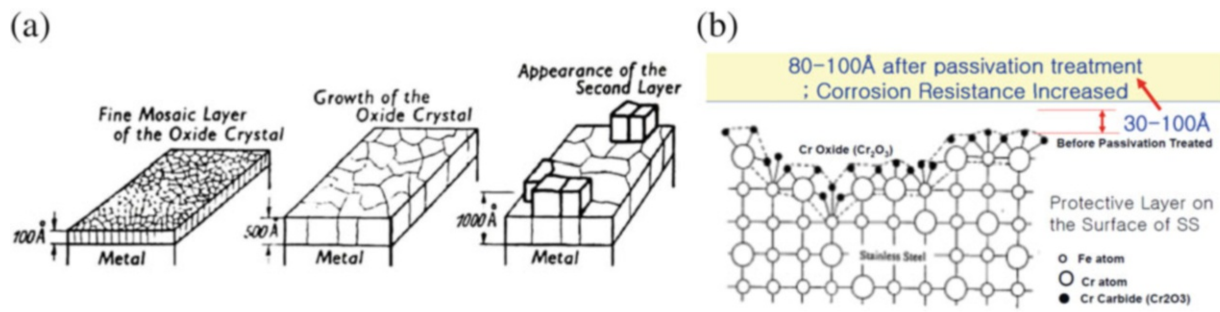


Figure 2.42 Active film on CS surface and protective passive film on the SS surface. (**a**) Active film on CS surface. (Source: Gulbasen and Ruka Report, 1982). (**b**) Protective passive film on the SS surface

2.1.5.3 General Classes of Stainless Steels

(a) Classes per Chemical Composition of Various Stainless Steels

Conventionally the stainless steels (SS) are classified by microstructures, such as ferrite (FSS), martensite (MSS), austenite (ASS), and dual phase of ferrite and austenite (DSS). Precipitation-hardened stainless steel also may be classified as stainless steel due to its unique characteristics. If the corrosion resistance is more developed (PREN >40) in chloride SCC environment, the stainless steel can be recognized as super stainless steel. So each class is called super FSS (SFSS), super MSS (SMSS), super ASS (SASS), or super DSS (SDSS).

- Austenite Stainless Steels (ASS): 300 Series
- Ferrite Stainless Steels (FSS): 405, 430, 410S, etc.
- Martensite Stainless Steels (MSS): 410, etc.
- Precipitation Hardening Stainless Steels (PHSS): 17–4, 17–7, etc.
- Duplex Stainless Steels (DSS): 2205, 2507, etc.
- Super Stainless Steels (PRE >40): Super Austenitic/Ferritic/Martensitic/Duplex Stainless Steels (SASS, SFSS, SMSS, SDSS): e.g., 6% Mo, Sea-Cure, UNS S44700, 2507 DSS, respectively. Figure 2.43 indicates the location and the microstructure of the ASS welding electrodes or base metals.

Table 2.41 shows the typical chemical composition and principal properties of various stainless steels.

Delta (δ) Ferrite is a residual structure of the solidification process, it is magnetic and brittle at low temperature. δ Ferrite is present in ASS and DSS at room temperature. In ASS, normally δ Ferrite can be found after welding. See Sect. 2.1.6.1 for more details.

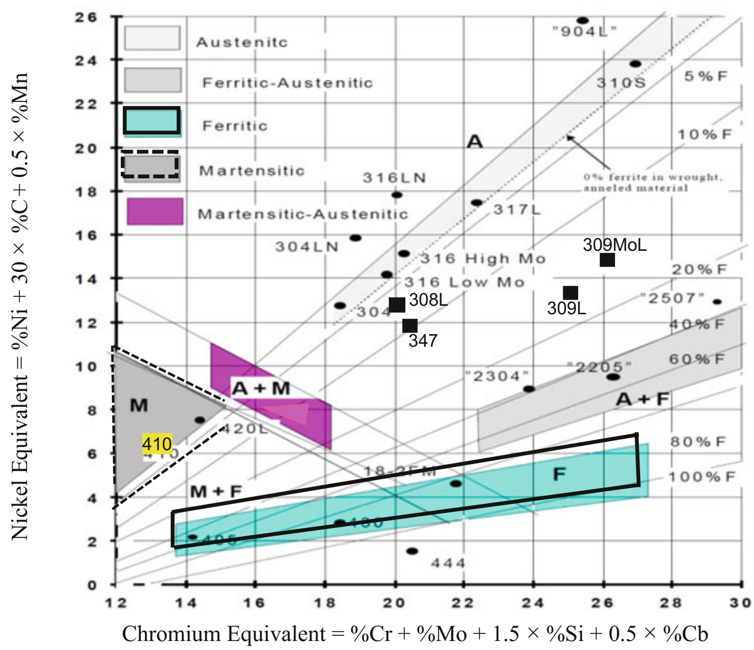


Figure 2.43 Indicates the location and the microstructure of the ASS welding electrodes or base metals

Table 2.42 shows a typical comparison of the characteristics of several stainless steels. The physical properties of MSS, FSS, DSS, PHSS is very close to CS while those of ASS is close to alloy metal.

Table 2.41 Characteristics of various stainless steels

SS category	Composition (wt %)					Hardenable	Ferro-magnetism
	C	Cr	Ni	Mo	Others		
Martensitic	> 0.10	11–14	0–1	–	V	Hardenable	Magnetic
	> 0.17	16–18	0–2	0–2			
Martensitic-austenitic	< 0.10	12–18	4–6	1–2		Hardenable	Magnetic
Precipitation hardening		15–17	7–8	0–2	AL	Hardenable	Magnetic
		12–17	4–8	0–2	AL, Cu, Ti, Nb		
Ferritic	< 0.08	12–19	0–5	< 5	Ti	Not hardenable	Magnetic
	< 0.25	24–28	–	–			
DSS (ferrite-austenite)	< 0.05	18–27	4–7	1–4	N,W	Not hardenable	Magnetic
Austenitic	< 0.08	16–30	8–35	0–7	N, Cu, Ti, Nb	Not hardenable	Nonmagnetic

Table 2.43 shows PRE (pitting resistance equivalent) of various stainless steels.

(b) Stress and Strain of Various Stainless Steels.
Figure 2.44 shows a typical values of tensile strengths. Martensitic structures indicate higher tensile strength values.

(c) Impact Test Energy Values of Various Stainless Steels.
Figure 2.45 shows CVN impact test absorbing energy (ITAE) ranges of various stainless steels. DSS, FSS, and MSS show a very similar with CS while ASS has a very high ITAE.

(d) High-Temperature Mechanical Properties of Various Stainless Steels.
Figure 2.46 shows high temperature mechanical properties of various stainless steels.

(e) Development History of Various FSS and MSS.
Figure 2.47 shows a development history tree of various conventional MSS and FSS families. Super MSS and Super FSS (PRE > 40) are not shown in these family tree.
Figure 2.48 shows a development history tree of various conventional 300 series ASS and DSS families. Super ASS and Super DSS (PRE >40) are not shown in this family tree.

Table 2.42 (1/2) Classes of conventional stainless steels (simple comparison for reference)

Material characteristics at room temperature	MSS (e.g., 410 SS, 13Cr)	FSS (e.g., 430 SS, 18 Cr)	ASS (e.g., 304, 316, 18–8)	DSS (e.g., 2205)	PHSS (e.g.,17Cr-7Ni-1Al)
Ferromagnetism	Yes	Yes	None (but, have s slight magnetic for the cold worked and welded parts)	Yes	Yes
Metallurgical structure	Martensite	Ferrite	Austenite	Austenite- ferrite	Semi-austenitic (17–7) or Martensite (17–4)
Rust in atmospheric	Often	Scarcely indoor, often outdoor	Scarcely indoor and outdoor	Nil	Scarcely indoor and outdoor
Density (s.g.), g/cm^3	7.70	7.72	7.95	7.88	7.67
Thermal expansion mm/mm ($\times 10^{-6}$/ °C) @200–600 °C	11.8 (cf, carbon steel; 13.4)	11.2	17.3	13.7	11.8
Thermal conductivity (W/m.°C) @ 20 °C	22 (cf, carbon steel; 43)	20	12	20	20
DBTT, °C (approx.)	−29 (−20 °F)	−29/−40 (−20/ −40 °F)	−254/−196 (−425/−320 °F)	−29/−40 (−20/ −40 °F)	−29/−46 (−20/−50 °F)
T.S (MPa)	450	450	520	620	1170
HB (for hot rolled)	215	183	187	256–293	375
Electrical resistivity $\times 10^{-6}$ (Ω.cm) @ 20 °C	58 (cf, carbon steel; 15)	60	70/73	85	98
Hardenability by HT, or hot work	High – Solid 410 SS to limit. Recommended clad metals instead of solid 410 SS	None	None	None	High
Hardenability by cold work	Slight	Medium	High	High	A little
Machinability	Medium to bad	Medium	Good	Medium to bad	Medium to good
Welding deformation	A little	A little	High	Medium	A little
Corrosive resistance	Medium	Medium to good	Good to excellent	Excellent	Good to excellent
475 °C (885 °F) Embrittlement; hardness↑, ductility↓, impact absorb. Energy↓, corrosion resistance ↓	None or just a little	After 400–500 °C (752–932 °F) for several tens hours. [Remedy] heating to 700–900 °C (1292–1652 °F) and rapid cooling	None or just A little	High under long exposure to temperatures in the 343–527 °C (650–980 °F); Cr ↑ - more rapid exposure	None or just A little
σ phase embrittlement; hardness↑, ductility↓, impact absorb. Energy↓, corrosion resistance ↓	After 500–970 °C (932–1778 °F) for several tens hours. [Remedy] heating to 950–1050 °C (1742–1922 °F) and SHT	After 600–800 °C (1112–1472 °F) for several hundred hours. [Remedy] annealing to 800–850 °C (1472–1562 °F)	A little	High under exposure to temperatures in the 593–996 °C (1100–1825 °F)	A little

Table 2.42 (2/2) Classes of conventional stainless steels (simple comparison for reference)

Material characteristics at room temperature	MSS (e.g., 410 SS, 13Cr)	FSS (e.g., 430 SS, 18 Cr)	ASS (e.g., 304, 316, 18–8)	DSS (e.g., 2205)	PHSS (e.g.,17Cr-7Ni-1Al)
Depletion of Cr carbides; IGC (intergranular corrosion cracking)	When slow cooling after heating of 420–850 °C (788–1562 °F). – mainly weldments [Remedy] heating to 850–930 °C (1562–1706 °F) and SHT	When heated over than 925 °C (1697 °F). [remedy] heating to 700~925 °C (1292–1697 °F) and slow cooling	When heated 427~871 °C (800–1600 °F) for several tens of minutes – mainly weldments (HAZ) and hot worked parts [Remedy] SHT, add stabilized elements, low carbon	Sometimes	Sometimes
Stress corrosion cracking (SCC) (chloride environment)	Sometimes [remedy] stress relieving, annealing	A little	Severe (especially under T.S.) [Remedy] stress relieving annealing/use SSS	Low	A little
PWHT requirements by ASME sec. VIII	≤0.08%C: Not required >0.08%C: Required min. 693 °C (1279 °F)	≤0.08%C: Not required >0.08%C: Required min.732 °C (1350 °F) rapid cooling between 732–650 °C (1350–1202 °F), and slow cooling, max. 56 °C (100 °F) /hr. below 650 °C (1202 °F).	ASME Sec. II Part D Appendix 6; solution heat treatment [1010–1121 °C (1850–2050 °F) and rapid cooling]	No	Around 1000 °C (1832 °F) and rapid cooling as per materials
Cost ratio (KCS = 1)	4 to 5	4.5–5	5 ~ 9	10–11	10
Others and use	Chemical equipment, decoration	Chemical equipment, decoration	Chemical/food equipment, decoration, architecture, kitchen appliance, aircraft, etc.	High chlorides, marine environments	High temperature strength, hot machining, for casting or forging

Table 2.43 PRE of various stainless steels

Grade	304L	316L	2304	317L	2205	904L	2507	254 SMO	654 SMO
PRE_{16xN}	19	26	26	30	35	36	43	43	56
PRE_{30xN}	20	26		30		37		46	63

PRE = %Cr + 3.3 × %Mo for stainless steels (by Lorenz in 1969): fundamental formula
PRE_{16xN} = %Cr + 3.3 × %Mo + 16 × %N for stainless steels (by Truman in 1978)
PRE_{30xN} = %Cr + 3.3 × %Mo + 30 × %N for stainless steels (by Herbsleb in 1982)
These PRE, PRE_{16xN}, PRE_{30xN} formulas are only applicable for stainless steels and Ni-Cr-Mo alloys

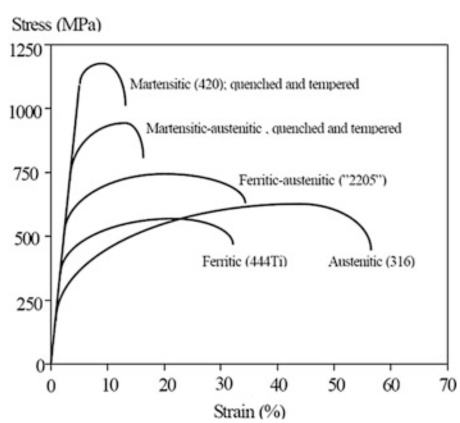


Figure 2.44 Typical stress and strain of various stainless steels. (Source: Outokumpu report, 2010)

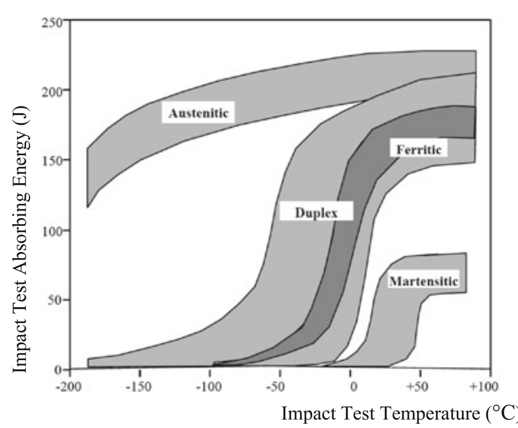


Figure 2.45 Typical impact test absorbing energy ranges of various stainless steels. (Source: Bela Leffler, SS and Their Properties, 1976)

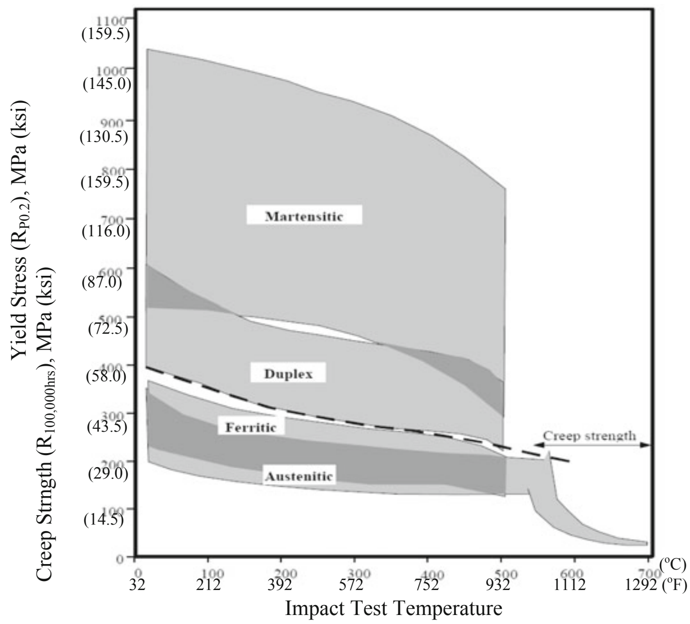


Figure 2.46 High mechanical properties of various stainless steels at elevated temperature. *The dashed line shows the yield stress of some very high-alloyed and nitrogen-alloyed ASS.* (Source: Bela Leffler, SS and Their Properties, 1976)

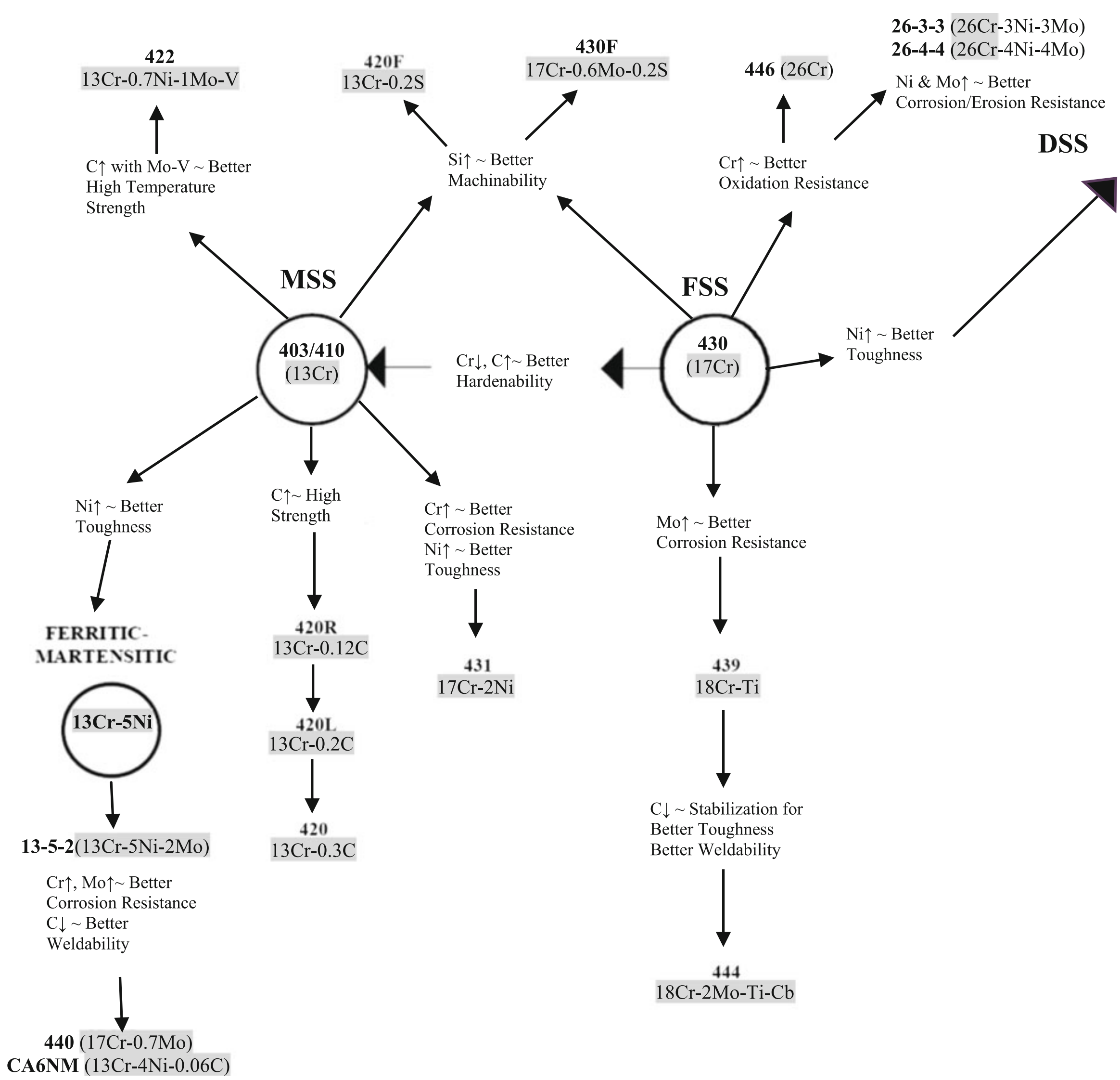


Figure 2.47 Development history of various MSS and FSS. (Source: Outokumpu report, 2008 & NiDI Publ. 9014, 1976 – modified)

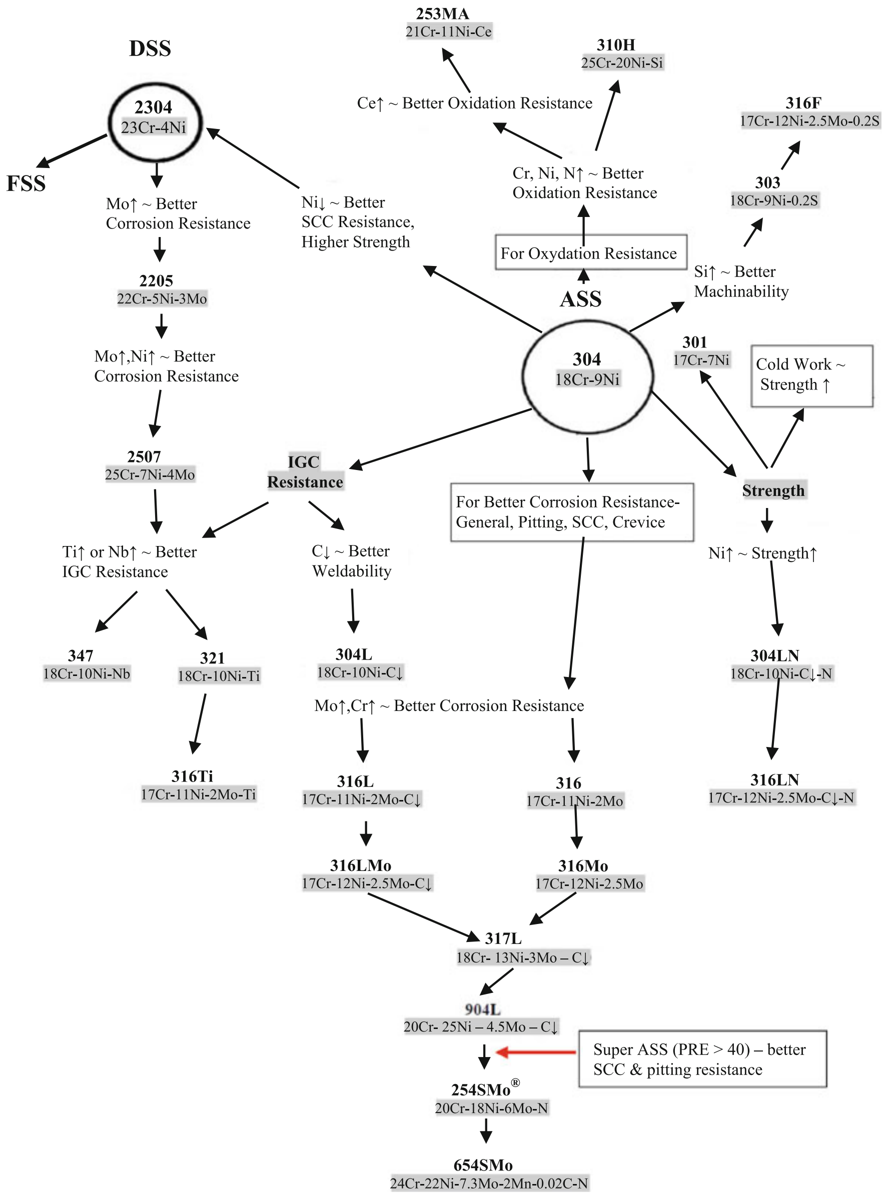


Figure 2.48 Development history of various ASS and DSS. (Source: Outokumpu report, 2008 & NiDI Publ. 9014, 1976 – modified)

2.1.5.4 Characteristics of Elements in Stainless Steels

(a) Characteristics of Elements in Stainless steels.

Table 2.44 shows typical characteristics of elements in stainless steels.

Table 2.45 shows the characteristics of elements in stainless steels in views of corrosion, strength, weldability, and machinability.

(b) Carbon Effect in Austenitic Stainless Steels.

1. The most important factor in stainless steels is to keep the strength and corrosion resistance.
2. Carbon easily makes the carbides (e.g., $Cr_{23}C_6$) that highly decrease the corrosion resistance even if they can increase the strength (up to 0.2 wt%C).
3. Cr and Mo may increase the strength instead of the strength loss due to lower carbon.
4. Carbon (up to about 0.1%) creates good fatigue resistance and creep strength at high temperatures.

(c) Characteristics of Suffix Symbols of Stainless Steels (Table 2.46)

Table 2.44 (1/3) Characteristics of elements in stainless steels

Element	Characteristics
Al (Aluminum)	Aluminum (Al) improves oxidation resistance, if added in substantial amounts. It is used in certain heat-resistant alloys for this purpose. In PHSS, Al is used to form the intermetallic compounds that increase the strength in the aged condition.
C (Carbon)	Iron is alloyed with carbon (C) to make steel and has the effect of increasing the hardness and strength of iron. C is a strong austenite former and strongly promotes an austenitic structure. It also substantially increases the mechanical strength. In the majority of stainless steel grades, carbon is usually held to 0.08% maximum in ASS and preferably much less because C reduces the resistance to intergranular corrosion. For example, the grade sometimes specified for welding, 304L SS or 316L SS, has carbon restricted to 0.03% maximum. Higher carbon contents up to 1.00% render not only some of ASS (e.g., 304H, 316H) higher creep-rupture strength, but also some of MSS (e.g., 440 SS) amenable to conventional hardening and tempering heat treatment for the purpose of developing high strength and hardness levels. In FSS, C will strongly reduce both toughness and corrosion resistance. In the MSS and martensitic-austenitic steels, C increases hardness and strength. In the MSS an increase in hardness and strength is generally accompanied by a decrease in toughness and in this way carbon reduces the toughness of these steels. Required composition limits (ASTM A959): It is recommended that limits be to only two decimal places for levels of 0.04% and higher because it is not necessary to control to such precision at levels above 0.04% (it should be recognized that limits such as 0.045% maximum may also be simply stated as 0.04% maximum.). It is also recommended that three decimal places be used at levels of 0.030% and lower, unless, e.g., it is clearly recognized that 0.03% maximum means that 0.035% is satisfactory.
Ca (Calcium)	Small additions of Calcium (Ca) are used to improve machinability, without the detrimental effects on other properties caused by Sulfur (S), Phosphorus (P), and Selenium (Se).
Ce (Cesium)	Cerium (Ce) is one of the rare earth metals (REM) and is added in small amounts to certain heat-resistant steels and alloys in order to increase the resistance to oxidation and high-temperature corrosion.
Co (Cobalt)	Cobalt (Co) becomes highly radioactive when exposed to the intense radiation of nuclear reactors, and, as a result, any stainless steel that is in nuclear service will have a Cobalt restriction, usually approximately 0.2% maximum. This problem is emphasized because there is normally a residual Co content in the Nickel used in producing ASS. Cobalt (Co) is only used as an alloying element in MSS where it increases the hardness and tempering resistance, especially at higher temperatures.
Cr (Chromium)	Chromium (Cr) is the most important alloying element for corrosion resistance of stainless steels. The minimum Cr content of standardized stainless steels is 10.5%. This better corrosion resistance is due to a Cr-oxide film (i.e., Cr_2O_3) that forms on the steel surface. This extremely thin layer, under the right conditions, is also self-repairing. It is a strong ferrite former. It also increases the resistance to oxidation at high temperatures. It will decrease the thermal conductivity, electrical conductivity, and thermal expansion coefficient. Cr promotes a ferritic structure. Required composition range limits (ASTM A959): A composition spread of max. 2% is recommended; existing broader limits were not reduced to less than a 3% spread, e.g., 17.5–19.5% for 304 SS, 20.5–23.5% for XM-19 (UNS S20910).
Cu (Copper)	Copper (Cu) is normally present in stainless steel as a residual element. However, it is added to a few alloys to produce precipitation hardening properties or to enhance corrosion resistance particularly in seawater environments and sulfuric acid. For instance, an addition of 3.0–4.0 wt% improves resistance to attack by sulfuric acid. Cu promotes an austenitic structure. In PHSS, Cu is used to form the intermetallic compounds that are used to increase the strength. Required composition limits (ASTM A959): It is recommended that copper limits having only a maximum limit but no minimum should not be used unless justified by specific technical effects (e.g., for better corrosion resistance in the specific environment)
Mn (Manganese)	Manganese (Mn) is added to steel to improve hot working properties and increase strength, toughness, and hardenability. Similar to Ni, Mn promotes the formation of austenite and in certain grades partially replaces Ni, e.g., 202 SS (see Table 2.48) as a substitute for 304 SS. High Mn ASS can be used in cryogenic services (see Sect. 2.1.4.4). Its effect on the ferrite/austenite balance varies with temperature. At low temperatures, Mn is an austenite stabilizer but at high temperatures it will stabilize ferrite. Mn increases the solubility of nitrogen and is used to obtain high nitrogen contents in austenitic steels. It is also used in the free-machining grades to which sulfur and selenium additions have been made. Required composition limits (ASTM A959): Except for the Cr-Ni-Mn grades (S2XXXX), it is recommended that limits of 2% maximum and 1% maximum be used for the austenitic and other grades, respectively, except for the free machining grades with high sulfur (S) or selenium (Se), or when necessary to promote nitrogen (N) solubility.
Nb & Ta (Niobium & Tantalum)	Niobium (Nb) or columbium (Cb) – it is the same name – is a carbide-stabilizing element and acts similarly to Ti. They are more commonly used in heavier sections. Nb (Cb) is both a strong ferrite and carbide former. Nb is used in stabilized welding rods and is preferred to Ti in this application. See Sect. 2.1.6.3 for more details. In ASS, it is added to improve the resistance to intergranular corrosion but it also enhances mechanical properties at high temperatures. In MSS, Nb lowers the hardness and increases the tempering resistance.
Mo (Molybdenum)	Mo in Cr-Ni ASS improves passivity of the surface resulting in increased corrosion resistance, particularly pitting and crevice corrosion especially in chlorides and sulfur (S)-containing environments. The corrosion-resistant effect is greater in high than in low temperatures. ASS, including more than 2.5%Mo, have good corrosion resistance in naphthenic acid environment. It improves high temperature strength and weldability and strongly promotes a ferritic structure. In FSS, ASS, and DSS, Mo also promotes the formation of secondary phases in ferritic, ferritic-austenitic (duplex), and austenitic steels. In MSS it will increase the hardness at higher tempering temperatures due to its effect on the carbide precipitation. In MSS and FSS, Mo can be σ phase former (degradation factor) in high temperatures. Required composition range limits (ASTM A959): It is recommended that the composition spread not exceed 1%, unless a broader range is justified by specific technical effects. Molybdenum limits having only a maximum limit but no minimum should not be used unless justified by specific technical effects, e.g., 2.00–3.00% for 316 SS.
N (Nitrogen)	Nitrogen (N) is a very strong austenite former and strongly promotes an austenitic structure. It will improve corrosion (pitting) resistance in Mo-containing stainless steels. It can dramatically improve the yield strength of austenitic grades. If N is added too much in stainless steel, the corrosion resistance will be diminished due to formation of Cr_2N. In FSS, N will strongly reduce toughness and corrosion resistance. In the MSS and martensitic-austenitic steels, N increases both hardness and strength but reduces the toughness. Required composition limits (ASTM A959): It is recommended that nitrogen limits having only a maximum limit but no minimum should not be used unless justified by specific technical effects (e.g., for SCC resistance). All "N" designated classes (e.g., 304LN) in the suffix have a range (with minimum and maximum values).

Table 2.44 (2/3) Characteristics of elements in stainless steels

Element	Characteristics
Ni (Nickel)	The main reason for Nickel (Ni) addition is to promote an austenitic structure. Ni is the most common element added to Cr-stainless steels and when added in quantities of 8.00% or greater, develops the austenitic series of grades. The toughness and ductility are increased because Ni is a strong austenitic former. Lesser amounts of Ni (2.5–7.5%) will produce the austenitic-ferrite (duplex) grades. Ni promotes the resistance to corrosion of Ni-based alloys as compared with Fe-based alloys under conditions where the passive layers may be absent, or may be destroyed locally or uniformly. For example, pitting and/or crevice corrosion tends to progress less rapidly in high-Ni alloys. It also reduces the corrosion rate in acid environments, high chloride solution, and high-temperature oxidation. Alloys that contain more than 45–50%Ni have excellent SCC resistance. See Figures below. In PHSS, Ni is also used to form the intermetallic compounds that are used to increase strength. Required composition range limits (ASTM A959): It is recommended that the composition spread not exceed 3% unless a broader (generally higher) spread is justified by specific technical effects, e.g., 8.0–11.0% for 304L SS, 10.0–14.0% for 316 SS.

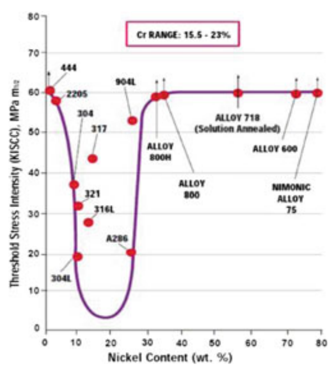


Figure 2.45a Effect of Ni content on SCC threshold stress at various alloys in aerated aqueous 22% NaCl solution at 105 °C (221 °F). (Source: M.O. Speidel, metallurgical transactions A, Vol 12A, p779, 1981)

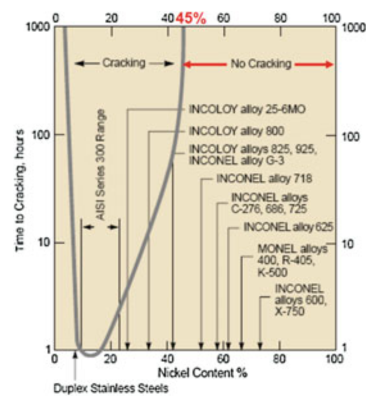


Figure 2.45b Copson curve tested in boiling 42% $MgCl_2$ at 155 °C (310 °F). The test has shown that alloys containing more than about 45% nickel are immune to chloride stress cracking

Element	Characteristics
P (Phosphorus)	Phosphorus (P) is usually added with S, to improve machinability. P present in ASS increases strength. However, it has a detrimental effect on corrosion resistance and increases the tendency of the material to crack (solidification) during welding. See Sect. 2.1.6.1 for more details. Required composition range limits (ASTM A959): It is recommended that 0.045% maximum be applied to austenitic grades, and 0.040% maximum to other grades unless the sponsoring producer recommends a lower limit for specific technical effects. *Exception*—some of the Cr-Ni-Mn austenitic grades have always been produced to 0.060% maximum.
S (Sulfur)	Sulfur (around 0.2%S) is added to certain stainless steels, the free-machining grades in order to increase the machinability. At the levels present in these grades, sulfur will substantially reduce corrosion resistance, ductility, and fabrication properties, such as weldability (like P) and formability. See Sect. 2.1.6.1 for more details on solidification cracking during welding. Other than for machinability, S in stainless steel is usually kept below 0.03%. Required composition range limits (ASTM A959): It is recommended that 0.030% maximum be applied to all grades except the free-machining grades unless lower limits have been required for specific technical effects.
Se (Selenium)	Selenium (Se) was previously used as an addition to improve machinability.
Si (Silicon)	Silicon (Si) is used as a deoxidizing (killing) agent in the melting of steel, and as a result most steels contain a small percentage of Si. Si increases the resistance to oxidation, both at high temperatures and in strongly oxidizing solutions at lower temperatures. It promotes a ferritic structure. Si is added in quantities of around 1.00% to improve scaling resistance of austenitic grades when used at higher temperatures. Required composition range limits (ASTM A959): Past practice has been to establish 0.75% maximum for tubular related products such as flat rolled and tubulars, and 1.00% maximum for long products and forgings. For grades produced both as long and flat-rolled products, 1.00% maximum was chosen since it will also include products melted to lower limits. Use of lower or higher limits should be based on specific technical effects.
Ti (Titanium)	Titanium (Ti) is a strong ferrite former and a strong carbide former, thus lowering the effective C content and promoting a ferritic structure in two ways. Ti as a carbide stabilization element combines with C to form Ti-carbides (prior to formation of Cr-carbide precipitation adjacent to welds which can result in intergranular corrosion (IGC) or weld decay), which are quite stable and hard to dissolve in steel, which tends to minimize the occurrence of intergranular corrosion. As a result, the precipitation of Cr-carbide during welding can be prevented or minimized. It combines with carbon to form Ti-carbides, which are quite stable and hard to dissolve in steel, which tends to minimize the occurrence of IGC. Adding approximately 0.25 to 0.60% Ti causes the carbon to combine with Ti in preference to Cr, preventing a tie-up of corrosion-resisting Cr as intergranular carbides and the accompanying loss of corrosion resistance at the grain boundaries. However, the use of Ti has gradually decreased over recent years due to the ability of steelmakers to deliver stainless steels with very low carbon contents that are readily weldable without stabilization In ASS it is added to increase the resistance to IGC but it also increases the mechanical properties at high temperatures. In FSS, Ti is added to improve toughness and corrosion resistance by lowering the amount of interstitials in solid solution. In MSS, Ti lowers the martensite hardness and increases the tempering resistance. In PHSS, Ti is used to form the intermetallic compounds that are used to increase the strength. See Sect. 2.1.6.3 for more details on sensitization, IGC, and stabilizing element's role.

Table 2.44 (3/3) Characteristics of elements in stainless steels

Element	Characteristics
V (Vanadium)	Vanadium (V) increases the hardness of martensitic steels due to its effect on the type of carbide present. It also increases tempering resistance. V stabilizes ferrite and will, at high contents, promote ferrite in the structure. It is only used in hardenable stainless steels.
W (Tungsten)	Tungsten (W) is a ferrite former. It will improve the strength due to W-carbide and corrosion resistance due to WO_3.

Source: ASM SS Handbook, 2008
Note: Sources; ASM Metal Handbooks, SS Handbook, NiDI publications, Euro-Inox 2004 report (alloying elements in SS)

Table 2.45 Summary of characteristics of elements in stainless steels

Properties	Cr	Ni	Mo	C	Ti	Nb (Cb)	S	Mn	Si	P	Cu	Se
Corrosion resistance (pitting & SCC)	B	B	B	---	---	---	D	---	---	D	---	---
Mechanical properties (strength)	B	---	B	B	B	B	---	B	B	B	B	---
High temperature (creep, sulfidation) resistance	B	B	B	---	B	B	D	---	---	---	---	---
Weldability	D	---	B	D	B	B	D	B	---	D	---	---
Cold workability & toughness	D	B	---	D	---	---	D	---	---	---	B	---
Machinability	D	---	---	D	---	---	B	---	---	B	---	B

Source: ASM SS Handbook, 2008
B: Beneficial, D: Detrimental, ---: may not be affected

Table 2.46 Suffix symbols of stainless steels (e.g., type 304“L”)

Suffix	Meaning	Remark
L	(Extra) low carbon (max. 0.03%)	1. e.g., max. 0.08% for no “L” mark 2. Improved anti-IGC and weldability
S	Low carbon (max. 0.08%)	1. e.g., max. 0.15% for no “S” mark (e.g., 400 series and 310 SS) 2. Improved anti-corrosion and weldability
ELC	Extra low carbon (max. 0.015%)	1. Improved anti-IGC & corrosion and weldability 2. Decreased strength 3. Mainly used for welding electrodes
ULC	Ultra extra low carbon (max. 0.0075%)	1. Improved anti-IGC & corrosion and weldability 2. Decreased strength 3. Mainly used for welding electrodes
N	0.10 ~ 0.16%N	1. e.g., max. 0.10% for no “N” mark “N” 2. Greatly improved the anti-corrosion with Mo.
H	0.04 ~ 0.10% carbon	1. Stands for “high carbon” 2. Useful for creep resistant materials in high temperature because of coarse grain. 3. When purchased, grain size, “ASTM no. 5 and coarse” is specified.
Cb	10 × Cb% min. ~1.10 max.	1. Added the high temperature stabilized elements (Nb) 2. Improved anti-IGC and weldability
Ti	5 (C + N)% min. ~0.70% max.	1. Improved anti-IGC 2. Required less than Cb content because of low solubility for C.
Mo	2.0 ~ 3.0% Mo	Improved anti-corrosion (naphthenic acid) except oxidizing acid (nitric acid).
Se	0.15% selenium	Improved machinability
LMN (MoLN)	Low carbon, Mo & N	Improved anti-sulfuric acid corrosion and anti-oxidized scaling in high temperature
F	Sulfur (0.06~0.15%)	Improved machinability

Source: ASTM

2.1.5.5 Types and Characteristics of Stainless Steels

Figure 2.49 shows typical microstructures of several stainless steels.

(a) Austenitic Stainless Steels (ASS)

1. General Characteristics

The carbon content is as low as it is commercially feasible to obtain. Chromium (Cr) can range from 16% to 26% and nickel (Ni) content is usually at least 8%, but can be as high as 22%.

The Ni effect is to promote a completely austenitic structure (Fig. 2.49a).

There are three types of ASS:

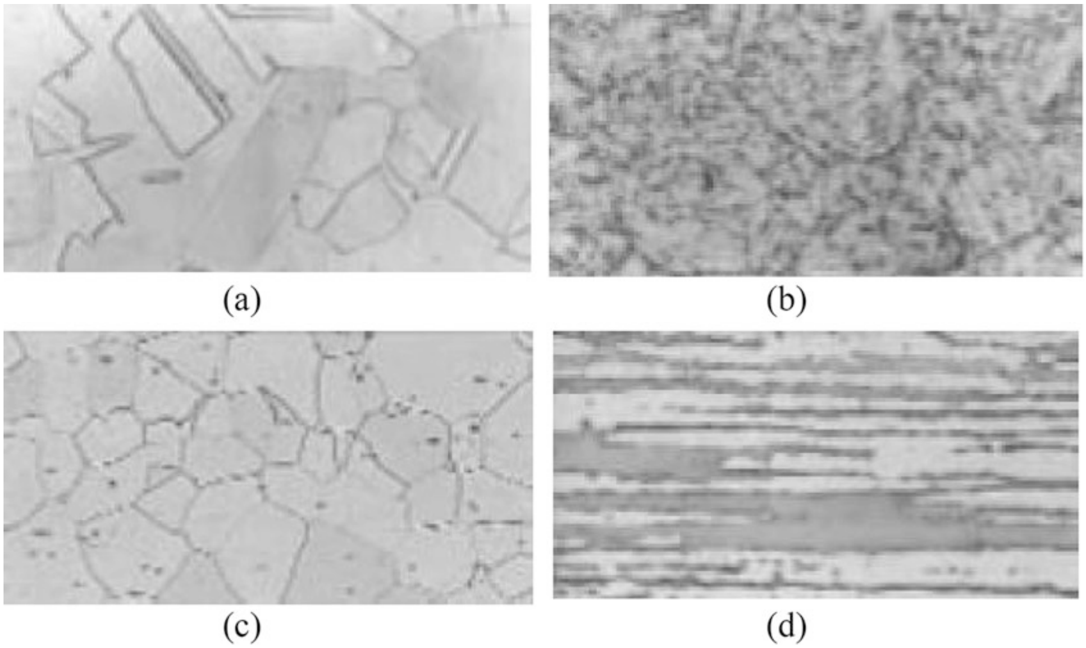


Figure 2.49 Typical microstructures of several stainless steels. (Source: Outokumpu technical report, 2010). (**a**) Austenite (γ-iron). Face-centered cubic with 12 atom neighbors. 74% close packing. (**b**) Martensite. Undercooled, oversaturated solution of carbon in ferrite, achieved by heat treatment or cold working. (**c**) Ferrite (α-iron). Body-centered cubic with 8 atom neighbors. 68% packing. (**d**) Duplex. (Austenitic-ferritic). Well-balanced two-phase structure with ferrite content between 30% and 50%

– Lean ASS (Minimum of Cr & Ni contents for austenitic structure) – 200 series ASS up to 0.20%C, 2.0–9.0%Mn, up to 2.0%Si, 16.0–23.0%Cr, 1.0–5.0%Ni, up to %3.0 Mo, up to 3.0%Cu, 0.1–0.35%N, up to 4.0%W, up to 0.01%B, up to 1.0%Co, iron and impurities,
– Regular ASS – 300 series ASS.
– Super ASS – PRE > 40.

In practice, most ASS have a completely austenitic structure. The difference between the equilibrium diagram and reality is due to the fact that all commercial alloys are used in the annealed condition. Annealing requires a water quench, so the austenitic structure is quenched in. It is really metastable, but at normal temperatures the structure remains austenitic.

However, some of the austenitic structures can be transformed to ferrite and/or martensite by ferrite number control to avoid solidification crack during welding and cold work.

2. Standard 300 series Austenitic Stainless Steels (ASS).

ASS with 16%Cr-6%Ni (as a minimum) composition were called 300 Series SS. Table 2.47 shows chemical compositions of several 300 series ASS which have Cr ≤ 20% and Ni ≤ 19% in accordance with the UNS numbering system.

Table 2.47 (1/2) Chemical compositions of several wrought 300 series[(4)] ASS (Cr ≤ 20% and Ni ≤ 19%) – UNS/SAE/AISI

Designation			Chemical composition % by mass max unless otherwise stated (Balance: Fe)								
UNS No	SAE No	AISI/Gr. No.	Cr	Ni	Mo	C	Si	Mn	P	S	Others/Remark
S30100	30301	301	16.0–18.0	6.0–8.0	–	0.15	1.00	2.00	0.045	0.03	N 0.10
S30103	–	301L	16.0–18.0	6.0–8.0	–	0.03	1.00	2.00	0.045	0.03	N 0.20
S30153	–	301LN	16.0–18.0	6.0–8.0	–	0.03	1.00	2.00	0.045	0.03	N 0.07–0.20
S30200	30302	302	17.0–19.0	8.0–10.0	–	0.15	0.75	2.00	0.045	0.03	–
S30215	30302B	302B	17.0–19.0	8.0–10.0	–	0.15	2.00–3.00	2.00	0.045	0.03	–
S30300	30303	303	17.0–19.0	8.0–10.0	0.60	0.15	1.00	2.00	0.20	0.15 min	Zr 0.60
S30310	–	XM-5(303Plus X)	17.0–19.0	7.0–9.0	–	0.15	1.00	2.50–4.50	0.20	0.25 min	–
S30303	–	303Cu	17.0–19.0	6.0–10.0	–	0.15	1.00	2.00	0.15	0.10 min	Cu 2.5–4.00, Se 0.10
S30323	30303Se	303Se	17.0–19.0	8.0–10.0	–	0.15	1.00	2.00	0.20	0.06	Se 0.15 min
S30400	30304	304	18.0–20.0	8.0–10.5	–	0.08	0.75	2.00	0.045	0.03	–
S30403	30304L	304L	18.0–20.0	8.0–12.0	–	0.03	0.75	2.0	0.045	0.03	–
S30403	–	302HQ	17.0–19.0	8.0–10.0	–	0.03	1.00	2.00	0.045	0.03	Cu 3.0–4.0

Table 2.47 (2/2) Chemical compositions of several wrought 300 series[4] ASS (Cr ≤ 20% and Ni ≤ 19%) – UNS/SAE/AISI

Designation			Chemical composition % by mass max unless otherwise stated (Balance: Fe)								
UNS No	SAE No	AISI/Gr. No.	Cr	Ni	Mo	C	Si	Mn	P	S	Others/Remark
S30430		304Cu	17.0–19.0	8.0–10.0		0.08	0.75	2.00	0.045	0.03	Cu 3.0–4.0
S30452	–	XM-21 (304HN)	18.0–20.0	8.0–10.0	–	0.08	1.00	2.00	0.045	0.03	N 0.16–0.30
S30453	–	304LN	18.0–20.0	8.0–12.0	–	0.03	0.75	2.00	0.045	0.03	N 0.10–0.16
S30454	–	–	18.0–20.0	8.0–11.0	–	0.03	1.00	2.00	0.045	0.03	N 0.16–0.30
S30500	30305	305	17.0–19.0	10.5–13.0	–	0.12	1.00	2.00	0.045	0.03	–
S30600[2]		310L	17.0–18.5	14.0–15.5	0.20	0.018	3.7–4.3	2.00	0.020	0.020	Cronifer 1815 LCSi
S30601[2]			17.0–18.0	17.0–18.0	0.20	0.015	5.0–5.6	0.50–0.80	0.030	0.013	Cu 0.05, N 0.35
S30800	30308	308	19.0–21.0	10.0–12.0	–	0.08	1.00	2.00	0.045	0.03	–
S30900		309	22.0–24.0	12.0–15.0		0.20	1.00	2.00	0.045	0.03	–
S30908		309S	22.0–24.0	12.0–15.0		0.08	1.00	2.00	0.045	0.03	–
S31000		310	24.0–26.0	19.0–22.0		0.25	1.50	2.00	0.045	0.03	–
S31008		310S	24.0–26.0	19.0–22.0		0.08	1.50	2.00	0.045	0.03	–
S31400		314	23.0–26.0	19.0–22.0		0.25	1.50–3.00	2.00	0.045	0.03	–
S31600	30316	316	16.0–18.0	10.0–14.0	2.0–3.0	0.08	1.00	2.00	0.045	0.03	–
S31603	30316L	316L	16.0–18.0	10.0–14.0	2.0–3.0	0.03	1.00	2.00	0.045	0.03	–
S31620		316F	16.0–18.0	10.0–14.0	1.75–2.50	0.08	1.00	2.00	0.20	0.10 min	
S31635[1]	–	316Ti	16.0–18.0	10.0–14.0	2.0–3.0	0.08	0.75	2.00	0.045	0.03	Ti 5x(C + N)-0.70
S31640[1]	–	316Cb	16.0–18.0	10.0–14.0	2.0–3.0	0.08	0.75	2.00	0.045	0.03	Nb 10xC-1.10
S31651	–	316N	16.0–18.0	10.0–14.0	2.0–3.0	0.08	0.75	2.00	0.045	0.03	N 0.10–0.16
S31653	–	316LN	16.0–18.0	10.0–14.0	2.0–3.0	0.03	0.75	2.00	0.045	0.03	N 0.10–0.16
S31700	30317	317	18.0–20.0	11.0–15.0	3.0–4.0	0.08	1.00	2.00	0.045	0.03	–
S31703	–	317L	18.0–20.0	11.0–15.0	3.0–4.0	0.03	0.75	2.00	0.045	0.03	N0.10
S31725	–	317LM	18.0–20.0	13.5–17.5	4.0–5.0	0.03	0.75	2.00	0.045	0.03	N 0.20
S31726	–	317LMN	17.0–20.0	13.5–17.5	4.0–5.0	0.03	0.75	2.00	0.045	0.03	N 0.10–0.20
S31753	–	317LN	18.0–20.0	11.0–15.0	3.0–4.0	0.03	0.75	2.00	0.045	0.03	N 0.10–0.20
S32100[1]	30321	321	17.0–19.0	9.0–12.05	–	0.08	1.00	2.00	0.045	0.03	Ti 5xC min
S32109[1]		321H	17.0–20.0	9.0–12.0	–	0.04–0.10	1.00	2.00	0.04	0.03	Ti 4xC-0.60
S32615[2]		Alloy SX	16.5–19.5	19.0–22.0	0.30–1.50	0.07	4.80–6.00	2.00	0.045	0.03	–
S34700[1]	30347	347	17.0–19.0	9.0–13.0	–	0.08	1.00	2.00	0.045	0.03	Nb + Ta 10xC min
S34720[1]	–	347F	17.0–19.0	9.0–12.0	0.75	0.08	1.00	2.00	0.040	0.18–0.35	Nb + 10x–/1.10, Cu 0.75, Ta 0.05
S34723[1]	–	347FSe	17.0–19.0	9.0–12.0	0.75	0.08	1.00	2.00	0.11–0.17	0.03	Nb 10xC- 1.10, Cu0.75, Se 0.15–0.35, Ta 0.05
S34800[1]	30348	348	17.0–19.0	9.0–13.0	–	0.08	0.75	2.00	0.045	0.03	Nb + Ta 10xC-1.00, Ta:0.10, Co 0.20
S38100		XM-15(18–18–2)	17.0–19.0	17.5–18.5	–	0.08	1.50–2.50	2.00	0.03	0.03	–
S38400	30384	384	15.0–17.0	17.0–19.0	–	0.08	1.00	2.00	0.045	0.03	–
S38815[2]			13.0–15.0	15.0–17.0	0.75–1.50	0.03	5.50–6.50	2.00	0.040	0.02	–
J92500		CF-3	17.0–21.0	8.0–12.0	–	0.03	2.00	1.50	0.040	0.040	(Ni + 2Mo) 8–12
J92600		CF-8	18.0–21.0	8.0–11.0	–	0.08	2.00	1.50	0.040	0.040	(Ni + 2Mo) 8–11
J92800		CF-3M	17.0–21.0	9.0–13.0	2.0–3.0	0.03	1.50	1.50	0.040	0.040	(Ni + 2Mo) 13–19
J92843[3]		AMS 5369	18.0–21.0	8.0–11.0	1.00–1.75	0.28–0.35	1.00	0.75–1.50	0.040	0.040	(Ni + 2Mo) 10–15
J92900		CF-8M	18.0–21.0	9.0–12.0	2.0–3.0	0.08	2.00	1.50	0.040	0.040	(Ni + 2Mo) 13–18
N08330		RA330	17.0–20.0	34.0–37.0		0.08	0.75–1.50	2.00	0.040	0.030	–

Note:
[1]Stabilized ASS
[2]High-silicon ASS. See ASME Sec. VIII, Div.1, Appendix 34 for requirements of toughness, welding, and heat treatment. Sandvik SX (Alloy SX) was originally developed by Monsanto. See Table 2.8 for more details
[3]Cu 0.50, Ti 0.15–0.50, W 1.00–1.75, Nb + Ta 0.30–0.70
[4]AISI 329 SS (S32900) is DSS

3. 200 series ASS – Composition, max. wt %

ASS with Cr-Mn-Ni-N composition were called 200 Series SS. The principal difference between 300 series SS and 200 series SS was that the Ni used in 300 series SS was partly replaced by Mn and N. Nickel prices have been relatively high over the last couple of years. As a result, there has been increased interest in low-Ni or no-Ni grades of stainless steel. The obvious advantage of 200 series was cost-effectiveness. Particularly, they have become popular in China and South East Asia, as seen in Fig. 2.41. Table 2.48 shows chemical compositions of several 200 series ASS in accordance with UNS numbering system.

Because the 200-series SS are austenitic, they are not magnetic and therefore very difficult to distinguish from the widely used 300-series grades, such as 304 SS, which are also nonmagnetic. This has led to confusion in the marketplace, including cases of incorrect labeling, etc., with 200-series material being sold as 304 SS. Therefore, when 200 or 300 series SS is used, PMI is normally required.

200 Series have 40% higher yield strength than 300 series SS. The physical and mechanical properties of both series are quite compatible. 200 series SS also has the additional component of Carbon, which gives higher effectiveness to the austenitic nature of Stainless Steel.

201 SS and 202 SS have properties similar to 301 SS and 302 SS in annealed and cold-rolled conditions and perform similarly.

4. Special Austenitic Grades (Super Austenitic Stainless Steels-SASS and Alloys) – Composition, max. wt %

Table 2.49 shows chemical compositions of several super austenitic SS and Alloys which have PRE more than 40 in accordance with UNS numbering system. Meanwhile super austenitic stainless steels (SASS) are fully austenitic and not as strong as duplex grades. Some of them offer much better resistance to seawater (with PREs in the 40 to 50 range and a few of 50 or more), acid chlorides, and many chemicals. Based on some research on nitrogen additions, the PRE is calculated with a factor of 30 (rather than 16) for the nitrogen. Also, so strengthened, the more commonly specified grades contain at least 20%Cr, 25%Ni, and 4%Mo. Their mechanical strength (e.g., up to 150% of the yield strength) is higher than that of the 18–8 steels. The most highly alloyed, 654 SMO (UNS S32654), is 25%Cr-22%Ni-7.5%Mo-3%Mn-0.5%Cu-0.5%N. It has a PRE of 54.

Before the development of the super-austenitic SS, the corrosion engineer faced with chloride attack on 316L SS or 317L SS had only one choice – to change to a Ni-rich alloy, such as Carpenter 20Cb3 (UNS N08020) or Incoloy 825 (UNS N08825). Those were arbitrarily assigned UNS numbers in the Nxxxxx series despite the fact that they do not contain >50%Ni.

Even though SASS (PRE ≥40) would solve most problems of chloride SCC, they may not resist pitting if they contain low Mo (<3–5%).

Table 2.48 Chemical compositions of several wrought 200 series ASS – UNS/SAE/AISI

Designation			Chemical composition % by mass max unless otherwise stated (Balance: Fe)								
UNS no	SAE no	AISI no/Gr. no./ common name	Cr	Ni	Mo	C	Si	Mn	P	S	Others
S20100	30201	201	16.0–18.0	3.5–5.5	–	0.15	1.00	5.5–7.5	0.060	0.03	N 0.25
S20103	–	–	16.0–18.0	3.5–5.5	–	0.03	0.75	5.5–7.5	0.045	0.03	N 0.25
S20153	–	–	16.0–17.5	4.0–5.0	–	0.03	0.75	6.4–7.5	0.045	0.015	N 0.10–0.25; Cu 1.00
S20161	–	Gall-tough	15.0–18.0	4.0–6.0	–	0.15	3.0–4.0	4.0–6.0	0.040	0.04	N 0.08–0.20
S20162	–	–	16.5–21.0	6.0–10.0	0.05–0.25	0.15	2.5–4.5	4.0–8.0	0.040	0.04	N 0.05–0.25
S20200	30202	202	17.0–19.0	4.0–6.0	–	0.15	1.00	7.5–10.0	0.060	0.03	N 0.25
S20300	–	XM-1 (203EZ)	16.0–18.0	5.0–6.5	–	0.08	1.00	5.0–6.5	0.045	0.18–0.35	Cu 1.75–2.25
S20400	–	–	15.0–17.0	1.50–3.0	–	0.03	1.00	7.0–9.0	0.040	0.03	N 0.15–0.30
S20500	–	205	16.5–18.0	1.0–1.7	–	0.12–0.25	1.00	14.0–15.5	0.060	0.03	N 0.32–0.40
S20910	–	XM-19 (Nitronic 50)	20.5–23.5	11.5–13.5	1.5–3.0	0.06	0.75	4.0–6.0	0.040	0.03	Nb 0.10–0.30; V 0.10–0.30
S21400	–	XM-31 (Tenelon)	17.0–18.5	1.00	–	0.12	0.30–1.00	14.0–16.0	0.045	0.03	–
S21460	–	XM-14	17.0–19.0	5.0–6.0	–	0.12	0.75	14.0–16.0	0.060	0.03	N 0.35–0.50
S21600	–	XM-17 (216)	17.5–22.0	5.0–7.0	2.0–3.0	0.08	0.75	7.5–9.0	0.045	0.03	N 0.25–0.50
S21603	–	XM-18 (216L)	17.5–22.0	5.0–7.0	2.0–3.0	0.03	0.75	7.5–9.0	0.045	0.03	N 0.25–0.50
S21800	–	Nitronic 60	16.0–18.0	8.0–9.0	–	0.10	3.5–4.5	7.0–9.0	0.060	0.03	N 0.08–0.18
S21900	–	21–6-9 (Nitronic 40)	19.0–21.5	5.5–7.5	–	0.08	1.00	8.0–10.0	0.045	0.03	N 0.15–0.40
S21904	–	XM-11 (Nitronic 40)	19.00–21.5	5.5–7.5	–	0.04	1.00	8.0–10.0	0.045	0.03	N 0.15–0.40
S24000	–	XM-29 (Nitronic 33)	17.0–19.0	2.3–3.7	–	0.08	0.75	11.5–14.5	0.06	0.03	N 0.20–0.40
S24100	–	18–2Mn (Nitronic 32)	16.5–19.0	0.5–2.5	–	0.15	1.00	11.0–14.0	0.045	0.03	N 0.20–0.45
S28200	–	18–18 plus	17.0–19.0	–	0.75–1.25	0.15	1.00	17.0–19.0	0.045	0.03	N 0.40–0.60; Cu 0.75–1.25

Table 2.49 Chemical compositions of several wrought super-austenitic SS and alloys – UNS/AISI

Designation		Chemical composition % by mass max unless otherwise stated (Balance: Fe)								
UNS no	AISI no/Gr. no./ common name	Cr	Ni	Mo	C	Si	Mn	P	S	Others [PREN]
N08007	Gr.CN7M	19.0–22.0	27.5–30.5	2.0–3.0	0.07	1.50	1.50	–	–	Cu 3.0–4.0, (Ni + 2Mo) 32–37 [26–32]
N08020[(1)]	20Cb-3	19.0–21.0	32.0–38.0	2.0–3.0	0.07	1.00	2.00	0.045	0.035	Cu 3.0–4.0; Nb 8xC- 1.00 [25.6–30.9]
N08024[(1)]	20Mo-4	22.5–25.0	35.0–40.0	3.5–5.0	0.03	0.50	1.00	0.035	0.035	Cu 0.50–1.50; (Nb + Ta) 0.15–0.35 [34–41]
N08026	20Mo6	22.0–26.0	33.0–37.2	5.0–6.7	0.03	0.50	1.00	0.030	0.030	Cu 2.00–4.00; N 0.10–0.16 [40–50]
N08028	Sanicro 28	26.0–28.0	30.0–34.0	3.0–4.0	0.03	1.00	2.50	0.030	0.030	Cu 0.6–1.4 [36–41]
N08320		21.0–23.0	25.0–27.0	4.0–6.0	0.05	1.00	2.50	0.040	0.030	(Ni + 2Mo) 33.0–39.0 [34–43]
N08366	AL-6X	20.0–22.0	23.5–25.5	6.0–7.0	0.035	1.00	2.00	0.040	0.030	[40–45]
N08367	AL-6XN	20.0–22.0	23.5–25.5	6.0–7.0	0.03	1.00	2.00	0.040	0.030	Cu 0.75; N 0.18–0.25 [43–49]
N08700[(1)]	JS700	19.0–23.0	24.0–26.0	4.3–5.0	0.04	1.00	2.00	0.040	0.030	Cu 0.50; Nb 8xC-0.40 [33–39]
N08904	904L	19.0–23.0	23.0–28.0	4.0–5.0	0.02	1.00	2.00	0.045	0.035	Cu 1.0–2.0 [32–40]
N08925	25-6Mo	19.0–21.0	24.0–26.0	6.0–7.0	0.02	0.50	1.00	0.045	0.030	Cu 0.8–1.5; N 0.1–0.2 [40–47]
N08926	1925 hMo	19.0–21.0	24.0–26.0	6.0–7.0	0.02	1.50	1.00	0.030	0.010	Cu 0.5–1.5; N 0.15–0.25 [41–48]
S31050	310MoLN	24.0–26.0	20.5–23.5	1.6–2.6	0.02	0.50	2.00	0.030	0.010	N 0.09–0.15 [31–37]
S31254[(2)]	254 SMO	19.5–20.5	17.5–18.5	6.0–6.5	0.02	0.80	1.00	0.030	0.010	Cu 0.50–1.00; N 0.18–0.25 [42–45]
S31266	Uranus B66	23.0–25.0	21.0–24.0	5.2–6.2	0.03	1.00	2.0–4.0	0.035	0.020	Cu 1.00–2.50; N 0.35–0.60; W 1.50–2.50 [46–62]
S31277	27-7Mo	20.5–23.0	26.0–28.0	6.5–8.0	0.02	0.50	3.00	0.030	0.010	Cu 0.5–1.50; N 0.30–0.40 [47–55]
S32050	SR-50A	22.0–24.0	20.0–23.0	6.0–6.8	0.03	1.00	1.50	0.035	0.020	Cu 0.40 [42–46]
S32200	NIC 25	20.0–23.0	23.0–27.0	2.5–3.5	0.03	0.5	1.0	0.030	0.005	(Ni + 2Mo) 28.0–34.0 [28–35]
S32654	654 SMO	24.0–25.0	21.0–23.0	7.0–8.0	0.02	0.50	2.0–4.0	0.030	0.005	Cu 0.30–0.60; N 0.45–0.55 [54–60]
S34565[(1)]	Nirosta 4565S	23.0–25.0	16.0–18.0	4.0–5.0	0.03	1.00	5.0–7.0	0.030	0.010	N 0.40–0.60; Nb 10xC-1.00 [43–51]
S35135[(1)]	Alloy 864	20.0–25.0	30.0–38.0	4.0–4.8	0.08	0.6–1.0	1.00	0.045	0.015	Ti 0.40–1.00 [33–40]
J93254	254 SMO (casting)	19.5–20.5	17.5–19.5	6.0–7.0	0.025	1.0	1.20	0.045	0.010	N 0.18–0.24; Cu 0.50–1.00 [42–47]

Notes: PREN = %Cr + 3.3%(Mo + 0.5 W) + 16%N
[(1)]Stabilized Austenitic Alloys
[(2)]J93254 for casting

(b) Ferritic Stainless Steels (FSS)

1. General Characteristics

FSS have bcc ferrite microstructure, low carbon (C) contents (usually less than 0.2%C), and Cr contents predominately in the range of 16–20%. C has the effect of expanding the gamma loop, the high-temperature range showing the presence of austenite. Figure 2.49 (c) shows the typical microstructure. The equilibrium structure of FSS is ferrite at room temperature as well as at all temperatures up to the melting point. Thus, these steels will not go through a crystal structure change, and they cannot be quench hardened. Table 2.50 shows chemical compositions of several FSS. FSS historically have not seen wide application for piping, tanks, and structural components because of their poor weldability and notch sensitivity. The weldability results from the formation of embrittling phases and carbide precipitation on cooling from welding temperature.

It has long been known that ferritics are subject to 475 °C (885 °F) embrittlement, a phenomenon involving decomposition of ferrite to two separate BCC phases that lower ductility and impact strength when the alloys are heated in the temperature range from 343 °C (650 °F) to 510 °C (950 °F).

For this reason the temperature of ferritics has always been limited to 343 °C (650 °F). The justification for using FSS over the easier to fabricate ASS is that they are not as susceptible to SCC.

If C and nitrogen (N) levels are reduced below 100 ppm, welds show improved ductility and minimal sensitization due to carbide precipitation.

Figure 2.50 shows variations in weld DBTT per titanium content for 1.5 mm (0.06 in.) thick of 409 SS (Ti <0.5%). The amount of 0.10–0.15%Ti improve the toughness remarkably.

Table 2.50 Chemical compositions of several wrought FSS – UNS/AISI

Designation			Chemical composition % by mass max unless otherwise stated (Balance: Fe)									
UNS no	Commercial no	AISI no/Gr. no Common name	Cr	Ni	Mo	C	Mn	N	P	S	Si	Others
S40500		405 SS	11.5–14.5	–	–	0.08	1.00	–	0.040	0.030	1.00	AI 0.10–0.30
S40900[1]		409 SS	10.5–11.7	0.5	–	0.08	1.00	–	0.040	0.03	1.00	Ti 6xC-0.75
S40910[1]		409S SS	10.5–11.7	0.5	–	0.03	1.00	–	0.040	0.010	1.00	Ti = 6 (C + N) min
S41008		410S SS	11.5–13.5	–	–	0.08	1.00	–	0.040	0.030	1.00	
S42900		429 SS	14.0–16.0	–	–	0.12	1.00	–	0.040	0.030	1.00	–
S43000		430 SS	16.0–18.0	–	–	0.12	1.00	–	0.040	0.030	1.00	–
S43020		430F SS	16.0–18.0	–	0.60	0.12	1.25	–	0.060	0.15 min	1.00	
S43023		430FSe SS	16.0–18.0	–	–	0.12	1.25	–	0.060	0.060	1.00	Se 0.15 min
S43400		434 SS	16.0–18.0	–	0.75–1.25	0.12	1.00	–	0.040	0.030	1.00	–
S43600[1]		436 SS	16.0–18.0	–	0.75–1.25	0.12	1.00	–	0.040	0.030	1.00	(Cb + Ta) 5xC-0.70
S43940[1], [2]			17.5–18.5	–	–	0.03	1.0	–	0.040	0.015	1.00	Ti 0.10–0.60, Cb [0.30 + (3xC)] min
S44200		442 SS	18.0–23.0	–	–	0.20	1.00	–	0.040	0.030	1.00	–
S44400[1]	18–2Mo	444 SS	17.5–19.5	1.0	1.75–2.5	0.025	1.00	0.025	0.040	0.030	1.00	(Ti + Cb)[0.20 + 4 (C + N)] min, 0.80 max
S44500			19.0–21.0	0.6	–	0.02.	1.00	0.030	0.040	0.012	1.00	Cb 10x(C + N)-0.80
S44600	26–1	446 SS	23.0–27.0	–	–	0.20	1.50	0.250	0.040	0.030	1.00	–
S44625	26–1 modified		25.0–27.5	0.5	0.75–1.5	0.01	0.40	0.015	0.020	0.020	0.40	(Ni + Cu) 0.50 Cu 0.20
S44626[1]	XM-33	26-1Mo	25.0–27.0	0.5	0.75–1.5	0.06	0.75	0.040	0.040	0.020	0.75	Ti 0.20–1.00, Ti 7x(C + N) min
S44627[1]	XM-27, E-Brite 26–1	26-1Mo	25.0–27.0	0.5	0.75–1.5	0.010	0.40	0.015	0.020	0.020	0.40	Cb 0.05–0.20 (Ni + Cu) 0.50
S44635[1]	Monit	26–4-4	24.5–26.0	3.5–4.5	3.5–4.5	0.025	1.00	0.035	0.040	0.030	0.75	(Ti + Cb) [0.20 + 4 (C + N)] min, 0.80max
S44660[1]	Sea-cure	SC-1	25.0–27.0	1.5–3.5	2.5–3.5	0.025	1.00	0.035	0.040	0.030	1.00	(Ti + Cb) 0.20–1.00, Ti + Cb = 6x(C + N) min
S44700	29Cr-4Mo	29–4	28.0–30.0	0.15	3.5–4.2	0.010	0.30	0.020	0.025	0.020	0.20	C + N 0.025 max Cu 0.15 max
S44735[1]	AL29-4C	29-4C	28.0–30.0	1.0	3.6–4.2	0.030	1.00	0.045	0.040	0.030	1.00	(Ti + Cb) 0.20–1.00, (Ti + Cb) = 6x (C + N) min
S44800	FS10	29–4-2	28.0–30.0	2.0–2.5	3.5–4.2	0.010	0.30	0.020	0.025	0.020	0.20	(C + N) 0.025 Cu 0.15

Notes:
(1)Stabilized FSS
(2)EN10088–2 (1.4509)

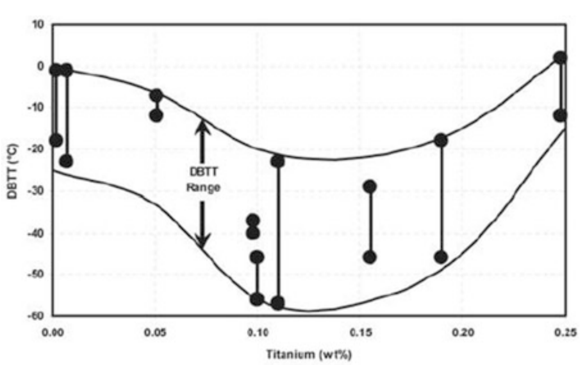


Figure 2.50 Variations in Weld DBTT per Titanium content for 1.5 mm thick 409 SS (source: ATI Techncial Data Blue Sheet for ATI 409HP)

2. Standard Ferritic Grades – Composition, max. wt %
   Table 2.50 shows chemical compositions of several FSS, which have Cr with 11.5–30% in accordance with the UNS numbering system.

(c) Martensitic Stainless Steels (MSS)
1. General Characteristics
   MSS are essentially alloys of chromium and carbon that possess a bcc or bct crystal structure (martensitic) in the hardened condition. They are ferromagnetic and hardenable by heat treatments. Their general resistance to corrosion is adequate for some corrosive environments, but not as good as other stainless steels. Figure 2.49(b) shows the typical microstructure.

The Cr content of these materials generally ranges from 11.5 to 18 wt%, and their carbon content can be as high as 1.2 wt%. The chromium and carbon contents are balanced to ensure a martensitic structure after hardening. MSS are chosen for their good tensile strength, creep, and fatigue strength properties, in combination with moderate corrosion resistance and heat resistance.

The most commonly used alloy within the MSS family is 410 SS, which contains about 11.5–13.5 wt% Cr and C < 0.15 wt% to provide strength. Mo can be added to improve mechanical properties or corrosion resistance. Ni can be added for the same reasons. When higher Cr levels are used to improve corrosion resistance, Ni also serves to maintain the desired microstructure and to prevent excessive free ferrite. The limitations on the alloy content required to maintain the desired fully martensitic structure restrict the obtainable corrosion resistance to moderate levels. CA6NM is a hardenable Fe-12Cr-4Ni-0.5Mo casting MSS based on the 13%Cr CA-15. Ductility, impact properties, saltwater corrosion resistance, and erosion resistance of CA6NM are raised by the addition of Ni & Mo. CA6NM is most generally used in the normalized and tempered condition, but variations in heat treatment are used to enhance specific properties. The standard specifications of CA6NM are introduced in Sect. 2.6.2.5 (1/5).

2. Standard Martensitic Grades – Composition, max. wt %

Table 2.51 shows chemical compositions of several MSS which have Cr with 11.5–18% in accordance with the UNS numbering system.

(d) Precipitation-Hardenable Stainless Steels (PHSS)

1. General Characteristics

The PHSS materials are Fe-Cr-Ni alloys. They generally have better corrosion resistance than martensitic stainless steels. The high tensile strengths of the PHSS is due to precipitation hardening of a martensitic or austenitic matrix. Cu, Al, Ti, Nb (Cb), and Mo are the primary elements added to these stainless steels to promote precipitation hardening. Some of these steels have been given an AISI number, but they are seldom used as it has become customary to maintain the trade name used by the company that developed the steel. PHSS are commonly categorized into three types – martensitic, semiaustenitic, and austenitic – based on their martensite start

Table 2.51 Chemical compositions of several wrought MSS – UNS/AISI

Designation		Chemical composition % by mass max unless otherwise stated (Balance: Fe)										
UNS no	AISI no/Common name	Cr	Ni	Mo	C	Mn	P	S	Si	V	W	Others
S40300	403 SS	11.5–13.0	–	–	0.15	1.00	0.040	0.030	0.50	–	–	
S41000	410 SS	11.5–13.5	–	–	0.15	1.00	0.040	0.030	1.00	–	–	
S41400	414 SS	11.5–13.5	1.25–2.50	–	0.15	1.00	0.040	0.030	1.00	–	–	
S41425	13–5-2	12.0–15.0	4.00–7.00	1.50–2.00	0.05	0.50–1.00	0.020	0.005	0.50	–	–	N 0.06–0.12 Cu 0.30
S41426	13–5-2	11.5–13.5	4.50–6.50	1.50–3.00	0.03	0.50	0.020	0.005	0.50	0.50	–	Ti 0.01–0.50
S41427	13–5-2	11.5–13.5	4.50–6.00	1.50–2.50	0.03	1.00	0.020	0.005	0.50	0.10–0.50		Ti 0.01
S41429		10.5–14.0	2.0–3.0	0.4–0.8	0.10	0.75	0.030	0.030	1.0	0.25		(2)
S41500	F6NM	11.5–14.0	3.5–5.5	0.5–1.0	0.05	0.5–1.0	0.030	0.030	0.6	–	–	
S41600	416 SS	12.0–14.0	–	0.6 (opt)	0.15	1.25	0.060	0.15 min	1.00	–	–	
S41623	416Se SS	12.0–14.0	–	–	0.15	1.25	0.060	0.060	1.00	–	–	Se 0.15 min
S41800	Greek Ascoloy	12.0–14.0	1.80–2.20	–	0.15–0.20	0.50	0.040	0.030	0.50	–	2.50–3.50	
S42000	420 SS	12.0–14.0	–	–	0.15 min	1.00	0.040	0.030	1.00	–	–	
S42020	420F SS	12.0/14.0	–	0.6 (opt)	0.15 min	1.25	0.060	0.15 min	1.00	–	–	
S42200	422 SS	11.5–13.5	0.50–1.00	0.75–1.25	0.15–0.25	1.00	0.040	0.030	0.75	0.15–0.03	0.75–1.25	
S42400	F6NM(1)	12.0–14.0	3.50–4.50	0.30–0.70	0.06	0.50–1.00	0.030	0.03	0.30–0.60	–	–	
S42500		14.0–16.0	–	0.30–0.70	0.08–0.20	1.00	0.020	0.010	1.00	–	–	N 0.2
S43100	431 SS	15.0–17.0	1.25–2.50	–	0.20	1.00	0.040	0.030	1.00	–	–	
S44002	440A SS	16.0–18.0	–	0.75	0.60–0.75	1.00	0.040	0.030	1.00	–	–	
S44003	440B SS	16.0–18.0	–	0.75	0.75–0.95	1.00	0.040	0.030	1.00	–	–	
S44004	440C SS	16.0–18.0	–	0.75	0.95–1.20	1.00	0.040	0.030	1.00	–	–	
J91150	CA-15	11.5–14.0	1.00	–	0.15	1.00	0.040	0.040	1.50	–	–	
J91151	CA-15 M	11.5–14.0	1.00	0.15–1.00	0.15	1.00	0.040	0.040	0.65	–	–	
J91540	CA6NM	11.5–14.0	3.50–4.50	0.40–1.00	0.06	1.00	0.040	0.030	1.00			
	420 M	12.0–14.0	0.5	–	0.15–0.22	0.25–1.00	0.020	0.010	1.00			Cu 0.25
K90941	F9	8.0–10.0	–	0.90–1.10	0.15	0.30–0.60	0.025	0.025	0.25–1.00	–	–	
	L80 13Cr	12.0–14.0	0.5	–	0.15–0.22	0.25–1.00	0.020	0.010	–	–	–	Cu 0.25

Note (1) equivalent with UNS J91540 (CA6NM) Casting

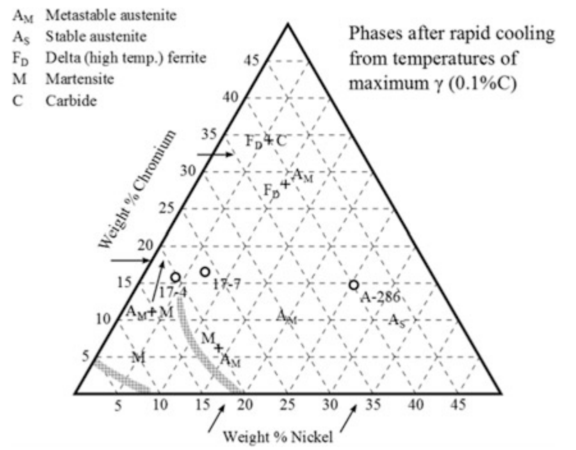


Figure 2.51 Phase plot of several PHSS per chemical composition. (Source: ASM SS Handbook)

and finish (Ms and Mf) temperatures and the resulting microstructures (Fig. 2.51 and Table 2.52). The issues involved in welding PHSS are different for each group. The Ms. temperature of the martensitic PHSS is required to be the room temperature in order to ensure a full martensite-to-austenite transformation upon quenching.

One of the empirical equations that is often used to predict the martensite start temperature (in °F) is as follows:

$$Ms = 2160 - 66\ (\%Cr) - 102\ (\%Ni) - 2620\ (\%C + \%N)$$

where Cr = 10–18%, Ni = 5–12.5%, and C + N = 0.035–0.17%.

Some of the PHSS solidify as primary ferrite and have relatively good resistance to hot cracking.

In other PHSS, ferrite is not formed, and it is more difficult to weld these alloys without hot cracking.

The three types of PHSS show the following characteristics:

(i) *Martensitic precipitation-hardenable SS (M-PHSS)* normally transform during cooling from the solution heat treatment temperature to martensite at temperatures above room temperature. M-PHSS have a relatively hard property because they are martensitic at room temperature. This group can be hardened by quenching from the austenitizing temperature [around 1038 °C (1900 °F)] then aging at 482–621 °C (900–1150 °F). If C < 0.07% (i.e., 17–4 PHSS, 15–5 PHSS, PH13-8 Mo, etc.-See Table 2.52), the martensite is not very hard and the main hardening is obtained from the precipitation aging reaction.

(ii) *Semi-austenitic precipitation-hardenable SS (S-A PHSS: 17–7, 15-7Mo, 14–8 Mo,* etc.*)* are commonly formed by a refrigerating cycle, cold deformation, and a carbide-precipitation thermal cycle that raises the martensite transformation temperature (MTT) above room temperature, causing the martensite to form on cooling, or with a combination of these cycles. S-A PHSS will not transform to martensite when cooled from the austenitizing temperature because the MTT is below room temperature. This group must be given a conditioning heat treatment in the range of 732–954 °C (1350–1750 °F) to precipitate carbon and/or alloy elements as carbides or intermetallic compounds. This process removes alloy elements from solution, thereby destabilizing the austenite, which raises the MTT so that a martensite structure will be obtained on cooling to room temperature. Aging at 454–593 °C (850–1100 °F) will stress relieve and temper the martensite to increase toughness, ductility, hardness, and corrosion resistance.

(iii) *Austenitic precipitation-hardenable SS* (A-PHSS) typically do not have martensitic transformation process. A-PHSS remains austenite after quenching from the solutioning temperature even after substantial amounts of cold work. The hardness and strength of this metal are mostly obtained by the aging reaction. Solution treatment at 982–1121 °C (1800–2050 °F) followed by oil or water quenching, and aging at 704–732 °C (1300–1350 °F) for up to 24 hours are performed.

The use of PHSS has normally the following limitations.

(a) High strength levels (normally by low aging temperatures) greatly increase the susceptibility to EAC. Especially the industrial standards for sour service have some limitations of heat treating, strength, and hardness for PHSS.
(b) Martensitic precipitation-hardenable stainless steels (M-PHSS) are not commonly used in the solution-annealed (as quenched) condition in sour environments. This condition contains an untempered martensitic structure.
(c) Low-temperature toughness of welded components of some alloys such as UNS S17400 is often reduced if they are not properly postweld heat treated.

2. Standard PHSS Grades

These three basic typical types are shown in Table 2.52 (per the UNS numbering system).

3. Heat Treatment of 17–4 PHSS and 17–7 PHSS Base Metals

Similar to a quench and temper heat treatment, these steels are also generally heat treated by a two-step process with the final step being the precipitation anneal. The steel type is related to the matrix that is present when the final precipitation hardening treatment is carried out. For example, the ASTM A-286 austenitic stainless steel lies in the stable austenite region in Fig. 2.51, and the final step of the heat treatment causes the precipitation to occur in an austenite matrix. Also, Fig. 2.51 shows that the martensitic 17–4 PH steel lies in the composition region where rapid cooling produces martensite, and in this steel the final precipitation occurs when the steel has a martensite structure; it also shows that the composition is right on the edge of the metastable austenite region.

The semi-austenitic steels (e.g., 17–7 PHSS with a slightly lower carbon composition plus the addition of Al needed to form the precipitate) are the most complex of the three types. A double heating is employed prior to the final precipitation anneal. The first heat treatment, usually done at the mill, produces an austenite matrix with minor amounts of delta ferrite.

The second heating forms Cr-carbides along the delta ferrite grain boundaries and changes the composition of the austenite matrix so that on cooling it now becomes a martensite matrix. Hence the final precipitation in the semi-austenitic stainless steels occurs in a predominately martensite matrix.

Table 2.52 Chemical compositions of several wrought PHSS – UNS/AISI

Designation (type)		Chemical composition % by mass max unless otherwise stated (Balance: Fe)										
UNS no	AISI no/Common name[(1)]	Cr	Ni	Mo	C	Al	Cu	Mn	Si	P	S	Others
S13800	PH 13–8 Mo, XM-13 (martensitic)	12.25–13.25	7.50–8.50	2.00–2.50	0.05	0.90–1.35	–	0.20	0.10	0.010	0.008	N 0.1
S14800	PH 14–8 Mo (semi-austenitic)	13.5–15.5	7.50–9.50	2.00–3.00	0.05	0.75–1.5	–	1.00	1.00	0.015	0.03	
S15500	15–5 PH, AMS 5659 (martensitic)	14.0–15.5	3.50–5.50	–	0.07	–	2.50–4.50	1.00	1.00	0.040	0.03	Cb 0.15–0.45
S15700	PH 15–7 Mo (semi-austenitic)	14.0–16.0	6.50–7.75	2.00–3.00	0.09	0.75–1.50	–	1.00	1.00	0.040	0.03	–
S17400	17–4 PH (martensitic)	15.5–17.5	3.00–5.00	–	0.07	–	3.00–5.00	1.00	1.00	0.040	0.03	Cb 0.15–0.45
S17600	Stainless W (martensitic)	15.0–17.5	6.00–7.50	–	0.08	0.40	–	1.00	1.00	0.040	0.03	Ti 0.40–1.20
S17700	17–7 PH (semi-austenitic)	16.0–18.0	6.50–7.75	–	0.09	0.75–1.50	–	1.00	1.00	0.040	0.04	–
S35000	AM 350 (semi-austenitic)	16.0–17.0	4.00–5.00	2.50–3.25	0.07–0.11	–	–	0.50–1.25	0.50	0.040	0.03	N 0.07–0.13
S35500	AM 355 (semi-austenitic)	15.0–16.0	4.00–5.00	2.50–3.25	0.10–0.15	–	–	0.50–1.25	0.50	0.040	0.03	N 0.07–0.13
S36200	Almar 362 (martensitic)	14.0–15.0	6.00–7.00	–	0.05	0.10	–	0.50	0.30	0.030	0.03	Ti 0.55–0.90
S45000	Custom 450 (martensitic)	14.0–16.0	5.00–7.00	0.50–1.00	0.05	–	1.25–1.75	1.00	1.00	0.030	0.03	Cb 8xC min.
S45500	Custom 455 (martensitic)	11.0–12.5	7.50–9.50	0.50	0.05	–	1.50–2.50	0.50	0.50	0.030	0.03	Cb 0.10–0.50 Ti 0.80–1.40
S66286	A286 (austenitic)	13.5–16.0	24.0–27.0	1.00–1.50	0.08	0.35	–	2.00	1.00	0.030	0.03	Ti 1.90–2.35 V 0.10–0.50 B 0.001–0.01
J92180	CB7Cu-1[(2)]	15.5–17.7	3.60–4.60	–	0.07	–	2.5–3.2	0.70	1.00	0.035	0.03	Cb 0.15–0.35[(3)]
J92110	CB7Cu-2[(2)]	14.0–15.5	4.50–5.50	–	0.07	–	2.5–3.2	0.70	1.00	0.035	0.03	Cb 0.15–0.35[(3)]

Notes:
[(1)]Semi-Austenitic structure has dual phase with austenitic and martensitic structures
[(2)]Castings
[(3)]When the H900 condition is ordered, the minimum Cb content shall not be applied

In the heat treating of these steels it is common to specify the various steps in the process with the term "condition." For example, a second step of heating to 790 °C (1455 °F) for 1.5 hrs and cooling to room temperature within 1 hr. and holding for 30 min. is called "condition T." If this is followed by the precipitation anneal of heating to 565 °C (1050 °F) for 1.5 hrs and air cooling, the final condition is called TH1050, whereas if the precipitation temperature is 510 °C (950 °F) the final condition is called TH950.

Figure 2.52 shows the heat treatment procedures of 17–7 PHSS at mill.

(e) Duplex Stainless Steels (DSS)

1. General characteristics

DSS are two-phase alloys based on the Fe-Cr-Ni system. DSS usually comprise approximately equal proportions of the body-centered cubic (bcc) ferrite and face-centered cubic (fcc) austenite phases [50/50 austenite/ferrite phase] in their microstructure. Generally DSS have a low carbon content as well as additions of Mo, N, W, and Cu. Typical Cr contents are 20–30 wt% and Ni contents are 5–10 wt%. Nitrogen is a stronger austenite former, helps achieve an equilibrium level of austenite and the desired phase balance, even at relatively rapid cooling rates during welding or casting. The specific advantages offered by DSS over conventional 300 series stainless steels are strength, chloride SCC resistance, and pitting corrosion resistance. Figure 2.49(d) shows the typical microstructure of DSS.

DSS are susceptible to hydrogen embrittlement, and the delayed hydrogen cracking sometimes occurs if these DSS are welded under conditions where hydrogen is introduced into the weld. The low diffusivity of hydrogen through the austenite phase at ambient and slightly elevated temperatures inhibits normal outgassing, and cracking occasionally continues for months. Also, DSS, which is used with cathodic protection for subsea facilities, can cause Hydrogen-Induced Stress Cracking (HISC) when the DSS have no coating or defective coating. See DNV RP-F112 for more detailed information and guidelines for use.

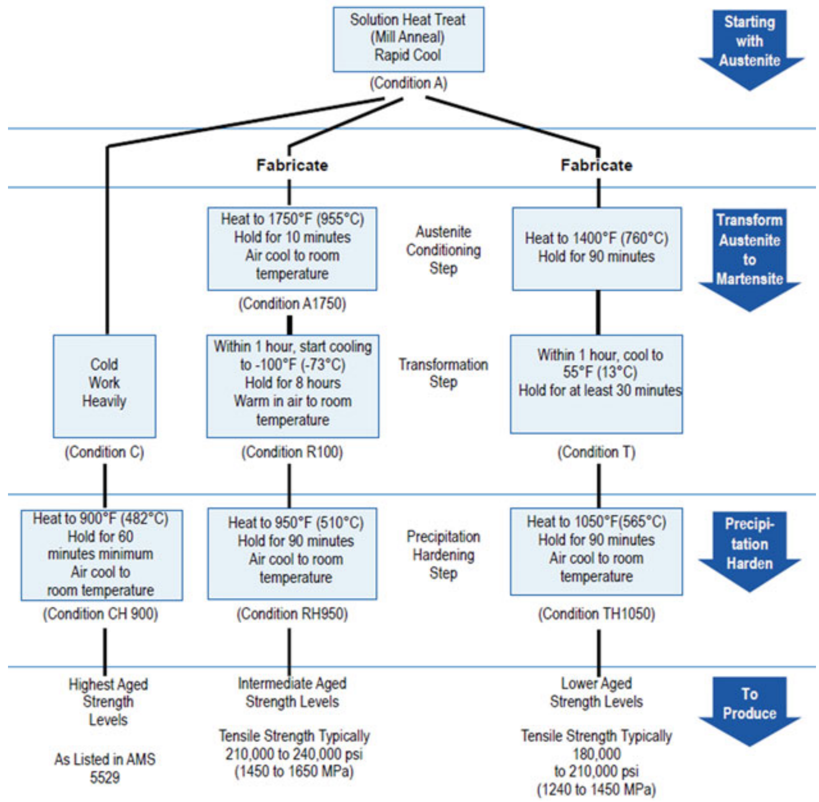


Figure 2.52 Heat treating at mill for PHSS (17–7 PHSS). (Source: ATI Allegheny Ludlum report, 2009)

The susceptibility of these alloys to 475 °C (885 °F) embrittlement limits the temperatures that are sometimes used to cause accelerated outgassing. At temperatures above 320 °C (608 °F) up to about 550 °C (1022 °F), the ferrite decomposes after long exposure, to precipitate alpha prime (α'). This phase causes a significant loss of ductility; hence, DSS are not normally used above 300 °C (572 °F). See Sects. 2.1.6.4 and 2.3.4 for more details on 475 °C (885 °F) embrittlement.

Several publications report that most DSS materials and the weldments have adequate toughness at −60 °C (−76 °F) and warmer and at −46 °C (−50 °F) and warmer, respectively. 2507 SDSS material is now available as pipes, fittings, and forgings (e.g., 5 1/8 in. 10,000 lb. hub connectors) with good toughness at −70 °C (−94 °F) and warmer. When toughness at *very* low temperatures is required for cast DSS, the use of a Ni alloy filler is sometimes considered, remembering that the Ni alloy weld commonly has the same strength as the parent DSS. Some researchers reported that Alloy C-276 filler (ENiCrMo-4) may be used to improve the impact toughness of cast SDSS welds (UNS J93380) at −120 °C (−185 °F) and warmer.

Extremely fast cooling rate on welding or casting with heavy wall section promotes higher ferrite contents which are subject to reducing corrosion resistance. Super- and hyper-grade DSS may minimize the corrosion, including SCC, because their higher Ni content promotes austenite formation during fast cooling processes. Meanwhile, too slow a cooling rate on welding may produce lower ferrite contents and intermetallic phases which have high risk of cracking and toughness loss. Higher nitrogen can greatly reduce this problem. See Sect. 4.11.7 for more detail on welding technology in DSS.

2. Classes of Duplex Stainless Steel (DSS)

There are several different type of DSS. The most common classes are grouped by PREN numbers [= %Cr + 3.3%Mo + 16%N, or = %Cr + 3.3(%Mo + 0.5%W) + 16%N] as below.

– Lean DSS: PREN <30
– Standard DSS: 30 ≤ PREN <40
– Super DSS: 40 ≤ PREN < 48
– Hyper DSS : 48 ≤ PREN ≤ 55, Cr ≤ 33%

The PREN measurement or calculation should be based on the bulk-microstructure, not for each structure, such as austenitic structure grain or ferritic structure grain unless otherwise specified or required.

Lean DSS are for more widespread use due to two reasons: firstly the modified alloy content (low Ni and Mo) results in lower cost and secondly the higher strength (compared to ASS) allows reductions in section thickness, while super DSS target the superior corrosion resistance against SCC and pitting compared to standard DSS in chloride-containing service. See Sect. 4.11.7 for welding of DSS, which is greatly related to corrosion resistance. Section 4.11.7 also introduces the welding techniques of DSS to sustain the corrosion resistance of the base metal.

Tables 2.53, 2.54, 2.55, and 2.56 shows chemical compositions of several DSS, wrought and casting, in accordance with the UNS numbering system.

3. Effects of intermetallic phases (e.g., σ, γ, Cr_2N) of DSS
   Intermetallic phases (e.g., σ, γ, Cr_2N) of DSS can decrease
   (a) Corrosion resistance in chloride solution.
   (b) Toughness (low temperature impact absorbing energy)
   (c) Mechanical properties (TS, YS). It is not a big deal if the values are above SMTS (specified minimum tensile strength) or SMYS specified minimum yield strength).
4. Requirements of ASTM A923 Detecting Detrimental Intermetallic Phase in DSS Test
   The purpose of ASTM A923 is to confirm whether the undesirable effects due to the intermetallic phases on base metals are within acceptable criteria. The following three test methods are used. One of them or both Method B & C may be typically applicable in accordance with the severity of the service.
   (i) *Method A*: Microstructure analysis in NaOH to detect detrimental intermetallic phases (for qualitative evaluation per A923, Figs. 1 to 4 microstructure types. The purpose in A923 is to count the area/profile of intermetallic phases compared to A923, Figs. 1 to 4 micro-structure types, and as a result, to evaluate the metallurgical mechanism with the results of *Method B* and *Method C*.
   (ii) *Method B*: Impact test as a mechanical test (for quantitative evaluation).
   The purpose is to confirm whether the toughness degradation due to intermetallic phases can be satisfied with the acceptable criteria, A923, Table 2.

Table 2.53 Chemical compositions of several lean DSS (wrought) – UNS/AISI

Designation		Chemical composition % by mass max unless otherwise stated (Balance: Fe)											
UNS no	AISI no/Common name	Cr	Ni	Mo	C	Cu	Mn	N	P	S	Si	W	PREN (minimum)
S32003	2003[1]	19.5–22.5	3.0–4.0	1.50–2.00	0.03	–	2.00	0.14–0.20	0.030	0.020	1.00	–	26.7
S32101	2101	21.0–22.0	1.35–1.70	0.10–0.80	0.04	0.10–0.80	4.0–6.0	0.20–0.25	0.040	0.030	1.00	–	24.5
S32202	2202	21.5–24.0	1.00–2.80	0.45	0.03	–	2.00	0.18–0.26	0.040	0.010	1.00	–	24.4
S32304	2304	21.5–24.5	3.0–5.5	0.05–0.60	0.03	0.05–0.60	2.50	0.05–0.20	0.040	0.030	1.00	–	22.5
S82011	2102	20.5–23.5	1.0–2.0	0.10–1.00	0.03	0.50	2.00–3.00	0.15–0.27	0.040	0.020	1.00	–	23.1
S82441	2404[2]	23.0–25.0	3.0–4.5	1.00–2.00	0.03	0.01–0.80	2.50–4.00	0.20–0.30	0.035	0.005	0.70	–	29.5

Notes: PREN = %Cr + 3.3%Mo + 16%N
[1]As listed by ASTM, a widely used common name (not a trademark and not associated with any one producer)
[2]See NACE Paper 12–1504 for more details
[3]See ASTM A1084 for Test Methods for Detecting Detrimental Phases in Lean DSS

Table 2.54 Chemical compositions of several standard DSS (wrought) – UNS/AISI

Designation		Chemical composition % by mass max unless otherwise stated (Balance: Fe)											
UNS no	AISI no/Common name	Cr	Ni	Mo	C	Cu	Mn	N	P	S	Si	W	PREN[1] (minimum)
S31200	UR47N[4], 44LN	24.0–26.0	5.5–6.5	1.2–2.0	0.03	–	2.0	0.14–0.20	0.045	0.030	1.00	–	30
S31500	3RE60	18.0–19.0	4.25–5.25	2.5–3.0	0.03	–	1.2–2.0	0.05–0.10	0.030	0.030	1.40–2.00		27.1–30.5
S31803	2205	21.0–23.0	4.5–6.5	2.5–3.5	0.03	–	2.0	0.08–0.20	0.030	0.020	1.00		30.5
S32205[2]	2205	22.0–23.0	4.5–6.5	3.0–3.5	0.03	–	2.0	0.14–0.20	0.030	0.020	1.00		34.1
S32404	Uranus 50	20.5–22.5	5.5–8.5	2.0–3.0	0.04	1.0–2.0	2.0	0.20	0.030	0.010	1.00		30.3
S32803[3]		28.0–29.0	3.0–4.0	1.8–2.5	0.01	–	0.5	0.025	0.02	0.005	0.50	–	34
S32900	329 SS	23.0–28.0	2.5–5.0	1.0–2.0	0.20	–	1.0	–	0.040	0.030	0.75		26.34
J93370[4]	NAS 75N	24.5–26.5	4.75–6.0	1.75–2.25	0.04		1.0	–	0.04	0.04			30-34

Notes: PREN = %Cr + 3.3%Mo + 16%N
[1]Nominal PREN will be 30.0 and above
[2]S32205 has slightly more pitting corrosion resistance and strength than those of S30803
[3]Nb/(C + N) = 12 min., (C + N) = 0.03% max., Nb = 0.15–0.50%
[4]Casting: See Table 2.56 for other DSS Castings
[5]See ASTM A923 for Test Methods for Detecting Detrimental Phases in DSS and Sect. 2.1.5.5(e)4) below

Table 2.55 Chemical compositions of several super & hyper DSS (wrought) – UNS/AISI

Designation		Chemical composition % by mass max unless otherwise stated (Balance: Fe)											
UNS no	AISI no/Common name	Cr	Ni	Mo	C	Cu	Mn	N	P	S	Si	W	PREN[1] (minimum)
S31260	DP3	24.0–26.0	5.5–7.5	2.5–3.5	0.03	0.20–0.80	1.00	0.10–0.30	0.030	0.030	0.75	0.10–0.50	33.9
S32520	UR52N+[4]	24.0–26.0	5.5–8.0	3.0–5.0	0.03	0.50–3.00	1.50	0.20–0.35	0.035	0.020	0.80	–	37.1
S32550	Ferrallium 255 & alloy 381[2]	24.0–27.0	4.5–6.5	2.9–3.9	0.04	1.50–2.50	1.50	0.10–0.25	0.040	0.030	1.00	–	35.2
S32707	SAF 2707, Fermanel, Altras 958, DPS 28[2],[3]	26.0–29.0	5.5–9.5	4.0–5.0	0.03	1.00	1.50	0.30–0.50	0.035	0.010	0.50	–	44-53
S32750	2507[2]	24.0–26.0	6.0–8.0	3.0–5.0	0.03	0.50	1.20	0.24–0.32	0.035	0.020	0.80	–	37.7
S32760	Z100	24.0–26.0	6.0–8.0	3.0–4.0	0.03	0.50–1.00	1.00	0.20–0.30	0.030	0.010	1.00	0.50–1.00	40.0
S32906	Safurex[5]	28.0–30.0	5.8–7.5	1.50–2.60	0.03	0.80	0.80–1.50	0.30–0.40	0.030	0.030	0.80	–	37.8
S39274	DP3W	24.0–26.0	6.0–8.0	2.50–3.50	0.04	0.20–0.80	1.0	0.24–0.32	0.03	0.02	0.80	1.50–2.50	39
S39277	DTS 25.7NWCu, AF918	24.0–26.0	6.5–8.0	3.0–4.0	0.025	1.2–2.0	0.80	0.23–0.33	0.025	0.002	0.80	0.8–1.2	39
J95370	HDSS	24.0–25.0	17.0–18.0	4.0–5.0	0.03	0.50	8.0–9.0	0.7–0.8	0.03	0.01	0.50	0.10	48–54

Notes: PREN = %Cr + 3.3%(Mo + 0.5 W) + 16%N
[1]Nominal PREN will be 40.0 and above
[2]As listed by ASTM, a widely used common name (not a trademark and not associated with any one producer)
[3]Co = 0.5–2.0%
[4]UR = Uranus
[5]See Table 2.8 for more details

Table 2.56 Chemical compositions of several DSS castings (ASTM A995)

Designation				Chemical composition % by mass max unless otherwise stated (Balance: Fe)											
Gr.	Type	UNS no	AISI no	Cr	Ni	Mo	C	Cu	Mn	N	P	S	Si	W	PREN[1] (minimum)
1B	25Cr-5Ni-Mo-Cu-N	J93372	CD4MCuN	24.0–26.5	4.7–6.0	1.7–2.3	0.04	2.7–3.3	1.00	0.10–0.25	0.040	0.040	1.00	–	31.2
2A	24Cr-10Ni-Mo-N	J93345	CE8MN	22.5–25.5	8.0–11.0	3.0–4.5	0.08	–	1.00	0.10–0.30	0.040	0.040	1.50	–	34.0
3A	25Cr-5Ni-Mo-N	J93371	CD6MN	24.0–27.0	4.0–6.0	1.75–2.50	0.06	–	1.00	0.15–0.25	0.040	0.040	1.00	–	32.2
4A	22Cr-5Ni-Mo-N	J92205	CD3MN	21.0–23.5	4.5–6.5	2.5–3.5	0.03	1.00	1.50	0.10–0.30	0.040	0.020	1.00	–	30.9
5A[2]	25Cr-7Ni-Mo-N	J93404	CE3MN	24.0–26.0	6.0–8.0	4.0–5.0	0.03	–	1.50	0.10–0.30	0.040	0.040	1.00	–	38.8
6A[2]	25Cr-7Ni-Mo-N	J93380	CD3MWCuN	24.0–26.0	6.5–8.5	3.0–4.0	0.03	0.5–1.0	1.00	0.20–0.30	0.030	0.025	1.00	0.5–1.0	37.9

Notes: PREN = %Cr + 3.3%(Mo + 0.5 W) + 16%N
[1]Nominal PREN will be 32–45
[2]Nominal PREN ≥40

(iii) *Method C*: Corrosion test by weight loss in $FeCl_3.6H_2O$ (for quantitative evaluation).
The purpose is to confirm whether the degradation of corrosion resistance due to intermetallic phases can be satisfied with the acceptable criteria, ASTM A923, Table 3. $FeCl_3.6H_2O$ (strong acid) is the most popular representative solution in lab test for chloride acidic service.

Tables 2.57, 2.58, and 2.59 show the applicability and acceptance criteria for test Methods A, B, and C in ASTM A923 for some DSS classes. See Sect. 4.11.7 for welding of DSS.

Table 2.57 Applicability and acceptance criteria for test method A in ASTM A923, Table 1

DSS grade	Acceptable, Etch structure	Nonacceptable, Etch structure
S31803, S32205, S32750, J92205, J93404	Unaffected structure (A923, Figs. 1 & 2)	Possible affected Structure (A923, Figs. 3 & 4) Affected structure (A923, Figs. 5 & 6) Centerline structure (A923, Fig. 7)

Table 2.58 Applicability and acceptance criteria for test method B in ASTM A923 Table 1

DSS grade	Condition	Test temperature	Minimum impact energy[A]
S31803, S32205, J92205	Base metal Heat-affected zone (HAZ) Weld metal	−40 °C (−40 °F) −40 °C (−40 °F) −40 °C (−40 °F)	40 ft-lb (54 J)[A] 40 ft-lb (54 J)[A] 25 ft-lb (54 J)[A]
S32750	Base metal	−40 °C (−40 °F)	[B]
J93404	Base metal	−46 °C (−50 °F)	40 ft-lb (54 J)[A]

Notes:
[A]Energy for a full-size specimen. Required energy for a subsize specimen is reduced in direct proportion to the reduced area of the subsize specimen relative to that of the full-size specimen
[B]The acceptable minimum impact energy shall be agreed upon by seller and purchaser

Table 2.59 Applicability and acceptance criteria for test method C in ASTM A923, Table 3

Grade	Condition	Test temperature	Maximum acceptable corrosion rate Calculated from weight loss
S31803, S32205	Base metal	25 °C (77 °F)	10 mdd
S32750	Weld metal Base metal	22 °C (72 °F) 40 °C (104 °F)	10 mdd 10 mdd

Notes: mdd milligrams per square decimeter per day

See Sect. 4.11.7 for welding of DSS.

References (for welding, crack, ferrite measurement, corrosion/CVN/mechanical/microstructuring tests) other than ASTM A923

- API TR938-C Use of DSS in the Oil Refining Industries
- ISO 17781 Petroleum, Petrochemical and Natural Gas Industries–TM for Quality Control of Microstructure of DSS
- API RP932-B Design, Materials, Fabrication, Operation, and Inspection Guidelines for Corrosion Control in HC REAC Systems
- DNV RP-F112 Design of DSS Subsea Equipment Exposed to CP
- ASME PVP 2016-63927 Evaluation of the Susceptibility of DSS 2205 to HAC in REAC Systems
- ASTM E562, NACE Paper 19-13263/13437/12814/12931, 18-10634/11084/11625, 17-9230, 16-7025, 15-6005, 14-3974/4345/4384, 02135, 05098, 07189, 96497, 86158, 86159, NACE Corrosion-pp1039-1048, Dec.2002, NACE Corrosion-pp125002-1 to 14, Dec.2011, TWI Research Report 298 (2005), Welding Research Supplement, pp182s-191s, May 1989, NiDI Publication 10044/14019/16000
- Others: Welding Journal Papers, DSS Journal Papers, NACE Papers (others), and OCT Conference Papers

2.1.6 Frailties of Stainless Steels

2.1.6.1 Solidification Cracking (Hot Crack) and Delta Ferrite Effect of ASS and DSS

The following transformation modes are typically observed during solidification of austenitic stainless steels (ASS) and duplex stainless steels (DSS).

Mode A: $L \rightarrow L + \gamma \rightarrow \gamma$
Mode AF: $L \rightarrow L + \gamma \rightarrow L + \gamma + \delta \rightarrow \underline{\gamma + \delta}$
Mode FA: $L \rightarrow L + \delta \rightarrow L + \delta + \gamma \rightarrow \underline{\gamma + \delta}$

Where L = liquid, δ = delta ferrite (F), γ = austenite (A). Underlined = Final phases

The remaining ferrite during/after casting and welds of ASS is not alpha (α) ferrite in ferritic steels. The ferrite in ASS is delta (δ) ferrite which is not phase-transformed from the high temperature, but formed on solidification. The remaining delta (δ) ferrite in ASS casting or weldment can reach up to 20 vol%. The alpha (α) ferrite in ferritic steels is physically similar to the delta ferrite except for some element solubility, e.g., carbon solubility of delta (δ) ferrite is higher than that of alpha (α) ferrite. So, delta (δ) ferrite is more hardened than alpha (α) ferrite, especially after cold work. However, the evolution of alpha (α) ferrite may also occur during aging* of 300 series ASS. * e.g., 525 °C/65,000 hrs, 650 °C/60,000 hrs, 700 °C/600 hrs, and 750 °C/25 hrs, and more aged.

When the welding pool is solidified from the melting temperature (>1500 °C (2732 °F), the centerline of weldment is cracked (Solidification Crack) during the final solidification in the pool due to the compound (S or P) with low melting temperature,

Table 2.60 Development history of Schaeffler diagram[(1)], Nb = Cb

Author	Year	Cr equivalent, w%	Ni equivalent, w%
Schaeffler	1949	Cr + Mo + 1.5Si + 0.5Nb	Ni + 30C + 0.5Mn
DeLong et al.	1956	Cr + Mo + 1.5Si + 0.5 Nb	Ni + 30C + 0.5Mn + 30 N
Hull	1973	Cr + 1.21Mo + 0.48Si + 0.14Nb + 2.27 V + 0.72 W + 2.20Ti + 0.21Ta + 2.48Al	Ni + (0.11Mn – 0.0086Mn^2) + 24.5 C + 14.2 N + 0.41Co + 0.44Cu
Schaefer diagram	1976	Cr + 1.5Si + Mo + Nb – 4.99	Ni + 30C + 0.5Mn + 26(N – 0.02) + 2.77
Hammar & Svenson	1979	Cr + 1.37Mo + 1.5Si + 2Nb + 3Ti	Ni + 0.31Mn + 22C + 14.2 N + Cu
Espy Percent Ferrite Diagram[(2)]	1982	Cr + Mo + 1.5Si + 0.5Nb + 5 V + 3Al	Ni + 30C + 0.87Mn + 0.33Cu + (N-0.045) × 30 when N 0.00–0.20 or Ni + 30C + 0.87Mn + 0.33Cu + (N-0.045) × 22 when N 0.21–0.25 or Ni + 30C + 0.87Mn + 0.33Cu + (N-0.045) × 20 when N 0.26–0.35
Leger diagram	1982	Cr + 1.5Si + Mo – 5.0	Ni + 30C + 0.5Mn + 2.8
Siewert and Kotecki (WRC-1992)	1992	Cr + Mo + 0.7Nb	Ni + 35C + 20 N + 0.25Cu
WRC-1998	1998	Cr + Mo + 0.7Nb	Ni + 35C + 20 N

Note: [(1)] See Figs. 2.53, 2.54, 2.55, 2.56, and 2.57 for more details
[(2)]See ASME Sec. II, Part C-2008, SFA 5.22, Fig. A3

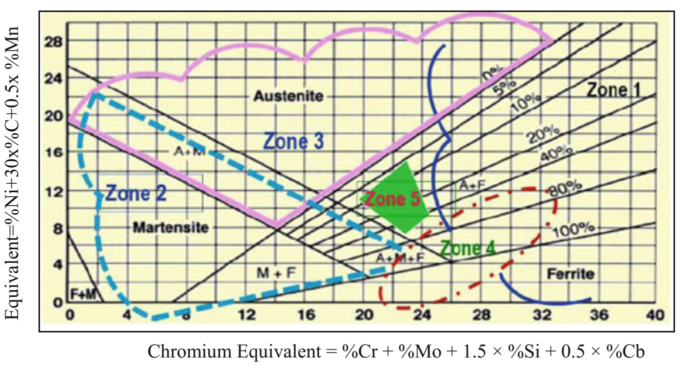


Figure 2.53 Phases and delta ferrite percentages in Schaeffler diagram. (Source: T. Eun, Practice of SS, 2000). *1 (Zone 1): σ (sigma) embrittlement and 475 °C (885 °F) embrittlement are expected. *2 (Zone 2): Martensite crack below 400 °C (752 °F) is expected. *3 (Zone 3): Solidification crack during cooling from 1250 °C (2282 °F) is expected. *4 (Zone 4): Embrittlement due to coarse grain over 1150 °C (2100 °F) is expected. *5 (Zone 5): Safe Zone (Recommended)

1000–1100 °C (1832–2012 °F). Cracks not only reduce the strength of the weld through the reduction in the cross section thickness but also can readily propagate through stress concentration at the tip, especially under impact loading or during service at low temperature. In addition, delta (δ) ferrite control promotes to avoid the solidification crack.

(a) Schaeffler and DeLong Diagrams and Delta (δ) Ferrite

It was initially developed by Schaeffler and further developed by DeLong. In addition, several modified formulas have been developed by others in Table 2.60. Figure 2.53 shows the phases and delta ferrite percentages in Schaeffler Diagram. The chemical control (as diluted condition on welds) at Zone 5 is mostly desirable to avoid the conventional cracks.

Schaeffler or DeLong Diagram is used for the limitation in stainless steels as follows:

1. To prevent solidification crack during welding
2. To evaluate dilution of dissimilar metals in welding
3. To evaluate the standard structure under casting and ingot metal condition
4. To evaluate precipitation, such as σ phase embrittlement and 475 °C (885°F) embrittlement during welding and long term operating at high temperature

Figure 2.54 shows DeLong (FN) Diagram for Stainless Steel Weld Metal which was used in ASME by 2008. Now ASME is using WRC 1992 (FN) diagram in Fig. 2.55.

General Notes

(a) The actual nitrogen content is preferred. If this is not available, the following applicable nitrogen value shall be used: (1) GMAW welds – 0.08%, except that when self-shielding flux cored electrodes are used – 0.12%. (2) Welds made using other processes – 0.06%.
(b) This diagram is identical to the WRC-1992 Diagram, except that the solidification mode lines have been removed for ease of use. It is for 5%, 8%, or 9%Ni steel as well as stainless steel.

Figure 2.56 shows phases of several stainless steel and alloy base metals from Schaeffler Diagram.

(b) Mechanism of δ Ferrite Effect.

The δ Ferrite which can be found during/after welding (weld overlay as well as solid welding) of ASS can reduce the solidification crack. A few ferrite structures (typically 3~11%) in ASS weld are required to prevent solidification crack by P or S (due to low melting temperature of their compounds) during welding even though it has poor anti-corrosion properties compare to 100% austenitic structured stainless steels. FN (ferrite number) is the standardized value plotted from chemical composition of weld metal as seen (d) below. Table 2.61 shows the solubility of P & S in ferrite and austenite structure. Ferrite structure has higher solubility for P & S than that of austenitic structure. As a result, ferrite structure can reduce the solidification crack due to the high solubility of P & S (Fig. 2.57).

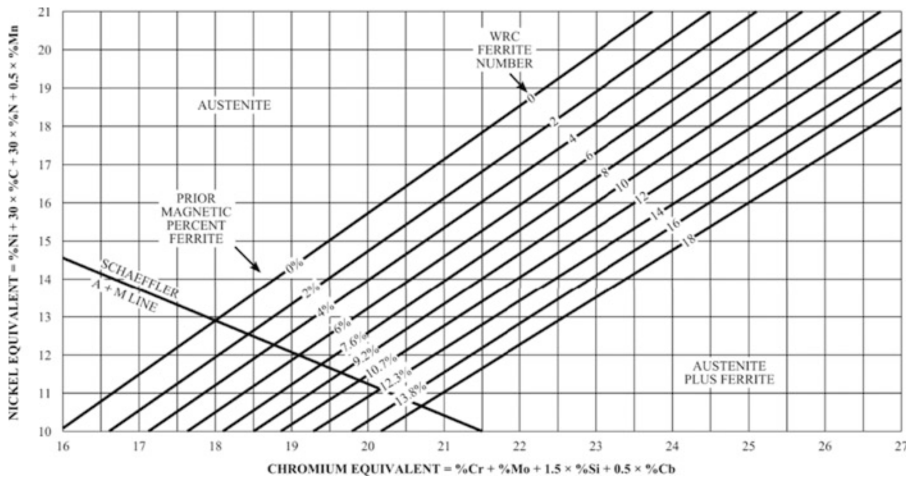
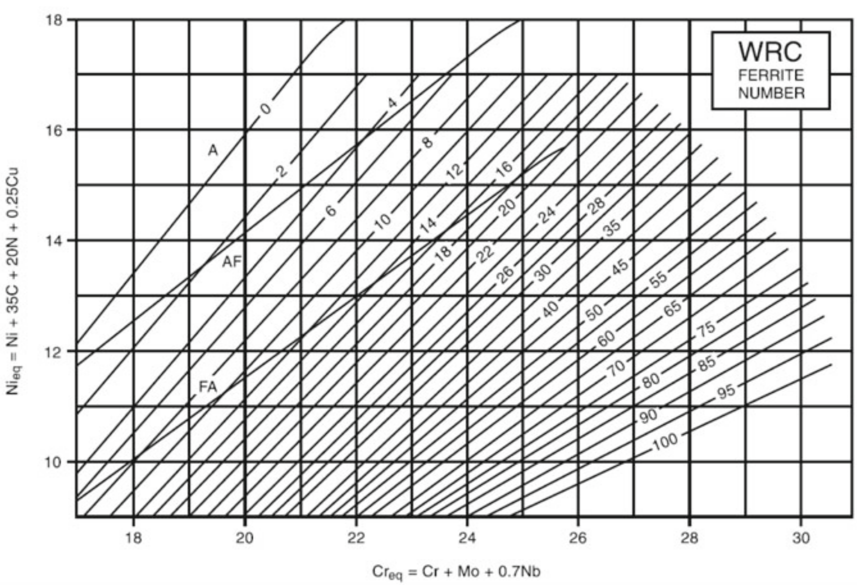


Figure 2.54 DeLong (FN) diagram for stainless steel weld metal. (Source: ASME Sec. II, Part C-2008, SFA 5.22, Fig. A4). Calculate the Ni and Cr equivalents from the weld metal analysis. If nitrogen analysis of the weld metal is not available, assume 0.06% GTAW and covered electrode, or 0.08% for GMAW weld metals. If the chemistry is accurate the diagram predicts the WRC Ferrite Number within ±3 in approximately 90% of the tests for 308, 309, 316, and 317 SS families



GENERAL NOTES:
(a) The actual nitrogen content is preferred. If this is not available, the following applicable nitrogen value shall be used:
(1) GMAW welds — 0.08%, except that when self shielding flux cored electrodes are used — 0.12%
(2) Welds made using other processes — 0.06%.
(b) This diagram is identical to the WRC-1992 Diagram, except that the solidification mode lines have been removed for ease of use. It is for 5%, 8%, or 9%Ni steel as well as stainless steel.

Figure 2.55 SS weld metal delta ferrite content – WRC 1992 (FN) Diagram. (Source: AWS A5.4/A5.4M, Fig.A.3 and ASME Sec. II, Part C, SFA-5.4, Fig. A.3, SFA-5.9/5.30, Fig.A.1, SFA-5.22, Fig.A.2)

Ideally the sum of (P + S) on the weld metal is lower than 0.01 wt% (0.005 wt% preferable) or Creq/Nieq >1.5 on the weld metal will be immune to the solidification (hot) cracking. Meanwhile, API RP582 requires 30–65% ferrite on weld metal, 40–65% ferrite on HAZ, and 40–60% ferrite for base metal in DSS weld; however, this requirement is not related with solidification cracking, but for corrosion resistance.

API RP582 requires minimum 5 FN (unless approved by purchaser) and 1–5 FN for 347 SS weld and 16–8-2 (UNS W36810 welding electrode; see Table 4.82 (5/5) for more details) weld, respectively, except maximum 9 FN for FCAW weld of ASS FCAW weld exposed to 538 °C (1000 °F) and above during fabrication and/or service. Unless otherwise specified, for materials requiring PWHT or

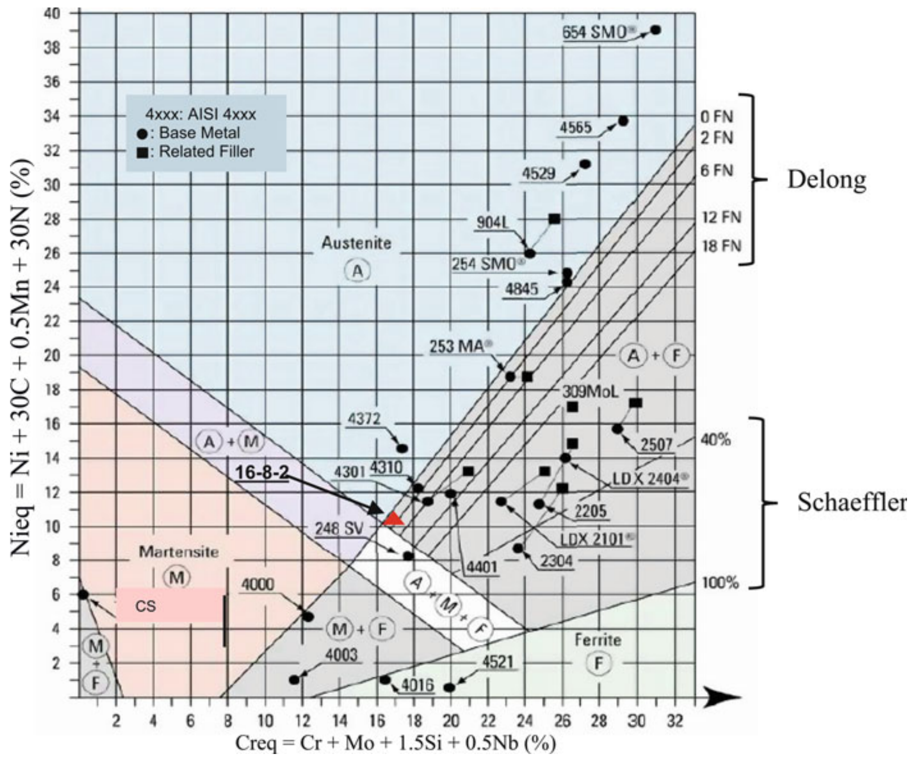
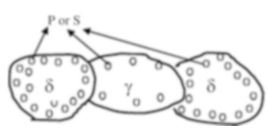


Figure 2.56 Phases of several low-alloy and stainless steels from Schaeffler-DeLong diagram. (Source: Outokumpu report, 2009)

Table 2.61 Solubility of P & S in ferrite and austenite structure

Element	Austenite structure (γ)	Ferrite structure (δ)
P	0.15%	0.40%
S	0.10%	2.80%



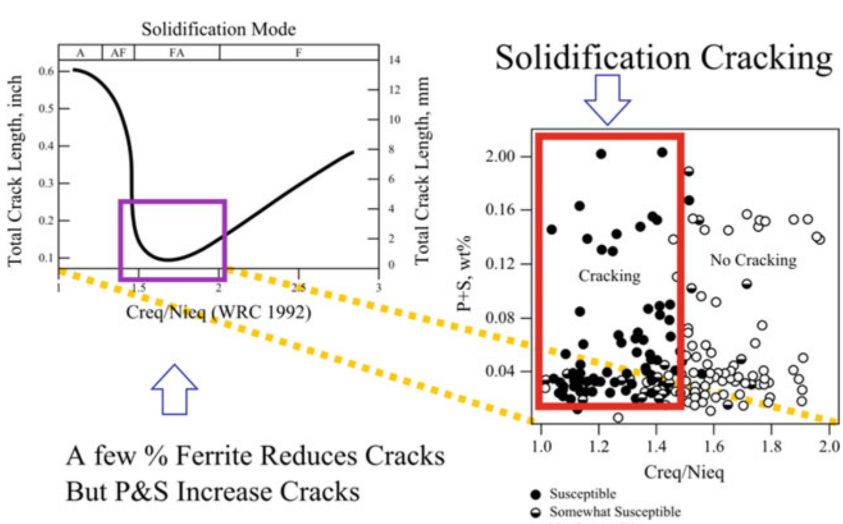


Figure 2.57 Crack Length as a function of (P + S) in Ferrite and Austenite Structure

materials in high-temperature service (see ASME Sec. II-D, Table A-360), the ferrite number (FN) for the deposited weld metal of ASS (P. No.8-Gr.1) should not exceed 10 FN measured prior to PWHT and the minimum FN for deposited weld metal should be 3 FN. If PWHT (for dissimilar welding with CS or LAS or weld overlayed CS or LAS/ solution heat treatment or thermally stabilized heat treatment including postfabrication strain relief, etc.) is performed, the FN shall be measured prior to the PWHT because the ferrite is dissolved in the matrix, and then most ferrites disappear after PWHT, as seen in Fig. 2.58, which shows the delta-ferrite transformation depending on the annealing temperature and holding time. In cryogenic service, the FN of ASS should be 1–7 (max. 5 preferable). ASME Sec. VIII codes require maximum 5 of FN for the production welding procedure of 316L SS weld filler metal when the MDMT is colder than −196 °C (−320 °F).

Meanwhile, the δ Ferrite in high percentage in ASS can cause the following problems:

– Sigma (σ) phase which is brittle at low temperature can be readily transformed from δ Ferrite.
– Decrease in corrosion resistance in chloride environment.
– Increase in the formation of martensite, in austenitic steel having a low nickel content and following cold work, with a consequent reduction of ductility.
– Magnetic behavior in ASS, due to the ferromagnetic nature of ferrite. It may not be desirable in certain industries (e.g., semiconductor, etc.)

(c) (Delta) ferrite content measuring methods for ASS weld metal

Ferrite content measuring methods for austenitic stainless steel weld metal are shown in Table 2.62.

The transformation (i.e., decomposition) of delta ferrite will occur during solution heat treatment or thermally stabilized heat treatment. If no hot crack on weld is verified and the user accepts, the welds with the slightly lower ferrite number than the required ferrite range may be used.

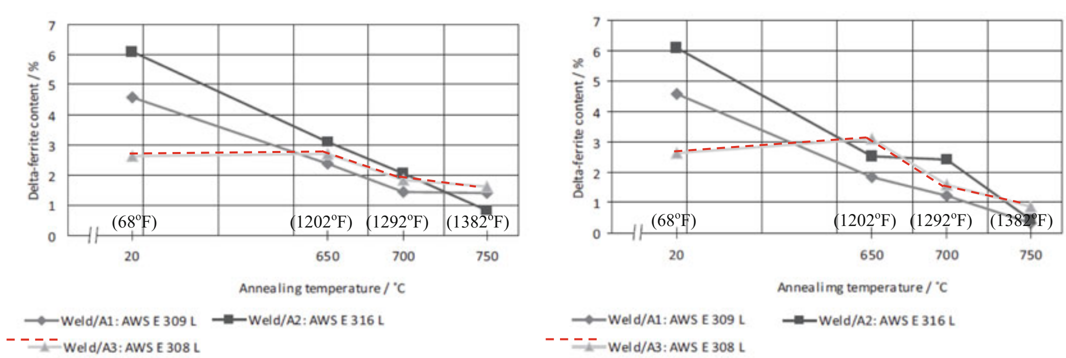
(d) Conversion of volume ferrite percentage (%) and ferrite number (FN).

Ferrite Number (FN) is an arbitrary standardized value designating the ferrite content of an austenitic stainless steel weld metal. It should be used in place of percent ferrite or volume percent ferrite on a direct replacement basis, while ferrite percent (%) is a volumetric fraction of ferric structures in the austenitic structure. The following conversion formula between volume ferrite percentage (ferrite %) and ferrite number (FN) may be used.

API RP582 states that the following for DSS can be used to convert from ferrite % to FN:

Ferrite vol% = 0.7 × FN for 22% Cr duplex stainless steel (DSS),

Ferrite vol% = 0.65 × FN for 25% Cr super duplex stainless steels (SDSS).



(a) (b)

Figure 2.58 Delta-Ferrite transformation depending on annealing temperature. (Source: B. Matesa et al., Metabk 51(2) 229–232, 2012). (**a**) After 2 hours holding. (**b**) After 10 hours holding

Table 2.62 Ferrite content measuring methods for austenitic stainless steel weld metal

Method	Measuring principle
Ferrite indicator	Comparing the magnetic attraction between a standard ferrite percent insert and a test specimen
Ferrite scope	Measuring a change of magnetic induction affected by the ferrite content of a test specimen
Magnetic gage	Measuring the pull off force necessary to detach a standard permanent magnet from a test specimen
Structure diagram	Calculating Ni equivalent and Cr equivalent of the chemical composition of a test specimen and reading the crossing point of the two equivalents in a structure diagram. Three structure diagrams are available: Schaeffler diagram, DeLong diagram, and WRC diagram. See Figs. 2.52, 2.53, 2.54, 2.55, and 2.56
Point counting	Calculating the area percentage of ferrite in the microstructure of a test specimen, by using an optical microscope

TWI introduces the conversions between ferrite % and FN as below:
[300 series SS] – TWI paper DA2–058, Duplex America 2000

$$FN = \frac{(vol\%ferrite) \times \left[-0.025813\ (Fe)^2 + 5.408679\ (Fe) - 102.3902\right]}{100}$$

When FN=Ferrite Number, Ferrite percent = vol% ferrite, (Fe) = wt% of Fe.
[DSS] – only for reference

$$\text{Ferrite vol\%} = 0.57FN + 8.82 \text{ for } 22\%Cr \text{ duplex stainless steel (DSS)} - \text{TWI Paper, Nov.1987}$$

$$= 0.55FN + 10.6 \text{ for } 22\%Cr \text{ duplex stainless steel (DSS)} - \text{Avesta (OutoKumpu) manual}$$

$$\text{Ferrite vol\%} = 0.82FN + 3.6 \text{ for } 25\%Cr \text{ super duplex stainless steels (SDSS)} - \text{TWI Paper, Aug.1992}$$

See NACE Paper 19–13437 for several Ferrite measurement methods and cautions for DSS.

(e) Minimizing Hot Cracking by Welding Techniques: See Sect. 4.2.8.
(f) However, the presence of delta ferrite causes the following problems with ASS other than welding/casting:
1. In the lower Ni-containing ASS, such as 301, 302, 304, and 316, cold working causes martensite to form. Higher delta (δ) ferrite means more martensite transformation. As the martensite increases, the ductility decreases and the potential for fracture increases, especially in cryogenic application.
2. If secondary operations like electropolishing are performed, the delta ferrite will preferentially dissolve, leaving a white or dull surface. This is especially true for welded parts. If the delta (δ) ferrite is too high, the part is unsuitable for service in this environment since it cannot be heat treated out.
3. In corrosive environments, especially if acid chlorides are present, the delta ferrite will preferentially dissolve. If the delta (δ) ferrite is present in welds, the weld will totally dissolve. If the delta ferrite is too high, the part is unsuitable for service in this environment since it cannot be heat treated out.
4. If the delta ferrite is below 2% the alloy is good for fabrication, but the alloy may develop microcracks during welding.

(g) Codes and Standards
– ASME Sec. II, Part D, A-213
– ASTM A799, Standard Practice for Steel Castings, Stainless, Instrument Calibration, for Estimating Ferrite Content
– ASTM A800 Standard Practice for Steel Casting, Austenitic Alloy, Estimating Ferrite Content Thereof
– ASTM A890, Standard Specification for Castings, Fe-Cr-Ni-Mo Corrosion-Resistant, DSS for General Application
– ASTM E562, Practice for Determining Volume Fraction by Systematic Manual Point Count
– ANSI/AWS A4.2M Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of ASS and DSS Weld Metal
– WRC Bulletin 132, The Measurement of Delta Ferrite in Austenitic Stainless Steels
– WRC Bulletin 342, Stainless Steel Weld Metal: Prediction of Ferrite Contents
– ASME Section II, Part C, Specifications for Welding Rods, Electrodes, and Filler Metals
– API RP582, Welding Guidelines for the Chemical, Oil, and Gas Industries
– EN 13445, Unfired Pressure Vessels
– ISO 8249, Welding – Determination of Ferrite Number in austenitic weld metal deposited by covered Cr-Ni steel electrodes

2.1.6.2 Chloride Corrosion Pitting, Crevice and Stress Corrosion Crack (SCC) of Stainless Steels

(a) Progress of Pitting and SCC

CLSCC and pitting typically occur in 300 series SS, DSS, and some nickel-based alloys under the combined tensile stress. The severity depends on the chloride concentration, temperature, pH, dissolved oxygen, PRE of the metal, stress condition, hardness, etc.

Typically, the progress of pitting and SCC are as follows:
(i) Small discrete spots on the steel surface like smallpox.
(ii) Occurs mainly in the presence of neutral or acidic solutions containing chlorides or other halides.
(iii) Chloride ions facilitate a local breakdown of the passive layer (e.g., SS surface), especially if there are imperfections in the metal surface.
(iv) Typical Process in Acidic Services: Dapple Dark Color → Small Spot at Dapple Color Center
→ Small Dimple → Digging & Caving → Large Dimple → SCC at stress environment (Fig. 2.59)
(v) Pitting & SCC have same root environments. In severe environments, SSC can directly occur without the pitting process.

Surface-initiated cracks caused by environmental cracking of 300 Series SS and some nickel based alloys under the combined action of tensile stress, temperature, and an aqueous chloride environment, as shown in Fig. 2.60.

Figure 2.61 shows a sample case for Stress Corrosion Cracking (SCC) in a 304 SS pipe GTAW and exposed to a corrosive liquid solution. In high-risk environments of SCC, the clad material (SS clad on CS) instead of solid ASS may be recommended because the base metal may have a buffer effect of the crack propagation.

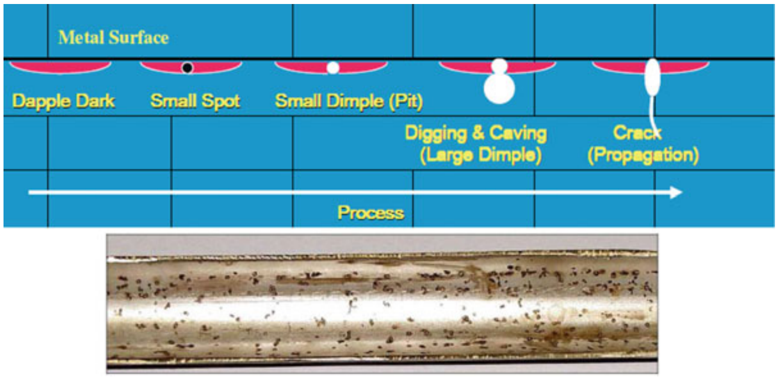


Figure 2.59 Process of pitting and SCC

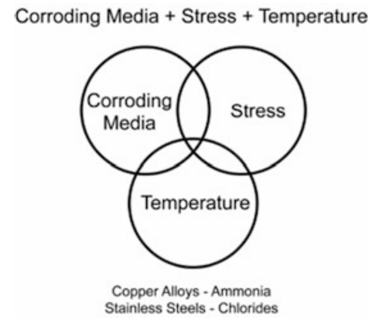


Figure 2.60 Three necessary factors for producing SCC

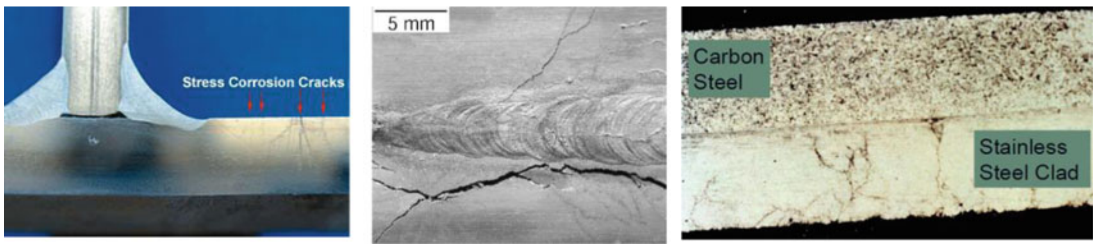


Figure 2.61 Chloride SCC in 304 SS. (**a**) SCC at the outer zone of HAZ. (**b**) SCC at HAZ of a 304 SS pipe GTAW joint. (**c**) SCC of Clad Material

The phenomena show the following characteristics.

1. A failure may be accelerated by the combined effect of chloride, pH, dissolved oxygen, and mechanical stress. The presence of dissolved oxygen (>0.5 ppm at pH 6.0) increases propensity for cracking.
2. Transgranular SCC commonly may develop in concentrated chloride-containing environments.
3. Intergranular SCC may develop in sensitized SS.
4. Conventional 304(L) SS or 316(L) SS mainly are exposed to high tensile/residual stress and contaminated with solid salt deposits and high humid atmosphere.
5. These two factors result in a thin liquid film saturated with chloride.
6. Other contaminants, such as H2S, may increase the risk of SCC in chloride-containing environments.
7. The formation of thin, branched cracks may occur.
8. As seen in Fig. 2.61c, clad material may be beneficial in mitigating the SCC propagation than solid CRA (corrosion resistant alloy).

Meanwhile, the pitting is normally measured by Critical Pitting Temperature (CPT) using ASTM G48 or other standards (Figs. 2.62 and 2.63).

(b) Crevice Corrosion

Crevice corrosion occurs in the very narrow gaps in steel, particularly in austenitic stainless steels. It typically occurs in gasket contact face of flanges, tubes to tubesheet, bolting materials, pad/backing strip on the steel without seal welding, stacked stock materials in storage area, etc., as seen in Table 2.124 (11). Normally the inside of the crevice has higher chloride concentration, lower oxygen content, and lower pH than those outside, so the inside surfaces are more exposed to fast corrosion environment.

The corrosion resistance of stainless steel is dependent on the presence of a protective oxide layer on its surface, but it is possible under certain conditions for this oxide layer to break down, e.g., in reducing acids, or in some types of combustion where the atmosphere is reducing. Areas where the oxide layer can break down can also sometimes be the result of the way components are designed, e.g., under gaskets, in sharp re-entrant corners, or associated with incomplete weld penetration or overlapping surfaces. These can all form crevices that can promote corrosion. To function as a corrosion site, a crevice has to be of sufficient width to permit entry of the corrodent, but sufficiently narrow to ensure that the corrodent remains stagnant. Accordingly, crevice corrosion usually occurs in gaps a few micrometers wide, and is not found in grooves or slots in which circulation of the corrodent is possible. This problem can often be overcome by paying attention to the design of the component, in particular avoiding the formation of crevices or at least keeping them as open as possible. Crevice corrosion is a very similar mechanism to pitting corrosion; alloys resistant to one are generally resistant to both. Crevice corrosion can be viewed as a more severe form of pitting corrosion as it can occur at significantly lower temperatures than does pitting.

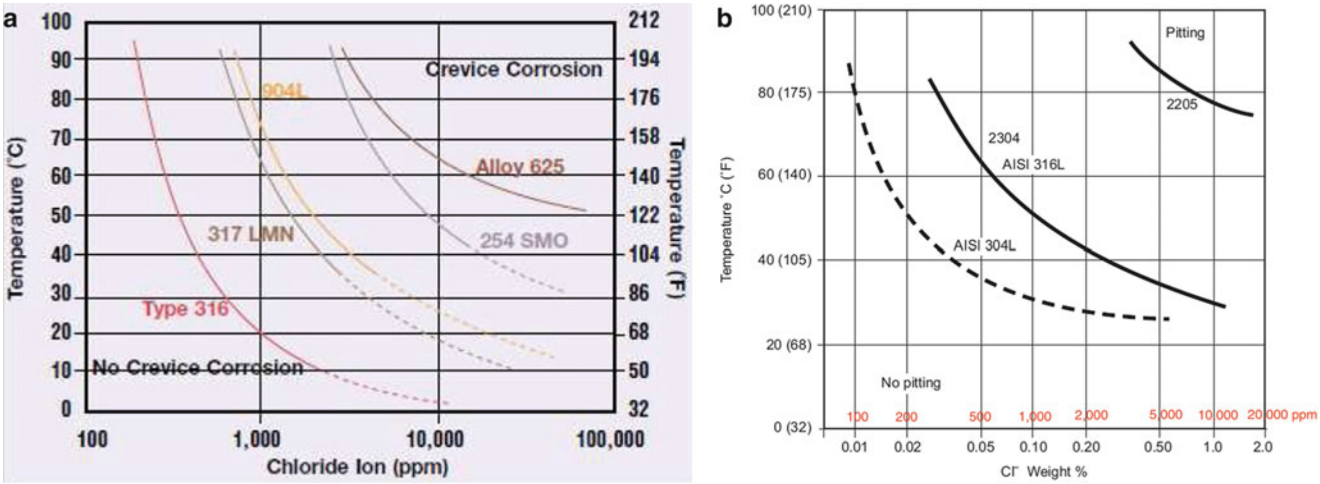


Figure 2.62 (**a**) CCT for 316L, 317, 904L, 254 SMO, and Alloy 625 in neutral chloride solutions. (Source: Outokumpu report, 2009). (**b**) CPT for 2304 DSS, 304L SS and 316L SS in neutral chloride solutions (potentiostatic determination at +300 mV/SCE, pH 7). (Source: API TR938-C)

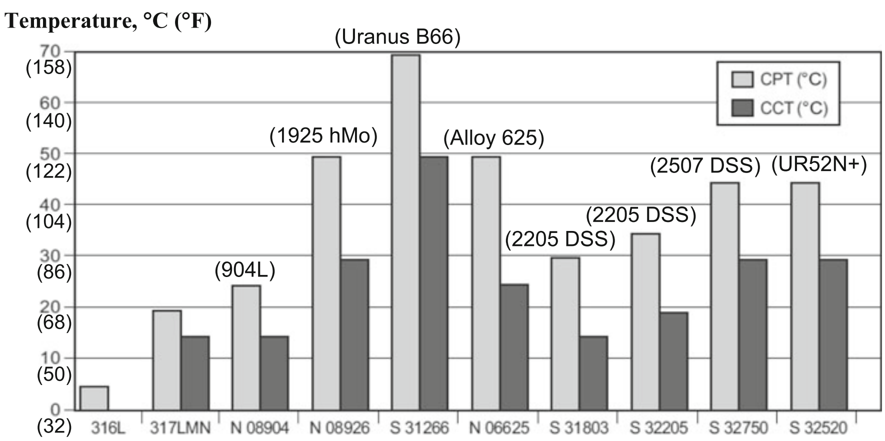


Figure 2.63 CPT and CCT of several stainless steels in 6% $FeCl_3$, 24 h, ASTM G48-A. (Source: API TR938-C)

(c) Susceptible Materials and Environment
1. Conventional ASS (304(L), 316(L), 321, 347, etc.)
2. Environment: Solutions of Chlorides, Fluorides, Iodides, Bromides, Sulfates, Phosphates, Nitrates, and Polythionic acids, etc.

(d) Remedy and Countermeasure
1. Low-Strength SS: Min. Specified T.S. ≤483 MPa (70,000 psi) for ASS
2. Low Residual Stress or Stress Relieving: Hardness ≤200~210 BHN or Solution Heat Treatment (Annealing) for ASS
3. Materials Selection: 405 (FSS), 410 (MSS), DSS, SSS-*Good* > 304, 316 (ASS)
4. Process Control and Chemical Treatment to Reduce Cl-
5. Drain parts should be Alloy 825 instead of 300 series SS if concentrated chloride is concerned.

Applicable Codes, Standards, or Reports

ASME Sec. II, Part D, A-701, API RP571, NACE SP0170/0204/0403/0472, NACE TM0111/0177/0198, ASTM C692, ASTM STD 610, NiDI Publ. 1279/10016/10066/14015/14017, TWI Report PR6744 (2003).

[Materials Test Practices]

- ASTM G30 – Practice for making and using U-bend SCC test specimens
- ASTM G35 – Susceptibility of SS or Ni-Cr-Fe alloys to SCC in polythionic acid
- ASTM G36 – SCC of SS in boiling $MgCl_2$ solution
- ASTM G38 – Practice for making and using C-ring SCC test specimens
- ASTM G39 – Practice for preparation and use of bent-beam SCC test specimens
- ASTM G44 – Practice for evaluation of SCC resistance of alloys in 3.5% NaCl solution
- ASTM G46 – Examination and evaluation of pitting corrosion
- ASTM G48 – Pitting and crevice corrosion resistance of SS and related alloys in $FeCl_2$ solution

- ASTM G49 – Practice for preparation and use of direct tension SCC test specimens
- ASTM G58 – Practice for preparation SCC for weldments
- ASTM G78 – Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments
- NACE TM0198 – Slow strain rate test method for screening CRAs for SCC in sour oilfield Service
- NACE SP0472 Methods and Controls to Prevent Cracking of CS Weldments in Corrosive Petroleum Refining Environments
- NACE Publ. 35103 – External Stress Corrosion Cracking of Underground Pipelines
- NACE Publ. 34105 – Effect of Non-Extractable Chlorides on Refinery Corrosion and Fouling
- NACE Publ. 24221 – External Stress Corrosion Cracking of Underground Pipelines
- NACE Publ. 34108 – Review and Survey of Alkaline Carbonate SCC in Refinery Sour Waters
- Others – ISO/TC 67/SC4/WG6, EEMUA 194, ISO 13628, etc.

[Fitness-for-Service]

- API RP581 – Risk-Based-Inspection, Chloride SCC (CISCC) part
- API RP570 – Piping Inspection, SCC part
- API 579–1/ASME FFS-1 – Fitness-for-Service, SCC part
- API TR939-D – SCC of CS in Fuel-Grade Ethanol: Review, Experience Survey, Field Monitoring, and Laboratory Testing

References; for More Details and/or Use as Check List

NACE Paper **19**-12685/12812/12868/13012/13077/13123/13132/13273/13320/13359/13362/13370/13374/13420/13430/13438,**18**-10544/10601/10617/10630/10632/10701/10816/10846/10873/10895/10953/10959/10979/11074/11084/11111/11112/11114/11150/11194/11201/11257/11311/11382/11387/11389/11438/11444/11450/11456/11472/11529/11566/11569/11634, **17**-8853/8899/8943/8953/8958/8975/8992/9036/9113/9147/9156/9162/9163/9187/9241/9269/9281/9288/9327/9345/9346/9408/9412/9416/9475/9513/9518/9596/9604/9689/9717/9779/9781, **16**-7070/7113/7135/7166/7170/7193/7196/7198/7199/7214/7250/7253/7287/7308/7325/7397/7444/7450/7595/7618/7653/7654/7688/7707/7760/7767/7772/7837/7843, **15**-5432/5469/5518/5527/5530/5583/5610/5620/5656/5699/5704/5739/5740/5746/5785/5888/5945/5961/5971/6000/6132, **14**-3754/3759/3760/3783/3830/3885/3904/3981/3985/4028/4070/4078/4132/4231/4249/4287/4289/4321/4249/4287/4289/4321/4469/4471, **13**-2086/2120/2130/2154/2157/2202/2235/2259/2282/2352/2361/2371/2411/2412/2418/2427/2442/2494/2504/2524/2531/2533/2539/2541/2547/2568/2616/2633/ 2676/2763/2774/2864, **12**-067/1070/1130/1137/1168/1181/1188/1189/1202/1206/1262/1263/1331/1334/1355/1361/1455/1470/1486/1501/1510/1526/1556/1613/1641/1644/1678/1703/1746/1924/1926/1929, **11**080/11097/11101/11137/11138/11141/11160/11168/11174/11202/11204/11224/11254/11255/11256/11257/11264/11273/11283/11284/11285/11286/11287/11316/11349/11425,10073/10075/10077/10156/10185/10194/10232/10237/10239/10241/10252/10284/10285/10287/10297/10300/10301/10303/10304/ 10332/10345/10352, 09092/09108/09121/09111/09121/09192/09194/09300/09364/09366/09411/09412/09414/09424/09434/09436/09461/09528/09530/ 09531/09532/09534/09535/09536, 08129/08174/08200/08232/08248/08254/08265/08266/08401/08428/08432/08481/08484/08485/08486/08492/08495/08500/08542/08545/08575/08580/08582/08599/08600/08601/08602/08604/ 08608/08675, 07091/07092/07093/07094/07114/07128/07130/07167/07194/07196/07198/07204/07206/07214/07376/07392/07415/07474/07476/07477/07479/07481/07485/07486/07487/07488/07493/07564/07574/07577/07578/07581/07582/07584/07587/07606/ 07607/07612/07658, 06095/06137/06140/06175/06213/06244/06467/06496/06500/06502/06505/06506/06508/06509/06513/06602/06603/06608/06618/06623/06625/06626/06641, 05094/0 51 19/05158/05160/05161/05196/05366/05458/05462/05463/05469/05470/ 05479/05505/05561/05591/05592/05594/05599/05610/0561 1/05627/05631/05643/05644/05645, 04066/04108/04124/04138/04189/04201/04240/04244/04281/04289/04290/04300/04304/04309/04428/04446/04452/04454/04462/04485/04492/04513/04514/04506/04518/04520/04539/04543/04553/04554/04555/04556/04560/04564/04565/04569/04570/0451/04611/04668/04671/04675/04678/04680/04681/04683/04695/04737, 03108/03177/03403/03447/03510/03511/03513/03515/03518/03519/03522/03523/03526/03527/03536/03539/03541/03660/03662/03664/03665/03666/03667/03675/03683/03685/30691, 02038/02039/02061/02067/02132/02159/02187/02194/02208/02213/02418/02423/02425/02426/02432/02434/02436/02437/02438/02439/02472/02495/02509/02510/02511/02519/02520/02523/02524/02529,01018/01067/01076/01085/01103/01117/01123/01128/01130/10034/10041/01211/01213/01214/01217/01220/01228/01233/01234/01235/01361/01462 /01496/01498/01551/12592/01631, 00355/00356/00359/00361/00362/00363/ 00365/00367/00370/00373/00379/00417/00456/00588/00596/00621/00634/00652/00686/00827, 99385, 98251/98262/98507,97102/97501, 93171, 92086, 90491/90494, 89099/89575/89625, etc.

2.1.6.3 Sensitization and Intergranular Corrosion Cracking/Attack (IGC), Weld Decay, and Knife Line Attack

IGC occurs when material in the grain boundaries of certain alloys is less resistant to the corroding agent than the grain themselves.

- Target of Cr in initial design: Random distribution at all grain boundaries
- IGC: Due to Carbide Precipitation at 427–900 °C (800~1650 °F), in 2~3 minutes (for 304, 316) @ grain boundary (Fig. 2.64)

  NACE SP0170 and API TR942-B state the most common Carbide (MC, $M_{23}C_6$, M_6C). Precipitation temperature ranges per several austenitic materials in Table 2.63 (M = Cr, Ti, Nb, etc.).

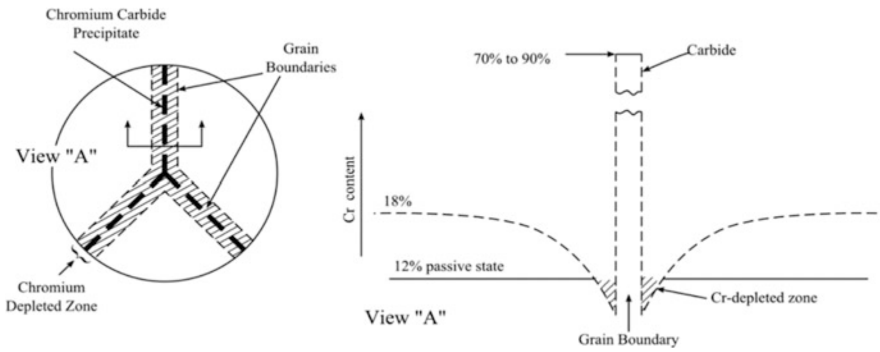


Figure 2.64 Mechanism of intergranular corrosion cracking

Table 2.63 Sensitization temperature range and formed carbides of austenitic SS and alloys[(1)]

Materials	Sensitization temperature range	Carbides formed	Remark
304, 316, 317, 304H, 316H, 304L, 316L, 317L, 321, 347 SS	370–815 °C (700–1500 °F)	MC	[(1)]See API TR942-B and NACE SP0170 for more detail
	600–950 °C (1100–1740 °F)	$M_{23}C_6$	
	700–950 °C (1290–1740 °F)	M_6C	
Alloy 800/800H/800HT	538–760 °C (1000–1400 °F)	Cr_7C_3	
	760–1093 °C (1400–2000 °F)	$Cr_{23}C_6$	
Alloy 825/625	650–760 °C (1200–1400 °F)	MC, $M_{23}C_6$, M_6C	

(a) Causes & Mechanisms
(b) Susceptible Materials, Heat Sources, and Environment (Fig. 2.65)
   1. Conventional ASS; 304 ($C \leq 0.08$ wt%), 316 ($C \leq 0.08$ wt%)
   2. Heat Sources: hot working (forming, molding, spinning, forging), heat treatment, welding, high-temperature operations
   3. Environment; In the service requires the ASS for corrosion resistance
(c) Remedy and Countermeasure
   1. Low Carbon SS; 304L ($C \leq 0.03$ wt%), 316L ($C \leq 0.03$ wt%)
      - 304ELC ($C \leq 0.015$ wt%), 316ELC ($C \leq 0.015$ wt%)
      - 304ULC ($C \leq 0.0075$ wt%), 316ULC ($C \leq 0.0075$ wt%)

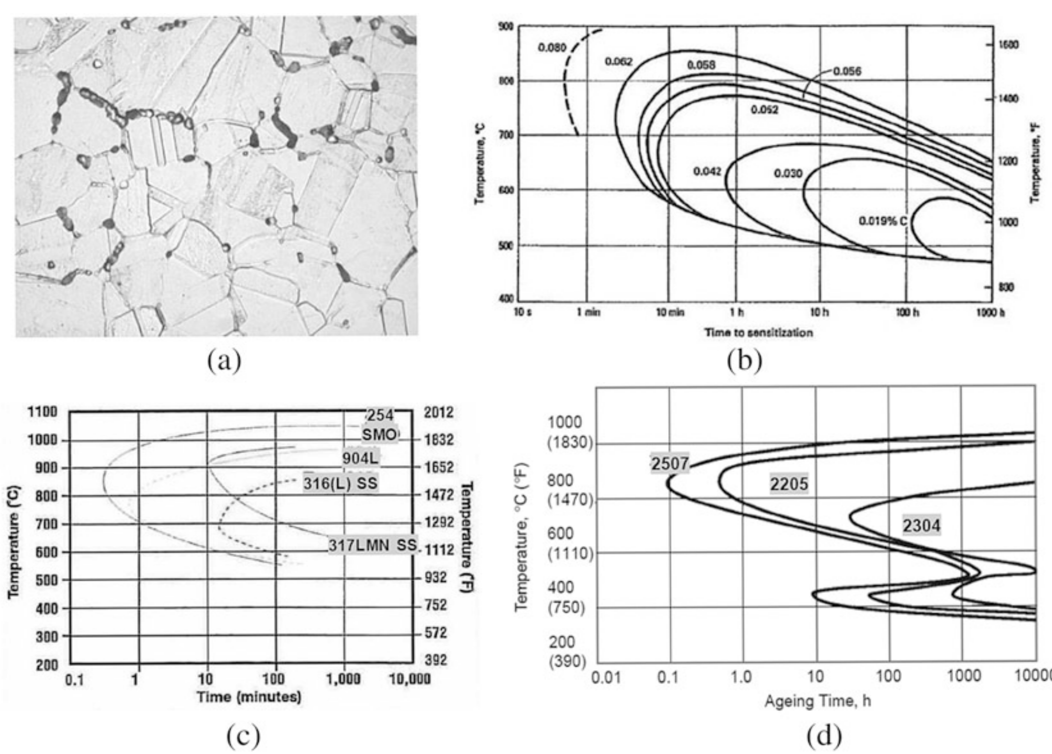
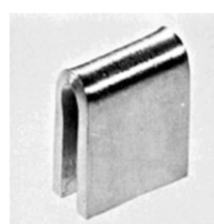


Figure 2.65 Sensitization/embrittlement curves of several stainless steels. (Source: NiDI Publ. 9004 & 9014). (**a**) *Sensitized Microstructure* (ASTM A262 Practice A, Dual Structure). (**b**) *304 SS with various C contents*. (**c**) *Several Austenitic Stainless Steels*. (**d**) *Several Duplex Stainless Steels*. Left section of the curves: Sensitization/Embrittlement Zone

Table 2.64 Test methods of intergranular corrosion cracking-IGC for ASS (summary of ASTM A262)

Item	Practice A	Practice B (Streicher test)	Practice C (Huey test)	Practice E (Strauss test)	Practice F
Test name	Oxalic acid Etch test – *Etching Test*	Ferric sulfate- Sulfuric acid test – *Immersion Test*	65% nitric acid test (it is not recommended for 6%Mo alloys.) – *Immersion Test*	Copper-copper Sulfate-16% sulfuric acid test – *Immersion Test*	Copper-copper Sulfate-50% Sulfuric acid test – *Immersion Test*
Solution temperature, exposure time	4–240 Hrs	120 Hrs in boiling solution	240 Hrs in boiling solution, boiled for five periods, each of 48 hours.	15 Hrs in boiling solution. The specimen to be bent through 180° and over a diameter equal to the thickness of the specimen being bent	Boiling solution
Detecting target materials	– Cr-carbides; 201, 202, 301, 304, 304L*, 304H, 316, 316L*, 316H, 317, 317L*, 321*, 347*, CF-3, CF-8, CF-3M, CF-8M	– Cr-carbides; 304, 304L, 316, 316L, 317, 317L, CF-3, CF-8 – Cr-carbides & Phase; 321, CF-3M, CF-8M	– Cr-carbides; 304, 304L, CF-3, CF-8, 309, 310, 348 – Cr-carbides & σ phase (must be when destined for service in nitric acid); 316, 316L, 317, 317L, 321, 347, CF-3M, CF-8M – End-grain pitting; all grades	– Cr-carbides; 201, 202, 301, 304, 304L, 316, 316L, 317, 317L, 321, 347	– Cr-carbides; CF-3 M, CF-8 M
Test purpose	To determine essentially free of susceptiblity to IGC associated with Cr-carbides precipitation. May be used to screen intended for testing in practice B, C, E, F.	To measure the susceptibility to IGC associated with the precipitation of Cr-carbides at grain boundaries	– Mainly be used as a check on whether the material has been correctly heat treated – Also, be used for materials that come into contact with strongly oxidizing agents, e.g., nitric acid – Also, be used to check the effectiveness of stabilizing elements and of reductions in C content in reducing susceptibility to IGC	To determine susceptibility to IGC associated with the precipitation of Cr-rich carbides	To measure susceptibility of "as received" stainless steels to IGC
Determination or acceptance	– No quantitative results – Be used for acceptance but not rejection of material – See Figs. 1 to 7 in A262	– Corrosion rate from weight loss determinations – See Table 3 for rapid screening per practice A (except 321, 347 -Cb, Ti contained SS)	– Corrosion rate during each boiling period is calculated from the decrease in the weight of the specimens – See Table 4 for rapid screening per practice A (except 316,316L, 317, 317L, 321, 347-Mo, Cb, Ti contained SS)	– Visual examination of the bent specimen – No quantitative results – See Table 5 for rapid screening per practice A – See Figure 11 through 13	Corrosion rate from weight loss determination
Alternatives/ test specimen	– May be used for a rapid method to screen specimens intended for testing in other practices 10% $(NH_4)_2S_2O_8$ solution	Total surface area of 5 to 20 cm^2. Specimens containing welds with max. 13 mm (1/2 in.) width of base metal included on either side of the weld			
Notes for test requirements/ condition	* After sensitizing HT at 649–677 °C (1200–1250 °F), 1 Hr		The purchaser must specify the max. Permissible corrosion rate and, in applicable cases, data on sensitizing HT		

2. Stabilized Elements Containing SS; 321 (Ti), 347 (Nb)
3. Solution Heat Treatment (304, 316); Rapid Cooling from 1038 to 1204 °C (1900 to 2200 °F)
4. Stabilizing Heat Treatment (321, 347); Slow Cooling from around 900 °C (1650 °F) – See Table 4.140.
5. IGC test should be performed if the risk is high. See Table 2.64.

Note: PWHT of ASS – Neither Required nor Prohibited for All Welds (ASME Sec. VIII-D1, Table UHA-32)

(d) Case Studies
  1. Hot Bending or Spinning of Shell and Head
  2. Weld Decay: There are various types (and causes) of selective attack of the grain boundaries. One of the best known types of IGC is the result of "sensitization" of the alloy (i.e., stainless steel), and when this is the result of a welding process, one often uses the term "weld decay" for the intergranular corrosion phenomenon (Figs. 2.66 and 2.67). See Sect. 4.11.6.6 and Table 2.141 for more detail mechanism. See Tables 2.143 and 2.144 for weld decay test.
  3. Knife Line Attack: Typically occurs in the stabilized ASS. See Sect. 4.11.6.7 for a more detailed mechanism.

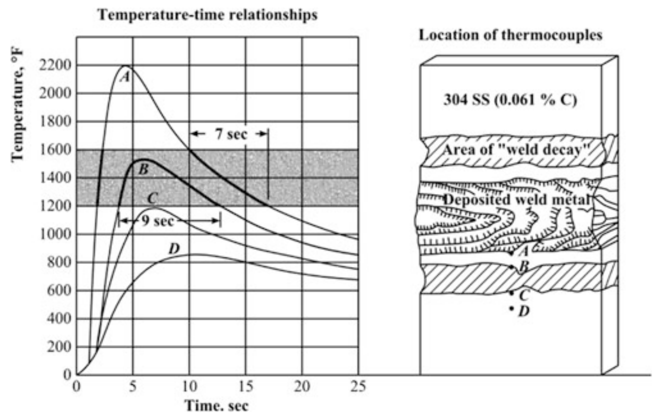


Figure 2.66 Temperature profile during SMAW of 304SS

Applicable Codes, Standards, or Reports
ASME Sec. II, Part D, A-210, API RP571

[Materials Test Practices]

(a) ASTM A262 – Detecting susceptibility to intergranular attack in ASS (see Table 2.63)
(b) ASTM G28 – Detecting susceptibility to intergranular attack in wrought, Ni rich, Cr-bearing alloys
(c) ASTM A763 – Detecting Susceptibility of Intergranular Attack in FSS
(d) *ASTM A923* – Detecting Susceptibility to Intermetallic Phase in Wrought DSS
(e) ASTM A312, S9 – Weld Decay Test for ASS Welded Pipes
(f) ASTM A249, S7 – Weld Decay Test for ASS Welded Tubes
(g) BS EN ISO 3651 **–** Determination of Resistance to Intergranular Corrosion of FSS, ASS, and DSS

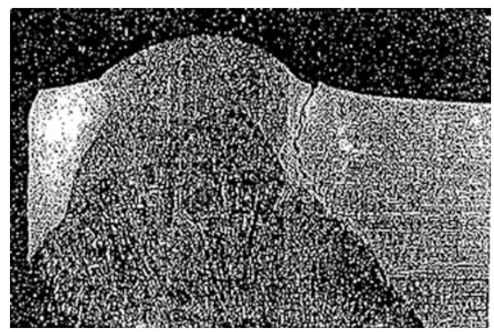


Figure 2.67 Crack by weld decay

References
NACE Paper 18-11175, 17-9575/9464/9427, 15-5609, 11101, 09180, 07382/07191/07094/07092/07091, 06158, 04444, 03667/03539/03395, 02428, 01233, 00226, 99450, 98542/98264, 97114/97103, 96536, 93044, 92117, 89487

2.1.6.4 475 °C (885 °F) Embrittlement of Stainless Steels

This phenomenon is proportional to the Cr (ferrite former) content and occurs in the temperature range of 425–550 °C (800–1025 °F). It is a result of the decomposition of the ferrite into two phases: a rich-Cr phase (α') and a rich-Fe phase (α). The more ferrite-former elements present (Cr, Mo, Nb, Si, Ti, etc.), the faster will be the reaction. The consequences of this reaction consist essentially in a selective corrosion of the rich-Fe phase (α). This α phase also has some characteristics like α', such as an increase in hardness and a loss in tensile, ductility, and toughness. Typically, this phenomenon is observed at Cr levels in excess of about 12%. This embrittlement may be due to carbide, nitride, or silicide precipitation, especially at the lower Cr levels, rather than precipitation of α' Cr-rich particles.

Fig. 2.68 shows the severity of embrittlement increases with increasing Cr content. Also, this effect is enhanced by certain alloying elements, notably Al, Mo, and W, which tend to increase and stabilize the ferrite content.

While the maximum rate of embrittlement occurs at 475 °C (885 °F), a typical C curve (like Fig. 2.68b) with time–temperature behavior is observed and some alloys with as little as 15–18% Cr have shown significant embrittlement with a few thousand hours exposure at temperatures as low as 260 °C (500 °F), as seen in Table 2.65, which provides precautionary guidelines with respect to ferrite content and temperature of exposure. See ASME Sec. II, Part D, A-207 for more details.

(a) Causes and Mechanisms (Fig. 2.68)
  1. 400 series SS with Cr ≥ 12% (FSS and MSS), PHSS and DSS are subject to embrittlement (increase hardness and T.S/ decrease toughness) when exposed to 371–510 °C (700–950 °F), critical temperature of 475 °C (885 °F), such as aging or operating, over an extended period. Sometimes the exposure temperature can be extended to 371–538 °C (700–1000 °F). Meanwhile, API RP571 and ASTM STP-706 introduce some failure cases for stainless steels with Cr ≤12%, such as 410 SS or 409 SS.
  2. This type of embrittlement is caused by fine, Cr-rich precipitates (σ') that segregate at grain boundaries; time at temperature directly influences the amount of boundary segregation of Cr-rich precipitates increases strength and hardness, decreases ductility and toughness, and changes corrosion resistance. This type of embrittlement can reverse by heating above the precipitation range. 12–13Cr steels may expose to this embrittlement after 500–1000 hours.
(b) Susceptible Materials and Environment
  1. MSS and FSS (i.e., 405, 410, 430, and 446), PHSS (i.e., 17-4PH): higher Cr, more susceptible.

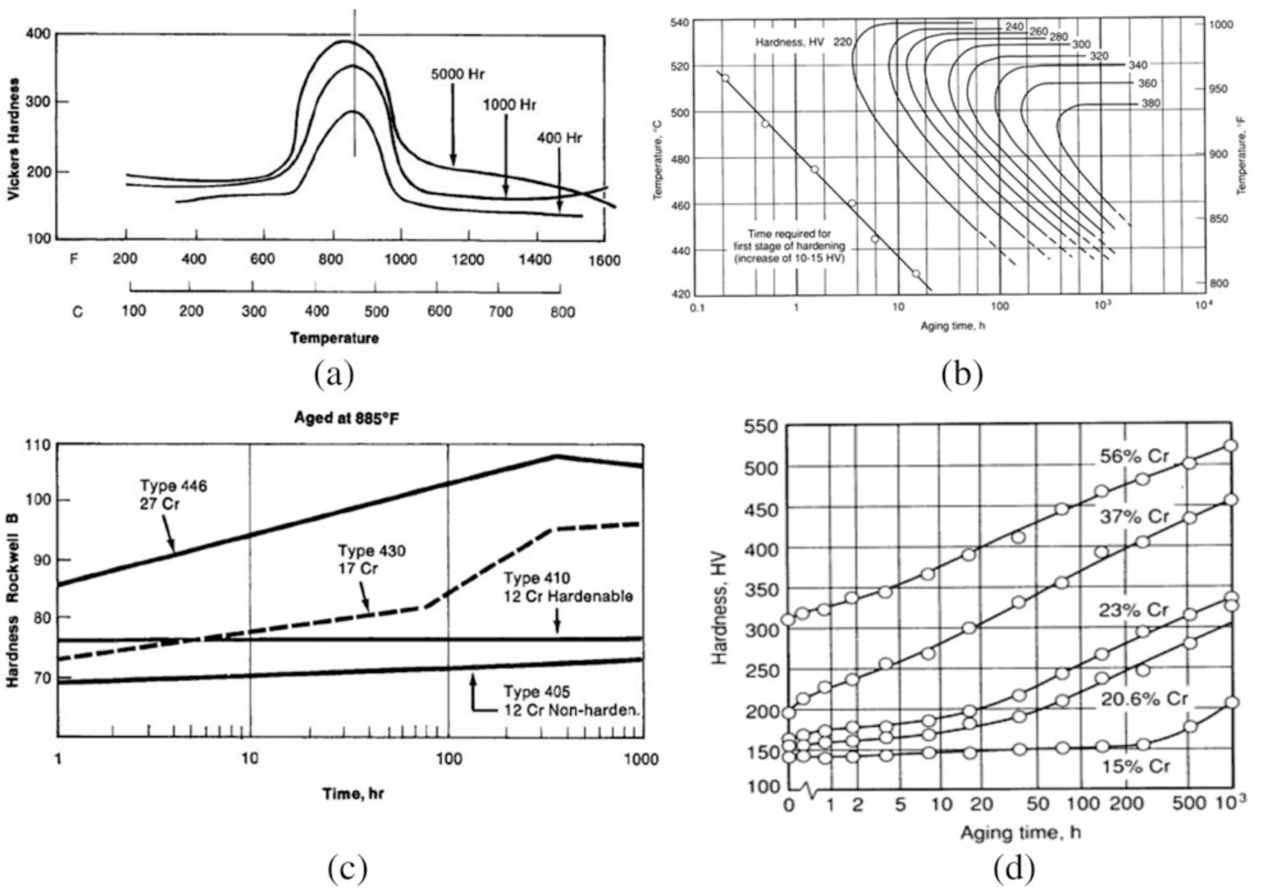


Figure 2.68 475 °C (885 °F) Embrittlement of FSS. (Source: NiDI #9004 and ASM Metal H/B, Vol.1). (**a**) Graph of hardness vs. aging temperature for 400 hours, 1000 hours, and 5000 hours, using 27% Cr Steel – Type 446. (**b**) Time-temperature-constant hardness curves for Fe-30Cr (Alloy 90) after aging done between 430 °C and 540 °C (805 °F and 1005 °F), around the region of 475 °C embrittlement. Specimens rolled at 900 °C (1650 °F); starting hardness, 195 HV to 205 HV. (**c**) Graph of hardness vs. aging time in hours for type 446 (27Cr), 430 (17Cr), 410 (12Cr), and 405 (12Cr) stainless steels. Hardening tendency increases with Cr content. Aged at 475 °C (885 °F). (**d**) Influence of aging time at 475 °C (885 °F) on the hardness of Fe-Cr alloys with 15, 20.6, 23, 37, and 56% Cr

Table 2.65 Cautionary ferrite guidelines – reference (ASME Sec. II, Part D, A-360-2011 OLD Edition)

%Ferrite	Temperature, °C (°F)						
	260 (500)	315(600)	370(698)	425(797)	480(896)	540(1004)	≥595 (1103)
0	–	–	–	–	–	–	C
5	–	–	–	–	–	–	C
10	–	–	–	–	C	C	C
15	–	–	–	C	C	C	C
20	–	–	C	C	C	C	C
25	–	C	C	C	C	C	C
30	–	C	C	C	C	C	C
35	C	C	C	C	C	C	C
40	C	C	C	C	C	C	C

General Notes:
(a) C stands for caution
(b) At the ferrite levels and temperatures identified with the letter C, the subject alloy will have significant reductions in CVN toughness values at room temperature and below following service exposure. This reduction indicates the potential for brittle fracture with high rate loading in the presence of sharp notches or cracks

2. DSS (2205, 2304, and 2507): Susceptible. Therefore, the maximum temperature for use is 316 °C (600 °F) in ASME.
3. Environment: Degradation of mechanical properties (mainly)/decreased corrosion resistance

(c) Remedy and Countermeasure
1. MSS, FSS, and PHSS:

   (a) Aging Time Control of Base Metal: not too long
   (b) Cooling Rate Control after Welding: not too long
   (c) Interpass Temperature Control during Welding: maximum 204 °C (400 °F)
   (d) Heat Treatment after Welding: at min. 622 °C (1150 °F) with air cooling
2. DSS (2205, 2207): maximum operating temperature ≤ 316 °C (600 °F)
   Interpass Temperature Control during Welding: maximum 149 °C (300 °F)

Applicable Codes, Standards, or Reports

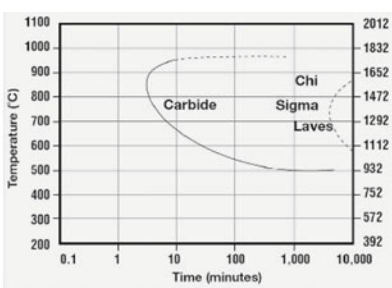
ASME Sec. II, Part D, A-207, API RP571, ASTM E23 (TM for Notched Bar Impact Testing of Metallic Materials), ASTM G129 (Slow Strain Rate Testing of Materials for Environmentally Assisted Cracking)

References

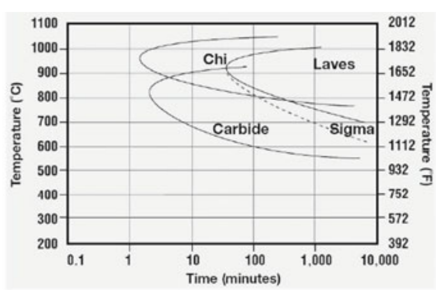
– ASM Metal Handbook, Vol.1
– D. Pecker et al., *Handbook of SS*, McGraw-Hill
– NACE Paper 18–10,612, In-service embrittlement of 25%Cr SDSS
– J.K. Sahua et al., Effect of 475 °C embrittlement on the mechanical properties of duplex stainless steel. Mat. Sci. Eng. A. **508** 1–14 (2009)
– C. Örnek et al., Effect of “475 °C Embrittlement” on the Corrosion Behaviour of Grade 2205 DSS Investigated Using Local Probing Techniques, p-9-11. Corrosion Management, Sep.-Oct.2013
– J.M. Vitek et al., *Microscopic evaluation of low temperature embrittlement in type 308 SS Welds*. International Metallographic Society Meeting, Jul 20–21, 2993
– Several Articles in DSS Conference Papers
– G.E. Miller, Experiences with 885 °F Embrittlement in FSS, NACE *Materials Protection*, May (1966)
– P.J Groebner, 885 °F (475 °C) embrittlement of ferritic steels. Metallurg. Trans. **4**, 251–260 (1973)
– T.J. Nichol et al., Embrittlement of FSS. Metallurg. Trans. **11A**, 573–585 (1980)
– S.S.M. Tavares et al., 475 °C embrittlement in a DSS UNS S31803. Mater. Res. **4**(4) (2001)
– F.A. Alhegagi, 475 °C Embrittlement in SS. Int. J. Sci. Eng. Res. **6**(9), ISSN 2229–5516 (2015)

2.1.6.5 Intermetallic Precipitation – Sigma, Chi, and Laves Phase Embrittlement

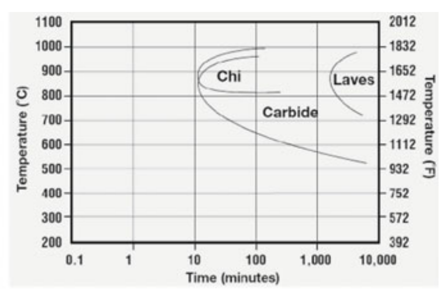
Sigma (σ), Chi (χ), and Laves phases [$(Ni,Fe,Cr,Si)_2(Nb,Mo,Ti,W)$] other than carbides are also critical factors for the reliability of SS application. Figure 2.69 shows Isothermal Precipitation of Intermediate Phases of Several Stainless Steels. These Intermetallic Precipitations are physically similar with delta ferrite.



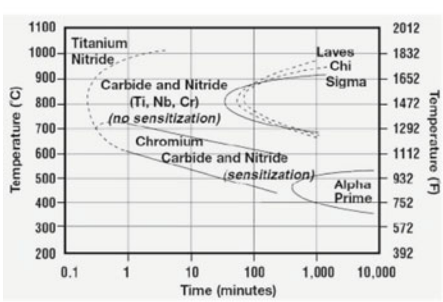
(a) 316 SS annealed at 1260°C (2300°F)



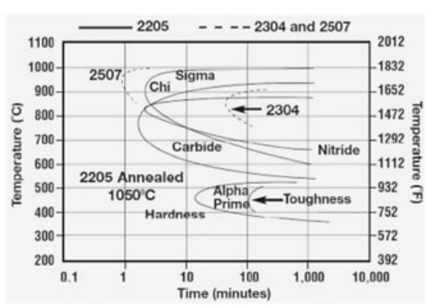
(b) 0.05%C-17%Cr-13%Ni-5%Mo-0.039%N SS annealed at 1100°C (2012°F)



(c) 0.05%C-17%Cr-13%Ni-5%Mo-0.145%N SS a nnealed at 1150°C (2102°F)



(d) 26%Cr-0 to 4%Ni-1 to 4%%Mo SS annealed at 1100°C (2012°F)



(e) 2205, 2304, and 2507 DSS

Figure 2.69 Isothermal precipitation of intermediate phases of several stainless steels. (Source-Outokumpu reports, 2009)

Sigma (σ) phase: The existence of σ phase (Cr-rich and very brittle phase) in all stainless steels may significantly reduce their ductility and toughness. σ phase is the product of transformation of the ferritic delta phase occurring when the microstructure is subject to a long exposure time in the temperature range of 540–925 °C (1000–1697 °F). This new phase forms rapidly in high Cr grades and Mo is also a promoting element for that transformation. The presence of this new phase alters both the corrosion resistance and the ductility of weld joints.

Factors contributing to the rate of formation of σ phase include the amount of ferrite, time in the σ phase transformation range, prior cold working, variation in composition due to progressive solidification, high Cr content, and the presence of ferrite-stabilizing elements, particularly molybdenum (Mo), columbium (Cb), and titanium (Ti). See ASME Sec. II, Part D, A-208.

Chi (χ) Phase: It forms predominantly in molybdenum bearing grades, mainly those of the third generation such as 29–4 (29Cr-4Mo) or 29–4-2 (29Cr-4Mo2Ni). This phase, stable up to 900 °C (1650 °F), forms mutually with Sigma phase.

Laves Phase: It may occur during alloy production or during service, and is another of the metallurgical phenomena that may occur during exposure of ASS-containing Mo, Ti, Nb in the temperature range from 593–871 °C (1100–1600 °F). Laves phase may also develop in other Fe-base, Fe-Ni-base, or Co-base superalloys, including the W-rich grades of the creep strength-enhanced ferritic steels (e.g., Gr. 92-UNS K92460 and 122-UNS K92930: See ASTM A335). Silicon and niobium promote formation of Laves phase in Alloy 718 (N07718). Laves phase precipitates within the grains, forming into globular particles or into platelets.

Laves phase forms during solidification of high-Nb alloys (e.g., N07718 that forms Ni_2Mg Laves phase in excessive desulfurization), and its presence can result in the embrittlement of welded materials unless a very high-temperature solution-annealing operation is performed.

The following describe the detail phenomena of Sigma (σ) and/or Chi (χ) phase embrittlement in stainless steels.

(a) Causes and Mechanisms
1. FSS, ASS, and DSS are subject to σ-phase embrittlement (greatly reduce the toughness) when exposed to 538~871 °C (1000~1600 °F) for FSS and ASS and 593~1093 °C (1100~2000 °F) for DSS over an extended period.
2. σ-Phase Intermetallic Compound consists of Fe-Cr-Mo (enriched in Cr, Mo, Si, and W/poor in Ni and Mn)
3. The embrittlement is most detrimental after the steel has cooled to temperatures below 260 °C (500 °F). At higher temperatures, stainless steels containing phase can usually withstand normal design stresses. However, cooling to 260 °C (500 °F) or below results in essentially complete loss of toughness.
4. Mainly Intergranular Corrosion Mode

(b) Susceptible Materials and Environment
1. FSS (405, 410S, 430 Cr-Ni steels) containing Mo are prone to sigma (σ) phase formation at 500~850 °C (932~1562 °F), with a maximum rate of formation at around 750 °C (1382 °F).
2. Advanced ASS (310, 309) containing about 25%Cr and 12–20% Ni σ-Phase is formed between 650~900 °C (1020~1652 °F), with a maximum rate of formation at 850 °C (1562 °F).
3. Stabilized ASS (321 & 347) with Ti or Nb are prone to σ-phase formation between 650 and 800 °C (1202~1472 °F), with a maximum rate of formation at 750 °C (1382 °F). Because of their good resistance against creep and oxidation, these steels are still using at the temperatures mentioned; by choosing a somewhat lower Cr content and somewhat higher Ni content, the σ-phase formation is kept to a minimum.
4. Nonstabilized 18–8 (304 & 316) may not normally give problems regarding σ-formation.
5. DSS (2205, 2304, 2507) when exposed to 593~1093 °C (1100~2000 °F) over an extended period.

(c) Remedy and Countermeasure

σ-phase, which is only one of several detrimental phase changes that can occur during high-temperature service, can be removed by dissolving the phase in the austenite during homogenizing at 1050~1100 °C (1922–2012 °F)-solution heat treatment.
1. Heat Treatment; air cooling at 1010 °C (1850 °F) for FSS
2. Advanced ASS; maximum operating temperature, 604 °C (1120 °F)
3. DSS; maximum operating temperature, 604 °C (1120 °F). However, 316 °C (600 °F) maximum should be applied because the 475 °C (885 °F) embrittlement occurs earlier.

Applicable Codes, Standards, or Reports

ASME Sec. II, Part D, A-208 (sigma) & 209 (laves), API RP571/ RP581/TR942-B

References

– *ASM Metal Handbook*, Vol.1
– D. Pecker et al., *Handbook of SS* (McGraw-Hill)
– NACE Paper 06578/11173/1201272/13–228/15–5595/17–9140
– S.P.V. Mahajanam et al., Study of EAC of DSS as a result of the presence of sigma phase, NACE Corrosion, **67**(12), 125,002–1–14 (2011)
– Several Articles in DSS Conference Papers

2.1.6.6 Zinc Embrittlement (as a Liquid Metal Embrittlement, LME) of Stainless Steels

See Sect. 2.3.6 for LME of Other Metals.

(a) Causes and Mechanisms

1. First Accident: 28 people died/36 people wounded due to Zn-contaminated stainless pipe explosion at Flixborough, UK, June 1974.
2. The most common liquid metal embrittlement problems associated with hot dip galvanizing and Zn-rich painting are with 300 series SS.
3. Zn [M.P; 420 °C (788 °F)] can penetrate into the intergranular of SS and form NiZn or $NiZn_2$ compound at high temperatures (on welding or firing). SS with $NiZn_x$ is greatly susceptible to IGSCC under tensile stress (Fig. 2.70).

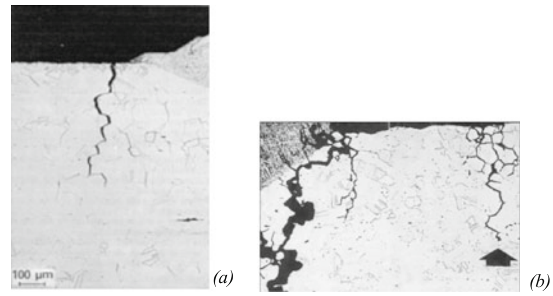


Figure 2.70 Intergranular cracking in HAZ of stringer bead weld on 304 SS due to zinc embrittlement weld area had been covered with zinc-rich paint. (Source: (**a**) Metal Handbook, vol.1, ASM, (**b**) Welding Research Supplement, Dec.1992)

(b) Susceptible Materials and Environment
   1. Conventional ASS (304(L), 316(L), 321, 347, etc.) and some Ni based Alloys (Alloy 800 & 825)
   2. Susceptible Environment; During Welding or Firing
(c) Detection of Zinc Contamination on the Stainless Steel Surfaces
   1. A sensitive field chemical test for detecting the presence of zinc on the stainless steel surfaces consists of a solution of 0.02 g dithizone and 100 ml of 10% sodium hydroxide (NaOH), which can detect both zinc and zinc oxides. The solution will cause the contaminated areas to show a "pink" color if zinc (or zinc oxide) is present. The method is highly effective for determining presence of zinc which has been smeared on surfaces, but is ineffective in the case of ferritic steel splatter (as might occur from arc cutting galvanized surfaces).
   2. Energy dispersive analysis (EDX) is a sensitive laboratory technique for detecting the presence of trace quantities of zinc existing on surfaces of metals.
(d) Remedy and Countermeasure
   1. When suspected, Zn contamination is to be analyzed.
   2. Attaching stainless steel fittings to mild steel items prior to galvanizing should be avoided for this reason as the molten zinc may affect the mechanical properties of the stainless steel.
   3. To isolate the stainless steel parts from the painting environment at shop and field.
   4. Slightly contaminated surface by Zn: Acid cleaning by 10% HNO_3 or wire brushing with motor-driven rotary stainless steel wire bristles (0.014-inch diameter).
   5. Contaminated surface by Zn rich paint: Acid cleaning by 10% HNO_3 after sand blasting

Applicable Codes, Standards, or Reports
API RP571

References

- LME of ASS when Welded to Galvanized Steel-Welding Journal, s455, Dec.1992
- LME of steel with Galvanized Coatings. Mater. Sci. Eng. 35, 012002 (2012)
- Liquid metal corrosion of 316L SS, 410 SS, and 1015 CS in molten zinc bath. Metallurg. Mater. Trans. 38A (2007)
- LME of ASS when welded to Galvanized Steel. Welding J. s455 (1992)
- M.G. Nicholas, C.F. Old: J. Mater. Sci. 14, 1 (1979)
- Dept. of Employment, U. K. Report of the Court of Inquiry, The Flixbrough disaster (1975)
- M. Andreani, P. Bastien: Metallurgy. 66(1), 21 (1969)
- H. Cottrell, P.R. Swann: The Chemical Engineer, April, 266 (1976)
- T. Shinohara, K. Matsumoto: Corrosion Science, 22(8), 723 (1982)
- IGSHO., The Institute of Chemical Engineers: Guide Notes on the Safe Use of SS in Chemical Process Plant, p.16 (1978)
- See the references in Sect. 2.3.6 for more various LME.

2.1.6.7 Alkaline Stress Corrosion Cracking (Alkaline SCC)

See Sects. 2.4.2.3 Amine SCC, 2.4.2.4 Caustic SCC & 2.4.2.5 Alkaline Carbonate SCC, and 2.4.2.10 Anhydrous Ammonia Cracking for various other materials. Typically, SS and Ni alloys can be prone to SCC at pH > 8.0 and high temperature.

(a) Caustic SCC

   In general, caustic SCC (Fig. 2.71) of SS occurs above the b.p. (dotline in Fig. 2.72) for the corresponding NaOH concentration, but it shifts below the b.p. at ~50% NaOH. Some users do not allow to use SS when the temperature is 120 °C (248 °F) and above regardless of the caustic concentration.

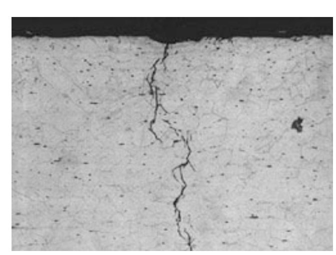
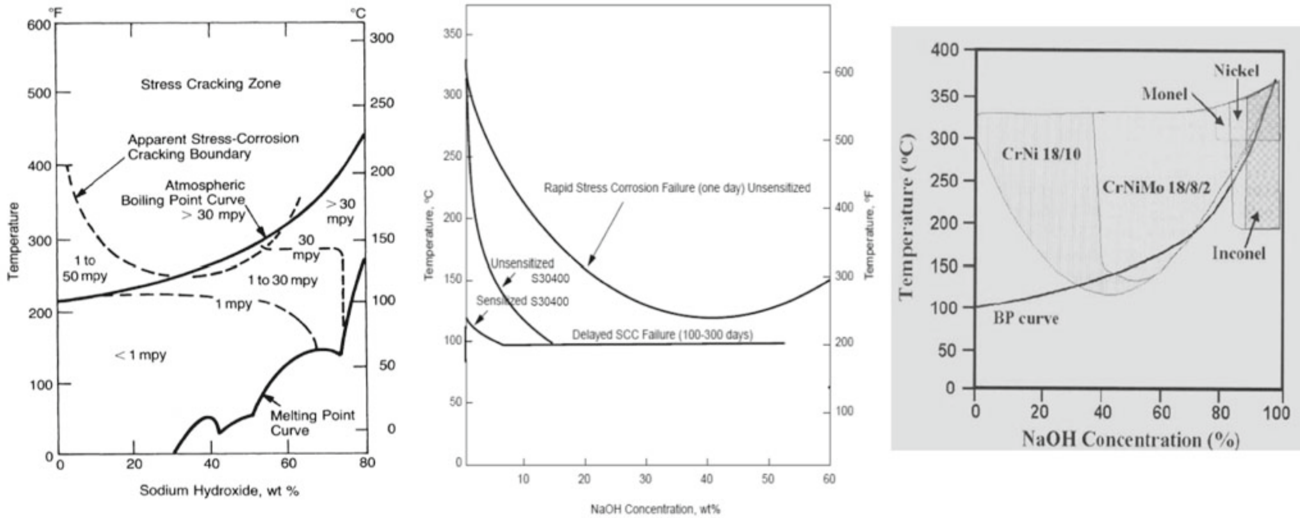


Figure 2.71 Caustic SCC of 304 SS



(a) (b) (c)

Figure 2.72 Corrosion rates and SCC of ASS and nickel-based alloys in NaOH solution. (**a**) Isocorrosion chart with SCC boundary superimposed for 304 SS and 316 SS in NaOH solution. (Source: NiDI #10019). (**b**) Caustic Service Chart for 300 Series ASS. (Source: NACE SP0403). (**c**) SCC boundary of SS and Nickel Based Alloys in NaOH solution. (Source: MTI MS-6)

Primarily 304 SS and 316 SS are highly resistant to caustic in concentrations up to 50% at 116 °C (240 °F) or colder. However, over 116 °C (240 °F), the caustic SCC in 300 series stainless steels (i.e., bellows-type piping expansion joints) are highly prone to rapid SCC if there is entrainment of caustic into the system (i.e., boilers).

Although 304 SS and 316 SS perform comparably in caustic and in standard SCC tests, 316 SS shows improved overall performance because of its pitting resistance (the role of dissolved oxygen may be significant in this effect). In addition, the low-carbon grades perform marginally better because of their resistance to sensitization. This suggests that 316L SS should be used unless significant controls are to be placed on the total exposure of the equipment. However, for long-term integrity, many users limit the temperature of maximum 93 °C (200 °F) for all 300 series ASS and all concentrations.

The nature of cast surfaces minimizes SCC problems, and castings are usually acceptable in situations considerably beyond the capabilities of wrought products. Corrosion rates are similar to those of wrought products.

Cautions for and effects of the caustic solutions are below.

1. More important concerns are those extraneous to the caustic solution itself.
   (a) External exposure to steam/electric tracing
   (b) Faulty insulation
   (c) Contaminated hydrotest water
   (d) Improper cleaning and storage
   (e) Raised temperature when mixing the different caustic concentration solutions
2. Experience for boiler water in power plant
   (a) Ingress of fresh water through leaking condensers, in the case of power stations cooled by river water containing Na_2CO_3.
   (b) Release of NaOH by ion exchange resins
   (c) Decomposition of Na_3PO_4 when used for water treatment.
   (d) While it is true that 304 SS and 316 SS perform comparably in caustic and in standard SCC tests, 316 SS shows improved overall performance because of its pitting resistance and the low carbon grades would perform marginally better due to their resistance to sensitization
   (e) Painting exteriors of SS equipment is also recommended, especially if insulation is adopted.
   (f) Cast stainless pumps and valves have performed very well in caustic application. The nature of cast surfaces minimizes SCC problems, and castings are usually acceptable in situations considerably beyond the capabilities of wrought products.
   (g) Corrosion rates would be expected to be similar to those of the wrought products.
3. Effects of inhibitors
   (a) The crack susceptibility of SS in 3% NaOH containing Cl^- falls as the chloride content increases, so NaCl may act as inhibitor in high-temperature caustic SCC of ASS.
   (b) It has been reported that Na_3PO_4, Na_2HPO_4, and $NaNO_3$ act as inhibitors for caustic SCC of ASS.

4. Effects of potential
   (a) The maximum anodic corrosion depth is relatively high at the potential where SCC susceptibility of 304 SS in boiling 60% NaOH is high.
   (b) SCC occurs when the film stability is poor. Therefore, the caustic cracking susceptibility of 304 SS is critically dependent on the NaOH concentration and temperature.
5. Effects of alloying elements
   C and S in 304 SS accelerates SCC in boiling 34% NaOH, while P has nearly no effect.
6. Effects of microstructure (FSS, DSS, and SASS)
   (a) While the conventional FSS show good SCC resistance in hot dilute NaOH, they show SCC in concentrated solutions. One source reports that UNS S44627 (E-Brite 26–1) is useful up to 148–177 °C (300–350 °F). Another reports that 26–1 has good resistance at 177–204 °C (350–400 °F) and 45% NaOH Based on their good resistance to caustic, particularly those containing oxidizing contaminants, they see extensive use as caustic evaporator tubes. However, the toughness and low strength at elevated temperature and oxidizing contaminated service may be a critical issue.
   (b) High-Cr ferritic steel becomes duplex type when more than 6% Ni is added; duplex high-Cr steel shows caustic SCC resistance appreciably better than ferritic high-Cr, while duplex containing sufficient Ni (≥7.5%) is satisfactory. 2205 DSS and 2906 DSS are reported to have useful caustic cracking resistance.
   (c) The high-nickel family of stainless steels are those containing approximately 25–35 wt% nickel, and include such nonpatented and proprietary alloys as 904L, Sanicro 28, Alloy 20Cb-3, Alloy 800, AL6-XN, etc. With these alloys, resistance to aggressive (high temperature) caustic solutions increases significantly compared with the 300 series ASS.

Applicable Codes, Standards, Reports, or Other References

See Sect. 2.4.2.4 Caustic Corrosion and Cracking.

(b) Hot alkaline (i.e., NaOH + Na_2S and/or NaCl) crack in several stainless steels.
1. MSS and FSS: Conventional straight Cr-grade MSS and FSS are unreliable in caustic above-ambient temperatures and/or in hot alkaline solutions. They may become active and may even exhibit less resistance than ordinary steel.
2. ASS
   (a) Selective dissolution of Fe, Cr, and Mo and/or enrichment of Ni as well as Mo takes place in the affected surface layer of the ASS, hot alkaline solution and temperature.
   (b) Alkaline (i.e., NaOH + Na_2S and/or NaCl) cracking of ASS is more susceptible than that of sole NaOH solution with same concentration.
   (c) 20~30%Cr – 20~24%Ni ASS: These ASS provide a SCC resistance against most alkaline services. Nickel shows good alkali SCC resistance, so high Ni alloys provide a straightforward choice.
   Materials such as 316(L) SS or Ni-based alloy (Alloy 625) are often selected for their resistance to alkaline corrosion SCC and their corrosion resistance.
   (d) While inhibitors could offset alkali cracking, they contaminate the solution and are thus to be avoided.
3. DSS in hot alkaline (NaOH + Na_2S and/or NaCl)-sulfide (SO_3^{-2}, SO_4^{-2}, $S_2O_3^{-2}$, etc.) solution, including trace of carbonate (CO_3^{-2}) and chloride (Cl^-) can be prone to SCC mostly (e.g., in pulp industries).
   Ferrite phase of DSS is in general always more severely affected by hot alkaline solution. Therefore, selective dissolution takes place more readily in the ferrite than in the austenite phase.

Applicable Codes, Standards, Reports, or Other References

- NACE Publication 34108
- NACE Paper 11160/11287
- See the references in Sect. 2.4.2.5.

2.1.6.8 Polythionic Acid Stress Corrosion Cracking (PTASCC)

Hydrotreating and hydrodesulfurization processes in refineries operate at high temperature and pressure. This can cause sensitization and reduced ductility in the material of construction because of the presence of sulfur and other impurities. By the reactions of sulfur impurities with water, air, or oxygen, H_2S and SO_2 are formed as intermediate products that further form complex compound products like tetrathionate ($S_4O_6^{2-}$), polythionate ($S_xO_6^{2-}$), and polythionic acid ($H_2S_xO_6$) (PTA). Among various known corrosion failures, intergranular SCC is a severe problem, which occurs mainly during turnarounds or shutdown/startup of hydroprocessor units. SO_2 and tetrathionate are the active agents for the formation of PTA, which causes SCC of steels (mainly unstabilized ASS) during shutdowns, when the piping or equipment is relatively cool. These cracks are often detected only when the system is pressurized again for starting up the unit (Figs. 2.73 and 2.74)

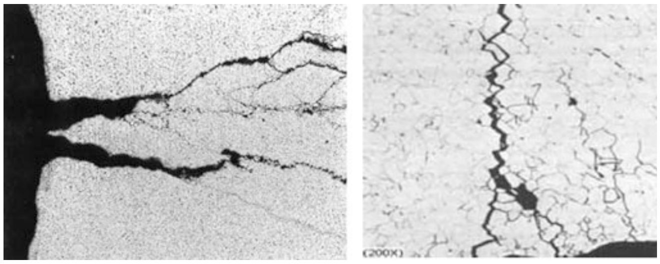


Figure 2.73 SEM photomicrograph of polythionic stress corrosion crack (PTASCC) in furnace tubes. (Source: NACE SP0170/NACE MP, April 2010)

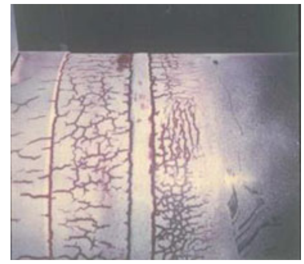


Figure 2.74 PT Inspection showing extensive PTASCC in the vicinity of welds. (Source: NACE SP0170)

(a) Causes and Mechanisms

1. Creation of Polythionic Acid ($H_2S_XO_6$): During a shutdown, in the presence of oxygen and liquid water (often dew point water), the sulfur compounds (H_2S, metal sulfide, S) convert to polythionic acid (PTA).
2. Temperature: During a shutdown from high temperature.
3. PTASCC occurs predominantly in ASS and Ni-Cr-Fe alloys that have become sensitized through thermal exposure. Sensitization occurs when carbon present in an alloy reacts with chromium to produce Cr- carbides at grain boundaries. As a result, the areas adjacent to grain boundaries become depleted in Cr and are no longer fully resistant to certain corrosive environment.
4. Acid environments and susceptible MOCs (sensitized or welded) lead to rapid intergranular cracking (IGC). PA will cause SCC in ASS and Ni-based alloys. The prevention requires relatively low tensile stress for initiation and propagation.
5. High carbon grades of SS (i.e., 304 SS/304H SS or 316 SS/316H SS) are more susceptible than low CS ($\leq$0.03% C).
6. PTA SCC is a type of IGSCC that is caused by ingress of PTA into the steel. PTA ($H_2S_XO_6$, where $x = 2, 3, 4$, or 5) forms by the reaction of oxygen and water with iron or chromium sulfide (Cr_2S_3) scales that cover the metal surfaces as a result of high temperature sulfide corrosion.
   (a) Interdependent parameters; S compounds, oxygen, water
   (b) Combined crack mechanism: IGC + SCC + sulfidation
   (c) Damage process is

$$3FeS + 5O_2 \rightarrow Fe_2O_2.FeO + 3SO_2 + 1/2O_2$$

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$H_2SO_3 + H_2S \rightarrow mH_2SxO_6 + nS; \quad \text{x is usually 2 to 5}$$

(b) Remedy and Countermeasures (by combination of several methods below)

1. Use low carbon: 304L SS & 316L SS (max. 0.03 wt% C)
2. Thermally stabilized heat treatment for 321 SS & 347 SS
3. Exclusion of O_2 (air) and water by dry N_2 Purge (Free O_2); dew point < -15 °C (or $-$ 40 °C)
4. N_2 purging is preferable for protection of vertical heater tubes if alkaline wash solutions (e.g., 2 wt% soda ash treatment (SAT-chloride free), to be soaked min. 2 hrs) cannot be drained completely. Before SAT is performed, the deposits/scales should be removed accordingly. The deposits/scales may be removed with pigging and SAT together.

Recommended Guidance (from some Companies)

Ti: Maximum Metal Skin Inside Temperature
To: Maximum Metal Skin Outside Temperature

(a) SAT (Inside) is not required when:
- Ti <371 °C (700 °F) for 304 SS, 316 SS, or 317 SS (only if not heat treated after welding).
- Ti <399 °C (750 °F) for 304 SS and 316 SS (only if not welded or heat treated after welding).
- Ti <399 °C (750 °F) for 304L SS, 316L SS, or 317L SS.
- Ti <441 °C (825 °F) for 321 SS (nonthermally stabilized condition for base metal).
- Ti <468 °C (875 °F) for 347 SS (nonthermally stabilized condition for base metal).
- Ti <538 °C (1000 °F) for 321 SS or 347 SS (thermally stabilized condition for base metal and weldments).
- Ti <649 °C (1200 °F) for Alloy 825 & 625.

(b) SAT (Outside) is required when:
- H_2S in Fuel gas or oil $\geq$100 ppm.
- Ti $\geq$371 °C (700 °F) for 304 SS, 316 SS, or 317 SS (only if not heat treated after welding).
- To $\geq$399 °C (750 °F) for 304 SS, 316 SS, or 317 SS (only if not welded or if heat treated after welding).
- To $\geq$399 °C (750 °F) for 304L SS or 316L SS, or 317L SS.

– To ≥441 °C (825 °F) for 321 SS (nonthermally stabilized condition for base metal).
– To ≥468 °C (875 °F) for 347 SS (nonthermally stabilized condition for base metal).
– To ≥538 °C (1000 °F) for 321 SS or 347 SS (thermally stabilized condition for base metal and weldments).
– To ≥649 °C (1200 °F) for Alloy 825 & 625.

5. Drain parts of heater tubes should be Alloy 825 due to concentrated chloride contents in case of an appropriate soda ash treatment.
6. If the equipment still remains closed and hot (i.e., above the water dew point of vapor in the equipment), additional protection for PTASCC is unnecessary.
7. When S-containing (> 100 ppm H_2S) fuels have been used for the heater firing, the protection of ASS heater tube externals should be considered.
8. If steam is being used for purging or steam air decoking, steam injection should be stopped before the metal temperature cools to 72 °C (130 °F) above the water dew point. When depressed, but before cooling lower than 72 °C (130 °F) above the water dew point, the system should be purged with dry N_2 [dew point < −46 °C (−50 °F) and oxygen free (< 5 ppm)]. A positive purge pressure should be maintained on the system after blinding.

Applicable Codes, Standards, or Reports

NACE SP0170, API RP571, API RP581, etc.

References

– NACE Paper 08557, 98,592, 97,501, 93,541, 91,324, 08557, etc.
– NACE MP Apr. 2010, p62–66/Sep. 1983, p22–24/Mar. 1979, p9, etc.
– NACE Corrosion Journal Aug. 1983, p331–334/Jun. 1985, p365–369/Jan. 1987, p26–30, /Aug. 1994, p256–262, etc.
– ASTM G35 Determining Susceptibility of SS and Related Ni-Cr-Iron Alloys to SCC in Polythionic Acids

2.1.6.9 Stress Relaxation Cracking-SRC (Reheat Cracking) of Austenitic Stainless Steels (ASS)

(a) Description of Damage

SRC of ASS can occur only by cold-forming, but also by the stress relaxation due to high residual stresses after multi-passes welding and/or postweld heat treatment (PWHT with multi-heating cycle) and/or in service at elevated temperatures. It is most often observed in heavy wall sections.

Whereas creep involves increasing strain at constant stress (load), SRC involves decreasing stress at constant strain (Fig. 2.75). At any stage after the initiation of creep or SRC, during a shutdown, there will be a permanent strain offset due to this creep degradation.

The term reheat cracking is also often used due to repeated PWHT to describe this subsolidus mode (by second or further PWHT) of failure and/or due to long-term high-temperature service.

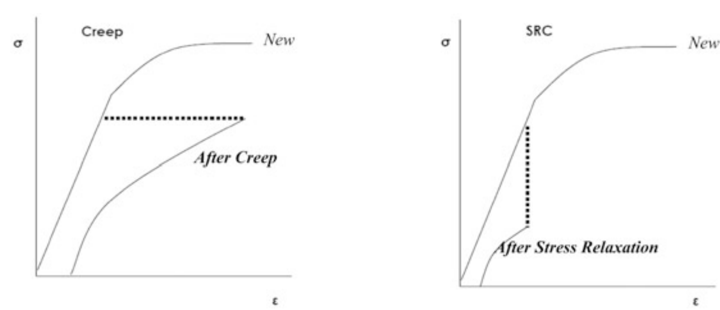


Figure 2.75 Mechanism comparison of creep & reheat cracking (SRC). (Source: NACE Paper 08454)

(b) Affected Materials
– Low-alloy steels (Cr-Mo steels) – See Sects. 2.1.4.2,(C), 2.1.4.3 for Cr-Mo Steel.
– 300 Series ASS (severity order: 347(H) > 321 (H) > 304(H) > 316(H))
– Nickel based alloys (i.e., Alloy 800H/HT, Alloy 617, Alloy 601)

(c) Critical Factors

Important parameters include type of material (chemical composition, impurity elements), grain size, residual stresses from fabrication (cold working, welding), section thickness (which controls restraint and stress state), notches and stress concentrators, weld metal and base metal strength, and welding and heat treating conditions.

From the various theories of reheat cracking for both 300 Series SS and low-alloy steels, cracking features are as follows:

1. Reheat cracking requires the presence of high stresses and is therefore more likely to occur in thicker sections and higher strength materials.
2. Reheat cracking occurs at elevated temperatures when creep ductility is insufficient to accommodate the strains required for the relief of the applied or residual stresses.
3. In many cases, cracks are confined to the HAZ, and initiate at some type of stress concentration, and may act as an initiation site for fatigue.
4. Reheat cracking can occur either during PWHT or in service at high temperatures. In both cases, cracks are intergranular and show little or no evidence of deformation.
5. Fine intergranular precipitate particles make the grains stronger than the grain boundaries and force creep deformation to occur at grain boundaries.
6. Stress relief (solution heat treatment) and stabilization heat treatment of 300 Series SS against chloride SCC and PTA SCC can cause reheat-cracking problems, particularly in thicker sections.

(d) Affected Units or Equipment

Reheat cracking is most likely to occur in heavy wall vessels in areas of high restraint, including nozzle welds and heavy wall piping.

(e) Appearance or Morphology of Damage

Reheat cracking is intergranular and can be surface breaking or embedded depending on the state of stress and geometry. It is most frequently observed in coarse-grained sections of a weld HAZ. Long-seam welds are particularly susceptible to mismatch caused by fit up problems.

(f) Prevention/Mitigation

1. Joint configurations in heavy wall sections should be designed to minimize restraint during welding and PWHT. Adequate preheat must also be applied.
2. The grain size has an important influence on high temperature ductility and on reheat cracking susceptibility. A large grain size results in less ductile HAZs, making the material more susceptible to reheat cracking.
3. Metallurgical notches arising from the welding operation are frequently the cause of HAZ cracking (at the boundary between the weld and the HAZ).
4. In design and fabrication, it is advisable to avoid sharp changes in cross section, such as short radius fillets or undercuts that can give rise to stress concentrations.

(g) Lessons Learned from 347(H) SS Cracking (Fig. 2.76)

At temperatures under 730 °C (1350 °F), residual stresses are reduced by less than half. In addition, if the prior condition of various microstructures associated with the weldments has free carbon available for intergranular Cr-carbide precipitation, a stress relief at these lower temperatures may be deleterious in severe corrosive environments (i.e., knife-line attack).

For these two reasons (i.e., inadequate relief of stresses and knife-line attack near the fusion line),

1. PWHT at temperatures below 730 °C (1350 °F) are considered suitable only for dissimilar metal welds involving 347 SS to carbon or low alloy steels.

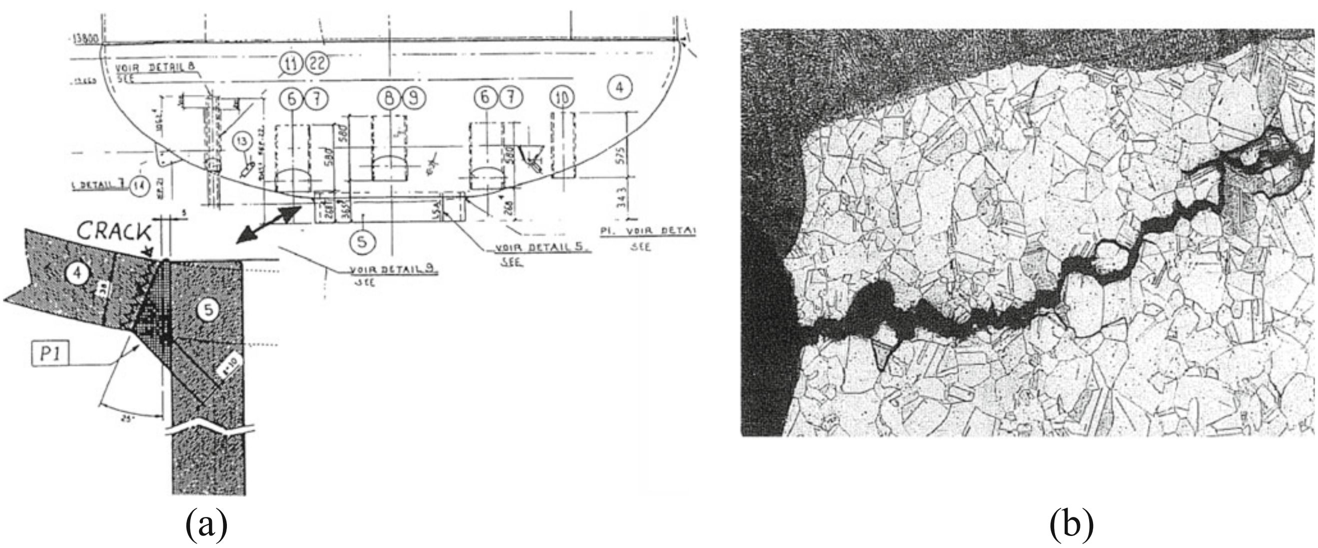


Figure 2.76 Location of cracking in nozzle welds and in 42-mm thick reduction piece in 321 SS with 347 SS during PWHT at 850–900 °C. (Source: Welding in the World 41 (1998), p206). (**a**) Location of cracking in nozzle welds with 347 SS. (**b**) Cracking in 42 mm thick Reduction Piece in 321 SS

2. Stress relief temperature: To avoid the risk of knife-line corrosion attack, much more stress relief is accomplished by employing temperatures in the range of 816–927 °C (1500–1700 °F). At this temperature, free carbon will combine with niobium. These carbides (referring to unwanted chromium carbides) will be completely dissolved if the stress-relieving temperature is above 927 °C (1700 °F).
3. Solution annealing temperature: Solution annealing usually has a minimum temperature of approximately 1010 °C (1850 °F). At temperatures over 1093 °C (2000 °F) ferrite becomes stable. In addition, at these temperatures Nb-carbide begins to re-dissolve (see Fig. 4.55). The solution annealing temperature is normally maintained around 1038–1052 °C (1900–1925 °F). Short times (i.e., typically 15 minutes per inch of thickness) for the solution annealing heat treatment are preferred (to avoid severe surface oxidation and grain growth)
4. Stabilization temperature and holding time: To assure that free carbon reprecipitates as niobium carbides. Too long a time at the lower end of the range, however, can run the risk of embrittlement due to sigma (σ) phase formation at 760–871 °C (1400–1600 °F), which takes 2 hours or more, hence PWHT cycle should be restricted to short soaking times. See Table 4.140 for more details on stabilizing heat treatment.
5. Heating and cooling cycles for PWHT – In thick wall piping a solution annealing at 1052 °C (1925 °F).
6. Repair welding for 347 SS: used E16.8.2–15 (AWS A5.4).

7. Considering WRC Technical Guidelines, for 347H SS with higher carbon content, higher free carbon to form unwanted Cr-carbides during welding processes, it would be a better option to consider a stabilization temperature of at least 954 °C (1750 °F).
   (a) Being sure to dissolve all unwanted chromium carbides (T > 927 °C (1700 °F))
   (b) To assure that free carbon reprecipitates as niobium carbides.
   (c) Staying above σ-phase formation temperature range 760–871 °C (1400–1600 °F)
   (d) Following the WRC guidelines for holding time to avoid severe surface oxidation and grain growth (especially for thin-wall). Or considering a two-step PWHT including stress-relief -solution annealing, stabilization at 954 °C (1750 °F), and forced air cooling (See NACE Paper 04640 – Optimized Heat Treatment, focused on 347H SS and 347HLN SS)

(h) Recommendation to prevent SRC of ASS in ASME Sec.VIII, Div.1, NM Appendix UHA-A
1. The design temperature does not exceed 540 °C (1000 °F).
2. The welding is limited to (i) the circumferential butt welds in pressure parts, (ii) circumferential fillet welds, (iii) attaching extended heat-absorbing fins to pipe and tube materials by ERW, (iv) attaching non-load-carrying studs, and (v) attaching bare-wire thermocouples by capacitor discharge welding or ERW (singularly or in combination). See ASME Sec.VIII, Div.1, NM Appendix UHA-A for more details.

Applicable Codes, Standards, or Reports

ASME Sec. VIII, Div.1, NM Appendix UHA-A, API TR942-B, API RP571, ASTM PVP2009–77554, etc.

References

- R. David Thomas Jr., R.W. Messer Jr., Welding 347 SS-An Interpretive Report, WRC Bulletin. **421** (1997)
- A. Dhooge, Survey on Reheat cracking in ASS and nickel based alloys. Welding in the World **41**, 206–219 (1998)
- L. Li, R.W. Messer Jr. Stress relaxation study of HAZ Reheat cracking in type 347 SS. Welding Research Supplement, 137–144 (2000)
- R.J. Christoffel, Cracking in 347 HAZ during stress relaxation. Welding Research Supplement. 251–256 (1962)
- H. Yamamoto et al., Reheat cracking sensitivity and hydrogen effect on mechanical properties of type 347 SS weld metal, PVP Vo. 380, FFS Evaluations in Petroleum and Fossil Power Plants, ASME 1998
- J. Kallqvist et al., Microanalysis of a stabilized ASS after long term aging. Mater. Sci. Eng. **A270**, 27–32 (1999)
- EFC WP15 Meeting Minutes (France), Apr. 26, 2007
- NACE Paper 11,364, 08454, 07421, 05402, 04640, 03647, 02478, etc.

2.1.6.10 Galvanic Corrosion of/by Stainless Steels (Typically as an Attacker)

In many cases, stainless steel will attack the contacted metal (less noble metals-anodic side) with itself in wet conditions (an electrolyte is an electrically conductive liquid). In addition, higher potential difference between two metals, more electrically conducting fluid (e.g., seawater, cooling water, etc.), and contact area effect (higher contact area of SS-cathodic side) will accelerate the galvanic corrosion rate on less noble metals. For example, it is common practice to fasten aluminum sheets with stainless steel screws, but aluminum screws in a large area of stainless steel sheet are rapidly corroded in wet conditions. Also, the CS contacted with stainless steel is likely to rapidly corrode in wet conditions (Fig. 2.77). See Sect. 2.4.1.3 and Table 2.124(8) for more information of several other materials and Table 2.138 (4) for galvanic corrosion in H/EX.

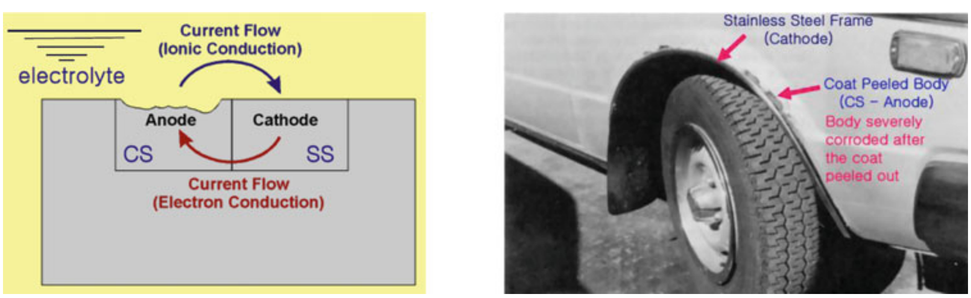


Figure 2.77 Galvanic corrosion on CS in the contact of SS and CS in corrosive environment. (Source: ASM Metal H/B vol.13)

2.1.6.11 Heat Tint of Austenitic Stainless Steels (ASS)

The heat tints of ASS may have to be removed before the part is placed in service for optimum corrosion resistance (Fig. 2.78). Table 2.66 shows the color exposed to hot temperature. The following remedies may be considerable as per the severity. The tints can be removed by the following procedures. See Sect. 4.11.6.1 for the applicable guide regarding to discoloring due to oxygen contamination in welds.

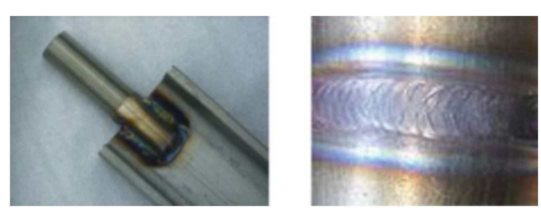


Figure 2.78 Heat tint of ASS

Table 2.66 Color exposed to hot temperature on ASS in air

Color Formed	Approx. Temperature, °C (°F)
Pale yellow	290 (554)
Straw yellow	340 (644)
Dark yellow	370 (698)
Brown	390 (734)
Purple-brown	420 (788)
Dark purple	450 (842)
Blue	540 (1004)
Dark blue	600 (1112)

Source: BSSA article-heat tint colors on SS surfaces heated in air, 2018

1. Light oxides can be removed with brushing.
2. Light tints (light brown color) and iron contamination may be cleaned with mechanical removal (brushing, grinding, or blasting) and/or citric acid solutions, or laser.
3. Darker tints (dark brown) may require cleaning with mechanical removal (brushing, grinding, or blasting) and/or pickling with various pickling pastes (for small surface), or laser.
4. Heavier and darker oxide films (near black color and thick scale) will require mechanical removal (brushing, grinding, or blasting) and/or pickling solutions (ASTM A380) or laser for large surfaces.

2.1.6.12 Strain (or Deformation)-Induced Martensite and Permeability of Stainless Steels after Cold Work

(a) Strain (or Deformation)-Induced Martensite after Cold Work.

The metastable austenite phase (γ) in ASS can be transformed to the thermodynamically more stable α'-martensite phase (very hardened structure magnetized) due to the plastic deformation. This is called Strain (or Deformation or Stress)-Induced Martensitic Transformation (SIMT). In most cases, this SIMT is detrimental to the native characteristics (corrosion resistance and non-permeability) of ASS. Solution heat treatment may be one of the solutions to remove the metastable α'-martensite phase.

Figure 2.79 shows the deformation-induced martensitic transformation measured in tensile test for some stainless steels. The data for 300 series SS indicates there are remarkable martensite structures when the elongation is 8% and above. Meanwhile, cold-worked ASS may be susceptible to hydrogen environment embrittlement when exposed to hydrogen charging conditions in the temperature range of −129 to 93 °C (−200 to 200 °F). The susceptibility to embrittlement may be worsened by the development of strain-induced martensite resulting from cold forming operations, especially cold spinning.

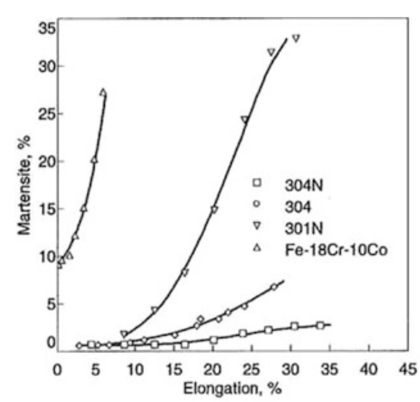


Figure 2.79 Deformation-induced martensitic transformation measured in tensile tests. (Source: ASM SS Handbook)

Corrosion resistance due to metastable α'-martensite phase in ASS shows no remarkable effects in chloride pitting, nitric acid, or phosphoric acid solution, but is reduced in strong acidic service, such as sulfuric acid solution. See NACE Paper 00507 for more details. A full solution annealing followed by rapid cooling after completion of cold forming operations will reduce potential embrittlement and subsequent loss of ductility and toughness. In addition, the metastable α'-martensite phase in ASS can reduce the toughness like delta ferrite in cryogenic service. See Sect. 3.1.4.1 and ASME Sec. II, Part D, A-205 for more information on cold working strain.

(b) Magnetic Permeability after Cold Work.

The magnetism of ASS normally comes from:

(i) i α'-martensite phase after cold work,
(ii) δ-ferrite after welding,
(iii) Iron contamination during SS handling (rolling, brushing, grinding, short blasting, transportation, etc.).

Wrought ASS, such as 304 SS and 316 SS, are generally regarded as nonmagnetic in the annealed condition, and they are not attracted significantly by a magnet. However, if they are cold worked, they will be attracted to a permanent magnet. The change occurs because the cold work deformation induces a transformation of the microstructure from austenite to martensite.

The effect is less marked in alloys with high concentrations of austenite stabilizers such as nickel, nitrogen, and carbon. Once the martensite is formed, it may also become magnetized sufficiently to pick up light objects such as paper clips. Magnetic attraction effects are most often noticed in heavily cold-worked fabrications such as wire or the dished end of a pressure vessel.

Table 2.67 shows the relative permeability of 304 SS and 316 SS at a low magnetic field strength and various cold reductions. The values may be compared with mild CS that has a ferritic structure and a relative permeability of at least 200 oersteds. Figure 2.80 shows that in 304 SS (no Mo containing) after heavy cold working may have quite a strong response to a magnet, while 316 SS (2–3%Mo containing) will in most instances be almost nonresponsive. In general, the higher ratio of Ni eq/Cr eq gives a more stable austenitic structure and less magnetic response by cold work.

Table 2.67 Relative permeability per cold reductions of 304 SS and 316 SS[(a)]

ASS	Cold reduction (% reduction in area)	Relative permeability[(b)] Compared to CS
304 SS (19Cr-10.7Ni)	0	1.0037
	13.8	1.0048
	32.0	1.0371
	65.0	1.540
	84.5	2.20
316 SS (17.5Cr-13.4Ni-2.4Mo)	0	1.003
	20.8	1.003
	45.0	1.004
	60.8	1.0065
	81.0	1.0070

Source: ASSDA Tech FAQ, 2010
Notes
[(a)]Rolled sheet: 2.4–3.2 mm thickness
[(b)]When measured at magnetizing forces of 200 oersteds (16 k A/m)

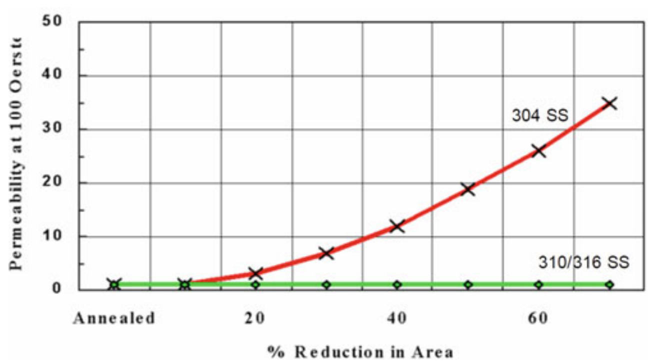


Figure 2.80 Magnetic response of ASS after cold work. (Source: Atlas Technical Handbook of SS, 2010)

The solution heat treatment with rapid cooling (see Tables 4.118, 4.119, and 4.120) can remove all magnetic response without reduced corrosion resistance due to carbides.

If magnetic permeability control is a factor of des4ign, this should be clearly indicated when purchasing the stainless steel from a supplier.

2.1.6.13 Iron Contamination of Stainless Steels

Iron Contamination on ASS surfaces will greatly reduce the corrosion resistance due to unstable passivation film on SS surface. See Sect. 3.3.2 for shop isolation to avoid iron contamination. Once the ASS surfaces are contaminated by iron (or iron oxide) during fabrication or transportation, the Copper Sulfate Test may be performed in accordance with ASTM A380 or MIL-STD-753. This test is hypersensitive and should be used and interpreted only by personnel familiar with its limitations. The test solution is prepared by first adding sulfuric acid to distilled water and then dissolving copper sulfate in the following proportions. The acid shall be added to cold water. See Table 2.144 for more detailed procedures of corrosion tests.

Recommended Solutions

– Distilled water: 250 cm^3 batch
– Sulfuric acid (H_2SO_4, s.g. 1.84): 1 cm^3
– Copper sulfate ($CuSO_4 \cdot 5H_2O$): 4 g

2.1.7 Nonferrous Alloy Metals (SB) – Ni/Cu/Al/Ti/Zr/Ta/W Alloys

2.1.7.1 Nickel and Nickel-Based Alloys

(a) The nickel-based alloys have good corrosion and erosion resistance as well as high creep-rupture strength. In addition, they show good weldability for dissimilar (especially with ferrous steel) metal because the physical properties are not much different between nickel-based alloys and ferrous steels.

Figure 2.81 shows classification per nickel content of stainless steels and nickel-based alloys. Table 2.68 shows the properties for various types of wrought and cast nickel-based alloys. See NACE Publication 1F192 for more details on oil and gas industry applications.

Typically, they have two groups: Solid Solution and Precipitation Hardened.

1. Solid Solution Ni Alloys

   Solid solution nickel-based alloys are generally used in the annealed or annealed and cold-worked condition. Cold working is commonly achieved by several different methods. These alloys are not intended to be strengthened by heat treatment.

   The maximum yield strength is generally governed by alloy composition, the cold-working characteristics of the alloy, but they should be incorporated and adjusted with the required hardness and ductility.

   Cold-worked alloys are usually not welded because the mechanical strength of the weldment would be lower than that of the cold-worked region.

   NACE Publication 1F192 noted the following limitations should be considered.

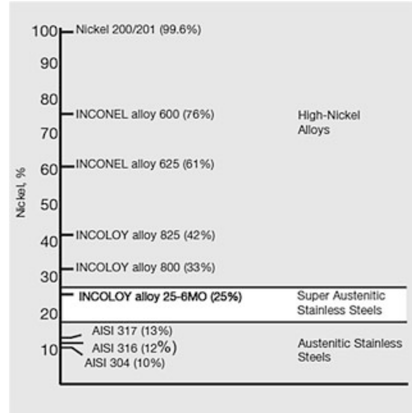


Figure 2.81 Nickel content and classification of stainless steels and nickel-based alloys. (Source: Special Metals Technical Report, 2010)

Table 2.68 (1/5) Classes of nickel and nickel-based alloys

Alloys [brand] (UNS no.)	Chemical composition (average or maximum %)	Density (g/cm^3) at room temp.	Mechanical properties (room temperature)				Related standard materials (see legend and notes) Some ASME SB are not registered.
			H.T. [type]	Min. T.S. ksi (MPa)	Min. Y.S ksi (MPa) at 0.2% Offset	Hardness max. Brinell (Rockwell)	
Nickel 200 (N02200)	99.1Ni-0.15C	8.89	SA	55–80 (380–550)	15–30 (100–210)	90–120	ASTM B (ASME SB-) 160, 161, 162, 163, 366, 564, 725, 730, *751*, *775*, *829*/ISO 6207, 6208, 9723, 9724/DIN 17740, 17750, 17751, 17753, 17754/BS 3072, 3074, 3076
Nickel 201 (N02201)	99.1Ni-0.02C	8.89	SA	55–80 (380–550)	15–30 (100–210)	90–120	ASTM B (ASME SB-) 160, 161, 162, 163, 366, B564/DIN No. 2.4068 (17740, 17750, 17751, 17752, 17753, 17754)/BS NA 12 (3072, 3074, 3076)/SAE AMS 5553
Alloy 20Cb3 (N08020)[(3),(7)]	35Ni-20Cr-2.5Mo-37Fe-3.5Cu-Cb	8.08	SA	80 (550)	35 (240)	183 (HRB 90)	ASTM B (ASME SB-) 366, 462, 463, 464, 468, 472, 473, 474, 475, 729, *751*, *775*, *829*, *906*/ ASTM A (ASME SA-) 240, 479, *480*/ISO 6207, 6208, 9723, 9724/DIN 17744, 17750, 17751, 17752, 17753, 17754/ ANSI/NACE MR0175/ISO15156
Alloy 20Mo6 (N08026)[(3)]	35Ni-24Cr-6Mo -30Fe-3Cu-Cb	8.13	SA	80 (550)	35 (240)	183 (HRB 90)	ASTM B (ASME SB-) 462, 463, 464, 468, 472, 473, 475, 729, *751*, *775*, *829*, *906*/ ANSI/NACE MR0175/ISO15156
Alloy 27-7Mo (S31277)[(8)]	27Ni-21.5Cr-7.2Mo -41Fe-1Cu	8.02	SA	112 (770)	52 (360)	–	ASTM A (ASME SA-) 182, 240, 213, 249, 312, 479 ASME Code Case 2458
Alloy 25-6MO (N08926)	25Ni-20Cr-6.5Mo-44Fe-1Cu-1.5Mn	8.03	SA	100 (690)	48 (300)	(HRB 86)	ASTM B (ASME SB-) 625, 649, 673, 674, 677, 472 ASME BPVC Code Case 2120, N-453, N-454, N-455/ ANSI/NACE MR0175/ISO15156
Alloy 28 Incoloy 028 (N08028) Sandvik Sanicro 28	32Ni-27Cr-3.5Mo--34Fe-1Cu	8.0	SA	73 (500)	31 (214)	(HRB 90)	ASTM B (ASME SB-) 668, 709/ASTM A 403/EN 10216-5, 10088-2, 10088-3/DIN 1.4563/ SEW 400/SS 14 25 84/NFA 49-217/ANSI/NACE MR0175/ISO15156
Alloy 31 VDM Alloy 31/Nicrofer 3127hMo (N08031)	31Ni-27Cr-6.5Mo-33Fe-1.2Cu-0.2N	8.10	SA	94 (648)	40 (276)	–	ASTM B (ASME SB-) 581, 625, 649, ASTM B-564/ API 5LD/ DIN 1.4562 – X1NiCrMoCu32-28-7 ANSI/NACE MR0175/ISO15156
Alloy 42 (K94100)	42Ni-58Fe	8.13	SA	71 (490)	37 (255)	139	ASTM F 30/DIN 17745/S. E. W. 385/DIN W. Nr.1.3922. 1.3926. 1.3927/AFNOR A54-301
Alloy 50 (N06950)	52Ni-20Cr-9Mo-17Fe	8.38	SA	115 (793)	110 (759)	(HRC38)	ANSI/NACE MR0175/ISO15156

Table 2.68 (2/5) Classes of nickel and nickel-based alloys

Alloys [brand] (UNS no.)	Chemical composition (average or maximum %)	Density (g/cm^3) at room temp.	Mechanical properties (room temperature)				Related standard materials (see legend and notes) Some ASME SB are not registered.
			H.T. [type]	Min. T.S. ksi (MPa)	Min. Y.S ksi (MPa) at 0.2% Offset	Hardness max. Brinell (Rockwell)	
Alloy 59 [Nicrofer 5923 hMo] (N06059)	57Ni-23Cr-16Mo-0.2Al	8.60	SA	100 (690)	55 (380)	(HRB100)	ASTM B (ASME SB-) 575, 619, 626, 574, 575, 564/DIN W. Nr. 2.4605 (NiCr23Mo16Al) ANSI/NACE MR0175/ISO15156
Alloy 230 (N06230)[9]	52Ni-22Cr-2Mo-14W-3Fe-4Co	8.97	SA	110 (760)	45 (310)	–	ASTM B (ASME SB-) 366, 435. 572, 564, 619, 622, 626/ ASME Code Case 2063/ DIN 17744 (W.Nr. 2.4733 and NiCr22W14Mo)
Alloy 330 (N08330)	35.5Ni-18.5Cr-44Fe-1.1Si	8.08	SA	70 (483)	30 (207)	(BRB 70-90)	ASTM B (ASME SB-) 511, 535, 536/ASTM B512, B829 SAE AMS 5592, 5716
Alloy 400 [Monel 400] (N04400)	66.5Ni-31.5Cu	8.83	SA	70–90 (480–620)	25–90 (170–340)	110–149	ASTM B(ASME SB-) 127, 163, 164, 165, 564, 725, 730, *751*, *775*, *829*/SAE AMS 4544, 4574, 4675, 7233/BS 3073NA13, 3074NA13, 3075NA13, 3076NA13/DIN 17750, 17751 (W. Nr, 2.4360, 2.4361)/AFNOR NU30/QQ-N-281/ANSI/NACE MR0175/ISO15156
Alloy 404 [Monel 404] (N04404)	55Ni-45Cu	8.91	SA	65 (445)	23 (156)	(HRB 55)	ASTM F96/DIN W. Nr, 2.4867
Alloy R-405 [Monel R-405] (N04405)	66.5Ni-31.5Cu 31.5-0.04S	8.80	SA	70–85 (480–590)	25–40 (170–280)	110–140	ASTM B(ASME SB-) 164/SAE AMS 4674, 7234/ QQ-N-281/MIL-N-894/ ANSI/NACE MR0175/ISO15156
Alloy K-500 [Monel K-500] (N05500)	65.5 Ni-29.5Cu-2.7Al-0.6Ti	8.46	Aged	140–190 (970–1310)	110–150 (760–1030)	265–346	ASTM B 865/ASME Code Case 1192/SAE AMS 4678/ISO 6208, 9723, 9724, 9725/BS 3073NA18, 3074NA18, 3076NA18/DIN 17750, 17751, 17752, 17753 (W. Nr. 2.4375)/QQ-N-286 ANSI/NACE MR0175/ISO15156
Alloy 600 [Inconel 600] (N06600)	76Ni-15.5Cr-8Fe	8.42	SA	80–100 (550–690)	30–50 (210–340)	120–170	ASTM B (ASME SB-) 163, 166, 167, 168, 366, 516, 517, 564, *751*, *775*, *829*, *906*/ASME Code Cases 1827, N-20, N-253, and N-576/SAE AMS 5540, 5580, 5665, and 5687/EN 10095/BS 3072NA14, 3075NA14 and 3076NA14/DIN 17742, 17752, 17753, 17754, 17750, and 17751/ISO 4955A, 6207, 9723, 9724, and 9725/MIL-DTL-23229/QQ-W-390/ AFNOR NC15Fe
Alloy 601 [Inconel 601] (N06601)	60.5Ni-23Cr-14Fe-1.3Al	8.06	SA	80–115 (550–790)	30–60 (210–340)	110–150	ASTM B (ASME SB-) 166, 167, 168, 751, 775, 829/ASME Code Cases 1500/DIN 17742, 17750, 17751, 17752, 17753, 17754/EN10095/ISO 6207, 6208, 9723, 9724, 9725, NW6601/MIL-DTL-23229/QQ-W-390/AFNOR NC15Fe
Alloy 617 [Inconel 617] (N06617)	46Ni-9Mo-22Cr-12.5Co-1.2Al	8.36	SA	110 (760)	51 (350)	173	ASTM B (ASME SB-) 166, 168, 546, 564,/ASTM B 167, 472/ASME Code Case 1956, 1982/SAE AMS 5887, 5888, 5889/ISO 6207, 6208, 9724, DIN 17750, 17751, 17752, 17753, 17754/DIN W.Nr. 2.4663a
Alloy 625 [Inconel 625] (N06625)	61Ni-21.5Cr-9Mo-3.6(Nb + Ta)	8.44	SA	135 (930)	75 (520)	180	ASTM B (ASME SB-) 366, 443, 444, 446, 564, 704, 705, *751*, *775*, *829*/ASTM B472/ASME Code Cases 1935/SAE AMS 5581, 5837/DIN 17744 (No. 2.4856), 17750, 17751, 17752, 17753, 17754/ EN10095/ISO 4955A, 6208, 9725/BS 3076NA21, 3072NA21, 3074NA21/W. Nr 2.4856/AFNOR 22 D Nb/ANSI/NACE MR0175/ISO15156
Alloy 654 SMO[8] [654 SMO] (S32654)	22Ni-24Cr-7Mo-46Fe-0.45Cu-0.5N	7.9	SA	109 (750)	62 (430)	250	ASTM A (ASME SA-) A240, A269, A312, A358, A479, A480, ASTM A276, ASME Code Case 2195-1

Table 2.68 (3/5) Classes of nickel and nickel-based alloys

Alloys [brand] (UNS no.)	Chemical composition (average or maximum %)	Density (g/cm^3) at room temp.	Mechanical properties (room temperature) H.T. [type]	Min. T.S. ksi (MPa)	Min. Y.S ksi (MPa) at 0.2% Offset	Hardness max. Brinell (Rockwell)	Related standard materials (see legend and notes) Some ASME SB are not registered.
Alloy 686 (N06686)	48Ni-21Cr-16.3 Mo-3.9W	8.72	SA	100 (690)	45 (310)	(HRB100)	ASTM B (ASME SB-) 163, 564, 574, 575, 619, 622, 626, 751, 775, 829, 906/ASTM F467, F468/SAE J2271(M), J2280, J2295, J2484, J2485/DIN 17750, 17751 ANSI/NACE MR0175/ISO15156
Alloy 690 [Inconel 690] (N06690)	60Ni-29Cr-9.5 Fe	8.19	SA	100 (690)	55 (379)	184	ASTM B (ASME SB-) 163, 166, 167, 168, 564, 829, 906/ASME Code Cases 2083, N-20, N-525/ISO 6207/6208/9723, NW6690/DIN W. Nr 2.4642/MIL-DTL-24801, 24802, 24803
Alloy 718 [Inconel 718] (N07718)	52.5Ni-19Cr-3Mo-18.5Fe-5.1(Nb + Ta)	8.19	Aged	196 (1350)	171 (1180)	382	ASTM B (ASME SB-) 637, 670, 906/ASME Code Cases 2206, 2222, N-62, N-253/SAE AMS 5589, 5590, 5596, 5597, 5662, 5664, 5832, 5914, 5950, 5962/DIN 17750, 17751, 17752, 17753, 17754 (W. Nr. 2.4668)/ISO 6208, 9723, 9724, 9725/AECMA Pr EN 2404, 2405, 2407, 2408, 2952, 2961, 3219, 3666/ANSI/NACE MR0175/ISO15156
Alloy 718SPF [Inconel 718SPF] (N07718)	52.5Ni-19Cr-3Mo-17Fe-5.0 (Nb + Ta) -0.9Ti	8.19	SA	162 (1114)	118 (815)	HRC 23	SAE AMS 5914, SAE AMS 5950
Alloy 725 (N07725)	57Ni-21Cr-8Mo -1.2Ti-3Nb-9Fe	8.31	Aged	124 (855)	62 (427)	(HRC 5)	ASTM B 805/ASME BPVC Code Case 2217/ ANSI/NACE MR0175/ISO15156
Alloy X-750 [Inconel X-750] (N07750)	73Ni-2.5Ti-15.5Cr-0.7Al-7 Fe-1(Nb + Ta)	8.25	Aged	162–193 (1120–1330)	115–142 (790–980)	300–390	ASTM B (ASME SB-) 637/SAE AMS 5542, 5598, 5667, 5668, 5669, 5670, 5671, 5698, 5699, 5747/EN 10269/ISO 6208, 9723, 9724, 9725/BA HR 505/AFNOR NC 15 Fe T ANSI/NACE MR0175/ISO15156
Alloy 800[(7)] [Incoloy 800] (N08800) **Alloy 800H**[(7)] [Incoloy 800H] (N08810)	32.5 Ni-46.0Fe-21Cr	7.95	SA	75–100 (520–690)	30–60 (210–410)	120–184	ASTM B (ASME SB-) 163, 366, 407, 408, 409, 514, 515, 564, *751*, *775*, *829*, *906*/ASTM A (ASME SA-) 240, 480/ASME Code Cases 1325, 1949, 2339, N-20/SAE AMS 5766/ISO 6207, 9725/BS 3074NA15, 3075NA15/DIN W. Nr. 1.4876
Alloy 800HT[(7)] [Incoloy 800HT] (N08811)	32.5Ni-21Cr-46Fe-1 (Al + Ti)-0.08C	7.95	SA	65–95 (450–660)	20–50 (140–340)	100–184	ASTM B (ASME SB-) 163, 366, 407, 408, 409, 514, 515, 564, *751*, *775*, *829*, *906*/ASTM A (ASME SA-) 240, 480/ASME Code Cases 1325, 1949, 1983, N-201, N-254/EN 10028-7, 10095/ISO 4955A, 6207, 9723, 9724, 9725/DIN 17459, 17460/BS 3074NA15, 3075NA15, 3076NA15/SEW 470
Alloy 825 [Incoloy 825] (N08825)	42Ni-21.5Cr-3Mo-2.2Cu-30 Fe	8.14	SA	85–105 (590–720)	35–65 (240–450)	120–180	ASTM B (ASME SB-) 163, 423, 424, 425, 564, 704, 705, *751*, *775*, *829*, *906*/ASME Code Cases 1936, N-572/EN 10028-7, 10095/ISO 4955A, 6207, 9723, 9724, 9725 DIN 17744, 17750, 17751, 17752, 17753, 17754/ ISO 6207, 6208, 9723, 9724, 9725/BS 3072NA16, 3073NA16/DIN W. Nr. 2.4858/ANSI/NACE MR0175/ISO15156
Alloy 925 (N09925)	44Ni-21Cr-3Mo-22Fe -2Cu-2Ti	8.08	Aged	99 (683)	39 (271)	(HRB 73)	ASME BPVC Code Case 2218 ANSI/NACE MR0175/ISO15156
Alloy 945 [Incoloy 945] (N09945)	50Ni-21Cr-3.5 Mo-19Fe-3.5Nb-2Cu	8.20	Aged	173 (1194)	133 (920)	(HRC 40)	ANSI/NACE MR0175/ISO15156
Alloy 2535 (N08535)	32Ni-25Cr-3Mo -38Fe	8.02	SA	115–145 (782–986)	110–140 (748–952)		ASTM B (ASME SB-) 622/ ANSI/NACE MR0175/ISO15156

Table 2.68 (4/5) Classes of nickel and nickel-based alloys

Alloys [brand] (UNS no.)	Chemical composition (average or maximum %)	Density (g/cm^3) at room temp.	Mechanical properties (room temperature)				Related standard materials (see legend and notes) Some ASME SB are not registered.
			H.T. [type]	Min. T.S. ksi (MPa)	Min. Y.S ksi (MPa) at 0.2% Offset	Hardness max. Brinell (Rockwell)	
Alloy B(4) [Hastelloy B] (N10001)	62Ni-28Mo-1Cr-5Fe-2.5Co	9.24	SA	115 (795)	50 (345)	(HRB100)	ASTM B (ASME SB-) 333, 335, 366, 619, 622, 626
Alloy B-2(4) [Hastelloy B-2] (N10665)	69Ni-28Mo-1Cr -2Fe-1Co-1Mn-0.1Si-0.01C	9.22	SA	133 (914)	57 (396)	228 (HRB95)	ASTM B (ASME SB-) 333, 335, 366, 462, 619, 622, 626 ASTM B 472, 564/DIN No. 2.4615, 2.4616, 2.4617 (17744)
Alloy B-3(4) [Hastelloy B-3] (N10675)	65Ni-28.5Mo-1.5Cr-3 W-3Co-3Mn-1.5Fe-0.5Al	9.22	SA	125 (860)	61 (420)	228 (HRB95)	ASTM B (ASME SB-) 333, 335, 366, 619, 622, 626/ASTM B 462, 472/ASME Code Case 2140/DIN W. Nr. 2.4600 (17744), 2.4695, 2.4696/TUV Werkstoffblatt 517
Alloy C-276(5) [Hastelloy C-276] (N10276)	54Ni-16Mo-15.5Cr-5.5Fe-4W-2.5Co-1Mn-0.01C	8.89	SA	107 (741)	50 (347)	184 (HRB90)	ASTM B (ASME SB-) 366, 462, 564, 575, 619, 622, 626, *751*, *775*, *829*, *906*/ASTM B 472/ISO 6207, 6208, 9723, 9724, 9725/DIN 17744, 17750, 17751, 17752, 17753, 17754 (W. Nr. 2.4819)/MIL-N-24390B/ ANSI/NACE MR0175/ISO15156
Alloy C-4(5) [Hastelloy C-4] (N06455)	66Ni-16Cr-15Mo-3Fe-2Co-0.7Ti-1Mn-0.01C	8.64	SA	116 (802)	60 (421)	194 (HRB92)	ASTM B (ASME SB-) 366, 574, 575, 619, 622, 626/DIN W. Nr. 2.4610 (17744), 2.4611, 2.4612/TUV Werkstoffblatt 424
Alloy C-22(5) [Hastelloy C-22] (N06022)	59Ni-22Cr-14Mo-3W-4Fe-2.5Co-0.01C	8.69	SA	116 (802)	58 (403)	184 (HRB90)	ASTM B (ASME SB-) 366, 462, 564, 574, 575, 619, 622, 626, *751*, *775*, *829*, *906*/ASTM B 472/ASME Code Case 2226, N-621/ISO 9723, 9724/DIN 17744 (W. Nr. 2.4602), 17750, 17751, 17752, 17753, 17754/TUV Werkstoffblatt 479/ANSI/NACE MR0175/ISO15156
Alloy C-2000(5) [Hastelloy C-2000] (N06200)	59Ni-23Cr-16Mo-1.6Cu-0.01C-0.08Si	8.50	SA	100 (690)	45 (310)		ASTM B (ASME SB-) 366, 462, 564, 574, 575, 619, 622, 626, *751*, *775*, *829*, *906*/ASTM B 472/ASME Code Case 2226, 2240, 2337, 2338/ DIN W. Nr. 2.4675 (17744), 2.4698, 2.4699/ TUV Werkstoffblatt 539
Alloy C-22HS (N07022) Type 1A,1B,2,3	61Ni-21Cr-17Mo-2Fe-1 W	8.60	Aged	145–185 per type	80–180 per type	228–479 per type	ASTM B (ASME SB-) 637/------ ANSI/NACE MR0175/ISO15156
Alloy G(6) [Hastelloy G] (N06007)	42Ni-22Cr-20Fe-6.5Mo-2Cu-1.5Co-2Cb-0.5W-1.5Mn-0.08Si	8.31	SA	90 (621)	35 (241)	(HRB100)	ASTM B (ASME SB-) 366, 619/ASTM B 581, 582, 626 ANSI/NACE MR0175/ISO15156
Alloy G-3(6) [Hastelloy G-3] (N06985)	40Ni-22Cr-7Mo -20Fe-2Cu-5Co -1.5W-1Mn-1Si	8.31	SA	90 (621)	35 (241)	(HRB100)	ASTM B (ASME SB-) 366, 581, 582, 619, 622, 626, 751, 775, 829/ISO 6208, 9724/DIN 17744, 17750, 17751 ANSI/NACE MR0175/ISO15156
Alloy G-30(6) [Hastelloy G-30] (N06030)	43Ni-29Cr-5Mo -15Fe-5Co-3W-1.5Cu-0.8Si-1.5Mn -0.8(Cb + Ta)	8.22	SA	85 (586)	35 (241)	–	ASTM B (ASME SB-) 366, 462, 581, 582, 619, 622, 626/ASTM B 472/DIN No. 2.4603 (NiCr30FeMo) ANSI/NACE MR0175/ISO15156
ACI HX-50 (N06050)	66Ni-17Cr-14Fe -1Si	8.03	SA	Per supplier	Per supplier	Per supplier	ASTM A608, ACI HX-50
IN-102 (N06102)	69Ni-15Cr-7Fe-3Cb-3 W-1Si-0.5Ti-0.4Al	8.80	SA	Per supplier	Per supplier	Per supplier	ASTM B (ASME SB-) 518, 519
Alloy X [Hastelloy X] [Inconel HX] (N06002)	47Ni-22Cr-9Mo -18Fe-1.5Co-0.6 W-1Mn-1Si-0.1C	8.22	SA	110 (755)	56 (385)	194 (HRB92)	ASTM B (ASME SB-) 366, 435, 572, 619, 622, 626/ASTM B 472/ASME Code Case N-253 (Sec III, Cl.2)/N-253 (Sec III, Cl.3)/SAE AMS 5390, 5536, 5588, 5798, 5799, 5888, 7237, 7554/ DIN W. Nr. 2.4665/ANSI/NACE MR0175/ ISO15156

Table 2.68 (5/5) Classes of nickel and nickel-based alloys

Alloys [brand] (UNS no.)	Chemical composition (average or maximum %)	Density (g/cm^3) at room temp.	Mechanical properties (room temperature)				Related standard materials (see legend and notes) Some ASME SB are not registered.
			H.T. [type]	Min. T.S. ksi (MPa)	Min. Y.S ksi (MPa) at 0.2% Offset	Hardness max. Brinell (Rockwell)	
Nichrome V (80) (N06003)	78Ni-20Cr-1.5 Mn-1Si	8.41	SA	(2)	(2)	(2)	ASTM B (ASME SB-) 344/SAE AMS 5676, 5677, 5682
Nichrome 60 (N06004)	58Ni-16Cr -20Fe-0.8Mn-1Si	8.25	SA	(2)	(2)	(2)	ASTM B (ASME SB-) 344
Invar [Nilo Alloy 36] (K93600)	36Ni-64Fe	8.13	SA	72 (490)	36 (250)	139	ASTM B(ASME SB-) 388, 753/DIN 1715/S. E. W. 385/W. NR.1.3912/AFNOR A54-301/MIL-I-23011 CL.7, MIL-S-16598
KOVAR (k94610)	29.5Ni-53Fe-17Co	8.16	SA	76 (525)	49 (340)	158	ASTM F 15/AMS 7726-7728/DIN 17745/S. E. W 385/AFNOR A54-301
Alloy G-3(6) [Hastelloy G-3] (N06985)	40Ni-22Cr-7Mo -20Fe-2Cu-5Co -1.5W-1Mn-1Si	8.31	SA	90 (621)	35 (241)	(HRB100)	ASTM B (ASME SB-) 366, 581, 582, 619, 622, 626, 751, 775, 829/ISO 6208, 9724/DIN 17744, 17750, 17751 ANSI/NACE MR0175/ISO15156
Alloy G-30(6) [Hastelloy G-30] (N06030)	43Ni-29Cr-5Mo -15Fe-5Co-3W-1.5Cu-0.8Si-1.5Mn -0.8(Cb + Ta)	8.22	SA	85 (586)	35 (241)	–	ASTM B (ASME SB-) 366, 462, 581, 582, 619, 622, 626/ASTM B 472/DIN No. 2.4603 (NiCr30FeMo) ANSI/NACE MR0175/ISO15156

Legend: Aged = Precipitation-hardened by aging, SA = solid solution annealed (nonhardened), Hastelloy: derived from the letters of the words of Haynes Stellite Alloy, Inconel: derived from Inco Corp's Nickel-based alloys (typically Ni ≥ 50%; or Ni is primary element). Incolloy: derived from *Inco* Corp's al*loy*s (typically Ni < 50%, Cr < 25%)

Notes:

Underbar = standards for general/common Requirements

(1)The mechanical properties indicated in this table are based on the specified heat treatment (hot-rolled and solution-annealed or precipitation-hardened). The values can be changed per the heat treatment, thickness, and product type

(2)For Electrical Heating Elements

(3)Alloy 20 was introduced in 1951 for sulfuric acid service. Later it was modified with Cb (Nb) additions as a Stabilized element, and was known as 20Cb. This allowed its service in the as-welded condition without the need for PWHT. Further research led to the alloy 20Cb3 (UNS N08020), known as Alloy 20, by increasing the Ni content. This modern version of Alloy 20 has been successful because of its superior corrosion resistance in sulfuric acid media and its resistance to SCC

Among its applications are the manufacture of synthetic rubber, high-octane gasoline, solvents, explosives, plastics, synthetic fibers, chemicals, pharmaceuticals, food processing, and many others. However, it contains insufficient Mo for localized corrosion resistance in low pH acidic chloride media

(4)*B-Family Ni-Cr-Mo alloys:* B/B-2/B-3 (source: Special Metals–High Performance Ni Alloys reports, 2015) – It does not cover a specific application, but only development history

- Hastelloy B family were developed by the chemicals of Ni-Mo-Cr-Co for excellent resistance to pitting corrosion and SCC in chloride-containing solutions. The first production of Alloy B (62Ni-28Mo-1Cr-2.5Co) in the B family is not much used because of the benefits of the advanced alloys, such as Alloy B-2 and B-3, which have significant resistance to reducing environments as well as excellent resistance to pitting corrosion and SCC in chloride-containing solutions. Hastelloy B-2 (69Ni-29Mo-1Cr-1Co: Alloy B-2) has significant resistance to reducing environments, such as HCl gas and sulfuric, acetic, and phosphoric acids. Alloy B-2 provides resistance to pure sulfuric acid and a number of nonoxidizing acids. The alloy should not be used in oxidizing media or where oxidizing contaminants are available in reducing media. Premature failure may occur if Alloy B-2 is used where Fe or Cu is present in a system containing HCl acid
- Alloy B-2 resists the formation of grain boundary carbide precipitates in the weld heat-affected zone, making it suitable for most chemical process applications in the as-welded condition. The heat-affected weld zones have reduced precipitation of carbides and other phases to ensure uniform corrosion resistance
- Hastelloy B-3 (65Ni-28.5Mo-1.5Cr-3W-3Co: Alloy B-3) has excellent resistance to hydrochloric acid at all concentrations and temperatures. It also withstands sulfuric, acetic, formic and phosphoric acids, and other nonoxidizing media. Alloy B-3 has a special chemistry designed to achieve a level of thermal stability greatly superior to that of its predecessors in Alloy B-2. Alloy B-3 has excellent resistance to pitting corrosion, to SCC and to knife-line and heat-affected zone attack

(5)*C-Family Ni-Cr-Mo alloys* (source: Special Metals–High Performance Ni Alloys reports, 2015) – It does not cover a specific application, but only development history

The Alloy C family, the oldest alloy of this family (Alloy C- now obsolete), was superseded by Alloy C-276 in the early 1960s as a direct result of improvements in melting technology. Between 1983 and 1996, four new alloys of this family were commercially introduced in the marketplace. As the chemical composition shows, Alloy 2000 is in reality Alloy 59 with the addition of 1.6% Cu to circumvent the Alloy 59 patent. Alloy 59, the purest ternary alloy of the Ni-Cr-Mo family, has the highest PRE number and the lowest Fe content. This provides for improved corrosion resistance over other alloys in a variety of standard laboratory environments. Eliminating W and Cu and reducing Fe content to very low levels resulted in an alloy with superior thermal stability characteristics. Not only is the uniform corrosion behavior and the thermal stability improved, but also its localized corrosion resistance is improved over alloy C-276, 22, and 2000. Localized corrosion has caused more failures in the chemical process industries than any other single corrosion phenomenon, and has led to many unscheduled shutdowns, causing huge economic losses. Uniform corrosion in these high alloys has not generally caused any major problems or unscheduled shutdowns. See Fig. 2.191 for corrosion rate of the Alloy C family in reducing and oxidizing services. A description of these alloys is presented below:

- *Alloy C (1930s to 1965)*: The compatibility of Ni with Cr and Mo, and optimization between Ni-Cr and Ni-Mo alloys, led to the first alloy of the "C" family, Alloy C in the 1930s. The development of this alloy was well described by McCurdy in 1939. It was the most versatile corrosion-resistant alloy available in the 1930s through the mid-1960s to handle the needs of the chemical process industry. However, it had a few severe drawbacks. For example, in the as-welded condition, Alloy C was often susceptible to serious intergranular corrosion (IGC) attack in the HAZ in many oxidizing, low-pH, and halide-containing environments. This meant that for many applications, vessels fabricated from Alloy C had to be solution-heat-treated to remove the detrimental weld HAZ precipitates. This put a serious limitation on its usefulness. During the late 1940s and 1950s, the chemical process industry was constantly coming up with new processes, which needed an alloy without the limitation of "solution heat treating" after welding. Another drawback was that in severe oxidizing media, this alloy did not have enough Cr to maintain useful passive behavior, thus exhibiting high uniform corrosion rates
- *Alloy C-276 (1965–present)*: To overcome one of the above serious limitations, the chemical composition of Alloy C was modified by a German company, BASF. The modification basically consisted of reducing both the C and Si levels by more than tenfold, to the very low levels of typically 50 ppm C and 400 ppm Si. This was possible only because of a new melting technology known as the Ar-O_2 decarburization (AOD) process. This low C and Si content alloy came to be known as Alloy C-276 (54Ni-16Mo-15.5Cr-4 W-2.5Co: UNS N10276), which then was produced in the USA under a license from BASF. (Their patent expired in 1982). The corrosion resistance of both alloys was essentially similar in many corrosive environments, but without the detrimental effects of continuous grain boundary precipitates in the weld HAZ of Alloy C-276. Thus, Alloy C-276 would be suitable for most applications in the as-welded condition without undergoing severe IGC attack
- *Alloy C-4 (1970s–present)*: In addition to the tenfold decrease in C and Si of Alloy C, Alloy C-4 (61Ni-16Cr-16Mo-2Co: UNS N06455) had three other major modifications: its basic chemical composition, reduction in the Fe level, and the addition of some Ti. The above changes resulted in significant improvement in the precipitation kinetics of intermetallic phases. When exposed in the sensitizing range of 550–1090 °C (1022–1904 °F) for extended periods of time, the intermetallic and grain boundary precipitation of the "mu (μ)" phase is practically eliminated. The μ phase has a $(Ni, Fe, Co)_3(W, Mo, Cr)_2$ type structure and various other phases. These phases are detrimental to ductility, toughness, and corrosion resistance. The general corrosion resistance of Alloy C-276 and Alloy C-4 was essentially the same in many corrosive environments, except that Alloy C-276 was better in strongly reducing media such as HCl acid. In highly oxidizing media (ASTM G28A solutions), the opposite was true, and Alloy C-4 was better. Alloy C-4 offers good corrosion resistance to a wide variety of media, including organic acids and acid chloride solutions
- *Alloy C-22 (1982–present)*: After the Alloy C-276 patent expired in the USA in 1982, a newer development in the C family, was introduced: Alloy C-22 (59Ni-22Cr-14Mo-3W-2.5Co: UNS N06022). Inventors claimed that the μ phase was controlled in Alloy C-4 by controlling the "electron vacancy" number by means of deleting W and reducing Fe. However, the result was less resistance to corrosion in reducing chloride solutions, where W is a beneficial element. In addition, both Alloys C-276 and Alloy C-4 had high corrosion rates in oxidizing non-halide solutions due to their relatively low Cr levels of 16%. Therefore, an alloy with higher Cr levels and an optimized balance of Cr, Mo, and W levels was needed for oxidizing environments, thus yielding superior corrosion properties and good thermal stability.

  Even though the corrosion resistance of Alloy C-22 was superior to Alloy C-276 and Alloy C-4 in highly oxidizing environments, and showed slightly better pitting corrosion resistance in "Green Death" solution (See Table 2.144), its behavior in highly reducing environments and in severe localized crevice corrosion conditions was still inferior to the 16% Mo Alloy C-276
- *Alloy 59 (1990–present)*: Research efforts during the 1980s in Germany led to another alloy development within the Ni-Cr-Mo family: Alloy 59 (55Ni-23Cr-16Mo-Al: UNS N06059). This overcame the shortcomings of both Alloy 22 and Alloy C-276. It also provided solutions to the most severe and critical corrosion problems of the chemical process, petrochemical, pollution control, and other industries. As the composition of the various members of the "C" family shows, Alloy 59 has the highest Cr + Mo content with the lowest Fe content (<1%). It is one of the highest Ni-containing alloy of this family, and is the purest form of a "true" Ni-Cr-Mo alloy without the addition of any other alloying elements, such as W, Cu, or Ti. This purity and balance of Alloy 59 in the ternary Ni-Cr-Mo system is mainly responsible for its superior thermal stability behavior
- *Alloy 686 (1993–present)*: Alloy 686 (57Ni-20Cr-16Mo-3.5W-Ti-N: UNS N06686) is another recent development in the "C" family of Ni-Cr-Mo alloys, and is very similar in composition to Alloy C-276. The difference is that the Cr level has been increased from 16% to 21%, while maintaining Mo and W at similar levels. This composition is highly over-alloyed, with the combined Cr, Mo, and W content of around 41%. To maintain its single-phase austenitic structure, it must be solution-annealed at a very high temperature of around 1200 °C (2192 °F), followed by very rapid cooling to prevent precipitation of intermetallic phases. Its thermal stability behavior is significantly inferior to Alloy 59 and its performance in a hazardous waste incinerator showed five times lower corrosion resistance than Alloy 59
- *Alloy 2000 (1995–present)*: Alloy 200 (59Ni-23Cr-16Mo-1.6Cu-0.01C-0.08Si: UNS N06200) is another recent introduction in the "C" alloy family, in which basically 1.6% Cu has been added to the Alloy 59 composition. Addition of Cu has resulted in significantly lower thermal stability behavior and lower localized corrosion resistance in comparison to Alloy 59 (see above)

(6)"G" family for G/G-3/G-30 (source: Special Metals–High-Performance Ni Alloys reports, 2015) – It does not cover a specific application, but only development history

- Alloy G was a development from addition of Cu (about 2%Cu), which significantly improved the corrosion resistance in both sulfuric and phosphoric acid environments. Alloy G has excellent corrosion resistance in the as-welded condition, and can handle the corrosive effects of both oxidizing and reducing agents. The alloy exhibited resistance to mixed acids, fluorosilicic acid, sulfate compounds, concentrated nitric acid, flue gases of coal-fired power plants, and hydrofluoric acid. Its higher Ni and Mo content (over Alloy 825) render it essentially immune to Cl-SCC. It also has significantly superior localized corrosion resistance. However, this alloy is now obsolete, and has been replaced by Alloy G-3
- Hastelloy G-3 (47Ni-22Cr-7Mo-2Cu: Alloy G-3): It is particularly suitable for handling reducing acids, such as phosphoric or sulfuric acids. It is used in flue gas desulfurization (FGD) systems (e.g., scrubbers, quencher, damper, and outlet ducting areas). It is used in other air pollution control systems in the chemical and pulp and paper industries. It is a good candidate for evaporators, H/EXs, tank liners, and other equipment in phosphoric acid manufacturing plants. Also, providing an excellent combination of mechanical properties and strength. It has been used extensively as OCTG materials in hot, sour environments
- Hastelloy G-30 (43Ni-30Cr—15Fe-5.5Mo-2.5W-2Cu-0.8Nb-Co: Alloy G-30): It is an improved version of Alloy G-3. With higher Cr, added Co and W, Alloy G-30 shows superior corrosion resistance over most other Ni- and Fe-based alloys in commercial phosphoric acids as well as complex environments containing highly oxidizing acids such as nitric/hydrochloric, nitric/hydrofluoric, and sulfuric acids. Alloy G-30 resists the formation of grain boundary precipitates in the HAZ, making it suitable in the as-welded condition

(7)Even though Ni is not the primary element, typically it is recognized as one of the nickel-based alloy family

(8)It is not in the nickel-based alloy family

(9)For vessels constructed of UNS N06230 and UNS N06210 and when welding is performed with filler metal of the same nominal composition as the base metal, only GMAW or GTAW processes are allowed. For applications using UNS N06230 above 900 °C (1650 °F), welding shall be limited to the GTAW and GMAW welding processes using SFA-5.14, ERNiCrWMo-1 (ASME Sec.VIII, Div.1, UNF-19)

Table 2.69 Characteristics of elements in nickel-based cast alloys

Element	Characteristics
Ni	Ni is present in cast heat-resistant alloys in amounts up to 70%. Its principal function is to strengthen and toughen the matrix. Microstructurally, Ni is an austenite former, which is stronger and more stable at elevated temperatures than ferrite. Ni contributes to resistance to oxidation, carburization, nitriding, and thermal fatigue.
Cr	Cr content in heat-resistant alloys varies from approximately 10–30%. Cr imparts resistance to oxidation (scaling) at elevated temperatures, and to sulfur-containing atmospheres. In addition, Cr-carbides precipitate in the matrix and contribute to high-temperature creep and rupture strength. In some alloys, Cr increases resistance to carburization. It also improves the resistance of the alloys to the action of many other corrosive agents at normal and elevated temperatures. Cr is a ferrite former. Ni and Cr have the greatest effect on the properties of heat-resistant castings but the minor alloying elements also influence the properties.
Mo	Mo improves the high-temperature creep and rupture strength by promoting stabilization of carbides. In some instances, it also increases high-temperature corrosion resistance. It slightly increases resistance to carburization.
C	Normally C content ranges from 0.20 to 0.75%. C promotes dispersion-strengthening through the formation of carbide in the structure. Increasing C content improves the high-temperature strength and creep resistance of the heat-resistant alloys at the expense of lower ductility.
Mn	Mn, although important in melting operations, has little or no effect on the mechanical properties or corrosion resistance when present in moderate amounts.
Si	Si has a beneficial effect on high-temperature corrosion resistance and on resistance to carburization. In amounts greater than 2%, it lowers the high-temperature creep and rupture properties and, in general, Si content is limited to 1.5% in castings intended for service above 816 °C (1500 °F). Si is a ferrite former.
Others	Work to improve the creep and stress rupture properties of the heat-resisting Cr-Ni-Fe alloys through the addition of small amounts of W, Zr, Ti, Cb, N, or combinations of them, has been pursued for several years under Steel Founders' Society of America sponsorship and by other associations in the world. Alteration of the carbide morphology from lamellar to discrete particles seems to be the important factor; e.g., HP-50WZ (Table I) and IN-657 (Tables I through IV)

Source: ASM Metal Handbook, Vol.2

- Lengthy aging of heavily cold-worked alloys, such as Alloy C-276 and UNS Alloy 625 at about 315 °C (600 °F) and higher is often detrimental to HE resistance.
- The high-Ni alloys are more difficult to cast than the common CS and ASS casts (e.g., UNS J92900- CF8M-316 SS, UNS J92800-CF3M-316L SS). The high-Ni alloy castings are usually more prone to defects such as hot tears, cracking, porosity, and gassing. These defects normally appear at any stage of the manufacturing process, such as shakeout, heat treating, machining, or final pressure testing. Although the wrought high-Ni alloys are routinely welded or weld repaired and some even hardfaced, welding the cast high-nickel alloys is considerably more difficult.
- Ordering castings to current ASTM and ASME standards and/or to "the equivalent" of wrought trade name alloys generally does not guarantee the quality and purity of the material desired to obtain corrosion resistance equal to that of the wrought alloys, casting integrity, and good weldability. Stringent specifications developed in close cooperation with the foundry have typically been used to optimize weldability and casting integrity. Items that are typically controlled include foundry processes, raw material quality, filler material composition, weld repair procedures, and heat treatment.

2. Precipitation Hardened Ni Alloys

These alloys are usually used in one of the following conditions: solution-annealed, solution annealed and aged, hot-worked and aged, or cold-worked and aged.

See Sect. 4.11.8 for welding and Sect. 4.12.3.10 for heat treatment of Ni-based alloys.

(b) Heat-Resistant Nickel-Based Alloy Castings

Stainless steel castings are classified as heat resistant if they are capable of sustained operation while exposed, either continuously or intermittently, to operating temperatures (as typically metal skin temperatures) in excess of 650 °C (1200 °F). Heat-resistant steel castings resemble high-alloy corrosion-resistant steels except for their higher C content, which imparts greater strength at elevated temperatures.

1. Element Effects: Table 2.69 shows typical characteristics of elements in nickel-based cast alloys.
2. Influence of Microstructure

The Fe-Cr-Ni heat-resistant alloys designed for service up to 649 °C (1200 °F) often have mixed ferrite-austenite matrices. However, alloys intended for service above 649 °C (1200 °F) are austenitic. The compositions of these alloys are generally adjusted to prevent the formation of ferrite that has a detrimental effect on high-temperature creep-rupture strength. Long-time exposure at high temperatures, e.g., 816 °C (1500 °F), can result in transformation of ferrite to the sigma (σ) phase with significant loss of toughness at room temperature. Thus, in these alloys, the high-temperature strength is based primarily on the solid solution strengthening of the austenite by the addition of nickel, chromium, and certain minor elements. Carbides also contribute to strengthening these alloys.

As noted previously, these alloys have carbon contents ranging from 0.20 to 0.75%. In the as-cast condition, the microstructures consist of carbides dispersed in an austenite matrix, which also contains dissolved carbon. By interfering with dislocation movement, these precipitated carbides assist in strengthening the alloy. During long service at elevated temperatures in the range 538–982 °C (1000–1800 °F), additional chromium carbides precipitate in finely divided form, and also assist in strengthening the alloys. At temperatures somewhat above 982 °C (1800 °F), the primary carbides have a tendency to coalesce and the secondary carbides to re-dissolve in the matrix. Ni and Cr retard this tendency.

3. Four principal categories of H-type cast alloys
   (a) Fe-Cr alloys: 10–30% Cr and little or no Ni – e.g., HA, HC, and HD
   These alloys have low strength at elevated temperatures and are useful mainly due to their resistance to oxidation. Use of these alloys is restricted to conditions, either oxidizing or reducing, that involve low static loads and uniform heating. Cr content depends on anticipated service temperature.
   (b) Cr-Ni-Fe alloys: > 13% Cr and 7% Ni (Cr > Ni) – e.g., HE, HF, HH, HI, HK, IN-519, and HL
   These austenitic alloys are ordinarily used under oxidizing or reducing conditions similar to those withstood by the ferritic Fe-Cr alloys, but in service they have greater strength and ductility than the straight Cr alloys. Therefore, they may be used to withstand greater loads and moderate changes in temperature. These alloys also are used in the presence of oxidizing and reducing gases that are high in S content.
   (c) Ni-Cr-Fe alloys: 25–75% Ni and 10–26% Cr (Ni > Cr) – e.g., HN, HP, HT, HU, HW and HX
   These austenitic alloys are used for withstanding reduction as well as oxidizing atmospheres, except where sulfur content is appreciable. In atmospheres containing $\geq$0.05% H_2S, e.g., Cr-Ni-Fe alloys are recommended. In contrast with Cr-Ni-bal.Fe alloys, Ni-Cr-Fe alloys do not carburize rapidly or become brittle and do not take up nitrogen in nitriding atmospheres. These characteristics become enhanced as Ni content is increased, and in carburizing and nitriding atmospheres casting life increases with Ni content. Austenitic Ni-Cr-Fe alloys are used extensively under conditions of severe temperature fluctuations, such as those encountered by fixtures used in quenching and by parts that are not heated uniformly or that are heated and cooled intermittently.
   They can be used satisfactorily up to 1150 °C (2100 °F) because no brittle phase forms in these alloys. They have good weldability and are readily machinable if proper tools and coolants are used. In addition, these alloys have characteristics that make them suitable for electrical resistance heating elements.
   (d) 50%Cr-50Ni alloys
      (i) Chromium-Nickel Alloy (50Cr-50-Ni)
      This alloy was developed to improve resistance against fuel oil ash. It is widely used for resistance to oil ash corrosion in power plants, oil refinery heaters, and marine boilers at temperatures up to about 900 °C (1650 °F). Its applications include such parts as sidewall and roof hanger supports in furnace radiant sections, tubesheets, and re-radiation cone tips in vertical furnaces and for burner parts.
      (ii) IN-657 (50Cr-48Ni-1.5Cb)
      This more recent development is a Nb (Cb) modification of the 50Cr-50Ni alloy also with high resistance to fuel oil ash corrosion but with creep and stress-rupture properties superior to those of the 50Cr-50Ni alloy. IN-657 is used in oil refinery heaters and marine and land-based boilers in such applications as convection section tubesheets.
4. Characteristics of several H-type cast steels
   Table 2.70 shows chemical compositions of commercial heat-resistant nickel-based casting alloys and Table 2.71 shows application guidance of heat-resistant nickel casting alloys.

Table 2.70 Chemical compositions of heat-resistant nickel-based casting alloys [E] (ASTM A297)

Grade	UNS no.	Type	Composition, % [A]							
			C	Mn, max	Si, max	P. max	S, max	Cr	Ni	Mo, max[B]
HF	J92603	19 Cr-9 Ni (302B*)	0.20–0.40	2.00	2.00	0.04	0.04	18.0–23.0	8.0–12.0	0.50
HH	J93503	25 Cr-12 Ni (309*)	0.20–0.50	2.00	2.00	0.04	0.04	24.0–28.0	11.0–14.0	0.50
HI	J94003	28 Cr-15 Ni	0.20–0.50	2.00	2.00	0.04	0.04	26.0–30.0	14.0–18.0	0.50
HK	J94224	25 Cr-20 Ni (310*)	0.20–0.60	2.00	2.00	0.04	0.04	24.0–28.0	18.0–22.0	0.50
HE	J93403	29 Cr-9 Ni	0.20–0.50	2.00	2.00	0.04	0.04	26.0–30.0	8.0–11.0	0.50
HT	N08605	15 Cr-35 Ni (330*)	0.35–0.75	2.00	2.50	0.04	0.04	15.0–19.0	33.0–37.0	0.50
HU	N08004	19 Cr-39Ni	0.35–0.75	2.00	2.50	0.04	0.04	17.0–21.0	37.0–41.0	0.50
HW	N08001	12 Cr-60 Ni	0.35–0.75	2.00	2.50	0.04	0.04	10.0–14.0	58.0–62.0	0.50
HX	N06006	17 Cr-66 Ni	0.35–0.75	2.00	2.50	0.04	0.04	15.0–19.0	64.0–68.0	0.50
HC	J92605	28 Cr (446*)	0.50 max	1.00	2.00	0.04	0.04	26.0–30.0	4.00 max	0.50
HD	J93005	28 Cr-5 Ni	0.50 max	1.50	2.00	0.04	0.04	26.0–30.0	4.0–7.0	0.50
HL	N08604	29 Cr-20 Ni	0.20–0.60	2.00	2.00	0.04	0.04	28.0–32.0	18.0–22.0	0.50
HN	J94213	20 Cr-25 Ni	0.20–0.50	2.00	2.00	0.04	0.04	19.0–23.0	23.0–27.0	0.50
HP	N08705	26 Cr-35 Ni	0.35–0.75	2.00	2.50	0.04	0.04	24.0–28.0	33.0–37.0	0.50
HG10MNN	J92604	19Cr-12Ni-4Mn [C]	0.07–0.11	3.0–5.0	0.70	0.04	0.03	18.5–20.5	11.5–13.5	0.25–0.45
CT15C	N08151	20Cr-33Ni-1Nb [D]	0.05–0.15	0.15–1.50	0.15–1.50	0.03	0.03	10.0–21.0	31.0–34.0	–

Notes: * Wrought alloy type numbers shown are for grades most closely corresponding to the casting alloys. It should be noted that the wrought alloy and cast alloy and cast alloy composition ranges are not the same
[A] Balance: Fe
[B] Castings having a specified molybdenum range agreed upon by the manufacturer and the purchaser may also be furnished under these specifications. Remarks including modified
[C] Others: Cu-max. 0.5%, Nb-min. 8xC%, max. 1.0%, N-0.20–0.30%
[D] Others: N-0.50–1.50%
[E] ASTM A351/A608 have more detail grades, i.e., HKxx = HK grade with 0.xx%C (HK30 has 0.30%C and HK40 has 0.40%C)

Table 2.71 (1/3) Use of heat-resistant SS and nickel casting alloys – NiDI Publ. 11022 modified

Alloy	ASTM	UNS	SS type	SMTS ksi	SMYS ksi	Typ. max. °C (°F)	Remarks, Note 1 & 2
HC 28Cr HC30	A297 A608	J92605 J92613	446	55 –	– –	980 (1800)	Good sulfur and oxidation resistance, minimal mechanical properties. Applicable where strength is not a consideration or for moderate load-bearing service around 650 °C (1200 °F). Ductility and impact toughness are very low at room temperatures and the creep strength is very low at elevated temperatures due to low Ni content. Typically used for boiler baffles, furnace grate bars, kiln parts, recuperators, salt pots, and tuyeres. HC30 (ASTM A608): 28Cr-0.30C, SMTS = 53 ksi at 760 °C (1400 °F)
HD 28Cr-5Ni HD50	A297 A608	J93005 J93015		75 –	35 –	1040 (1900)	Excellent oxidation and sulfur resistance plus weldability. To use for load-bearing components at 650 °C (1200 °F) and light loads at 1040 °C (1900 °F). May be hardened and with significant loss of ductility due to sigma phase formation after long-term exposure at 705–815 °C (1300–1500 °F). Ductility can be restored by solution heat treatment at 980 °C (1800 °F) followed by a rapid cooling to below 650 °C (1200 °F). HD50 (ASTM A608): 28Cr-5Ni-0.50C, SMTS = 74.5 ksi at 760 °C (1400 °F) – -higher creep strength and carburization & oxidation resistance.
HE 29Cr-9Ni HE35	A297 A608	J93403 J93413		85 –	40 –	1093 (2000)	Higher temperature and sulfur-resistant capabilities than HD. Shows moderately high hot strength and excellent ductility. This type has excellent high-temperature corrosion resistance and is frequently recommended for service in high-sulfur atmospheres where alloys containing higher Ni cannot be used. Because of its high alloy content, it is suitable for use up to 1093 °C (2000 °F). Prolonged exposure at temperatures around 816 °C (1500 °F) may promote formation of the sigma phase with consequent low ductility at room temperature. Used widely in parts such as conveyors in furnaces, recuperators, coke oven exhaust castings, roasting furnace center shafts and tube support castings. HE35 (ASTM A608): 29Cr-9Ni-0.35C
HF 19Cr-9Ni HF30	A297 A608	J92603 J92803	302B	70 –	35 –	871 (1600)	Excellent general corrosion resistance to 816 °C (1500 °F) with moderate mechanical properties. This type is comparable to the popular wrought corrosion-resisting 18–8 compositions and is suitable for use up to around 871 °C (1600 °F). It approaches the HH grade in many properties and combines moderately high hot strength and ductility. Its microstructure is essentially austenitic. Typically used for burnishing and coating rolls, furnace dampers, annealing furnace parts, etc. HF30 (ASTM A608): 19Cr-9Ni-0.30C, SMTS = 26.0 ksi at 760 °C (1400 °F)
HH 25Cr-12Ni HH30 HH33	A297 A447 A608	J93503 J93303 J93513 J93633	309	75 – –	35 – –	1093 (2000)	Good strength and oxidation resistance at 760–982 °C (1400–1800 °F). This type is one of the most popular of the heat-resistant alloys and accounts for about one-fifth of all heat-resistant casting production. This alloy contains the minimum quantities of Cr and Ni to supply a useful combination of strength and corrosion resistance for elevated temperature service above 871 °C (1600 °F). The Cr range is high enough to assure good scaling resistance up to 1093 °C (2000 °F) in air or normal products of combustion. Sufficient Ni is present, aided by C, N and Mn, to maintain austenite as the major phase; however, the microstructure is sensitive to composition balance. For high ductility at 982 °C (1800 °F), a two-phase structure of austenite and ferrite is appropriate but such a structure has lower creep strength. If high creep strength is needed and lower ductility can be tolerated, a composition balanced to be completely austenitic is desirable. The maximum magnetic permeability & (SMTS) of the following Type 1 & 2; Note 4 HH-Type I (ASTM A447, J93303) – partially ferritic: 1.70 μ (SMTS = 80 ksi) HH-Type II (ASTM A447, J93303) – predominately austenitic: 1.05 μ (SMTS = 80 ksi) Type I has a relatively low creep stress between 815–1095 °C (1500–2000 °F) and relatively high ductility at room temperature after aging for a short time between 705–815 °C (1300–1500 °F). It is more prone to sigma phase formation between 650–870 °C (1200–1600 °F) than Type II. Therefore, Type I alloy is used where hot ductility is more important than hot strength, and is preferred for welding. Because of its high creep strength and relatively low ductility, Type II is useful in parts subject to high constant load conditions in the range from 1200 to1800°F (650–982 °C). Some typical uses are for furnace shafts, beams, rails and rollers, tube supports, cement, and lime kiln ends. Both types of HH alloy have good resistance to surface corrosion under the various conditions encountered in industry, but are seldom used for carburizing applications because of embrittlement caused by absorption of carbon. Experience has indicated that HH alloys can withstand repeated temperature changes or differentials reasonably well; however, they are not generally recommended for where severe cyclic temperature changes occur. HH30 (ASTM A608): approx. 0.30%C HH33 (ASTM A608): approx. 0.33%C

Table 2.71 (2/3) Use of heat-resistant SS and nickel casting alloys – NiDI Publ. 11022 modified

Alloy	ASTM	UNS	SS type	SMTS ksi	SMYS ksi	Typ. max. °C (°F)	Remarks, Note 1 & 2
HI 28Cr-15Ni HI35	A297 A608	J94003 J94013		70	35	1093 (2000)	Improved oxidation resistance compared with HH. This alloy is resistant to oxidation up to 1177 °C (2150 °F). Its composition is such that it is more likely to be completely austenitic than the lower alloys of this group, hence it has more uniform high-temperature properties. This type is used for billet skids, conveyor rollers, furnace rails, lead pots, retorts for magnesium production, hearth plates, and tube spacers. HI35 (ASTM A608): approx. 0.35%C, SMTS = 20 ksi at 870 °C (1600 °F)
HK 25 Cr-20 Ni HK30 HK40	A297 A351 A608 A351 A608	J94224 J94203 J94204	310	65 65 62	35 35 35	1149 (2100)	Basic: -2Mn-2Si Better strength/oxidation resistance than HH. Useful range up to 1038 °C (1900 °F). The HK alloy provides one of the most economical combinations of strength and surface stability at temperatures up to and above 1038 °C (1900 °F) and accounts for almost half of the heat-resistant alloy tonnage. It can be used in structural applications up to 1150 °C (2100 °F) but is not recommended where severe thermal shock is a factor. It is used for parts where high creep and rupture strengths are needed such as steam methane reformer tubing, ethylene pyrolysis tubing, gas turbines, furnace door arches and chain, brazing fixtures, cement kiln nose segments, rabble arms and blades, radiant tubes, retorts, and stack dampers. HK30 (J94203): approx. 0.30%C (A351, A608), SMTS = 26 ksi at 760 °C (1400 °F) HK40 (J94204): approx. 0.40%C (A351, A608), SMTS = 29 ksi at 760 °C (1400 °F) IN·519 (24Cr-24Ni-1.5Cb): C content has been reduced and Nb (Cb) has been added. As a result, the high-temperature stress-rupture strength has been improved. It is used for centrifugally cast catalyst tubes in steam-hydrocarbon reformer furnaces.
HL 30Cr-20Ni HL30 HL40	A297 A608	J94604 N08613 N08614		65 –	35 –	982 (1800)	Improved sulfur resistance compared with HK. This alloy has excellent resistance to oxidation at temperatures over 1093 °C (2000 °F), and is resistant to corrosion in flue gases containing a moderate amount of sulfur up to 982 °C (1800 °F). It is used where a higher strength than obtainable with lower nickel content alloys is required. Leading applications are for radiant tubes, furnace skids, and stack dampers where excessive scaling must be avoided, such as in enameling furnace carriers and fixtures. HL30 (ASTM A608): 30Cr-20Ni-0.30C HL40 (ASTM A608): 30Cr-20Ni-0.40C
HN 20Cr-25Ni HN40	A297 A608	J94213 N28701		63 –	– –	1093 (2000)	Very high strength at high temperatures. This alloy has properties somewhat similar to the more widely used HT alloy but has better ductility. It is used for highly stressed components in the 982–1093 °C (1800–2000 °F) range. It has also given satisfactory service in several specialized applications, notably brazing fixtures at temperatures up to 1150 °C (2100 °F). Among its applications are chain, furnace beams and parts, pier caps, brazing fixtures, radiant tubes, tube supports, and torch nozzles. HN40 (ASTM A608): 20Cr-25Ni-0.40%C
HP 25Cr-35Ni HPNb HPNbS	A297 A608 A608	N08705 N28701 N28702		62.5 – –	34 – –	1093 (2000)	Resistant to both oxidizing and carburizing atmospheres at high temperatures. Related to the HN and HT types but contains more nickel than the HN alloy and more Cr than the HT alloy. This composition makes the HP alloy resistant to both oxidizing and carburizing atmospheres at high temperatures and provides high stress rupture properties in the range 982–1093 °C (1800–2000 °F). To use ethylene pyrolysis tubing, steam methane reformer tubing, heat treating fixtures and radiant tubes. Several proprietary modifications containing Nb and/or W are also being used. HPNb (HP-Mod.Nb) in ASTM A608: 25Cr-35Ni-1Nb-1Si HPNbS (HP-Mod.Nb with microalloys) in ASTM A608: 25Cr-35Ni-1Nb-2Si
HT 15Cr-35Ni HT30 HT50	A297 A351 A608	J94605 N08030 N08050	330	65 65 –	– 28 –	1149 (2100)	Good thermal shock/fatigue resistance/carburization resistance. About one-seventh of the total production of heat-resistant castings is HT alloy because of its value in resisting thermal shock, its resistance to oxidation and carburization at high temperatures, and its good strength at heat treating furnace temperatures. Except in high-sulfur gases, it performs satisfactorily up to 1150 °C (2100 °F) in oxidizing atmospheres and up to 1093 °C (2000 °F) in reducing atmospheres. It is used for load-bearing members in many furnace applications, retorts, radiant tubes, cyanide and salt pots, hearth plates, and trays quenched with the work. HT30 (ASTM A351): 15Cr-35Ni-0.30%C HT50 (ASTM A608): 15Cr-35Ni-0.50%C

Table 2.71 (3/3) Use of heat-resistant SS and nickel casting alloys – NiDI Publ. 11022 modified

Alloy	ASTM	UNS	SS type	SMTS ksi	SMYS ksi	Typ. max. °C (°F)	Remarks, Note 1 & 2
HU 18Cr-39Ni HU50	A297 A608	J95405 N08005		65 –	– –	1149 (2100)	Elevated temperature strength increases over HT. Good resistance to corrosion by either oxidizing or reducing hot gases containing moderate amounts of sulfur. This type has an exceptionally high combination of creep strength and ductility up to 1093 °C (2000 °F) and is used where high hot strength is required. To use for severe service conditions involving high stress and rapid thermal cycling. Typical uses are heat treating salt pots, quenching trays, fixtures, and gas dissociation equipment. HU50 (ASTM A608): 18Cr-39Ni-0.50%C
HW 12Cr-60Ni HW50	A297 A608	N08001 N08006		60	–	982 (1800)	Higher thermal shock/fatigue and carburization resistance with higher Ni. The HW alloy performs satisfactorily up to 1121 °C (2050 °F) in strongly oxidizing atmospheres and up to 1038 °C (1900 °F) in oxidizing or reducing products of combustion, if sulfur is low or not present in the gas. The adherent nature of its oxide scale makes HW alloy suitable for enameling furnace service where even small flecks of dislodged scale could ruin the work in process. High-temperature strength, resistance to thermal fatigue, and resistance to carburization are obtainable with this alloy, and its high electrical resistivity suits it for electrical heating elements. Other applications are cyanide pots, gas retorts, hardening fixtures (quenched with the work), hearth plates, lead pots, muffles, and other parts in cyaniding and carburizing operations. HW50 (ASTM A608): 12Cr-60Ni-0.50%C
HX 17Cr-66Ni	A297	N06006		60	–	1149 (2100)	Resistant to hot gas corrosion under cycling conditions without cracking or warping. The high-alloy content of this grade confers high resistance to hot gas corrosion even in the presence of some sulfur and permits it to be used for severe service applications where corrosion must be minimized at temperatures up to 1150 °C (2100 °F). It is used to great advantage where maximum and widely fluctuating temperatures are encountered because of its ability to withstand cycling without cracking or severe warping. Thus, a leading application is for quenching fixtures. It is also useful in carburizing and cyaniding equipment. Typical applications in which it gives excellent service include nitriding, carburizing, and hardening fixtures (quenched with the work), heat-treating boxes, retorts, and burner parts.
HG10 MNN 19Cr-12Ni-4Mn	A297 A351	J92604		76	33		Austenitic stainless steel (ASS). Typically furnished as fabricated (no temper or treatment) condition. Improved resistance to mechanical and thermal fatigue and used in many naval propulsion systems.
CT15C 20Cr-33Ni-1Nb	A297 A351	N08151		63	25	870 (1600)	Although the "C" in its name indicates that CT15C is designed for corrosion-resistant applications, it is primarily used in heat-resisting applications at temperatures up to 870 °C (1600 °F) for tubes, manifolds, ball valve housing, and fittings in reformer, ethylene plant, and other high-temperature petrochemical processes. It retains good ductility and weldability and can be used in applications of severe thermal cycling.

Notes: 1 ksi = 6.895 MPa, blank = no data

1. High-alloy austenitic steels have been widely used in petrochemical plants for ethylene pyrolysis furnace tubes. They are exposed to extremely high temperatures of approximately 800–1100 °C during operation. Some damage mechanisms such as carburization, oxidation, and creep during high-temperature operation that greatly degrade the mechanical properties can occur, requiring the tubes to be replaced at shortened intervals, less than 5–7 years. In addition, the repair welding is very difficult due to the aged condition. Therefore, appropriate solution heat treatment and/or repair welding procedures are to be prepared before using and/or repair welding
2. ASTM A297 & A447: CastingASTM A351 & A608: Centrifugal Casting
3. All mechanical properties at the designed temperature shall be provided by the mill supplier unless the applicable industrial standards specify the certain values
4. The magnetic permeability (permeability is the measure of the ability of a material to support the formation of a magnetic field within itself, μ: defined as magnetic flux density *B*/magnetic field strength *H*) test gives a qualitative indication of the ferrite content for alloys falling within the range of chemical composition specified in ASTM A447, Section 7, excluding iron and other elements as may be agreed upon. When special alloying elements are specified, the magnetic permeability test is not recommended because its significance has not yet been established for such alloys
5. See ASTM A703 for Steel Castings, General Requirements, for Pressure-Containing Parts

5. Comparison of Several H-grade cast steels
   High-temperature equipment is exposed to many different atmospheres and corrosive conditions and an important requirement of heat-resistant alloys is surface film stability. No single alloy will show satisfactory resistance to all of the high-temperature environments.

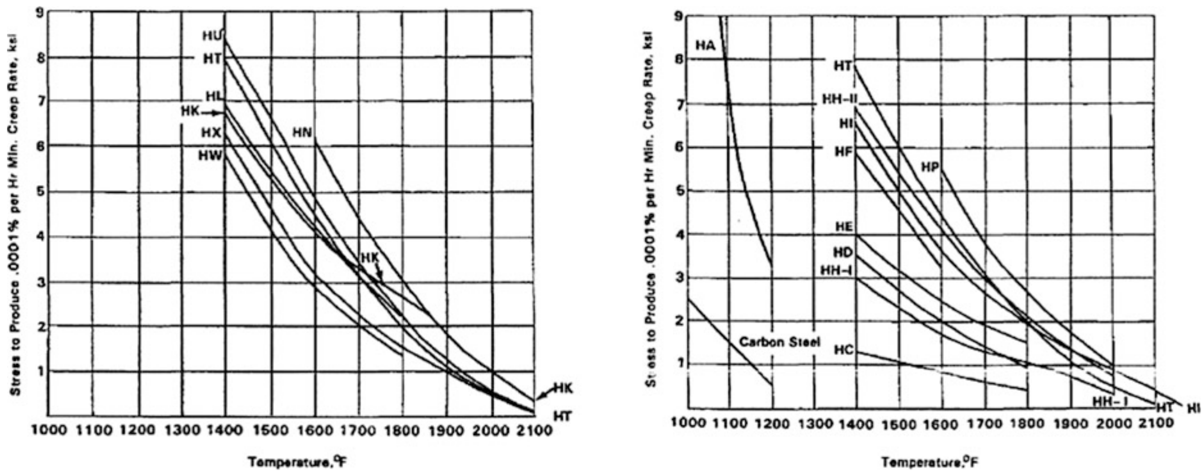


Figure 2.82 Creep strength of heat-resistant alloy castings. (Source: NiDI Publ. 266) – HT curve is included in both graphs for ease of comparison

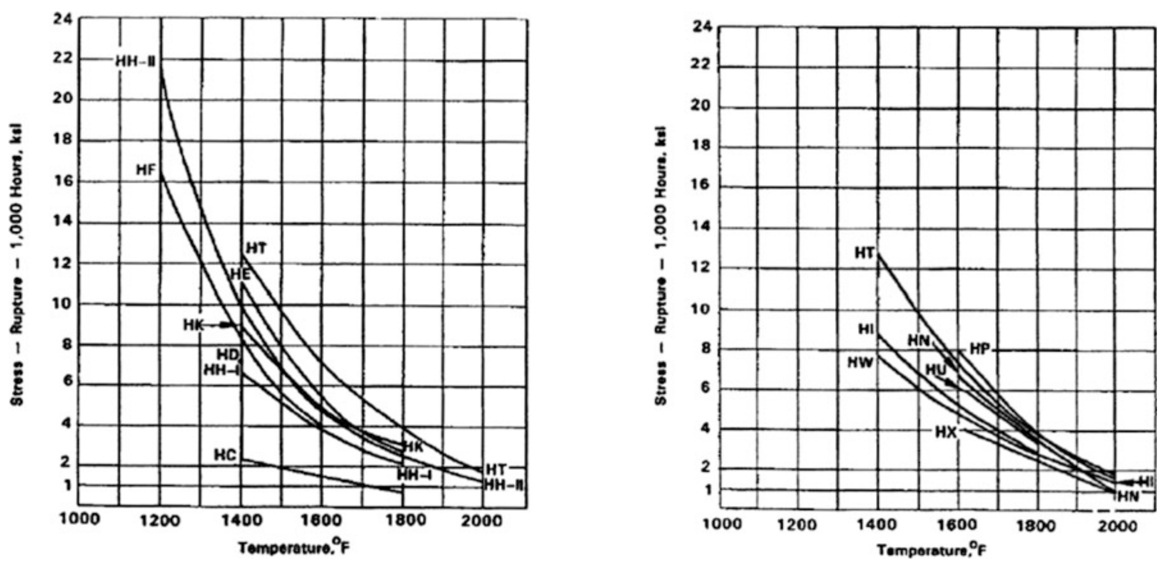


Figure 2.83 100,000-hour stress-rupture properties of heat-resistant alloy castings. (Source: NiDI Publ. 266) – HT curve is included in both graphs for ease of comparison

High-temperature corrosive conditions may involve simple oxidizing or reducing atmospheres; however, it may be able to be complicated by sulfur compounds in the products of combustion. Oxidizing flue gases are slightly more corrosive than air if the sulfur concentration is low. Corrosive attack by reducing flue gases is similar to that of an oxidizing gas if the sulfur content is not greater than 100 ppm. At higher sulfur concentrations, attack by reducing gas is much more severe. The high nickel alloys, types HN to HW, give good service under oxidizing and reducing conditions if the sulfur content of the gas is low. Figures 2.82, 2.83, and 2.84 show the creep-rupture strength of several "H"-type alloys.

Types HH and HL, e.g., should be considered for service in sulfur-bearing atmospheres.

Cyclic heating under reducing conditions increases metal loss in alloys containing from 10 to 50% Ni.

Under oxidizing conditions, cyclic heating has little effect in alloys containing more than 20% Ni.

Different corrosive conditions are encountered with equipment contacted with fused salts or molten metals. Types HT to HX should be considered for service under these conditions. Still other conditions are met in the chemical, petroleum, and petrochemical industries where new processes with new corrosive conditions are constantly under development.

Figures 2.84, 2.85, 2.86, and 2.87 show nickel and carbon effects to carburization of several "H"-type alloys.

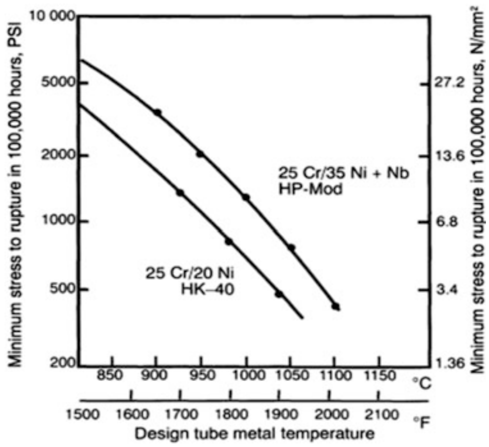


Figure 2.84 Average stress data plot minimum creep rupture stress in 100,000 hrs. (Source: NiDI Publ. 10058)

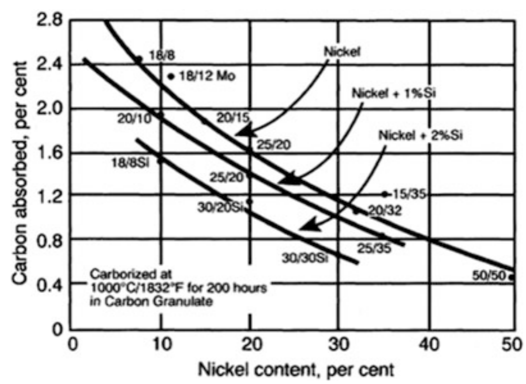


Figure 2.85 Effect of nickel on the resistance of Cr-Ni alloys to carburization. (Source: NiDI Publ. 10058)

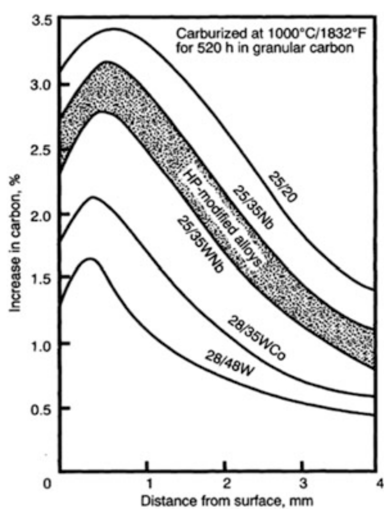


Figure 2.86 Carbon absorption in Cr-Ni alloys: beneficial role of Ni Cr and W is evident in steam cracking furnace. (Source: NiDI Publ. 10058)

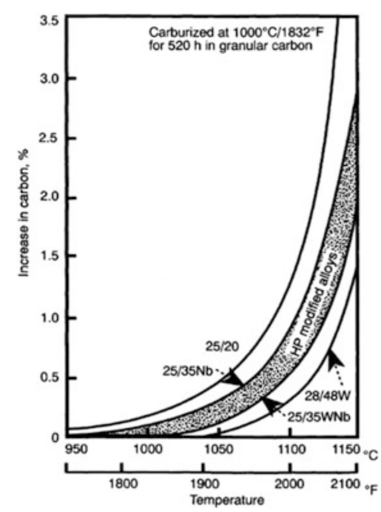


Figure 2.87 Rate of carbonization roughly doubles for every 55 °C (100 °F) increase in temperature in steam cracking furnace. (Source: NiDI Publ. 10058)

(c) Limitations of Corrosion Resistance in Nickel Alloys

1. Sulfur Embrittlement

Nickel combines with sulfur at elevated temperatures to form a brittle sulfide. This phenomenon takes place preferentially at the grain boundaries, and results in embrittlement that exhibits itself as a network of cracks when the material is stressed or bent. Nickel is affected most, Ni-Cu somewhat less, and Ni-Cr-Fe still less affected, Ni-Cu somewhat less, and Ni-Cr-Fe still less.

The more sulfur present or the higher the temperature, the more rapid and deep will be the attack. Material which has been sulfur-embrittled cannot be salvaged. It must be scrapped. Prior to any operation which involves heating to a higher temperature, such as welding, brazing, annealing, hot forming, and forging, it is imperative to remove all sulfur-containing substances, such as oil, grease, marking pencil marks, paint, and drawing or threading lubricants. In addition, the atmosphere of the furnace in which heating is done should be essentially sulfur free. A city gas or natural gas containing less than 25 grains of sulfur per 100 ft^3 (2.8 m^3) or a fuel oil containing less than 0.5% sulfur will be satisfactory for heating. Coal and coke are not satisfactory. Therefore, the welding electrodes should be carefully selected in sulfur containing high-temperature service, as seen in Table 4.95. Table 2.14 lists the normal limits of service temperatures in ASME.

2. Lead Embrittlement
   Lead causes embrittlement in all nickel-base alloys in much the same manner as sulfur. Lead-containing drawing or threading lubricants must be removed prior to a heating operation. Welding must not be done adjacent to or over soft solder. Buttering of threads with a lead-containing anti-galling compound is to be avoided if the temperature of operation exceeds 204 °C (400 °F) or if seal welding is done.
3. IGC (Intergranular Corrosion Cracking)
   Figure 2.88 shows the sensitization curves of several nickel-based alloys. The mechanism is the same as that of ASS (see Sect. 2.1.6.3). The right side of each curve indicates the zone of carbides precipitations.

(d) Characteristics of Corrosion-Resistant Ni Alloy Castings
   In the heat-treating industry, only the high Ni-Cr alloys give satisfactory service under nitriding conditions. Another important process in the heat treating industry is carburization, which is considered in some detail below. Fe-based corrosion-resistant alloys can be classified according to composition and metallurgical structure into four broad groups: See Table 2.72 for chemical compositions of corrosion-resistant high-alloy casting steels and nickel-based alloys.
   (i) MSS
   (ii) FSS
   (iii) PHSS
   (iv) ASS
   (v) Nickel
   (vi) Ni-Cu alloys
   (vii) Ni-Mo alloys
   (viii) Ni-Cr alloys

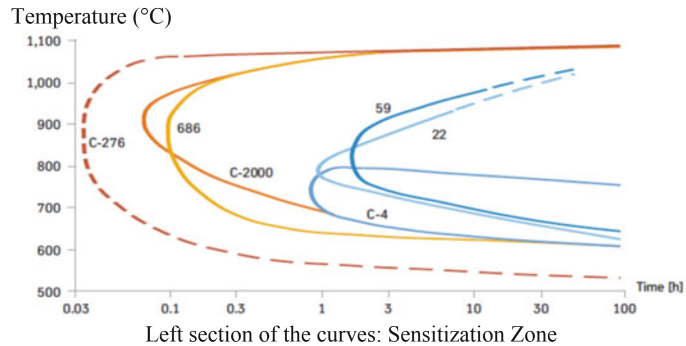


Figure 2.88 Time-temperature sensitization of nickel alloys. (Source: Thyssenkrupp technical report, 2008)

In addition, Ni-based corrosion-resistant alloys include Ni, high-Ni-Cu alloys, high-Ni-Cr alloys and other proprietary alloys. Table 2.73 shows major use and application of corrosion-resistant high-alloy casting steels and nickel-based alloys

Table 2.72 (1/2) Chemical compositions of corrosion-resistant high-alloy casting steels and nickel alloys

Cast alloy designation	Alloy family	Wrought alloy type (a)	Composition, % (b)								
			C	Mn	Si	P	S	Cr	Ni	Fe	Other elements
Stainless steels (high alloy steels)											
CA-6NM	MSS		0.16	1.00	1.00	0.04	0.03	11.5–14	3.5–4.5	Bal	0.4–1.0Mo
CA-15		410	0.15	1.00	1.50	0.04	0.04	11.5–14	1.0	Bal	
CA-15M			0.15	1.00	0.65	0.04	0.04	11.5–14	1.0	Bal	0.15–1.0Mo
CA-40		420	0.2–0.4	1.00	1.50	0.04	0.04	11.5–14	1.0	Bal	
CB30	FSS	442	0.30	1.00	1.50	0.04	0.04	18–21	2.0	Bal	
CB7Cu	PHSS	17-4PH	0.07	1.00	1.00	0.04	0.04	15.5–17	3.6–4.6	Bal	2.3–3.3Cu
CC50	FSS	446	0.50	1.00	1.50	0.04	0.04	26–30	4.0	Bal	
CD4MCu	DSS	25–5 DSS	0.04	1.00	1.00	0.04	0.04	25–26.5	4.75–6.0	Bal	1.75–2.25Mo, 2.75–3.25Cu
CE30	ASS		0.30	1.50	2.00	0.04	0.04	26–30	8–11	Bal	
CF3		304L	0.03	1.50	2.00	0.04	0.04	17–21	8–12	Bal	
CF8		304	0.08	1.50	2.00	0.04	0.04	18–21	8–11	Bal	
CF20		302	0.20	1.50	2.00	0.04	0.04	18–21	8–11	Bal	
CF3M		316L	0.03	1.50	1.50	0.04	0.04	17–21	9–13	Bal	2.0–3.0Mo
CF8M		316	0.08	1.5	1.50	0.04	0.04	18–21	9–12	Bal	2.0–3.0Mo
CF8C		347	0.08	0	2.00	0.04	0.04	18–21	9–12	Bal	Cb $\geq$ 8xC, <1.0
CF16F		303	0.16	1.50 1.50	2.00	0.17	0.04	18–21	9–12	Bal	1.5Mo,0.20–0.35Se
CG8M		317	0.08	1.50	1.50	0.04	0.04	18–21	9–13	Bal	
CH20		309	0.20	1.50	2.00	0.04	0.04	22–26	12–15	Bal	
CK20		310	0.20	1.50	1.75	0.04	0.04	23–27	19–22	Bal	
CN7M		320	0.07	1.50	1.50	0.04	0.04	19–22	27.5–30.5	Bal	3.4–4.0Cu

Table 2.72 (2/2) Chemical compositions of corrosion-resistant high-alloy casting steels and nickel alloys

Cast alloy designation	Alloy family	Wrought alloy type (a)	Composition, % (b)								
			C	Mn	Si	P	S	Cr	Ni	Fe	Other elements
Nickel-based alloys											
CZ-100	Ni	N02100	1.00	1.50	2.00	0.03	0.03	–	Min. 95	3.0	<1.25Cu
M25S	Ni-Cu	N24025	0.25	1.50	3.5–4.5	0.03	0.03	–	Bal	3.5	27-33Cu
M30C		N24130	0.30	1.50	1.0–2.0	0.03	0.03	–	Bal	3.5	26-33Cu, 1.0–3.0Nb
M30H		N24030	0.30	1.50	2.7–3.7	0.03	0.03	–	Bal	3.5	27-33Cu
M35-1		N24135	0.35	1.50	1.25	0.03	0.03	–	Bal	3.5	26-33Cu, Nb < 0.5
M35-2		N24020	0.35	1.50	2.0	0.03	0.03	–	Bal	3.5	26-33Cu, Nb < 0.5
N3M	Ni-Mo	J30003	0.03	1.00	0.50	0.04	0.03	1.0	Bal	3.0	
N7M		J30007	0.07	1.00	1.00	0.04	0.03	1.0	Bal	3.0	
N12MV		N30012	0.12	1.00	1.00	0.04	0.03	1.0	Bal	3.0	0.2–0.6V
CU5MCuC	Ni-Cr	N08826	0.05	1.00	1.00	0.03	0.03	19.5–23.5	38.0–44.0	Bal	1.5–3.5Cu, 0.6–1.2Nb
CW2M		N26455	0.02	1.00	0.80	0.03	0.03	15.0–17.5	Bal	2.0	W < 1.0
CW6M		N30107	0.07	1.00	1.00	0.04	0.03	17.0–20.0	Bal	3.0	
CW6MC		N26625	0.06	1.00	1.00	0.015	0.03	20.0–23.0	Bal	5.0	3.15–4.50Nb
CW12MW		N30002	0.12	1.00	1.00	0.04	0.03	15.5–17.5	Bal	4.5–7.5	3.75–5.25W, 0.2–0.4V
CX2M		N26059	0.02	1.00	0.50	0.02	0.03	22.0–24.0	Bal	1.5	
CX2MW		N26022	0.02	1.00	0.80	0.025	0.03	20.0–22.5	Bal	2.0–6.0	2.5–3.5W, V < 0.35
CY40		N06040	0.40	1.50	3.00	0.03	0.03	14.0–17.0	Bal	11.0	
CY5SnBiM	Other	N26055	0.05	1.50	0.50	0.03	0.03	11.0–14.0	Bal	2.0	3.5–5.0Bi, 3.0–5.0Sn

Notes: (source: ACI, ASTM, ASME Sec. II, UNS, AWS, etc.)
(a) Wrought alloy type numbers are AISI designations for grades most closely corresponding to casting alloys. Wrought alloy type numbers are given only as a guide for determining corresponding cast and wrought grades. Buyers should use cast alloy designations when specifying castings
(b) Maximum unless range is given

Table 2.73 (1/2) Use of corrosion-resistant high-alloy casting steels and nickel-based alloys

ACI (UNS) designation	Formula	ASTM	Application
CA-6NM (J91540)	12Cr-4Ni-0.7Mo	A487 A351	Major use in large hydraulic turbine runners for power generation; other uses include casings, compressor impellers, diaphragms, discharge spacers, impulse wheels, packing housings, propellers, pump impellers, suction spacers, valve bodies and parts in chemical marine, petrochemical, pollution control, and power plant industries.
CA-15 (J91150) CA-15M(J91151)	12Cr-1Ni-0.5Mo-<0.15C	A217 A743	Burning torch gas distributor heads, bushings & liners, catalyst trays, fittings, furnace burner tips & pilot cones, gears, hydration parts, impellers, jet engine components, letters, plaques, pump casings, railings, shafts, ship propellers, skimmer ladles, stuffing boxes, turbine blades, valve bodies, valve trims.
CA-40 (J91153)	12Cr-1Ni-0.5Mo-0.3C	A743	Various castings used in food processing, glass, oil refining, power plants, pulp & paper making.
CB7Cu-1/2 (J92180/J92110)	16Cr-4Ni-3Cu	A747	Various castings where machining is involved; in aerospace, aircraft, chemical, food processing, gas turbine, marine, petrochemical, pulp & paper industries.
CB-30 (J91803)	20Cr	A743	Various castings used in chemical processing, food processing, heat treating, oil refining, ore roasting, and power plant equipment.
CC-50 (J92615)	28Cr	A743	Various castings used in chemical manufacturing, mining, pulp & papermaking, and synthetic fiber manufacturing equipment.
CD-4MCu (J93370/J93372)	26Cr-5Ni-2Mo-3Cu	A351 A743 A744	Various castings used in the chemical processing, marine, municipal water supply, paint, petroleum refining, power plant, pulp & paper, soap & detergent manufacturing, textile & transportation industries.
CE-30 (J93423)	29Cr-9Ni	A743	Various castings used in chemical processing, mining, oil refining, pulp & papermaking, synthetic fiber manufacturing.
CF-3 (J92500) CF-3A	19Cr-10Ni		Widely used in riverboat service, beverage, brewery, distillery, food, heavy water manufacturing, marine, nuclear power, petroleum, pipeline, soap & detergent.
CF-3M (J92800) CF-3MA	19Cr-11Ni-2.5Mo		Mixer parts, pump casings & impellers, tubes, valve bodies and parts requiring field welding where postweld treatment is inconvenient or impossible.
CF-8 (J92600) CF-8A	19Cr-9Ni	A743 A744 A351	Various castings used in the aircraft, aerospace, architectural, beverage & brewing, brass mill, chemical processing, electronic food processing, marine, military and naval, nuclear power, oil refining, oxygen manufacturing, pharmaceutical, photographic, plastics, power plant, pulp & paper, sewage, soap manufacturing, steel mill, synthetic fiber and textile industries

Table 2.73 (2/2) Use of corrosion-resistant high-alloy casting steels and nickel-based alloys

ACI (UNS) designation	Formula	ASTM	Application
CF-8C (J92710)	19Cr-10Ni-1Nb		Various castings used in the aircraft, nuclear, chemical processing, marine, oil refining & plastic industries.
CF-8M (J92900) CF-12M	19Cr-10Ni-2.5Mo		Various castings for use in aircraft, chemical processing, electronic, nuclear, fertilizer, food, marine, mining, oil refining, guide missile, pharmaceutical, medical body implants, photographic, plastics, power plant, soap, synthetic fiber, synthetic rubber, and textile industries.
CF-16F (J92701)	19Cr-10Ni-0.3Se-0.12C	A743	Bearings, bushings, fitting, flanges, machinery parts, pump casings, and valves.
CF-20	19Cr-9Ni-0.20C	A743	Various castings used in the architectural, chemical processing, explosives manufacturing, food and dairy, marine, oil refinery, pharmaceutical, power plant, pulp & paper and textile industries.
CG-8M (J93000)	19Cr-11Ni-3.5Mo	A743 A744	Dyeing equipment, flow meter components, propellers, pump parts, valve bodies and parts used in heavy water manufacturing, nuclear, petroleum, pipeline, power, pulp & papermaking, and printing & textile industries.
CH-10 CH-20 (J93402)	24Cr-13Ni	A743 A351	Digester fittings, pump and parts, roasting equipment, valves and water strainers for use in chemical processing, power plants, and pulp & papermaking.
CK-20 (J94202)	25Cr-20Ni	A743 A351	Various castings used in special service conditions at high temperatures where specific requirements warrant the cost, in aircraft, chemical processing, oil refining, and pulp & paper manufacturing.
CN-7M (J08007) CN-7MS	20Cr-29Ni-2.5Mo-0.5Cu	A743 A744 A351	Various castings used in chemical processing, metal cleaning and plating, mining, munitions manufacturing, oil refining, paint and pigment, pharmaceutical, plastics, pulp and paper, soap and detergent, steel mill, synthetic rubber, textile and dye industries.
Illium P	28Cr-8Ni-2Mo-3Cu		Castings used in phosphoric acid and other chemicals.
Illium PD	27Cr-5Ni-2.5Mo-7Co		Castings used in food processing, chemical, alumina refining, pulp and papermaking industry.

Source: ACI/ASTM/UNS

Codes and Standards

- ASTM B160, B163, B165, B333, B335, B336, B369, B466, B474, B514, B619, B622, B626, B637, B705, B710, B751, B755, B829, B983
- ASTM STP-368, 458, 551, 633, 639, 681, 728, 754, 815, 824, 830, 917, 939, 966, 1023, 1132, 1245, 1295, 1354, 1423, 1467, 1471, 1505, 1529, 1543, 1597
- AWS A5.11(M) Nickel and Nickel Based Alloy Welding-SMAW, A5.14(M) Nickel and Nickel Alloy Welding Electrodes/Rods, G2.1 (M) Guide of the Joining of Wrought Nickel-based Alloys
- ASME B31.3 Process Piping/ASME B31.1 Power Piping/ASME Sec. II-D Properties

References

- NiDI Publications – Several Publications
- Several papers in Nuclear Engineering Technology (http://www.journals.elsevier.com/nuclearengineering-and-technology/)
- Several papers in NACE – Corrosion, Papers, and Materials Performance (https://www.nace.org)
- Nickel Based Alloys Suppliers' Technical Reports and Data Sheets

2.1.7.2 Copper and Copper-Based Alloys

(a) Characteristics

Copper and its alloys constitute one of the major groups of commercial metals. They are widely used because of their excellent electrical and thermal conductivity, outstanding resistance to corrosion (especially against chloride containing service), and ease of fabrication, together with good strength and fatigue resistance. They are generally nonmagnetic. Table 2.74 shows the types and chemical compositions of copper and copper-based alloys.

They can be readily brazed, and many coppers and copper-based alloys can be welded by various gas, arc, and resistance methods. For decorative parts, standard alloys having specific colors are readily available. Copper-based alloys can be polished and buffed to almost any desired texture and luster. They can be plated, coated with organic substances, or chemically colored to further extend the variety of available finishes.

Most wrought alloys are available in various cold-worked conditions, which have room temperature strengths and fatigue resistances that depend on the amount of cold work more than on alloy content. Typical applications of cold-worked conditions (cold worked tempers) include springs, fasteners, hardware, small gears, and cams. Certain types of parts – most notably plumbing fittings and

Table 2.74 Classes of copper and copper-based alloys (per UNS numbers)-Note 1

Groups	UNS numbers	Types and chemical compositions
[Wrought]		
Pure coppers	C10100-C12099	Cu + trace (Ag, As, Sb, P, Te, O_2, Bi, B)
	C12100-C14199	Cu + trace (Ag, As, Sb, P, Te, Bi, Pb, Ni, Fe, Sn, Zn, Cd, C)
	C14200-C15699	Cu + trace (Ag, As, Sb, P, Te, Pb, Ni, Fe, Sn, Zn, Cd, Mn, S, Zr, Mg, Co)
	C15700-C15999	Cu + trace (Al, Fe, Pb, O2, B, C, Ti)
High copper alloys	C16000-C18099	Cu + (Cd, Be) + trace (Ag, Fe, Sn, Ni, Co, Cr, Si, Be, Pb, Cd, Al, Zr, Mg, Te, Zn, P, Ti)
	C18100-C18899	Cu + (Cr) + trace (Ag, Fe, Sn, Ni, Co, Si, Be, Pb, Mg, Zr, Cd, Al, Zn, As, Ca, Li, P, T)
	C18900-C19199	Cu + trace (Ag, Fe, Sn, Ni, Co, Cr, Si, Be, Pb, Al, Mn, P, Zn, Mg, Zr)
	C19200-C19999	Cu + (Fe) + trace (Sn, Zn, Al, Pb, P, B, Ni, Mn, Si, Mg, Ti, Co)
Brasses	C20000-C29999	*Yellow Brasses*: Cu + Zn + trace (Pb, Fe, Si, Al, As, P, Sn, B, S, Zr, Mn, C, Sb, Ti)
	C30000-C39999	*Leaded Brasses*: Cu + Zn + Pb + trace (Fe, Ni, P, As, Sn, Al, Sb)
	C40000-C49999	*Tin Brasses*: Cu + Zn + Sn + trace (Pb, Fe, P, Ni, Mn, Se, Te, As, Sb, Al, Bi, Cd, Si, B)
Bronzes (including Silicon Brasses)	C50000-C52999	*Phosphor Bronzes*: Cu + Sn + P (Pb, Fe, Zn, Zr, Ni, Co, Mn)
	C53000-C54999	*Leaded Phosphor Bronzes*: Cu + Sn + Pb + P + trace (Fe, Zn, Mn, Ni)
	C55000-C55299	*Brazing Alloys*: Cu + (Ag) + P
	C55300-C60799	Cu + (Ag) + (Zn) + others/trace (P, Si, Sn, Ni, P, Sn, Al, Fe)
	C60800-C64699	*Aluminum Bronzes*: Cu + Al + trace (Ag, Pb, Fe, Zn, Sn, Mn, Si, Ni, Al, As, P, Sb, Mg, Cr, Co)
	C64700-C66199	*Silicon Bronzes and Silicon Brasses*: Cu + Si + trace (Ag, Pb, Fe, Sn, Zn, Mn, Si, Ni, Mg, Ca, Cr, P, Zr, Ti, Zr, Al, Co)
	C66200-C69999	Cu + (Zn) + (Mn) + (Al) + trace (Ag, Pb, Fe, Sn, Ni, Si, P, Co, Nb, Ti, Zr, As, Sb, Cd, Zr, C)
Copper-nickel	C70000-C73499	Cu + Ni + trace (Ag, Pb, Fe, Zn, Sn, Mn, Si, Mg, P, Ca, Cr, Zr, Al, Co, C, S, Ti, Be, Hg, Nb, Sb, Bi, B)
Nickel-silver	C73500-C79999	Cu + Ag + Ni + trace (Pb, Fe, Zn, Mn, Sn, Al, P, Si)
[Castings] See Table 2.100a for more details on the applicable ASTM standards		
Pure coppers	C80000-C81399	Cu + trace (As, Ag, B, Be, Co)
High copper alloys	C81400-C83299	Cu + (Be) + others/trace (Ag, Co, Si, Ni, Fe, Al, Sn, Pb, Zn, Cr)
Brasses (including silicon brasses)	C83300-C83999	Cu + Zn + Sn + Pb + trace (Fe, Sb, As, Ni, S, P, Al, Si, Mn)
	C84000-C84999	Cu + Zn + Sn + (Pb) + trace (Fe, Sb, Ni, S, P, Al, Bi, B, Mn, Zr, C, Ti)
	C85000-C85999	*Yellow Brasses*: Cu + Zn + Sn + Pb + trace (Fe, Sb, Ni, Mn, As, S, P, Al, Si, Be, B, Zr, Ti, C)
	C86000-C86999	*High Strength Yellow Brasses*: Cu + Zn + Al + Mn + Pb + (Fe) + (Ni) + Sn + trace (Si)
	C87000-C87999	*Silicon Bronzes and Silicon Brasses*: Cu + Zn + Si + trace (Sn, Pb, Fe, Al, Mn, Mg, Ni, S, P, As, Sb, P)
	C88000-C89999	Copper-Bismuth and Copper-Bismuth-Selenium Alloys: Cu + Bi + (Se) + Sn + Zn + trace (Pb, Fe, Sb, Ni, S, P, Al, Si, B, Cd, Mn)
Bronzes	C90000-C91999	*Tin Bronzes*: Cu + Sn + Zn + trace (Pb, Zn, Fe, Sb, Ni, S, P, Al, Si, Mn, B, Zr, C, Ti)
	C92000-C92900	*Leaded Tin Bronzes*: Cu + Sn + Pb + Zn + trace (Fe, Sb, Ni, S, P, Al, Si, Mn)
	C93000-C94500	*High-Leaded Tin Bronzes*: Cu + Pb + Sn + others/trace (Zn, Fe, Sb, Ni, S, P, Al, Si)
	C94600-C94999	*Nickel-Tin Bronzes*: Cu + Sn + Ni + Zn + (Pb) + trace (Fe, Sb, Mn, S, P, Al, Si)
	C95000-C95999	*Aluminum Bronzes*: Cu + Al + (Fe) + (Mn) + (Ni) + trace (Pb, Mg, Si, Zn, Sn, Cr, Co, P)
Copper-nickel	C96000-C96999	*Copper-Nickels*: Cu + Ni + (Sn) + Fe + trace (Pb, Mn, Si, Nb, C, Be, P, S, Ti, Zr, Mg, Sn, Zn)
Nickel-silver	C97000-C97999	*Nickel Silvers*: Cu + Ag + Ni + (Zn) + Pb + Sn + others/trace (Fe, Sb, S, P, Al, Mn, Si)
Leaded copper	C98000-C98999	Copper-Lead Alloys: Cu + Pb + (Ag) + trace (Sn, Zn, P, Fe, Ni, Sb)
Special alloys	C99000-C99999	Special Alloys: Cu + Ni + (Mn) + others/trace (Sn, Pb, Fe, Al, Co, Si, Zn, C, Bi, P)

Notes: Source: CDA & UNS
1. Properties of Wrought and Cast Copper-Based Alloyshttp://www.copper.org/resources/properties/db/CDAPropertiesSelectionServlet.jsp?mode=basic
2. See Table 2.100a for Cast Copper-Based Alloys

valves – are produced by hot forging simply because no other fabrication process can produce the required shapes and properties as economically.

Copper and its alloys are relatively good conductors of electricity and heat. In fact, copper is used for these purposes more often than any other metal. Alloying invariably decreases electrical conductivity and, to a lesser extent, thermal conductivity. For this reason, coppers and high copper alloys are preferred over copper-based alloys containing more than a few percent total alloy content when high electrical or thermal conductivity is required for the application.

Meanwhile, copper surface turns green (from the initial red color Cu_2O cuprous oxide) when exposed to oxygen, water, or moisture condensation or rain, and the level of pollution (e.g., sulfur, sulfates, CO_2, etc.) in the atmosphere (Fig. 2.89), while cupric oxide (CuO) surface turns black after heating at 300 °C (572 °F) or above. Traditionally, copper, which is based on Cu_2O scale, exhibits good corrosion resistance in urban, marine, and industrial atmospheres. The surface colors change per the following chemical reactions:

Chemical reaction 1: $4Cu + O_2 \rightarrow 2Cu_2O$ [red to pink]
Chemical reaction 2: $2Cu_2O + O_2 \rightarrow 4CuO$ [black]
Chemical reaction 3: $Cu + S \rightarrow CuS$ [black]
Chemical reaction 4: $2CuO + CO_2 + H_2O \rightarrow Cu_2CO_3(OH)_2$ [malachite-dark green to blue]
Chemical reaction 5: $3CuO + 2CO_2 + H_2O \rightarrow Cu_3(CO_3)_2(OH)_2$ [azurite-blue to purple]
Chemical reaction 6: $4CuO + SO_3 + 3H_2O \rightarrow Cu_4SO_4(OH)_6$ [brochantite-dark green to emerald]

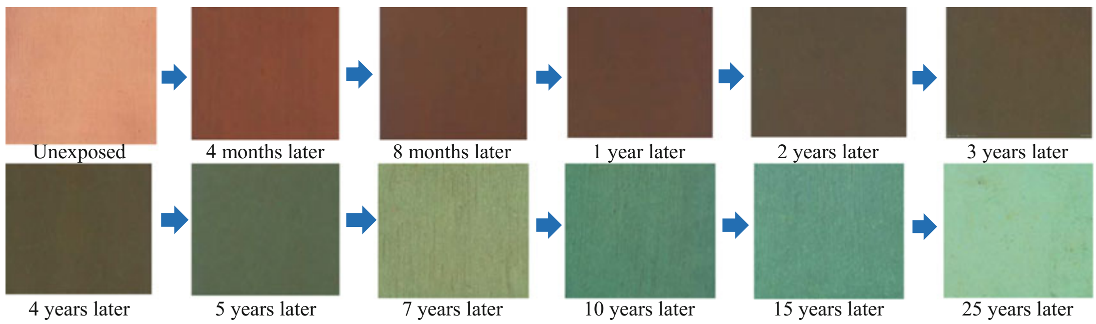


Figure 2.89 Color transformation of copper surface in the atmosphere. (Source: Metal-Architecture report, May 2007)

After exposure of copper to the atmosphere, the bright copper surface takes on a dull tan tarnish due to the copper oxidize.After a few years, this tarnish gradually changes to dark brown or black. At a later stage, the corrosion products of copper turn green due to the formation of copper sulfate, carbonate, and chloride salts in varying concentrations (called as Patina). See Figs. 2.90 and 2.91.

Figure 2.90 Copper roof on the Minneapolis City Hall, coated with patina. (Source: Wikipedia)

Figure 2.91 The Statue of Liberty (copper surface coated with patina)

Patina, which is a coating of various chemical compounds such as oxides, carbonates, sulfides, or sulfates that form on copper or its alloy surface during exposure to atmospheric elements, can provide a protective covering to materials that would otherwise be damaged by corrosion or weathering. Patina may also be aesthetically appealing.

Copper alloys are not recommended in the following industrial services.

– Flammable or hazardous service.
– Process stream containing caustic, amines, ammonia or anhydrous ammonia, sour water, wet H_2S, or mercury. However, aluminum bronze (UNS C61300) or inhibited admiralty brass (UNS C44300) may be used in wet H_2S service if amine or ammonia is not present. Cupronickel is highly susceptible to attack in wet H_2S service where the Al-brass is almost resistant. Figure 2.92a, b show the failure and Intergranular Crack (IGC) in wet H_2S (sour) service. Typically, most copper-based alloys can undergo severe metal loss if the service contains oxygen.

Figure 2.92 Failure of Cupronickel (90Cu-10Ni) tube in wet H_2S service. (**a**) Cracked cupronickel (90:10) tube in wet H_2S service. (**b**) IGC of Cupronickel (90:10) tube

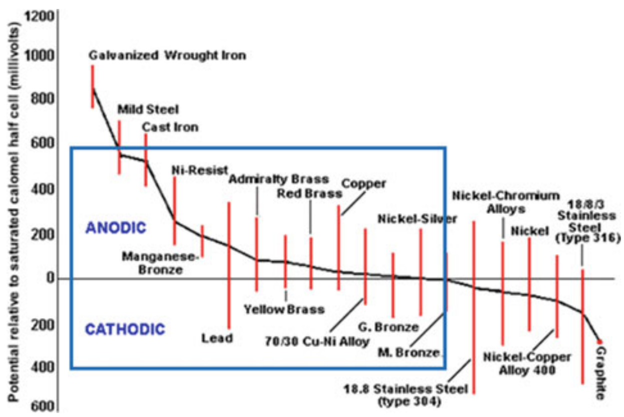


Figure 2.93 Galvanic potentials of several copper-based slloys (in box) in Seawater. (Source: ASM Metal Handbook Vol.13 & 13A-Modified)

Figure 2.93 shows the galvanic potentials of several copper-based alloys in seawater. The use of copper-alloy valves may be desirable in copper-alloy pipe systems to retain galvanic compatibility.

See Fig. 2.146 for the galvanic potential of various metals in seawater.

Table 2.75 shows the characteristics of several major elements in copper and copper alloys.

See Sect. 4.11.10 for welding and Sect. 4.12.3.8 for heat treatment of copper-based alloys.

(b) Copper-Based Alloys in Utility Service

Copper-based alloys have high thermal conductivity as well as very good corrosion resistance in chloride-containing services. Figure 2.94 shows some advantages and associated problems of copper alloys.

Table 2.75 (1/2) Characteristics of several elements in copper-based alloys

Elements	Characteristics
Al (Aluminum)	Cu-Al alloys may contain up to 15% Al as well as additions of Fe, Ni, Sn, and Mn. The solubility of Al in copper is 7.8%, although this is slightly increased with the usual addition of Fe. Alloys with less than 8% Al are single-phase, with or without Fe additions. When Al is between 9 and 15%, the system is two-phase and capable of either a martensitic or a eutectoid type of transformation. Increasing amounts of Al increase tensile strength, increase yield strength and hardness, and decrease elongation of the alloy. Al forms a refractory oxide that must be removed during welding, brazing, or soldering.
As (Arsenic)	As is added to copper alloys to inhibit dezincification corrosion of Cu-Zn alloys in water. As additions to copper alloys do not cause welding problems unless the alloy also contains Ni. As is detrimental to the welding of copper alloys that contain Ni.
Be (Beryllium)	The solubility of Be in copper is approximately 2% at 871 °C (1600 °F) and only 0.3% at room temperature. Therefore, easily forms a supersaturated solution with copper that will precipitate in an age-hardening treatment. Because thermal conductivity and melting point decrease with increasing Be content, the higher Be content alloys are more easily welded. Be forms a refractory oxide that must be removed for welding, brazing, or soldering.
B (Boron)	B strengthens and deoxidizes copper. B-deoxidized copper is weldable with matching filler metals, and other coppers are weldable with B-containing filler metals.
C(Carbon)	Carbon is practically insoluble in copper alloys unless large amounts of iron, manganese, or other strong carbide formers are present. Carbon embrittles copper alloys by precipitating in the grain boundaries as graphite or as an intermetallic carbide.
Cd (Cadmium)	The solubility of Cd in copper is approximately 0.5% at room temperature. The presence of Cd in copper up to 1.25% causes no serious difficulty in fusion welding because it evaporates from copper rather easily at the welding temperature. A small amount of cadmium oxide may form in the molten metal, but it can be fluxed without difficulty. Cd-Cu rod is Resistance Welding Manufacturers Association Class 1 alloy. The small amount of Cd strengthens pure copper while maintaining a very high conductivity. This combination of properties makes this material ideal for electrodes used for resistance welding high-conductivity alloys such as aluminum. Cd-alloyed copper has been largely replaced by an averaged chromium-copper because of federal restrictions regarding the use of heavy metals in manufacturing.

Table 2.75 (2/2) Characteristics of several elements in copper-based alloys

Elements	Characteristics
Cr (Chromium)	The solubility of Cr in copper is approximately 0.55% at 1038 °C (1900 °F) and less than 0.05% at room temperature. The phase that forms during age hardening is almost pure Cr. Cr-Cu can develop a combination of high strength and good conductivity. Like aluminum and beryllium, Cr can form a refractory oxide on the molten weld pool that makes oxyfuel gas welding difficult unless special fluxes are used. Arc welding should be done using a protective atmosphere over the molten weld pool.
Fe (Iron)	The solubility of Fe in copper is approximately 3% at 1038 °C (1900 °F) and less than 0.1% at room temperature. Fe is added to Al-bronze, Mn-bronze, and Cu-Ni alloys to increase their strength by solid solution and precipitation hardening. Iron increases the erosion and corrosion resistance of Cu-Ni alloys. Iron must be kept in solid solution or in the form of an intermetallic to obtain the desired corrosion resistance benefit, particularly in Cu-Ni alloys. Iron also acts as a grain refiner. Iron has little effect on weldability when used within the alloy specification limits.
Mn (Manganese)	Mn is highly soluble in copper. It is used in proportions of 0.05–3.0% in Mn-bronze, deoxidized copper, and Cu-Si alloys. Mn additions are not detrimental to the weldability of copper-based alloys. Mn improves the hot working characteristics of multiphase copper-based alloys.
Ni (Nickel)	Cu & Ni are completely solid soluble in all proportions. Although Cu-Ni alloys are readily welded, residual elements may lead to embrittlement and hot cracking. There must be sufficient deoxidizer or desulfurizer in the welding filler metal used for Cu-Ni to provide a residual amount in the solidified weld metal. Mn is most often used for this purpose.
P (Phosphorus)	P is used as a strengthener and deoxidizer in certain coppers and copper-based alloys. P is soluble in copper up to 1.7% at the eutectic temperature of 649 °C (1200 °F), and approximately 0.4% at room temperature. When added to Cu-Zn alloys, P inhibits dezincification. The amount of P that is usually present in copper-based alloys has no effect on weldability.
Pb (Lead)	Pb is added to Cu alloys to improve machinability or bearing properties and the pressure tightness of some cast Cu alloys. Pb does not form a solid solution with copper and is almost completely insoluble (0.06%) in copper at room temperature. Pb is present as pure, discrete particles and is still liquid at 327 °C (620 °F). Leaded Cu alloys are hot-short and susceptible to cracking during fusion welding. Pb is the most harmful element with respect to the weldability of Cu alloys.
Si (Silicon)	The solubility of Si in copper is 5.3% at 816 °C (1500 °F) and 3.6% at room temperature. Si is used both as a deoxidizer and as an alloying element to improve strength, malleability, and ductility. Cu-Si alloys have good weldability, but are hot-short at elevated temperatures. In welding, the cooling rate through this hot-short temperature range should be fast to prevent cracking. Silicon oxide forms on Cu-Si alloys at temperatures as low as 204 °C (400 °F). This oxide will interfere with brazing and soldering operations unless a suitable flux is applied prior to heating.
Sn (Tin)	The solubility of Sn in copper increases rapidly with temperature. At 788 °C (1450 °F), the solubility of Sn is 13.5%; at room temperature, it is probably less than 1%. Alloys containing less than 2% Sn may be single-phase when cooled rapidly. Cu-Sn alloys tend to be hot-short and crack during fusion welding. Tin oxidizes when exposed to the atmosphere, and this oxide may reduce weld strength if trapped within the weld metal.
Zn (Zinc)	Zn is the most important alloying element used commercially with copper. Zn is soluble in Cu up to 32.5% at 927 °C (1700 °F) and 37% at room temperature. A characteristic of all Cu-Zn alloys is the relative ease that Zn will volatilize from the molten metal with very slight superheat. Zn is also a residual element in Al bronze and Cu-Ni and may cause porosity or cracking, or both.
Others	Calcium (Ca), Magnesium (Mg), Lithium (Li), Sodium (Na), or combinations of these elements are added to copper-based alloys as deoxidizers. Very little of these oxidizing elements remain in copper-based alloys and are seldom a factor in welding. Antimony (Sb), Arsenic (As), Phosphorus (P), Bismuth (Bi), Selenium (Se), Sulfur (S), and Tellurium (Te) may cause hot cracking when alloyed in single-phase aluminum bronze and in copper-nickel alloys. The small amounts of antimony added to brasses have little influence on their weldability.

Source: ASM Metal H/B Vol. 2

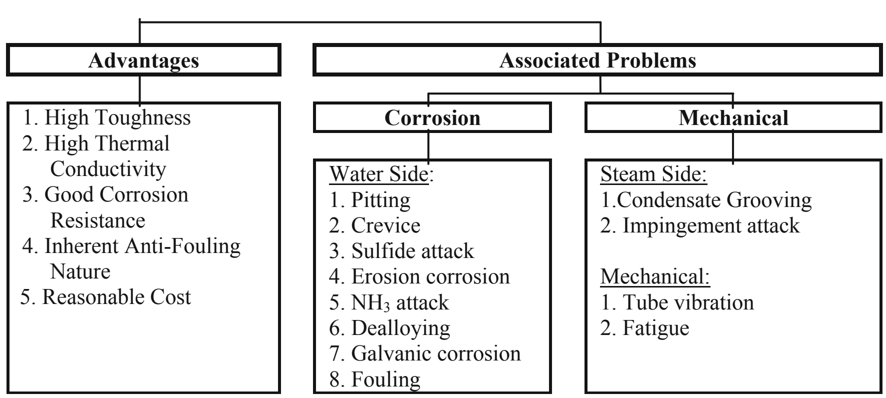


Figure 2.94 Advantage and associated problems of copper-based alloys

(c) Classes of Copper-Based Alloys

Table 2.76 shows the classes of copper alloys used in water containing chlorides. The dezincification (Fig. 2.95) is a major concern in brass materials.

Table 2.77 shows brass and bronze materials used for valve components (ASTM B763)

Table 2.78 shows European Standards for Product Forms in Copper and Copper Alloys

Table 2.79 shows a simple description for use of copper and copper Alloys

Table 2.80 shows the service velocity limitation of copper alloy tubes used for cooling water to avoid erosion-corrosion (Recommendation).

(d) Typical Considerations for Good Practices in Corrosion/Erosion Environment

Table 2.79 gives a simple description of the initial considerations for use of copper and copper-based alloys. For a more in-depth understanding of these and other issues, the reader is referred to the source documents under the table.

Figure 2.95 Dezincification corrosion of brass

Table 2.76 Classes of the most common copper-based alloys in water-containing chlorides (Note 1, 2, 4)

Characters / Materials	Advantage	Disadvantage (except cost)	Use in industries (for seawater or cooling water)	Remarks
Admiralty Brass (71Cu-28Zn-1Sn)	Good corrosion resistance in water and seawater	1. SCC occur in NH_3 and its compound services 2. Dezincification of Admiralty/Naval brass (Zn > 15%) in water or hot dilute alkaline solution 1. Dealumination of Al-brass in water or hot alkaline solution	H/EX Tubes	[Admiralty Brass] Add As, Sb, P (Inhibitor Elements-Inhibited) to prevent Dezincification As: C44300/C46500/ C68700 Sb: C44400 P: C44500 Note: The tubes of process H/EX should be inhibited material
Aluminum Brass [Al-Brass] (76Cu-22Zn-2Al) C68700	Good erosion & corrosion resistance in water and seawater due to alumina film on the metal surface		H/EX Tubes	
Naval Brass (69Cu- 30Zn-1Sn) C46420/C46400	Good corrosion resistance in water and seawater Supplied as a plate type		Tubes, Tubesheet, Baffle of H/EX	
Cupro Nickel (70Cu-30Ni) C71500 (90Cu-10Ni) C70600	Excellent SCC/erosion resistance and high strength		H/EX Tubes	1. See Fig. 2.96
Tungum (84Cu-1.1Ni-1.1Si-1Al-13Zn) C69100	Excellent SCC/erosion resistance and very high strength	Poor Weldability Strength and corrosion resistance will be somewhat reduced after welding.	H/EX Tubes	1. Useful in offshore (splash zone) 2. See Note 3, Figs. 2.97 and 2.98
Ni-Al Bronze (9 to 11Al-2 to 5.5Ni-Fe-Mn-bal.Zn)	Excellent SCC/cavitation/erosion resistance and very high strength	Carefully select the heat treatment condition The retained beta (β) phase (martensitic-	Propeller, Impellers, Shaft, Valve Stem	See ASTM A148/271/ 505 and BS EN 1982

Common Notes:

a. Most copper alloys have an FCC structure and used at cryogenic temperatures, but with limited high temperature (<200–316 °C)

Notes

1. Copper-based alloys require a limitation of fluid velocity, max. 6 ft/sec unless otherwise specified, except Fig. 2.98 for Tungum
   Table 2.80 shows service velocity limitation of several copper based-alloy tubes in cooling water
2. Figure 2.97 shows general strength comparison of several copper-based alloys
3. "Tungum tubing for general use" exceeds the minimum requirements of BS2871 part 2 (CZ127). The specification is available in three ratings:
   – TCL100A: Eddy Current Tested – Standard Specification
   – TCL100B: tested to 310 bar (4500 psi)
   – TCL100C: tested to 465 bar (6750 psi)
4. Table 2.77 shows the required strength of several copper-based alloys for brass and bronze for valve application (ASTM B763)

Table 2.78 shows European standards for product forms in copper and copperbased alloys.

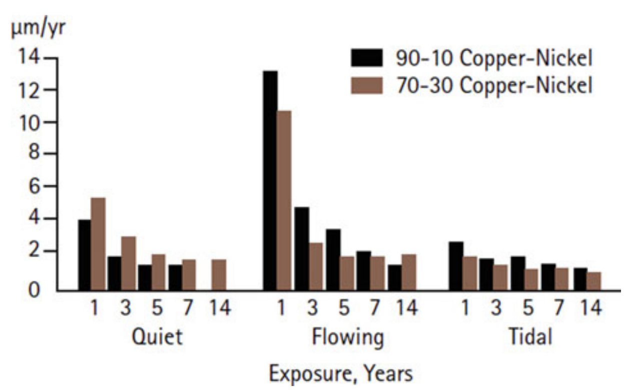


Figure 2.96 One to fourteen years corrosion rate data at LaQue Center for Corrosion Technology, North Carolina, for 90-10 and 70-30 Cu-Ni. (Source: www.coppernickel.org)

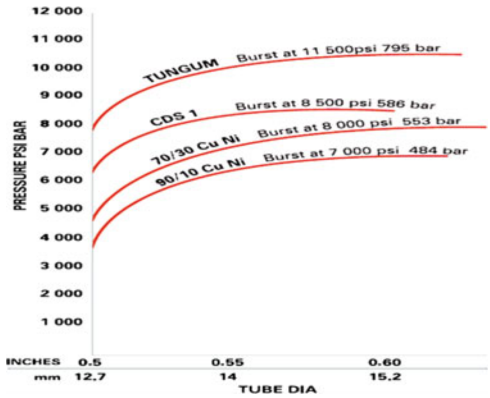


Figure 2.97 Threshold pressures of several copper-based alloys. (Source: Tungum report, 2011)

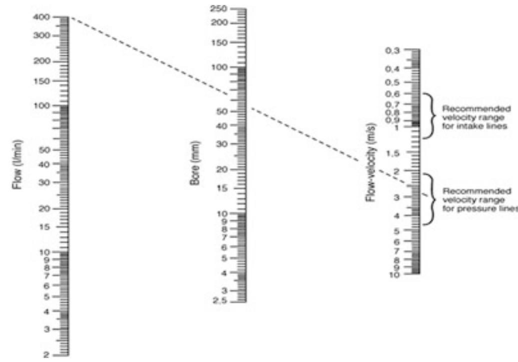


Figure 2.98 Nomograph for recommended velocity of tungum. (Source: Tungum report, 2011)

Table 2.77 Copper-based alloys (brass and bronze) for valve components (ASTM B763)

Classes	UNS no.	Commercial description	SMTS, ksi	SMYS, ksi
Leaded red brass	C83450	88Cu-6.5Zn-2.5Sn-2Pb	30	14
	C83800	83Cu-4Sn-6Pb-7Zn or commercial red brass	30	13
Leaded semi-red brass	C84400	81Cu-3Sn-7Pb-9Zn or valve composition	29	13
	C84800	76Cu-2.5Sn-6.5Pb-15Zn or semi-red brass	28	12
Leaded yellow brass	C85200	High-copper yellow brass, 72Cu-24Zn-3Pb	35	12
	C85400	Commercial No. 1 yellow brass, 67Cu-29Zn-3Pb	30	11
	C85700	Leaded naval brass, 61Cu-37Zn	40	14
High-strength yellow brass	C86200	High-strength manganese bronze, 63Cu-27Zn-4Al-3Fe-3Mn	90	45
	C86300	High-strength manganese bronze, 61Cu-27Zn-6Al-3Fe-3Mn	110	60
	C86400	Leaded manganese bronze, 58Cu-38Zn-1Pb	60	20
	C86500	No. 1 manganese bronze, 58Cu-39Zn-1Pb-1Mn	65	25
	C86700	Leaded manganese bronze, 58Cu-34Zn-1Pb-2Mn-2Al-2Fe	80	32
Silicon bronze and silicon brass	C87300	Silicon bronze, 95Cu-4Si	45	18
	C87400	Silicon brass, 82Cu-14Zn-3.5Si	50	21
	C87500	Silicon brass, 82Cu-14Zn-4Si	60	24
	C87600	Silicon bronze, 89Cu-6Zn-5Si	60	30
	C87610	Silicon bronze, 92Cu-4Zn-4Si	45	18
	C89530	Bismuth-Selenium, 86.5Cu-8Zn-4.7Sn-1.5Bi		
	C89535	Bismuth, 86.5Cu-7Zn-3Sn-1.4Bi		
Bismuth brass	C89720[a]	67.5Cu-29.8Zn-1Sn-0.7Bi	30	16
Bismuth semi-red brass	C89844	Bismuth brass, 84.5Cu-8Zn-4Sn-3Bi	28	13
Tin bronze and leaded tin bronze	C90300	88Cu-8Sn-4Zn or modified “G” bronze	40	18
	C90500	88Cu-10Sn-2Zn, on “G” bronze	40	18
	C92300	87Cu-8Sn-1Pb-4Zn, or Navy PC	36	16
	C92600	87Cu-10Sn-1Pb-2Zn	40	18
High-lead tin bronze	C93200	83Cu-7Sn-7Pb-3Zn	30	14
	C93500	85Cu-5Sn-9Pb-1Zn	28	12
	C93700	80Cu-10Sn-10Pb	30	12
	C93800	78Cu-7Sn-15Pb	26	14
	C94300	71Cu-5Sn-24Pb	24	–
Nickel-tin bronze and leaded nickel-tin bronze	C94700	Nickel-tin bronze grade “A”, 88Cu-5Sn-2Zn-5Ni	45	20
	C94800	Leaded nickel-tin bronze grade “B”, 87Cu-5Sn-1Pb-2Zn-5Ni	40	20
	C94900	Leaded nickel-tin bronze grade “C”, 80Cu-5Sn-5Pb-5Zn-5Ni	38	15
Aluminum bronze	C95200	Grade A, 88Cu-9Al-3Fe	65	25
	C95300	Grade B, 89Cu-10Al-1Fe	65	25
	C95400	Grade C, 85Cu-11Al-4Fe	75	30
	C95410	84Cu-10Al-4Fe-2Ni	75	30
Silicon aluminum bronze	C95600	Grade E, 91Cu-7Al-2Si	60	28
Nickel aluminum bronze	C95500	Grade D, 81Cu-11Al-4Ni-4Fe	90	40
	C95800	81.3Cu-9Al-4.5Ni-4Fe-1.2Mn	85	35
Leaded nickel bronze	C97300	12% leaded nickel silver, 57Cu-20Zn-12Ni-9Pb-2Sn	30	15
	C97600	20% leaded nickel silver, 64Cu-8Zn-20Ni-4Pb-4Sn	40	17
	C97800	25% leaded nickel silver, 66Cu-2Zn-25Ni-2Pb-5Sn	50	22
Special alloys	C99400	87Cu-4.4Zn-3Ni-3Fe-1.6Al-1Si	60	30
	C99500	87Cu-1.5Zn-4.5Ni-4Fe-1.7Al-1.3Si	70	40

Notes; [a]Antimony 0.07, Boron 0.001

Table 2.78 European standards for product forms in copper and copper-based alloys

Product form	EN no.	Standard title
Plate, sheet, strip and circles	1652	Copper and copper alloys. Plate, sheet, strip and circles for general purposes
Strip (springs and connectors)	1654	Copper and copper alloys. Strip for springs and connectors
Seamless tubes	12449	Copper and copper alloys. Seamless, round tubes for general purposes
Seamless heat exchanger tube	12451	Copper and copper alloys. Seamless, round tubes for heat exchangers
Rod	12163	Copper and copper alloys. Rod for general purposes
Wire	12166	Copper and copper alloys. Wire for general purposes
Profiles and rectangular bar	12167	Copper and copper alloys. Profiles and rectangular bar for general purposes
Forgings	12420	Copper and copper alloys. Forgings
Ingots and castings	1982	Copper and copper alloys. Ingots and castings

Table 2.79 A simple description for use of copper and copper-based alloys

Issue	Typical operation	Remark
Galvanic Corrosion	1. Avoid mixed metal connections where the copper-based alloy chosen is the anode, particularly where it has a relatively small surface area 2. Insulate the connection or apply distance piece to stop galvanic connection 3. Coat cathode part.	See Sect. 2.4.1.3, Tables 2.124(8) and 2.138(4)
Erosion due to Velocity	1. Stay within flow velocity guidelines. 2. Avoid tight angle bends, misalignments and other obstructions which can cause areas of local turbulence.	See Table 2.80 for velocity limitation in seawater.
Pitting (in copper-based alloys this is largely due to polluted seawater and brine water)	1. Avoid extended exposure to quiet and stagnant conditions or polluted waters which can encourage sulfides and sulfate-reducing bacteria. 2. Periodically clean systems to remove deposits. 3. Plan and implement good commissioning and startup procedures. Aimed at achieving good surface film formation 4. Ferrous sulfate dosing.	
Stress corrosion cracking (SCC normally due to ammonia or its compounds)	1. Stress relief heat treatment. 2. Cathodic protection if immersed. 3. Select copper-based alloy which has a high resistance.	
Selective phase corrosion	*Brasses* 1. Select alloy composition that is immune to dezincification or is inhibited against it. 2. Cathodic protection. *Aluminum Bronzes* 1. Process to avoid unwanted structural phases. 2. Heat treatment. 3. Build up sound surface films at outset. 4. Galvanic or cathodic protection.	See Tables 2.76, 2.124(13) and 2.138(15) for inhibited brass.
Unexpected levels of fouling (due to polluted seawater and brine water, one through water, SRB contaminated water, etc.)	1. Avoid contamination (by filtering or frequent cleaning). 2. Insulate from galvanic or cathodic protection. 3. Avoid extended exposure in quiet waters (fouling will normally only be loosely attached and readily removed by a light scraping or pressurized water clean before it dries out).	To consider use of DSS, Alloy 825, 6%Mo SS, Alloy 625, Titanium, etc. for H/EX tubes in severe environment.

Sources: Corrosion of Copper and Its Alloys – A Practical Guide for Engineers. R Francis. NACE International. 2009 and Galvanic Corrosion: A Practical Guide for Engineers. R Francis. NACE Press. 2001

Table 2.80 Service velocity limitation of copper alloy tubes in cooling water with seawater (recommendation)

Tube material	Operating velocity limit m/s (ft/s)	
	Min.	Max.
Admiralty brass	1 (3.3)	1.5 (5.0)
Aluminum or copper	1 (3.3)	1.5 (5.0)
Aluminum brass	1 (3.3)	2.4 (8.0)
Aluminum bronze	1 (3.3)	3.0 (10.0)
Cupro-nickel 70/30	1 (3.3)	3.0 (10.0)
Cupro-nickel 90/10	1 (3.3)	2.4 (8.0)

Codes and Standards

- ASTM B16 (Solder Joint Fittings), B68 (Seamless Tube-bright annealed), B75 (Seamless Tubes), B88 (Seamless Water Tubes), B98 (Cu-Si Rods/Bars), B111 (Seamless Condenser Tubes), B171 (Sheets/Plates), B187 (Bus Bars & Rods), B281 (Electroplating/Conversion Coating), B369 (Cu-Ni Castings), B395 (U-Bend Seamless Condenser Tubes), B422 (Copper Alloys Plates/Sheets), B466 (Seamless Cu-Ni Pipe & Tubes), B467 (Welded Cu-Ni Pipes), B584 (Sand Castings), B706 UNS C69100 Seamless Pipes/Tubes, B763 (Sand Castings for Valves), B882 (Pre-Patinated for Architectures),
- ASTM STP- 367, 585, 585A, 831
- ASME B31.3 Process Piping, ASME B31.1 Power Piping, ASME Sec.II-D Properties

References

- NACE Seawater Corrosion Handbook
- NACE Paper 19-13010, 17-9382, 08231, 08229, 08228, 07246, 06299, 05462,05238, 05222, 02196, 00627, 94491, 93636, 92396, 92213, 76146
- NACE MP Nov. 2007, p48-50/Jun. 2006, p38-41/Aug. 1993, (1) Corrosion by Potable Waters in Building Systems, (2) Water Treatment to Mitigate Corrosion of Copper Plumbing Systems/Oct. 1995 Pitting Corrosion of Copper in Cold Potable Water Systems
- NiDI Publications 12003/206/12014/12007/4319/1305/1265/1107/515
- Power Engineering Aug. 1982, p60-062/
- CDA (copper development association) Various Papers, Reports, Guides, Records, Information, and Publications
- Suppliers' Reports & Catalogs (Antimicrobial Copper, Brush Wellman, Tungum Alloy, etc.)
- Others Associations-Various Papers and Publications (Journal of Metal, International Congress on Marine Corrosion & Fouling, Foundation of Water Research, Metal-Architecture, American Water Works Association, etc.)
- Others (Handbooks for Metals, Corrosion, and Welding, etc.)

2.1.7.3 Aluminum Alloys

(a) Characteristics

Pure aluminum is soft, ductile, and corrosion resistant, and has a high electrical conductivity. In consequence it is widely used for foil and conductor cables (air cooler fin, insulation jacket, silo, etc., in oil refinery and petrochemical plants), but alloying with other elements is necessary to provide the higher strengths needed for other applications. Aluminum should not be used in the ammonia or anhydrous ammonia service.

See Sect. 4.11.9 for welding and Sect. 4.12.3.12 for heat treatment of aluminum alloys.

(b) Classes

Table 2.81 shows characteristics, product shapes, and use of several aluminum and aluminum alloys.

Figure 2.99 shows the types and family of aluminum alloys

Table 2.82 shows the temperature limitations (maximum design temperature-Max. DT) of aluminum alloys per the components and materials code for cryogenic service (cold box in LNG plant) in ALPEMA (The Standards of The Brazed Aluminum Plate-Fin Heat Exchanger Manufacturers' Association).

Table 2.83 shows aluminum alloy products available for structural application.

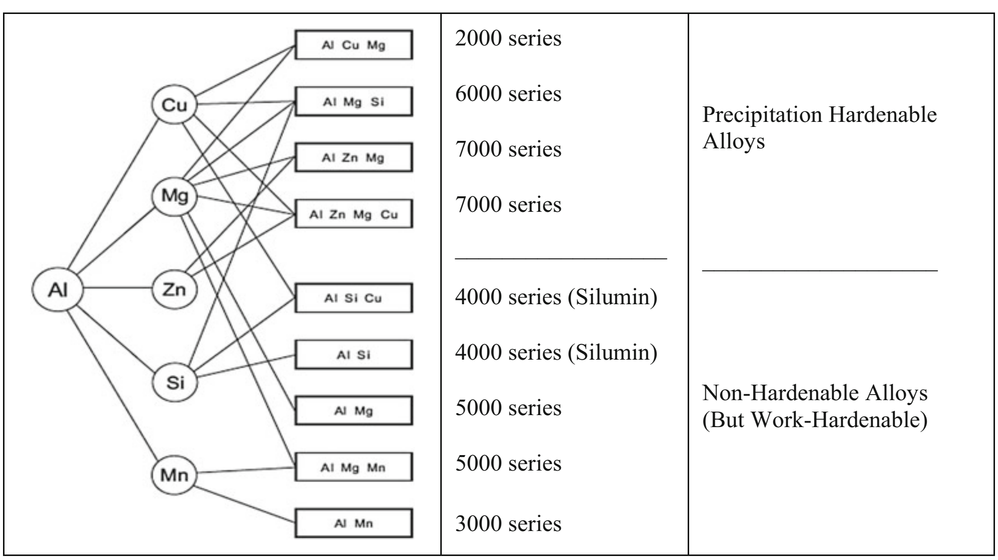


Figure 2.99 Types and families of aluminum alloys. (Source: ASM Metal H/B Vol.2 -modified)

Table 2.81 Classes of aluminum and aluminum alloys(2)

Group	Alloys	Characteristics	Product shapes(1)	Use
Pure aluminum	1080	Good corrosion resistance in atmospheric, good machinability	P, S, T, B, W	Chemical tanks and piping, electric facilities, wire, light facilities, etc.
	1070	Good weldability, low strength		
	1050	Good brightness		
	1100 1200	Good corrosion resistance in atmospheric, good machinability, good weldability, low strength	P, S, T, B, W	Architecture & house facilities, etc.
Corrosion-resistant aluminum alloys	3003 3203 (Al + Mn)	More higher strength than pure aluminum, good corrosion resistance in atmospheric, good machinability, good weldability	P, S, T, B, W	Vehicle, architecture, natural gas cold boxes, etc.
	5052 (Al + Mg)	High strength, poor machinability, good corrosion resistance in seashore environment	P, S, T, B, W	Ships, structures, and architecture
	5056/5083 (Al + Mg)	High strength, poor machinability, good corrosion resistance in seashore environment	P, S, T, B, W	Ships, structures, natural gas cold boxes, etc.
	6061 (Al + Mg + Si)	High strength, good machinability, good weldability, good corrosion resistance in seashore environment, possible the artificial aging	P, S, T	Structures, natural gas cold boxes, etc.
	6063 (Al + Mg + Si)	Good machinability, good weldability, good corrosion resistance in seashore environment, possible the artificial aging, low strength	S, B	Architecture (window frame)
High strength aluminum alloys (Al + Cu)	2014	High strength, poor machinability, poor corrosion resistance, poor weldability, possible the artificial aging	P, S	Structures, furniture, etc.
	2017	High strength, good machinability, poor corrosion resistance, poor weldability	P, S, T, B	Structures, furniture, etc.
	2024	High strength, poor machinability, poor corrosion resistance, poor weldability	P, S, T, B	Structures, aircraft, etc.
Readily weldable aluminum alloys	4043 (Al + Si)	Excellent weldability and good machinability	P, S, W	Architecture, welding electrode
	Al-Zn-Mg (7N01)	Good water corrosion resistance, high strength and good weldability	P, S, T, B	Welding structures

Notes
(1)Abbreviation: P; plate B; bar, T; Tube, W; Wire, S: Shape structure
(2)7000 series: aluminum and zinc. (These are high-strength aerospace alloys that may have other alloying elements added)

Table 2.82 (1/2) Common aluminum alloy materials in cryogenic service (LNG plants)

Components	ASME		DIN		JIS	
	Alloy no.	Max. DT, °C (°F)(1)	Alloy no.	Max. DT, °C (°F)(2)	Alloy no.	Max. DT, °C (°F)(3)
Heat transfer fin	SB209-3003 -3004	204 (400) 204 (400)	Al Mn Cu	65 (150)	H4000-A3003P -A3004P	200 (392) 200 (392)
Distributor fin	SB209-3003 -3004	204 (400) 204 (400)	Al Mn Cu	65 (150)	H4000-A3003P -A3004P	200 (392) 200 (392)
Side bar	SB221-3003	204 (400)	Al Mn Cu	65 (150)	H4000-A3003S	200 (392)
Center bar	SB221-3003	204 (400)	Al Mn Cu	65 (150)	H4000-A3003S	200 (392)
Parting sheet(4)	SB221-3003	204 (400)	Al Mn Cu	65 (150)	H4000-A3003P	200 (392)
Cap sheet	SB221-3003	204 (400)	Al Mn Cu	65 (150)	H4000-A3003P	200 (392)
Header	SB209, 221&241 -3003 -5052 -5083 -5454 -6061	204 (400) 204 (400) 65 (150) 204 (400) 204 (400)	Al Mg 3 Al Mg 4.5 Mn	150 (302) 80 (176)	H4000 -A3003P -A5052P -A5083P -A5454P -A6061P	200 (392) 200 (392) 65 (150) 200 (392) 200 (392)
Nozzle	SB209, 221&241 -3003 -5052 -5083 -5086 -5454 -6061 SB221&241 -6063	204 (400) 204 (400) 65 (150) 65 (150) 204 (400) 204 (400) 204 (400)	Al Mg 3 Al Mg 4.5 Mn	150 (302) 80 (176)	H4000 & 4080 A3003TID&TE-A3003P A5052TID&TE -A5052P A5083TID&TE -A5083P -A5086P A5454TE -A5454P A6061TD&TE -A6061P A6063TD&TE	200 (392) 200 (392) 65 (150) 65 (150) 200 (392) 200 (392) 200 (392)

Table 2.82 (2/2) Common aluminum alloy materials in cryogenic service (LNG plants)

Components	ASME		DIN		JIS	
	Alloy no.	Max. DT, °C (°F)[(1)]	Alloy no.	Max. DT, °C (°F)[(2)]	Alloy no.	Max. DT, °C (°F)[(3)]
Flange	SB247-5083 -6061	65 (150) 204 (400)	Al Mg 4.5 Mn Al Mg 3	80 (176) 150 (302)	H4000-A5083FD -A6061FD	65 (150) 200 (392)
Support	SB209 & 221 -5052 -5083 -6061 -6083	204 (400) 65 (150) 204 (400) 204 (400)	Al Mg 3 Al Mg 4.5 Mn G Al Si7Mg	150 (302) 80 (176) 130 (266)	H4000 -A5052P -A5083P -A6061P	200 (392) 65 (150) 200 (392)

Sources: ALPEMA – modified
Notes
[(1)]Maximum applicable temperature is as per ASME Sec. VIII, Div.1, where the official unit is British (°F)
[(2)]Maximum applicable temperature is as per AD-Merkblatter/Vd-TuV, where the official unit is Metric (°C)
[(3)]Maximum applicable temperature is as per Japanese High Pressure Gas Safety Law, where the official unit is Metric (°C)
[(4)]They *may* be clad

Table 2.83 Aluminum alloy products available for structural application (AWS D1.2, Table 4.1)

Alloy no[(a)]	B209 Sheet, plate	B211 Rolled/ cold finished rod, bar, wire	B221 Extruded rod, bar, wire, profile, tubes	B308 Standard structural profiles	B241	B429	B210	B483	B313 Welded tubes	B361 Welding fittings	B247 Forgings	B26 Sand castings	B108 Permanent mold castings	B618 Investment castings	B686 High-strength castings
					Seamless extruded tubes/pipes		Seamless drawn tubes/pipes								
1000	x	x	x		x		x	x		x					
1100	x	x	x		x		x	x	x	x	x				
2219	x	x	x		x						x				
3003	x	x	x		x		x	x	x	x	x				
Alclad 3003	x		x		x		x			x					
3004	x		x						x						
Alclad 3004	x								x						
5005	x						x	x							
5050	x						x	x	x						
5052	x	x	x		x		x	x	x						
5083	x		x		x		x			x	x				
5086	x		x		x		x		x	x					
5154	x	x					x		x	x					
5254	x		x		x										
5454	x		x		x										
5456	x		x		x		x								
5652	x				x										
6005			x												
6005A			x												
6061	x	x	x	x	x	x	x	x	x	x	x				
Alclad 6061	x														
6063			x		x	x	x	x		x					
6082			x												
6351			x		x										
7005			x												
A201.0															x
354.0													x		x
C355.0												x	x	x	x
356												x	x	x	
A356.0												x	x	x	x
357.0													x		
A357.0													x		x
359.0													x		
443.0												x	x	x	
A440.0													x		
514.0												x		x	
535.0												x	x	x	

Notes;
[(a)]Wrought alloys, 1xxx, 3xxx, 5xxx, and cast alloys 4yy.z, and 5yy.z are non-heat treatable alloys. Wrought alloys, 2xxx, 6xxx, and 7xxx and cast alloys, y2yy.z and y3yy.z are heat treatable alloys

(c) Mercury Embrittlement

Mercury is a natural component of certain hydrocarbon reservoirs, so exposure to liquid mercury can occur in oil and gas production and processing plants.

On 1 January 2004, the Moomba, South Australia, natural gas processing plant operated by Santos suffered a major fire. The gas release that led to the fire was caused by the failure of a heat exchanger (cold box) inlet nozzle in the liquids recovery plant. The failure of the inlet nozzle was due to liquid metal embrittlement of the train B aluminum cold box by elemental mercury.

In oil refineries, mercury is found in some crude oils and can condense in the atmospheric tower overhead system thereby embrittling aluminum exchanger components as well as brass, Alloy 400, titanium components.

Failure of process instruments that utilize mercury can introduce the liquid metal into refinery streams.

Mercury embrittlement that is a significant problem in natural gas facilities using aluminum cold boxes has led to a number of major plant incidents. It has been postulated that the natural passive layer on aluminum provides an effective barrier between droplets of mercury and the underlying aluminum and that this prevents mercury embrittlement. However, under certain circumstances, this barrier breaches and embrittlement can occur. Complete mercury removal [Hg in the gas stream concentration of $<0.01\ \mu g/Nm^3$ ($10\ ng/Nm^3$)] is the best way to prevent the metal (i.e., aluminum and its alloys).

See Sect. 4.11.9.3 for the mercury embrittlement during welding.

Codes and Standards (Excluded Aluminum Anodes)

- ASTM B26 (Sand Castings), B209 (Plates), B210 (Seamless Tubes), B211 (Bars/Rods/Wires), B241 (Seamless Pipes/Extruded Tubes), B345 (Seamless Pipes/Seamless Extruded Tubes), B547 (Welded Round Tubes), B548 (UT of Aluminum Alloy Plate for Pressure Vessels), E716 (Sampling of Aluminum Alloys-Determination of Chemical Composition)
- ASTM STP- 585, 585A, 890, 1134
- AWS A5.3 (M) Aluminum and Aluminum Alloy Welding -SMAW, A5.10 (M) Aluminum and Aluminum Alloy Welding -Electrodes/Rods, B2.1 GTAW of Aluminum, C3.7 Aluminum Brazing, D1.2 Structural Welding Code-Aluminum, D3.7 Aluminum Hull, D8.14 Automotive and Light Truck Components Weld Quality-Aluminum Arc Welding, D10.7(M) GMAW of Aluminum and Aluminum Alloy Pipe
- CSA W47.2 Certification of companies for fusion welding of aluminum, W55.3 Certification of companies for resistance welding of steel and aluminum, W59.20M Welded Aluminum Construction
- API RP571 Part of Liquid Metal Embrittlement (LME)
- API 650, Annex AL Aluminum Storage Tanks
- ASME B31.3 Process Piping, ASME B31.1 Power Piping, ASME Sec. II-D Properties

References (Excluded Aluminum Anodes): For More Detail and/or Use as Check List

- NACE Paper 16-7512/7486/7199, 15-5963/5699/5570/5509, 14-3958/3959/4489, 13-2449, 12-1101/1675, 11316, 11298, 10294, 08206, 07504, 06496, 04719, 04558, 04456, 03600, 03568, 03244, 03006, 02558, 02435, 02138, 02019, 01551, 01146, 00285, 00284, 00276, 00200, 99516, 99515, 99513, 99506, 99477, 99287, 99187, 98740, 98604, 98547, 98544, 98220, 98341, 98234, 98162, 97546, 97522, 97218, 96625, 96560, 96134, 95430, 95429, 95382, 94422, 94128, 93285, 93028, 92243, 92166, 90462, 90450, 90289, 90093, 89574, 89573, 89040,
- NACE MP Dec. 2011, p14/Aug. 2011, p14/Jun. 2011, p80/Oct. 2010, p8-9/Sep. 2010, p62-66/Jan. 2010, p50-54/Jun. 2008, p14/
- NACE Corrosion Feb. 2016, p136-143 & 144-159/Nov. 2014, p1101-1114/Aug. 2013, p752-767/Jun. 2008, p517-531/Sep. 2006, p773-780 & p1133-1145/Jun. 2005, p571-578/Mar. 2005, p285-292/Feb. 2004, p181-186/Oct. 2003, p881-889/Oct. 2000, p1023-1032/Jun. 2000, p563-571/Dec. 1999, p1127-1135/Oct. 1999, p937-941/Jan. 1995, p71-78/Mar. 1994, p216-227/Oct. 1993, p821-828/Oct. 1992, p854-863/Sep. 1992, p785-791/Jul. 1992, p546-552/Jan. 1991, p62-66/Nov. 1990, p820-824/Dec. 1990, p989-993/Oct. 1990, p798-803/Nov. 1989, p951-957/Apr. 1989, p303-307/Jul. 1988, p414-422/Jun. 1988, p354-360/Mar. 1988, p165-169/Mar. 1987, p153-158/Sep. 1986, p554-556/Aug. 1986, p470-475/May 1986, p277-288/Mar. 1985, p127-136/Dec. 1984, p644-649/Sep. 1984, p459-465/Dec. 1983, p481-483/Apr. 1983, p151-158/Dec. 1982, p561-570
- Welding Journal Jan. 2000, p9s-17s/May 1999, p151s-155s
- S. Mark Wilhelm, Risk Analysis for Operation of Aluminum Heat Exchanger Contaminated by Mercury, Process Safety Progress, Vol.28, Issue 3, P259-266, Sep. 2009
- Aluminum Design Manual, AA, 2010
- G. Huang, Corrosion Behavior of Aluminum Alloys in Seawater, Corrosion Science and Technology, Mar. 2002, p215-218
- Process Specification for Heat Treatment of Aluminum Alloys, NASA Report PRC-2002, Aug. 2009
- Suppliers' Reports & Catalogs (Linde, Chart, ESAB, etc.)
- Others (AWS Aluminum Welding Conference Papers, Metal Handbooks, Norsok M-102, etc.)

2.1.7.4 Titanium Alloys

(a) General Characteristics

1. Excellent pitting and SCC resistance in seawater, chloride salt solutions (i.e., $FeCl_2$, $CuCl_2$, etc.), hypochlorites, wet chlorine, and nitric acid, including fuming acids.

2. Maximum temperature is strictly limited to 300 °C (572 °F). Up to 260 °C (500 °F) in refinery and petrochemical plant service.
3. Limited to 175 °C (350 °F) in service containing hydrogen or if these alloys are galvanically coupled to certain metals (i.e., CS) in H_2S-containing aqueous media (ANSI/NACE MR0103/ISO17945 or ANSI/NACE MR0175/ISO15156) due to the formation of hydride.
4. Titanium should not be used in straight type (relatively pure Ti) for hydrochloric, sulfuric, and HF acids, or in dry chlorine service.
5. Very difficult to weld with another metals.
6. This is a phenomenon that occurs in specific environments at temperatures above 74 °C (165 °F) and at a pH below 3, pH above 8 or neutral pH with high H_2S Tcontact between titanium and more active materials such as CS and 300 Series ASS promotes damage. However, hydriding can occur in the absence of a galvanic coupling.
8. Embrittlement occurs over a period of time as hydrogen is absorbed by the component and reacts to form embrittling hydride phases. The depth and extent of hydriding will continue to increase until a complete loss of ductility results.
9. Hydriding has also occurred in some chemical environments, as a result, the corrosion of iron has been accidentally embedded into the surface of titanium during fabrication. Corrosion of iron and iron sulfide scale in the process streams brought in from upstream units can result in hydrogen pickup.
10. The solubility of hydrogen in pure titanium and alpha-beta alloys is limited (50–300 ppm) and once this is exceeded, hydride is formed. Beta alloys, on the other hand, are more tolerant of hydrogen and 2000 ppm can be tolerated.
11. See Sect. 4.11.11 for welding and Sect. 4.12.3.13 for heat treatment of titanium alloys.

(b) Classes of Titanium and Titanium Alloys (Tables 2.84 and 2.85)
Figure 2.101 shows the family chart from the development of titanium alloys.

Table 2.84 (1/2) Classes of titanium and titanium alloys

Grade	UNS No.	Chemical composition in ASTM B265 (Ti + others below)	Metallic structure[2)]	Heat [1)] treatment	TS/YS min., ksi	Remark[2)] [registered/patent name]
1	R50250	Pure Ti, ≤0.18O	α	Anneal	35/25	– Low oxygen – Good elongation, formability; for clad materials – May occur under deposit corrosion
2 [4)]	R50400	Pure Ti, ≤0.25O	α	Anneal	50/40	– Good weldability – Excellent in aqueous chlorides, sulfides, sulfur dioxide; for overhead condensers in refinery units – Approved for sour service (ANSI/NACE MR0175/ ISO15156) – 2H: enhanced strength from Gr. 2
2H	R50400	Pure Ti, ≤0.25O	α	Anneal	58/40	
3	R50550	Pure Ti, ≤0.35O	α	Anneal	65/55	– Moderate oxygen – High strength, good weldability – For surface condenser tubesheet
4	R50700	Pure Ti, ≤0.40O	α	Anneal	80/70	– High strength
5	R56400	6Al, 4V, ≤0.25Fe, ≤0.2O	$\alpha + \beta$	Anneal or age	130/120	– Significantly high strength – Excellent combination of strength, corrosion resistance, weld, and fabricability
6	R54520	5Al, 2.5Sn	α	Anneal	120/115	– Used in airframes and jet engines due to its good weldability, stability, and strength at elevated temperatures
7	R52400	0.12–0.25 Pd, ≤0.25O	α	Anneal	50/40	– Good crevice corrosion resistance due to Pd – 7H: enhanced strength from Gr. 7
7H	R52400	0.12–0.25 Pd, ≤0.25O	α	Anneal	58/40	
9	R56320	3Al, 2.5V, ≤0.15O	$\alpha + \beta$	Anneal or CW-SR	90/70	– A compromise between the ease of welding and manufacturing of the "pure" grades and the high strength of Gr. 5 – Used in aircraft tubing for hydraulics and in athletic equipment
10	R58030	11.5Mo, 6Zr, 4.5Sn	β	SHT	100/90	– For aircraft fasteners
11	R52250	0.12–0.25 Pd, ≤0.18O	α	Anneal	35/25	– Good crevice corrosion resistance – Especially suitable for deep drawing – Permissible hydrogen content depends on form – Very good weldability
12 [4)]	R53400	0.3Mo, 0.8Ni, ≤0.25O	α	Anneal	70/50	– Good Heat and Wear resistance – Good corrosion resistance. But very susceptible to hydriding – Highly weldable – Used for shell & tubes H/EX
13	R53413	0.5Ni, 0.05Ru, ≤0.2Fe, ≤0.10O	α	Anneal	40/25	

Table 2.84 (2/2) Classes of titanium and titanium alloys

Grade	UNS No.	Chemical composition in ASTM B265 (Ti + others below)	Metallic structure[2)]	Heat [1)] treatment	TS/YS min., ksi	Remark[2)] [registered/patent name]
14	R53414	0.5Ni, 0.05Ru, ≤0.3Fe, ≤0.15O	α	Anneal	60/40	
15	R53415	0.5Ni, 0.05Ru, ≤0.3Fe, ≤0.25O	α	Anneal	70/55	
16	R52402	0.04–0.08 Pd, ≤0.3Fe, ≤0.25O	α	Anneal	50/40	– Good crevice corrosion resistance[3)] – 16H: enhanced strength from Gr. 16
16H	R52402	0.04–0.08 Pd, ≤0.3Fe, ≤0.25O	α	Anneal	58/40	
17	R52252	0.04–0.08 Pd, ≤0.2Fe, ≤0.18O	α	Anneal	35/25	– Good crevice corrosion resistance[3)]
18	R56322	3Al, 2.5V, 0.04–0.08 Pd, ≤0.25Fe, ≤0.15O	$\alpha + \beta$	Anneal or CW-SR	90/70	– High strength, good crevice corrosion resistance[3)]
19 [4)]	R58640	3Al, 8V, 6Cr, 4Zr, 4Mo, ≤0.3Fe, ≤0.12O	β	SHT	115/110	– Decreased weld strength, [Beta-C]
20	R58645	3Al, 8V, 6Cr, 4Zr, 4Mo, 0.04–0.08 Pd, ≤0.3Fe, ≤0.12O	β	SHT	115/110	– Decreased weld strength, [Beta-C/Pd][3)]
21	R58210	15Mo, 3Al, 2.7Nb, 0.25Si, ≤0.4Fe, ≤0.17O	β	SHT	115/110	– Decreased weld strength, improved oxidation resistance, [TIMETAL ®21S]
23	R56407	6Al, 4V, ≤0.25Fe, ≤0.13O, ELI	$\alpha + \beta$	Anneal or age	120/110	– Good weldability – Improved SCC resistance due to higher ductility & fracture toughness
24	R56405	6Al, 4V, 0.04–0.08 Pd, ≤0.4Fe, ≤0.20O	$\alpha + \beta$	Anneal or age	130/120	– Good weldability [3)]
25 [4)]	R56403	6Al, 4V, 0.3–0.8Ni, 0.04–0.08Pd, ≤0.4Fe, ≤0.20O	$\alpha + \beta$	Anneal or age	130/120	Good weldability [3)]
26	R52404	0.5Ni, 0.08–0.14Ru, ≤0.3Fe, ≤0.25O	α	Anneal	50/40	– Good weldability, improved corrosion resistance – Competitive alternative to Gr. 2, 7 & 16 – 26H: enhanced strength from Gr. 26
26H	R52404	0.5Ni, 0.08–0.14Ru, ≤0.3Fe, ≤0.25O	α	Anneal	58/40	
27	R52254	0.5Ni, 0.08–0.14Ru, ≤0.2Fe, ≤0.18O	α	Anneal	35/20	– Excellent weldability, very resistant to crevice corrosion, high-impact toughness – Equivalent of Grades 1, 11, and 17 in mechanical and physical properties and corrosion resistance – Cheaper than Gr.11
28 [4)]	R56323	3Al, 2.5V, 0.08–0.14Ru, ≤0.25Fe, ≤0.15O	$\alpha + \beta$	Anneal or CW-SR	90/70	– Improved corrosion resistance – High strength with enhanced corrosion – Alternative to Grade 18
29 [4)]	R56404	6Al, 4V, 0.08–0.14Ru, ≤0.25Fe, ≤0.13O, ELI	$\alpha + \beta$	Anneal or age	120/110	– High crevice corrosion & SCC resistance a higher temperatures and/or very low pH levels – Developed from Gr.23
30		0.3Co-0.05Pd, ≤0.3Fe	α	Anneal	50/40	[3)] Not much used recently
31		0.3Co-0.05Pd, ≤0.3Fe	α	Anneal	65/55	[3)] Not much used recently
32	R55111	5Al-1Sn-1Zr-1V-0.8Mo, ≤0.25Fe, ≤0.11O	$\alpha + \beta$	Anneal	100/85	– Excellent corrosion resistance in seawater
33	R53442	0.4Ni, 0.015Pd, 0.025Ru, 0.15Cr, ≤0.3Fe, ≤0.25O	α	Anneal	50/40	[3)]
34	R53445	0.4Ni, 0.015Pd, 0.025Ru, 0.15Cr, ≤0.3Fe, ≤0.35O	α	Anneal	65/55	[3)]
35	R56340	4.5Al, 2Mo, 1.6V, 0.5Fe, 0.3Si, 0.5Fe, ≤0.25O	$\alpha + \beta$	Anneal or age	130/120	
36	R58450	45Nb, ≤0.03Fe, ≤0.16O	α	Anneal or age	65/60	Resistance to ignition in oxygen-rich environments (for aircraft engine)
37	R52815	1.5Al, ≤0.3Fe, ≤0.25O	α	Anneal	50/31	
38	R54250	4Al, 2.5V, 1.5Fe, 0.20–0.30O	$\alpha + \beta$	Anneal or CW-SR	130/115	– Fe reduces the amount of V needed as a beta stabilizer – Its mechanical properties are very similar to Gr. 5, but has good cold workability similar to Gr. 9 – See NACE Paper 07183 for corrosion performance
39	R53390	0.25Fe, 0.4Si, ≤0.15O				

Source: ASTM B265

General Notes

a. H grade material is identical to the corresponding numeric grade (that is, Grade 2H = Grade 2) except for the higher guaranteed minimum UTS, and may always be certified as meeting the requirements of its corresponding numeric grade. Grades 2H, 7H, 16H, and 26H are intended primarily for pressure vessel use. Grade xxH can always be dual-certified as Grade xx. Grade xx will meet the requirements of Grade xxH except the strength

b. Grades 1–4 are unalloyed and considered commercially pure. Generally, the tensile and yield strength goes up with grade number for these "pure" grades. The difference in their physical properties is primarily due to the quantity of interstitial elements. They are used for corrosion resistance applications where cost, ease of fabrication, and welding are important

c. Pd Added Grades: Gr.7, 11, 16, 17, 18 and 24

d. Ru Added Grades: Gr.26, 27, 28 and 29

Notes

[1] Anneal: annealing, SHT: solution heat treatment (+aged), ELI: Extra Low Interstitial Elements, CW-SR: cold worked and stress relievedUnless specified, cold-worked pipe shall be heat treated at a temperature of not less than 538 °C (1000 °F). Hot-worked pipe finishing above 760 °C (1400 °F) need not be further heat treated. The minimum heat treatment conditions for Grade 9, 18, and 28 pipe delivered in the stress relieved condition shall be 316 °C (600 °F) for at least 30 min

[2] Characteristics as per metallic structures

[3] Improved for Ti hydride resistance

[4] Approved ANSI/NACE MR0175/ISO 15156 and ANSI/NACE MR0103/ISO 17945 for wet H_2S (sour) service. However, the maximum hardness required are below:100 HRBS for R50400, 92 HRBS for R53400, 45HRC for R56260, 32 HRC for R56323, 36 HRC for R56403, 35 HRC for R56404, and 42 HRC for R58640. In addition, R53400 for wet H_2S (sour) service shall be annealed at 774 ± 14 °C (1425 ± 25 °F) for 2 hours, air cool.

Table 2.85 Classes of titanium and titanium alloys

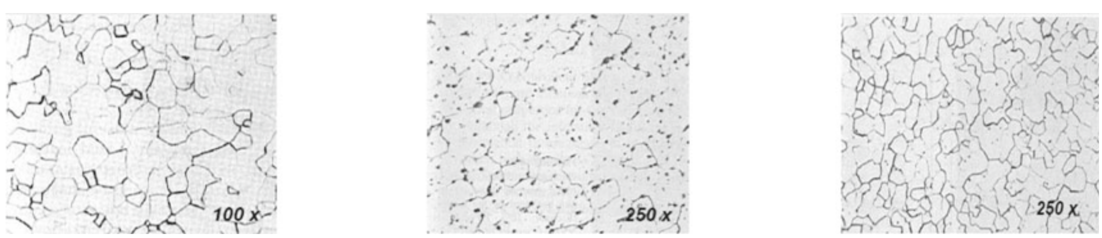
Item	Characteristics	Metallic structures				Characteristics
Specific gravity	Light					Heavy
Heat treatment hardening	Low					High
Creep strength	High	α	Near α	$\alpha + \beta$	β	Low
Plastic formability	Bad					Good
Weldability	Good					Bad
		← (Al, O, N, etc.)		(V, Mo, Fe, Cr, Mn, etc.) →		

Source: ASTM B265

(i) α *(alpha) alloys* are generally more ductile and weldable. The single-phase and near-single-phase α alloys of titanium exhibit good weldability. The generally high aluminum content of these alloys assures that they have low to medium strength, good notch toughness, reasonably good ductility, excellent properties at cryogenic temperatures, and oxidation resistance at elevated temperatures [in the range of 316–593 °C (600–1100 °F)]. The more highly alpha or near-alpha alloys offer high-temperature creep strength and oxidation resistance. The α alloys cannot be heat-treated to develop higher strength since they are single -phase alloys. (Fig. 2.100a) Near-α (alpha) alloys contain a small amount of ductile β (beta)-phase. Besides α-phase stabilizers, near-α alloys are alloyed with 1–2% of β phase stabilizers such as Mo, Si, or V

(ii) $\alpha \pm \beta$ *(alpha + beta) alloys* are the workhorse alloys of the titanium industry. Such alloys are fully heat treatable in section sizes up to 15 mm and used at temperatures of up to approximately 400 °C (750 °F). Most alloys are weldable with the risk of some loss of ductility in the weld area. Their strength levels are medium to high. Hot forming qualities are good but cold forming often presents difficulties. Creep strength is not usually as good as in most alpha alloys. The addition of controlled amounts of β-stabilizing alloying elements causes some β phase to persist below the β transus temperature, down to room temperature, and results in a two phase system. Even small amounts of β stabilizers will stabilize β phase at room temperature. A group of alloys designed with high amounts of α stabilizers and with a small amount of β stabilizers are alpha α-β alloys, usually called high-α or near-α alloys. (Fig. 2.100b). As larger amounts of β stabilizers are added, a higher percentage of the β phase is retained at room temperature. Such two-phase titanium alloys can be significantly strengthened by heat treatment. *Applications*: Blades, discs, rings, airframes, fasteners, components/vessels, cases, hubs, forgings/biomedical implants

(iii) β *alloys* are readily heat treatable, generally weldable, and show extensive strengthening, which can occur by the precipitation of α during aging. In the solution-treated condition, cold formability is generally excellent. The high percentage of β-stabilizing elements in this group of titanium alloys results in a microstructure that is metastable β after solution annealing (Fig. 2.100c)



(a) (b) (c)

Figure 2.100 Structures of titanium alloys. (Source: ASM Metal H/B Vol.2). (**a**) α structures (hcp), (**b**) $\alpha + \beta$ structures, (**c**) β structures (bcc)

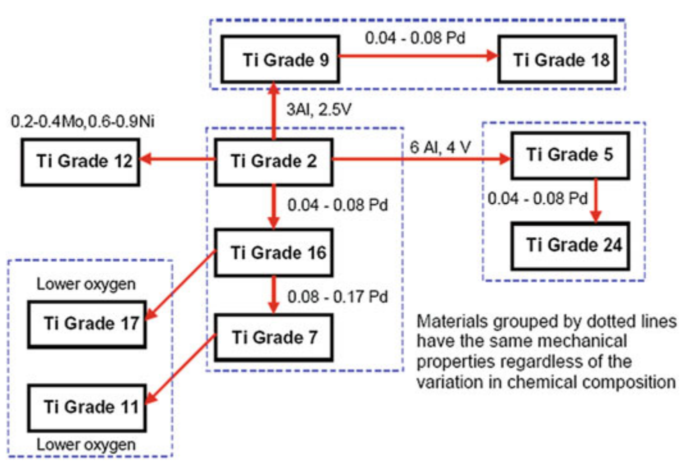
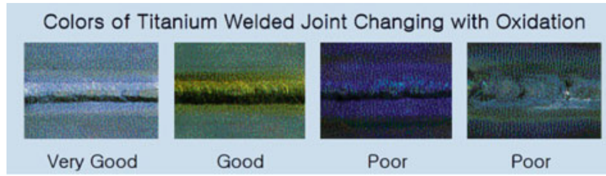


Figure 2.101 Development of titanium alloys. (Source: ASM Metal H/B Vol.2 -modified)

(c) Tempering Colors of Titanium
When oxidation occurs, the thin layer of surface oxide generates an interference color. The color (Fig. 2.102) can indicate whether the shielding was inadequate or an unacceptable degree of contamination has occurred:
Silver or straw color shows satisfactory gas shielding was achieved.
For certain service conditions, *dark blue* may be acceptable.
Light blue, gray, and white show an unacceptable level of oxygen contamination.



Color : (Silver) (Straw) (Dark Blue) (Light Blue, Grey, White)

Figure 2.102 Tempering colors of titanium. (Source: AZO Materials report, 2005)

(d) Phenomena of Titanium Hydriding
1. Reaction with Hydrogen to form a hydride phase in titanium alloys.
2. The hydrides that form as platelets within the grains and preferentially along crystallographic planes severely embrittle the Ti alloys and lead to brittle failure.
3. The embrittlement occurs when the hydrogen content exceeds 50–300 ppm for α and α-β-type Titanium alloys and 2000 ppm for β-type Ti alloys.
4. The hydride can occur:
In acidic solutions at a metal temperature above 74 °C (165 °F) and pH < 3
In alkaline solution (pH 6–11) at up to 77 °C (170 °F) with high H_2S when the titanium alloys are coupled to a more active metal (galvanic couple), e.g., SWS overhead system
5. Hydriding is often caused by increased temperatures due to fouling of CW side of H/EX.
6. The burned titanium tubes by ignition or fire showed significant amounts of hydride.

(e) Relative Cost Ratios (simplified) of Titanium Alloys (Table 2.86)

Table 2.86 Relative cost ratios of titanium alloys

Titanium alloys	Approx. relative cost ratios
1–3	1.0
12	1.25
16 & 26	1.4
7 & 11	2.25
9	1.3
5, 23 & 32	1.5
29	1.8

Codes and Standards

– ASTM B265 (Plates), B363 (Fittings), B367 (Castings), B338 (H/EX Tubes), B348 (Bars/Billets), B381 (forgings), B600 (Cleaning), B861 (Seamless Pipes), B862 (Welded Pipes)
– ASTM STP- 204, 397, 432, 651, 728, 796, 830, 917, 1253, 1272, 1471
– API RP571 Part for Titanium Hydriding
– ASME Code Case 2425-3
– AWS A5.16(M) Titanium and Titanium Alloy Welding -Electrodes/Rods, G2.4 Fusion Welding of Titanium and Titanium Alloys
– ASME B31.3 Process Piping, ASME B31.1 Power Piping, ASME Sec. II-D Properties

References

– NACE Paper 09078, 07183, 03458, 02170, 01329, 00691, 00641, 99499, 98417, 98267, 98261, 98158, 98006, 97554, 97032, 96121,
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– Mechanical Engineers' Handbook Part 1, Chapter 5 A Guide to Engineering Selection of Titanium Alloys for Design, Wiley
– Suppliers' Reports & Catalogs (ATI, TIMET, RMI, NS&SM, JFE, AW, etc.)
– Titanium Alloys in Subsea and Offshore Production Systems, MTD Publication 96/100
– F. Hua et al., The potential for the SCC of titanium alloys under repository-relevant environments for US Nuclear Waste. JOM, 66–72 (2008)

2.1.7.5 Zirconium Alloys

Zirconium, a reactive metal, has a high affinity for oxygen that results in the formation of a protective oxide layer in air at room temperature. It has a high melting point of 1855 °C (3371 °F).

(a) Zirconium alloys exhibit good ductility even at cryogenic temperatures and good strength comparable with other common engineering alloys. In addition to being integral to the oxide layer, oxygen is an interstitial strengthening element.

(b) Zirconium machines to an excellent surface quality and requires low power input compared to steel. However, care must be taken to minimize very fine chips since they are pyrophoric (i.e., may spontaneously ignite in the presence of air). Zirconium does show a tendency to gall and work-harden, which requires tool clearance angles higher than normal.
Although Zr 702C possesses good tensile properties, it does have relatively low impact strength compared to most corrosion-resistant alloys. However, with proper care, zirconium equipment can provide excellent service. Zr 705C offers a higher-impact strength and, more importantly, a higher pressure temperature limit, which could eliminate the need for higher pressure class products.
Due to moderate strength and low elastic modulus of Zirconium alloy, spring back is higher than that of stainless steel and must be taken into account.

(c) A properly formed, enhanced oxide layer serves as an excellent bearing surface against a variety of materials, imparts impressive erosion resistance in high-velocity systems, and can improve corrosion resistance in certain aggressive environments. The protective oxide of zirconium alloys gives superior corrosion resistance to HCl acid (not containing oxidizing species such as cupric chloride, ferric chloride, or wet chlorine), sulfuric acid (<55–70 wt%), organic acids, and alkaline media such as NaOH, highly resistant to corrosion in oxidizing acids, such as HNO_3 and CrO_3 solutions, unless halides are also present in considerable amounts. However, it shows poor resistance to HF acid, concentrated H_3PO_4 acid, ferric chloride, cupric chloride, wet chlorine, and other oxidizing chloride environments. This protective oxide gives superior corrosion resistance to HCl acid (not containing oxidizing species such as cupric chloride, ferric chloride, or wet chlorine), sulfuric acid (<55–70 wt%), organic acids, and alkaline media such as NaOH. Highly resistant to corrosion in oxidizing acids, such as HNO_3 and CrO_3 solutions, unless halides are also present in considerable amounts. However, it shows poor resistance to HF acid, concentrated H_3PO_4 acid, ferric chloride, cupric chloride, wet chlorine, and other oxidizing chloride environments. The oxide layer can be enhanced through a heat-treating process to attain a surface microhardness of approx. 480 HV (47 HRC).

(d) Weld repair is performed but must be done in an inert gas atmosphere to prevent oxidation of the weld and HAZ. All welds are closely examined for evidence of serious contamination. Insufficient shielding can be readily detected by blue to purple or gray to white colors in the weld whereas silver-bright or straw-yellow colors are indicative of proper shielding during welding. Zirconium castings are not normally heat treated but Zr 702C castings are stress relieved after major weld repair and Zr 705C castings are stress relieved within 14 days of all welds. Cleanliness and adequate purging are always essential to good-quality zirconium weld joints, and zirconium batten strap welds in zirconium-clad plate are no exception.

See Sect. 4.11.12 for welding and Sect. 4.12.3.13 for heat treatment of Zirconium alloys.

(e) Classes of Commercial Zirconium Alloys

Table 2.87 shows the classes of commercial zirconium alloys. Zirconium tubes can be bent at room temperature using standard bend tools and techniques. However, when bending thin sheet or if a tight bend radius is needed, a mandrel should be used for adequate support of the ID (inside diameter). The mandrel should be well lubricated in order to prevent galling of the ID surfaces.

(f) Tempering Colors of Zirconium

When oxidation occurs, the thin layer of surface oxide generates an interference color. The color can indicate whether the shielding was adequate or an unacceptable degree of contamination has occurred (See Fig. 2.103).

Table 2.87 Classes of commercial zirconium alloys

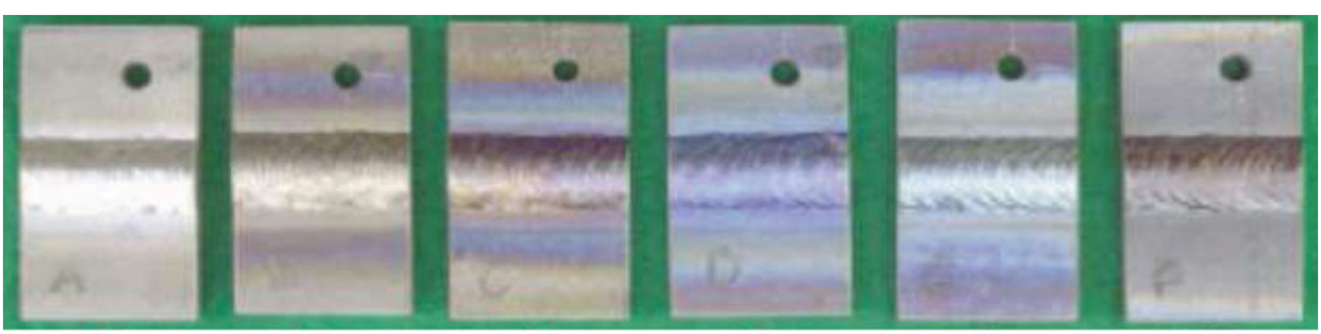
Alloys		Mechanical properties in ASTM B551					
		Min. UTS	Max. UTS	Min. YS	Max. YS	Min. elongation	Min. bend radius
Alloy	UNS #	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	%	Multiple of thickness (T)
700	R60700	N/A	380 (55)	N/A	305 (40)	20	5T
702	R60702	380 (55)	N/A	205 (30)	N/A	16	5T
704	R60704	415 (60)	N/A	240 (35)	N/A	14	5T
705	R60705	550 (80)	M/A	380 (55)	N/A	16	3T
706	R60706	510 (74)	N/A	345 (50)	N/A	20	2.5T

ASTM B551 grades of zirconium (Zr)

Alloys		Chemical composition, wt %								
Alloy	UNS #	Zr + Hf min.	Hf max.	Nb	Sn	Fe + Cr	O_2 max.	N max.	C max.	H max.
700	R60700	99.2	4.5			0.2 max	0.10	0.025	0.05	0.005
702	R60702	99.2	4.5			0.2 max	0.16	0.025	0.05	0.005
704	R60704	97.5	4.5		1–2	0.2–0.4	0.18	0.025	0.05	0.005
705	R60705	95.5	4.5	2–3		0.2 max	0.18	0.025	0.05	0.005
706	R60706	95.5	4.5	2–3		0.2 max	0.16	0.025	0.05	0.005

Source: ASTM B551

No.	Color	Action required
A	Silver	Good weld, no treatment required
B	Light & dark straw	Remove by wire brushing
C	Light blue	Remove by wire brushing
D	Dark blue	Weld metal contamination, remove by grinding
E	Blue-gray	Weld metal contamination, remove by grinding
F	Gray, white, loose deposit	Failure of primary and secondary shielding; remove weld metal and some base metal



A B C D E F

Figure 2.103 Tempering Colors of Zirconium. (Source: ATI Wah Chang report, 2005)

Codes and Standards

- ASME B31.3 Process Piping, ASME Sec. II-D Properties
- AWS A5.24(M) Zirconium Alloy Welding -Electrodes/Rods
- ASTM B493, B523, B551, B614, B658
- ASTM STP- 368, 458, 551, 633, 639, 681, 728, 754, 815, 824, 830, 917, 939, 966, 1023, 1132, 1245, 1295, 1354, 1423, 1467, 1471, 1505, 1529, 1543, 1597

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- R. Adamson et al., In-reactor creep of Zr alloys, Advanced Nuclear Technology International (www.antinternational.com), 2009
- Several papers in Nuclear Engineering Technology (http://www.journals.elsevier.com/nuclearengineering- and-technology/)
- Several papers in NACE-Corrosion, Papers, and Materials Performance (https://www.nace.org)
- Zirconium Alloys Suppliers' Technical Reports and Data Sheets

2.1.7.6 Tantalum Alloys

(a) Tantalum is a shiny, silvery (dark blue-gray)-colored metal, which is heavy, dense, malleable, and ductile when pure. Tantalum oxidizes in air at temperatures above 300 °C (570 °F). Above 300 °C (570 °F), there is a possibility it will react with all gases except inert gases. Below 300 °C (570 °F), there is possibility of embrittlement of tantalum by nascent (monatomic) hydrogen (but not molecular hydrogen). Nascent hydrogen is produced by galvanic action or as a product of corrosion by certain chemicals. The metal can be embrittled by hydrogen if it is the cathodic member of a galvanic couple exposed in an acid environment or if it is exposed to a hydrogen-containing atmosphere at elevated temperatures. Tantalum is extremely corrosion resistant due to the formation of a tenacious oxide film, and is also resistant to most acid attack. However, it is attacked by HF acid, fuming sulfuric acid, and strong alkalis. Salts that hydrolyze to form hydrofluoric acid or strong alkalis also attack tantalum. Other agents that can attack tantalum include bromine plus methanol, and halogen gases (fluorine at or above room temperature; chlorine at 250 °C (480 °F); bromine at 300 °C (570 °F); and iodine at somewhat higher temperatures).

Tantalum is also used in vacuum systems as it has a high absorption rate for residual gases. It is also used as an alloying element with, e.g., nickel and molybdenum, to produce alloys that have good corrosion resistance, strength, and ductility. See Sect. 4.11.13 for welding of Tantalum alloys.

(b) Types of Tantalum Alloys (under annealed condition) (Table 2.88).

Table 2.88 The most common types of tantalum alloys

Alloys	Composition	Hardness (HV)	Density (g/cm^3)	Melting point (°C)	Tensile strength (MPa)[1]	Yield strength (MPa)[1]	Elastic modulus (GPa)[1]
R05200	Unalloyed Ta	35 HRB	16.7	2996	207 (t < 0.06″) 172 (t ≥ 0.06″)	138 (t < 0.06″) 103 (t ≥ 0.06″)	179
R05400	Powder (unalloyed Ta)		16.65	3017	172	103	186
R05252	Ta – 2.5% W	130	16.7	3005	276	207 (t < 1/8″) 122 (t ≥ 1/8″)	195
	Ta – 7.5% W	245	16.8	3030		460	205
R05255	Ta – 10% W	325–400	16.8	3025	482	379	200
R05240	Ta – 40% Nb				244	138 (t < 0.06″) 103 (t ≥ 0.06″)	

Source: ASTM B708, ASTM STP-1471
Notes: t = nominal thickness
[1] 1 MPa = 0.145 ksi, 1 GPa = 1000 MPa = 145 ksi

Codes and Standards

- ASTM B364/B365/B521/B708
- AMS 7846/7847/7848
- ASTM STP- 1471

References

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- NASA Technical Note TN D-5424: Statistical analysis of high-temperature creep-rate data for alloys of tantalum, molybdenum, and columbium, Sep. 1969
- NASA Technical Memorandum TM X-67879: Specifications for cleaning, fusion welding, and post heating tantalum and columbium alloys, Jul. 1971
- A New Tantalum Alloy with Improved Corrosion and Hydrogen Embrittlement Resistance, Corrosion Solutions Conference Paper 3B1, 2009

– Sia Nemat-Nasser et al., Deformation behavior of tantalum and a tantalum tungsten alloy. Int. J. Plast. **17**, 1351–1366 (2001)
– Several papers in NACE-Corrosion, Papers (11106, 08182, 03463, 01330, 95253) and Materials Performance (https://www.nace.org)
– Several papers in Welding Journal
– Several papers in NASA
– Tantalum Alloys Suppliers' Technical Reports and Data Sheets

2.1.7.7 Hardfacing Alloys (Table 2.89)

Hardfacing is one of the most useful and economical ways to improve the performance of components submitted to severe wear conditions in various temperature zones. The most common processes and alloy groups to obtain harder or tougher material on the metal surface than that of the base metal are below.

Table 2.89 (1/2) Classes of hardfacing alloys

Alloy	Normal analysis (wt%) of welding electrode (diluted)									UNS	ASME/AWS	Hardness (HRC)
	Co	Cr	W	C	Ni	Mo	Fe	Si	Others			
Cobalt base alloy bare welding rods rods [3]												
Stellite 1	Bal	32	12	2.45	<3.0	<1.0	<3.0	<2.0	<0.5	R30001	(SF)A 5.21 ERCoCr-C	51–56
Stellite 6 [2]	Bal	30	4–5	1.2	<3.0	<1.0	<3.0	<2.0	<0.5	R30006	SFA 5.21 ERCoCr-A	40–45
Stellite 12	Bal	30	8	1.4–1.8	<3.0	<1.0	<3.0	<2.0	<0.5	R30012	(SF)A 5.21 ERCoCr-B	46–51
Stellite 20	Bal	33	16	2.45	<3.0	<1.0	<3.0	<2.0	<0.5			53–59
Stellite 21	Bal	28	–	0.25	3	5.2	<3.0	<1.5	<0.5	R30021	(SF)A 5.21 ERCoCr-E	28–40 [1]
Stellite 22	Bal	28	–	0.30	1.5	12	<3.0	<2.0	<0.5			41–49 [1]
Stellite 25	Bal	20	14	0.1	10	<1.0	<3.0	<1.0	<0.5	R30605		20–45 [1]
Stellite 31	Bal	26	7.5	0.5	10	–	<2.0	<1	<0.5	R30031		20–35 [1]
Stellite F	Bal	26	12	1.7	22	<1.0	<3.0	<2.0	<0.5	R30002	(SF)A 5.21 ERCoCr-F	40–45
Stellite 107	Bal	31	4	2	24	–	<2.0	<3.0	<0.5			38–47
Stellite 190	Bal	27	13.5	3.2	<1	<1.0	<3.0	1.0	<0.5	R30014	(SF)A 5.21 ERCoCr-G	54–59
Stellite 250	Bal	28	–	0.1	–	–	21	<1.0	<0.5			20–28
Stellite 306	Bal	25	3	0.5	6	–	4	1	6% Nb			32–42 [1]
Stellite 694	Bal	28	19	1	5	–	<3.0	1	1% V			48–54
Stellite 706	Bal	31	–	1.2	<3.0	4	<3.0	<1.0	<1.0			39–44
Stellite 712	Bal	31	–	1.5/1.9	<3.0	8	<3.0	<2.0	<1.0			46–51
ULTIMET	Bal	26	2	0.06	9	5	3	–	<1.0	R31233		28–45 [1]
Alloy	Normal analysis (wt%) of welding electrode (diluted)									UNS	ASME/AWS	Hardness (HRC)
	Co	Cr	W	C	Ni	Mo	Fe	Si	Others			
Nickel-based alloy bare welding rods [3]												
Nistelle C	–	17	5	0.1	Bal	17	6	–	0.3% V	N30002		17–27 [1]
Nistelle 625	–	21	–	<0.10	Bal	8.5	<5	–	3.3% Nb	N06625	(SF)A 5.14 ERNiCrMo-3	
Deloro 40	–	12	–	0.4	Bal	–	2–3	2.9	1.6% B	N99644	(SF)A 5.21 ERNiCr-A	36–42
Deloro 50	–	12	–	0.5	Bal	–	3–5	3.5	2.2% B	N99645	(SF)A 5.13/21 ERNiCr-B	48–55
Deloro 55	–	12	–	0.6	Bal	–	3–5	4.0	2.3% B		(SF)A 5.21 ERNiCr-B	52–57
Deloro 60	–	13		0.7	Bal		3–5	4.3	3.0% B	N99646	(SF)A 5.21 ERNiCr-C	57–62
Intermetallic laves phase alloy welding rods (tribaloy alloys) [3]- Ni or Co base												
T-400	Bal	8.5	–	<0.08	<1.5	28	<1.5	2.5	<1.0	R30400		54–58
T-400C	Bal	14	–	<0.08	<1.5	27	<1.5	2.6	<1.0			54–59
T-401	Bal	17	–	0.2	<1.5	22	<1.5	1.3	<1.0			47–53
T-700 (Ni based)	<1.5	16	–	< 0.08	Bal.	32	<1.5	3.4	<1.0			50–58

Table 2.89 (2/2) Classes of hardfacing alloys

Alloy	Normal analysis (wt%) of welding electrode (diluted)									UNS	ASME/ AWS	Hardness (HRC)
	Co	Cr	W	C	Ni	Mo	Fe	Si	Others			
T-800	Bal	18	–	< 0.08	<1.5	28	<1.5	3.4	<1.0			55–60
T-900	Bal	18	–	< 0.08	16	22	–	2.7	<1.0			52–57

Source: Stellite brochure, 2008, UNS, AWS

General Notes: Bal = balance; blank = no data

a. Nominal analysis is a guideline only for standard products, and does not include all incidental elements and may differ depending on the exact specification/ standard used when ordering

b. When written certification to a standard is required, please specify this when ordering. Certain products are also being certified to AMS, SAE, and other standards

c. All chemical compositions are based on the undiluted weld metal. The actual hardness values depend on the hardfacing process and degree of cold-working

d. Typical Characteristics

Alloy	Mechanical wear resistance	Corrosion resistance	High temperature resistance
Stellite®	Very good	Very good	Excellent
Deloro®	Very good	Fair	Fair
Tribaloy®	Very good	Very good	Excellent
Nistelle®	Low	Excellent	Very good
Delcrome®	Very good	Low	Fair
Stelcar®	Excellent	Fair	Fair
Jet Kote®	Excellent	Low	Fair

e. The results of this investigation reveal that a high preheat temperature is essential to avoid microcracking of the deposits. Microcracks were observed in deposits prepared by employing a preheat of 150–300 °C (302–572 °F). Preheating to 900 °C (1652 °F) followed by air cooling to 450 °C (842 °F) after deposition to avoid any further sensitization of the base and then furnace cooling to room temperature produced sound deposits without any undesirable features

Microprobe analysis across the deposits indicated that there is a smoother variation in composition across the interface in deposits with high preheat temperature. Microhardness measurements along the microprobe traverses revealed a correlation of microhardness with cobalt content of the deposits [source: Welding Journal 1980_07_s213]

f. The most common applications of hardfacing: valve seat inserts, bearing, cutter edge, engine valve, high temperature & pressure valves, mixing point, turbine blade, mining machines and tools, drilling machine head, saw teeth, screw flights, brass casting die, high-temperature and corrosion-resistant sealing ring, extrusion dies, etc.

Notes:

1) Depending upon the degree of cold-working

2) Stellite 6 may not be recommended in steam with coke particles at 650 °C (1200 °F) and above due to spalling

3) There are several other alloys in this group. Only some are shown in this table

(a) Hardfacing processes: GTAW (TIG), oxy-acetylene welding, SMAW (MMAW), GMAW (MIG/MAG), SAW, plasma transferred arc welding (PTA welding), laser welding, flame spraying with subsequent fusing, powder welding, plasma spraying, high velocity oxygen fuel flame spraying (HVOF), and coating (e.g., ceramic, cementing, etc.).

- Plasma Transferred Arc (PTA) Welding

  PTA process recommends itself due to its ease of automation and thus a high degree of reproducibility of the welded overlays. In addition, because of the highly concentrated heat source, this process benefits from high powder utilization and can achieve a very low level of iron dilution in the overlay. It is possible to produce overlays from many different materials and combinations of materials with a wide range of hardness and other properties because the hardfacing materials are in powder form.

  The main benefits are: (i) high automation, (ii) high powder utilization, (iii) low dilution, and (iv) use of a very wide range of hardfacing materials.

- JetKote®

  Carbide–metal combination powders specifically designed for thermal spraying. Thermal spray coatings are used to enhance, salvage, and improve component life, competing with surface treatments such as Cr-plating or heat treating. The HVOF thermal spray process produces extremely high-quality coatings. It provides well-bonded, high-density coatings with high hardness, delivering outstanding performance in aggressive wear and corrosive environments.

- HVOF

  In the HVOF process, powder is introduced axially into a chamber in which a gas flame is constantly burning under high pressure. The exhaust gas exits through an expansion nozzle that produces a high-velocity gas stream. The powder particles are heated in this gas stream and transferred by it with kinetic energy to the surface of the work piece, forming a dense coating with excellent bonding properties. Due to the moderate transfer of heat to the powder particles and to the work piece, which remains relatively cool, there is little metallurgical change to either the sprayed material or work piece.

- Plasma Spray

  In the Plasma Spraying Process, powder is softened or melted in the plasma gas stream, which also transfers the particles to the work piece. The plasma arc is not transferred to the work piece; it is contained within the plasma torch between an axial electrode and a water-cooled nozzle. The process is operated in normal atmosphere, in a shielding gas stream (e.g. Argon), in a vacuum or under water. Due to the high temperature of the plasma gas stream, the Plasma process is especially suitable for spraying high melting point metals as well as their oxides and carbides.

- Spray-Fuse and Powder Welding
  Deloro Stellite powders are gas-atomized powders. Spray-Fuse and Powder Welding are available in standard size ranges.
  A specially designed Oxy Acetylene torch is used for powder welding. The work piece is heated with the torch. The powder is introduced into the gas stream from the integral powder hopper and then transferred to the work piece through a flame. This process is similar to the Oxy Acetylene process with the exception that the hardfacing takes place at lower temperatures. This minimizes oxidation and distortion of the work piece and enables easy surfacing of edges.
- PM (Powder Metallurgy)
  Powder Metallurgy produces fully dense pressed components and is economic for high volume production of small simple shapes. This technology allows us to manufacture uniform microstructures, which are free of nonmetallic inclusions and defects. PM components are proven to have outstanding wear resistance and mechanical properties and provide exceptional reliability needed for anything from aerospace bearings to industrial saw teeth. Surface finish is typically 125 RMS, with dimensional control dependent on part size and geometry. Components should weigh less than 0.5 lbs and have a maximum surface area of 2.5 in^2. A variety of shapes can also be extruded such as diamond, wedge, rectangular, and circular sections up to 1" diameter and up to 40" long. These extrusions are excellent for hardfacing consumables, cutters, and wear pads.

(b) Common alloy materials for hardfacing: WC-Cr-Ni, Ni-Cr-Bo, Ni-Aluminide, 410 or 420 SS, Aluminum Bronze, MCrAlY, NiCrB-WC, Co-based alloys, Nickel Aluminide Bond, Aluminum Oxide, Zr Oxide, Premium Cr Oxide, and Cr Carbides (See Table 2.89).
Normally the hardened surfaces supply erosion and or wear resistance while the base metal has strength and toughness.
Figure 2.104 shows the hardness values at high temperature of various materials
Figure 2.105 shows the hardness values of various materials at 700 °C (1290 °F)
Figure 2.106 shows the effective combination of hardfacing on 9Cr-1Mo steel, which is used for refinery coker furnace outlet line. The ideal layers were Alloy 625 + Stellite 6 + Stellite 1 (alternative FusionStell 720)

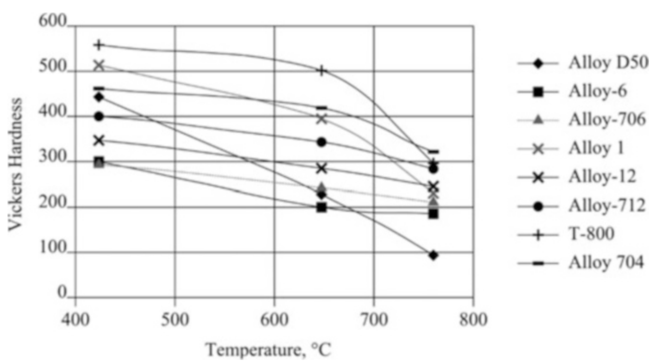


Figure 2.104 High-temperature hardness values of various materials. (Source: NACE Paper 01513)

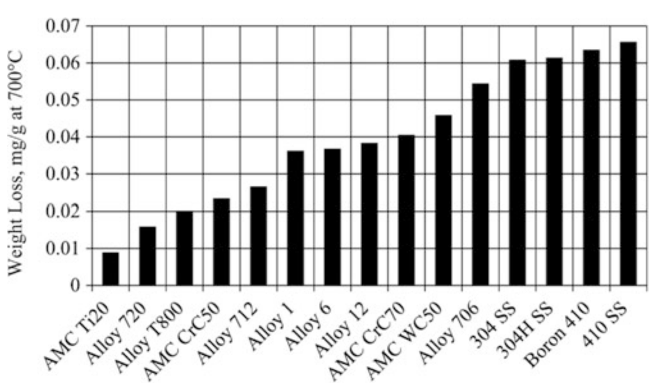


Figure 2.105 Hardness values of various materials for FCC regeneration at 700 °C (1290 °F). (Source: NACE Paper 01513)

Codes and Standards for Hardfacing

– API 600 series Valve Standards.

References for Case Studies of Hardfacing

– NACE Paper C2016-7221 Fe-based Hardfacing Weld Overlay Alloys for Erosion-Wear Resistance in Coal-Fired Fluidized-Bed Boilers
– NACE Paper 03247 Corrosive Degradation of Hardfacing Alloy in Chlorinated Seawater Valve Applications
– NACE Paper 94404 Hardfacing of High Temperature Alloys for Ethylene Pyrolysis Applications
– NACE Paper 89058 Applications for Hardfacing in The Pulp and Paper Industry
– NACE Paper 07694 Guideline for material selection and qualification of wear and corrosion protective hard face coatings for piston rods
– NACE Paper 01513 High Temperature Erosion Resistant Materials for petroleum Refinery Equipment
– NACE Paper 04302 Corrosion Resistant Hard Coating Material in Seawater Application
– NACE Paper 07685 Assessing Erosion Corrosion Properties of Materials for Slurry Transportation and Processing in the Oil Sands Industry
– NACE Paper 97016 Recent Developments in Wear and Corrosion Resistant Alloys for Oil Industry
– NiDI Publication 11017 Ni-Hard
– NiDI Publication 14009 Electroless Ni Coating
– Deloso Stellite® Reports/Manuals/Presentation Materials/Catalogs
– Postalloy® Reports/Manuals/Presentation Materials/Catalogs
– Triballoy® Reports/Manuals/Presentation Materials/Catalogs
– Elsevier Papers for Wear

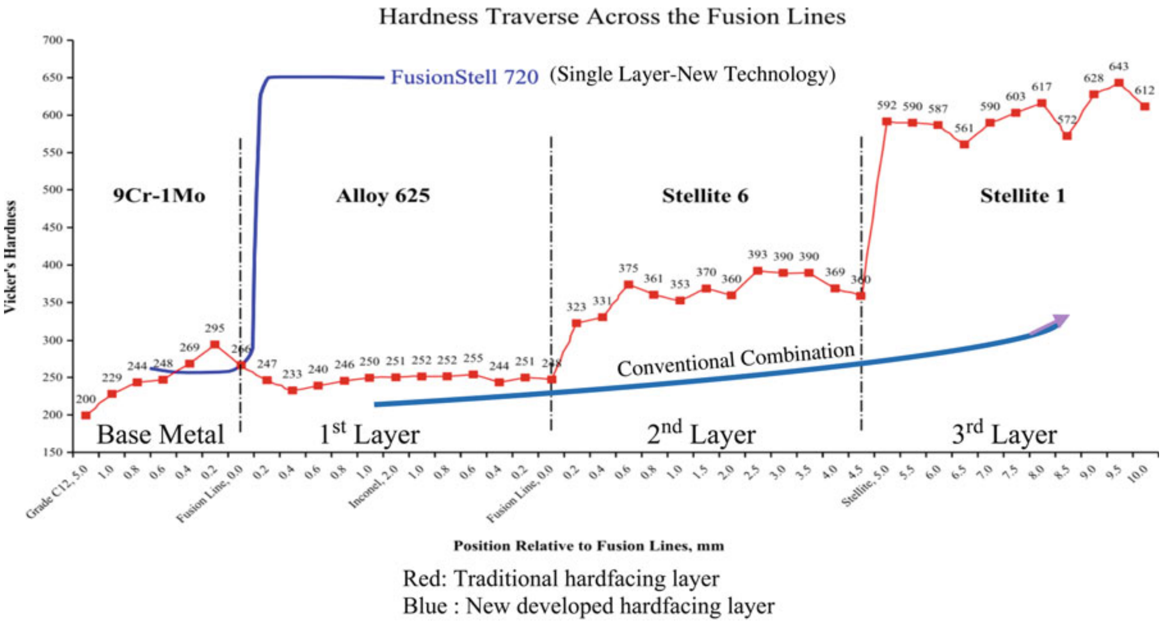


Figure 2.106 Effective combination of hardfacing on 9Cr-1Mo steel. (Source: Kennametal report, 2010). Red: traditional hardfacing layer. Blue: new developed hardfacing layer

2.1.8 Bonding of Metals

A metallic bonding system which consists alloys as environmental resistance and carbon or low-alloy steel as strength-sustaining base metal is normally selected for lower cost compared to base corrosion/erosion-resistant alloy in corrosion and erosion environments. Sometimes it is also used to mitigate the corrosion crack propagation of bare 300 series stainless steel in chloride SCC environment.

2.1.8.1 Metal-Clad Types Allowed by Codes

Table 2.90 shows bonding types and their characteristics of metals.

Table 2.90 General characteristics of bonding types on internal metal surfaces(1)

Bonding type	Procedures and characteristics	Use	Remark
Rolled clad (R)	The usual practice is to prepare a "sandwich," consisting of two alloy inserts between two backing plates and separated by a parting compound applied between the alloy inserts to prevent sticking. Dilution zone in thickness is negligible. Bonding shear stress shall be 140 MPa (20 ksi) and above.	Common for large-size equipment/ pipeline	
Explosion clad(2) (E)	Uses a very short-duration high-energy impulse explosion to drive two slightly separated metal surfaces together. Dilution zone in thickness is very small. Working shop is greatly limited due to safety.	Applied when rolled clad is difficult	Bonding strength is high
Weld overlay(3) (W)	Chemical composition, hardness values, and ferrite numbers in diluted welds shall meet the requirements. Dilution zone in thickness exists. Deformation can occur.	Small/medium areas (on flange faces, tube sheets, etc.)	Economic, rough surfaces-not recommended for H/EX shell without sliding shoes
Lining (L)	Degassing treatment or vent hole may be required. No dilution zone in thickness exists.	Used for nontoxic, non-hydrogen, non-high pressure, non-vacuum service Used for wear and corrosion resistance locally or entirely	Economic, but the use is limited Not recommended for equipment and piping which are designed with vacuum condition and/or hydrogen
Powder metallurgy(4) (P)	For erosion/wear resistance	Small area (e.g., valve trim)	Used for small size piping components

Notes
(1) Bonding test for clad meatal: See Sect. 5.2.2.7 for more detailed technical information
(2) Explosion Clad: See Sect. 4.11.16 for more detailed technical information
(3) Weld Overlay: See Sect. 4.11.15 for more detailed technical information
(4) Hardfacing with Powder: See Sect. 2.1.7.7 for more detailed technical information

References for Bonding of Metals

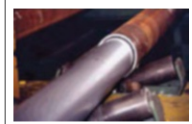
ASME Sec. VIII, Div.1, Part UCL,
ASME Sec. VIII, Div.2, AF-550, 560, 561
ASTM A263, 264, 265, B898 (Reactive and Refractory Metal Clad Plate), and B343
API Spec 5LC (CRA Line Pipe)/5LD (CRA Clad or Lined Steel Pipe)
NiDi Publication-Technical Series No. 10039/10064 (Engineering with Clad)/11020/14035
NDE for Type (R) & (E): Normally to apply UT per ASME SA578

Meanwhile, clad pipes are also used in corrosive and/or erosion environments, as shown in Table 2.91

Table 2.91 (1/2) Typical clad pipes/piping for energy and chemical industries

Types	Characteristics	Remark
Weld overlayed pipe	Most of welding processes can be applied if the dissimilar metallic combination for welding is available per Sect. 4.11.1 in this book. Normally the disbonding test is not required for weld overlayed clad materials unless the purchaser requires it. The main factors for application are the base metal, corrosion resistance alloy (CRA), pipe size (ID, length, thickness, and curvatures), welding process, etc.	
Longitudinally welded clad pipe	Longitudinally welded pipe is made from clad plates like the longitudinal welding for the shell of a rolled clad pressure vessel. The edges of the plate are machined for welding, and the plate is formed into pipe in a UOE (U (**U**-in) forming, O molded (**O**-in) and the enlarged diameter (**e**xpanding) combining) process, press bend, or rolling mill. The longitudinal seam is usually welded from outside with SAW on the base metal (CS and LAS). Tandem welding with two or three welding heads is usually employed to speed up productivity. Longitudinal welds are then back gouged to prepare a smooth surface and to remove the oxidized area for internal welding to complete the internal CRA layer. See Sect. 4.1.5.2 in this book as well as API Spec 5LD for weld joint, filler metal selection and typical welding procedure.	
Centrifugally casted clad pipe	First the well-refined molten steel is poured into a rotating metal mold with a flux. After casting, the temperature of the outer steel is monitored. At a suitable temperature after solidification, the molten CRA is introduced into the opposite end of the mold with a new flux. The selection of the flux, temperature of the outer shell when the molten CRA is poured into the bore, and the pouring temperature of the CRA have been factors in achieving a sound metallurgical bond. When these various parameters have been controlled, it has been possible to achieve minimum mixing at the interface and maintain homogeneous wall thickness.	 NiDI 10064
Seamless clad pipe	Seamless pipe can be produced by making a composite billet of CRA "nested" inside the backing steel (base metal). This composite billet can be processed through standard pipe mills such as a plug mill, mandrel mill, or extrusion press or forge. The increase in surface area breaks down the oxide layer on the CRA and allows a bond to form under the forces induced by the plastic deformation within the mills. The two metals in the billet are fastened together in some way before going into the mill to prevent them from rotating or separating. Different manufacturers use welding or diffusion bonding (sometimes assisted by an activator on the interface surfaces). There are fewer cladding alloys available as seamless tubes because of the need to balance the hot workability of the cladding alloy and the backing steel. The mechanical properties of the backing steel are controlled while the corrosion resistance of the cladding is optimized, as is the case with longitudinally welded pipe. This is normally achieved by a final solution heat treatment, followed by quenching and tempering. Careful control of the backing steel composition has ensured that it meets typically specified requirements in the quenched and tempered condition. The finished length of seamless pipe depends on the diameter because the weight of the incoming billet that can be handled is usually fixed. Thus, small-diameter pipe can be obtained in long lengths, while larger-diameter and heavier-wall pipe may well be shorter than standard lengths depending on the manufacturer's capacity. The commercial diameter may be available up to 660 mm (26 in.) OD.	
Explosively bonded clad pipe	A number of explosive fabricators worldwide are capable of manufacturing pipe with an internal explosively fully bonded clad layer. The setup for making this product varies between different manufacturers, but takes one of two forms: expansion or implosion. In both cases a small annular separation is maintained between the CRA and the carbon steel pipe surfaces to be joined so that there is an acceleration of the materials, which therefore impact and bond together. Normally the disbonding test is not required for explosion-bonded clad materials unless the purchaser requires it.	 NiDI 10064

Table 2.91 (2/2) Typical clad pipes/piping for energy and chemical industries

Types	Characteristics	Remark
Mechanically bonded pipes (lined)	Lining of pipe implies that there is no metallurgical bond between the liner and backing steel pipe, except possibly in small areas at the pipe ends or along the pipe. The methods of making lined pipe described below do not employ heating of the liner to a temperature range at which any metallurgical changes occur. Thus the mechanical properties of the backing steel can be optimized during the normal pipe production route and the solution annealed liner can be inserted into this finished pipe. A wider range of alloys is available using these technologies provided the liner is weldable. At its simplest, pipe can be lined by simply hydraulically expanding the liner into the outer pipe. Alternatively, in the thermohydraulic gripping (THG) method, which is similar to a multilayer pressure vessel in ASME Sec. VIII, Div.1, ULW, the outer pipe is first heated and then the liner pipe is inserted with water cooling to prevent temperature rise during insertion. The water pressure is controlled so that the liner is plastically deformed until it touches the outer pipe; then the outer pipe is elastically expanded. Next, the pressure is removed so that both the outer pipe and the liner pipe shrink elastically. The outer pipe is then cooled down to its initial diameter, which is smaller than the diameter of the liner. This generates the gripping stress on the liner and induces a compressive residual stress in the liner. The final method available for manufacturing a lined pipe is the explosive forming approach. The explosive force is sufficient to plastically deform the inner liner while the outer pipe is only elastically deformed. thus the characteristic dimensions of the product are given by the outer pipe, which retains its original dimensions. The process is a cold process so that it is highly suitable for a wide range of alloy and backing steel combinations, particularly high-strength outer pipes, because there are no metallurgical effects to control. One product incorporates explosively bonded strips along the pipe length to prevent any risk of collapse in larger-diameter pipes. The liner is welded to the backing steel at the pipe ends to facilitate girth welding. In some cases the pipe is supplied with the pipe end completely overlay welded using an alloy appropriate to the liner material or with a special sleeve of solid CRA to facilitate beveling or machining of couplings at the pipe ends. The limitations of use are noted in Table 2.90.	 NiDI 10064
Clad fittings	Fittings can be produced from clad pipe by hot- or cold-forming processes. Bends and elbows are made using high-frequency induction bending, hot mandrel, or hot-die bending. Tees are made by hot extruding or cold bulge forming. In principle, any kind of fitting can be produced from clad pipe or plate. Much care has typically been taken in maintaining strict tolerances, particularly on the ends, in order to facilitate welding into adjacent piping or other equipment. The heating and cooling cycles of the part have been controlled to avoid any metallurgical damage to the backing steel or cladding alloy.	
Power metallized HIP clad pipe	Hot isostatic pressing (HIP) is a pressure-assisted sintering/diffusion bonding process that has been used for the production of clad components and can be used for pipe production. The CRA can be in the form of a powder or a solid foil or sleeve, depending on technical and economic considerations. The surfaces to be bonded are first prepared and cleaned and then brought into contact under pressure at elevated temperatures. HIP is normally performed at a temperature above 1100 °C (2000 °F) and at a pressure above 100 MPa (14.5 ksi) for a few hours at full temperature and pressure, depending on the type of alloy. The total cycle time is about 8–12 hours. Controlling the temperature and holding time allows the diffusion zone depth to be controlled and limited, so there is no zone of dilution. The temperature used depends on the type of alloy and has always been lower than the alloy melting temperature. When powder coating is used, it is held in place by a can that is evacuated and sealed prior to HIP. The powder reaches 100% density during HIP and atomically bonds at the surfaces. After HIP the can is removed from the finished surface and the product can be heat treated to optimize the mechanical properties of the backing steel. Almost any combination of materials can be bonded, and there are many HIP manufacturers worldwide. Although the manufacturing process is labor intensive, it is possible to HIP many parts simultaneously, depending on the size and capacity of the equipment. HIP is widely applied for producing clad fittings including tees, flanges, elbows, reducers, and branches.	 NiDI 10064
Power metallized solid HIP	In addition to cladding, hot isostatic pressing (HIP) has been used to produce solid, complex shapes in CRAs. The technique has been employed for minimum section thickness of more than 15 mm (0.59 in.). The 22% Cr duplex and 25% Cr super duplex alloys have both been used in solid HIP forms. The methods of production are similar to those described in power metallized HIP clad pipe above. A common technique employs a mild steel container in the approximate shape of the desired component (allowing for consolidation and shrinkage), which is filled with CRA powder, evacuated, and sealed. The container is then subjected to a combination of heat and external pressure. After the HIP process, the mild steel container is either machined or pickled away. The process becomes more economical with increasing shape complexity; the process can result in material savings and a near net shape that minimizes machining operations. The process has been used for manifolds, tees, valve blocks, and barrel casings for injection pumps.	

References and Sources: NACE Publ.1F192, API Spec 5LD/5LC, ASME Sec. VIII, Div.1, ULW, NiDI Publ. 11064/14035, etc.

2.1.8.2 Classes of Clad Materials in ASME (Table 2.92)

2.1.8.3 Selection of Cladding Materials from a Cost Standpoint

The cost depends on the material, and base metal thickness, as seen in Figs. 2.107 and 2.108 and Table 2.93.

Table 2.92 ASME material numbers for cladding materials [(1),(2),(3),(4)]

Mat'l no.	Specification	Clad materials	Bonding type
SA-263	CRA Cr-steel clad plate, sheet, and strip	400 series (FSS & MSS)	R & E
SA-264	CRA Cr-Ni steel clad plate, sheet, and strip	300 series (ASS)	R & E
SA-265	Ni and Ni-base alloy clad plate	Nickel-based alloys	R & E
SB-898	Ti, Zr, Ta, Nb, and their alloys integrally bonded to a base metal plate of steel or any other metal	Ti, Nb, Zr, Ta, and their alloys, ASTM B265, B393, B551, and B708 respectively	R, E, and W
API 5LD	CRA clad or lined steel pipe		R, E, P, W, and L

Legend: *R* rolled, *E* explosion bonded, *W* weld overlayed, *L* lined, *Clad* Integrally clad

Notes

(1) The cladding shall not be used when the CVN impact test results of the base metal (backing steel) at the MDMT do not pass the acceptance categories.

(2) Typically the additional corrosion allowance for base metal (backing steel) is not required when the cladding is used for corrosion resistance only.

(3) ASME Sec.VIII, Div.1, UCL-24 requires that the use of corrosion resistant integral or weld metal overlay cladding or lining material of stainless steel with Cr > 14% is not recommended for service metal temperatures above 425°C (800°F) due to high difference of thermal expansion between two metals.

(4) ASME Sec.VIII, Div.1, UCL-11 requires a minimum shear strength of 140 MPa (20,000 psi) between base metal (backing steel) and clad metal when the rolled cladding is used.

Figure 2.107 Lowest cost zone of clad options – for reference. (Source: DMC Clad Metal, 2006-modified). Dotted lines: The explosion application may be narrowed per geometry, size, and delivery factors

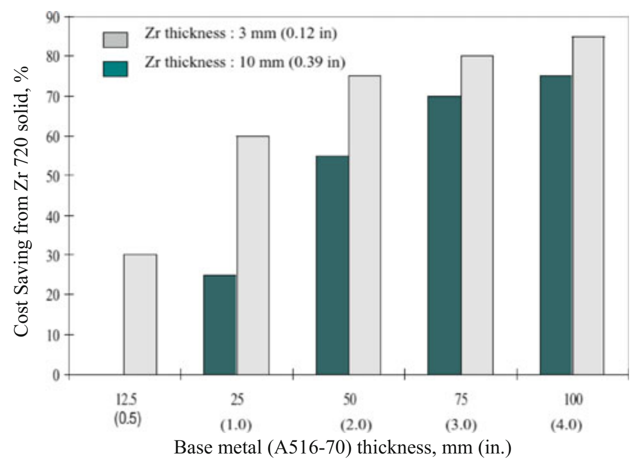


Figure 2.108 Cost saving of zirconium 702 clad steel. For reference. (Source: DMC Clad Metal, 2006-modified)

Table 2.93 Economic turning point of rolled cladding materials (only reference)

Thicknesses as a solid metal		Evaluation
SS or nickel-based alloys	Titanium and titanium alloys	
$T \leq 16$ mm (5/8 inch)	$T \leq 25$ mm (1 inch)	Use solid
16 mm (5/8 inch) < t < 19 mm (¾ inch)	25 mm (1 inch) < t < 38 mm (1.5 inch)	Equivalent cost
$T \geq 19$ mm (¾ inch)	$T \geq 38$ mm (1.5 inch)	Use clad plate

2.1.9 Nonmetallic Materials: Plastic, Elastomer, Ceramic, and Composite Materials

Nonmetallic materials have been mostly used for functional purpose, such as corrosion-erosion-fire resistance. The application has been extended to pressure parts, but still limited to low-pressure components. The threshold temperature, pressure, and strength depend on the exposed environments, and their combination. Therefore, material engineers should consider the worst combination for material selection. Table 2.94 shows a summary of characteristics for most popular nonmetallic materials. Table 2.95 shows typical properties of thermoplastic materials (ASME RTP-1). Table 2.96 shows nonmetallic material and product standards (ASME B31.1, B31.9. See Table 3.13 and Sect. 2.6.2.7 for insulation materials and their purpose and applicable standards. See Sect. 2.6.2.7 for refractory materials. ASME RTP-1, M12C-200 states that the following factors will be considered for proper material selection for a lining application:

(a) Chemical resistance at the temperature of operation and at maximum upset temperatures.
(b) The potential for environmental stress cracking, considering

Table 2.94 (1/3) Nonmetal materials – plastic, elastomer, ceramic, and composite materials (reference only) – see general notes

Non-metals	Group	Types	General name	Other name or reinforcing/resin material	Trade name	Brand/patent	Note no	Physical properties: s.g.	Min temp °C for use *(9)*	Max temp °C for use *(9)*	Thermal conduct. W/m. K	No
Plastics	Thermoplastics	Polyolefin	Polyethylene (PE)	Polyethylene (PE)			*(8)*	0.93–0.94		60–80		1
Plastics			Polyethylene (PE)	Ultralow Density (ULDPE)			*(8)*	0.90–0.91				2
Plastics			Polyethylene (PE)	Linear Low Density (LLDPE)			*(8)*	0.91–0.94				3
Plastics			Polyethylene (PE)	Low Density (LDPE)			*(8)*	0.91–0.93		80–100	0.30–0.33	4
Plastics			Polyethylene (PE)	High Density (HDPE)			*(8)*	0.94–0.97	-40	60–82	0.39–0.43	5
Plastics			Polyethylene (PE)	High Molecular Weight/ Density (HMW-HDPE)			*(8)*	0.95–0.97			0.39–0.43	6
Plastics			Polyethylene (PE)	Ultrahigh Molecular Weight (UHMWPE)			*(8)*	0.97		93		7
Plastics			Polypropylene (PP)	Polypropylene (PP – type 1)			*(8)*	0.90–0.91	−18	66–107	0.10–0.16	8
Plastics			Polypropylene (PP)	Polypropylene (PP – type 2)			*(8)*	0.90–0.91	−18	66–107	0.10–0.16	9
Plastics			Polypropylene (PP)	Polypropylene (PPS)			*(8)*	0.90–0.91	−18	66–107	0.10–0.16	10
Plastics		Chloropolymer	Polyvinyl Chloride (PVC)	Polyvinyl Chloride (PVC)	Tygon	Norton, Plastics and Synthetics	*(8)*	1.35–1.45	−18	60–70	0.16–0.18	11
Plastics			Polyvinyl Chloride (PVC)	Chlorinated PVC (CPVC)		Dow Chemical	*(8)*	1.49–1.58	−18	93–99	0.12	12
Plastics			Polyvinyl Chloride (PVC)	Polyvinylidene Chloride (PVDC)			*(8)*	1.63	−18	120	0.13	13
Plastics		Fluoropolymers	Polyvinyl Fluoride (PVF)				*(8)*	1.37–1.77		150		14
Plastics			Polyvinylidene Fluoride (PVDF)	Homopolymer	Kynar	Pennwalt Corp/ Atochem Inc.	*(8)*	1.75–1.79	−18	135	0.09–0.11	15
Plastics			Polyvinylidene Fluoride (PVDF)	Homopolymer	Sygef	George Fisher Sieget Inc.	*(8)*	1.75–1.79	−18	135	0.09–0.11	16
Plastics			Polytetrafluoroethylene (PTFE)		Teflon/ Fluon/ Halar	DuPont/I.C.I/ Allied Chemical	*(8)*	2.15–2.30	−198	200–260	0.25	17
Plastics			Fluorinated Ethylene Propylene (FEP)				*(8)*	2.12–2.17	−73/−198	149–204	0.21	18
Plastics			Perfluoroalkoxy (PFA)				*(8)*	2.12–2.17	−46/−198	230–260	0.21	19
Plastics			Polychlorotrifluoroethylene (PCTFE)				*(8)*		−269	190	0.20–0.21	20
Plastics			Ethylene Chlorotrifluoroethylene (ECTFE)		Halar	Ausimont	*(8)*	1.68–1.70	−198	165–171	0.14	21
Plastics			Fluorinated Chlorotrifluoroethylene (FCTFE)				*(8)*	2.14	−253		0.20–0.21	22
Plastics			Ethylene Fluoroethylene (ETFE)				*(8)*	1.7	−198	149	0.2	23
Plastics					Saran	Dow Chemical	*(8)*					24
Plastics		Engineered Polymer	Acrylonitrile Butadiene Styrene (ABS)				*(8)*	1.05–1.14	−40	71–80		25
Plastics			Polyamide (Nylon)		Nylon 11		*(8)*		−65	120		26
Plastics			Polyether Ether Ketone (PEEK)				*(8)*		−30/−198	135–230		27

Table 2.94 (2/3) Nonmetal materials – plastic, elastomer, ceramic, and composite materials (reference only) – see general notes

Non-metals	Group	Types	General name	Other name or reinforcing/resin material	Trade name	Brand/patent	Note no	Physical properties: s.g.	Min temp °C for use *(9)*	Max temp °C for use *(9)*	Thermal conduct. W/m.K	No
Plastics	Thermosets		Epoxies	Epoxy Resin – bis A			*(8)*	1.06–1.40	−29	80–260		28
Plastics			Epoxy Novalacs				*(8)*	1.12–1.24	−29	95–260		29
Plastics			Polyester	Glass filled BMC			*(8)*	1.7–2.3	−29	150–180		30
Plastics			Polyester	Glass filled SMC			*(8)*	1.7–2.3	−29	150–180		31
Plastics			Polyester	Glass cloth reinforcing			*(8)*	1.3–2.1	−29	150–180		32
Plastics			Vinyl Esters	Common (Derakane)	Derakane 470	Ashland	*(8)*		−29	120		33
Plastics			Vinyl Esters	High temperature (Epoxy Niovalac)			*(8)*		−29	175		34
Plastics			Urethane	Polyurethane			*(8)*	1.13–1.2	−20/−197	90–177		35
Plastics		Reinforced Resin (FRP)	Vinyl Esters	Glass fiber Reinforced Vinyl Ester (GRP)			*(8)*		−29/−54	80–230		36
Plastics			Polyester	Glass fiber Reinforced Polyester (GRP)			*(8)*	1.38–1.39	−29/−54	40–175		37
Plastics			Epoxy	Glass fiber Reinforced Epoxy (GRP)			*(8)*		−29/−54	95–150		38
Elastomers	Rubber and The Compounds		Natural Rubber (NR)	Soft NR			*(6),(7)*	0.93	−29	70–100		39
Elastomers			Natural Rubber (NR)	Semi Hard NR			*(6),(7)*	0.93	4	70–82		40
Elastomers			Natural Rubber (NR)	Hard NR			*(6),(7)*	0.93	10	70		41
Elastomers			Nitrile Rubber (NBR)	High Temperature Type	Buna N		*(6),(7)*		−20/−30	120–130		42
Elastomers			Nitrile Rubber (NBR)	Low Temperature Type	Buna N		*(6),(7)*		−20/−30	105		43
Elastomers			Chloroprene Rubber (CR)				*(6),(7)*		−20	70		44
Elastomers			Butyl Rubber (BR)				*(6),(7)*			60–105		45
Elastomers			Chlorobutyl Rubber				*(6),(7)*		−51	60–127		46
Elastomers			Fluorocarbon Rubber (FKM)		Viton A	DuPont	*(6),(7)*	1.4–1.95	−5/−30	205		47
Elastomers			Silicon Rubber (VMQ or SIL)				*(6),(7)*		−116	232		48

Table 2.94 (3/3) Nonmetal materials – plastic, elastomer, ceramic, and composite materials (reference only) – see general notes

Non-metals	Group	Types	General name	Other name or reinforcing/resin material	Trade name	Brand/patent	Note no	Physical properties: s.g.	Min temp °C for use *(9)*	Max temp °C for use *(9)*	Thermal conduct. W/m. K	No
Elastomers					Neoprene		*(6),(7)*		−20	90		49
Elastomers			Hydrogenated Acrylonitrile Butadiene *HNBR				*(6),(7)*		−20			50
Elastomers			Ethylene Propylene (EPM, EPDM)				*(6),(7)*	0.86	−57	155–180		51
Elastomers			Chlorosulfonated Polyethylene (CSM)		Hypalon	Du Pont de Nemours & Co.	*(6),(7)*	1.11–1.26	−10	110		52
Elastomers			Perfluoroelastomer		Kalrez	Du Pont de Nemours & Co.	*(6),(7)*		−29	100		53
Elastomers			Perfluoroelastomer (FFKM)		Chemraz	Green, Tweed & Co.	*(6),(7)*		−12	260		54
Elastomers			Polyacrylate (ACM, ANM)				*(6),(7)*			175		55
Elastomers			Fluorosilicon (FVMO)				*(6),(7)*	1.4		175		56
Elastomers			Epichlorohydrin (CO, ECO)				*(6),(7)*	1.32–1.49		135		57
Elastomers			Polysulfide (PTR)				*(6),(7)*			105		58
Carbon	Carbon							1.4–1.8		350–2800		59
Carbon	Graphite						*(4)*	1.75	*(4)*	*(4)*		60
Carbon	Flexible Graphite			Graphite foil	Grafoil (gasket)	Union Carbide Corp.	*(5)*		−240	400 *(3)*		61
Cement			Portland Cement					2.2		300–400		62
Cement			Furan	Carbon filled cement				1.52–1.92	−29	93		63
Cement					Gunite (lining)							64
Glasses(13)					Gunite (lining)							65

Legend: VP: Very Poor/P: Poor/G: Good/E: Excellent
General Notes: See brand report/catalogs or consult with the brand for more details
a. Blank: No Data. See ASTM D1781 for Climbing Drum Peel Testing of Dual Laminates
b. Standards for Materials and Products: See Table 2.96
c. Use temperature range may be narrowed per service, pressure, exposed time, lining/solid, and each code
d. See API 610 for non-metallic wear parts for pumps
e. The properties can be changed per the reinforcing/resin/filler materials
f. Piping: See ASME B31.3, Table A323.4.2C & A323.4.3 Temperature Limits, Table B-1(M) Hydrostatic Stresses, Table C-5 Thermal Expansion Coeff
g. For more detail, see ASME Sec.X for FRP; Table 2.95 for thermoplastic properties; and Sect. 2.6.2.7 for insulation and fireproofing materials
h. See EEMUA #192 for valves in low temperature
i. Typical Properties: ASME RTP-1 (See Table 2.95 in this book)
j. Normally nonmetallics are not allowed for ASME B31.4 Liquid Transfer System (HC, LPG, Anhydrous NH3, Alcohol, etc.;)
k. Glasses: API 579–1/ASME FFS-1 shows Thermal Expansion/Shock Resistance/Stress Resistance, Modulus of Elasticity, Softening Point, and Working Point.
l. See BS EN ISO 21457 for Oil and Gas Production Industries
m. Consult with materials & corrosion specialist or manufacturer for detailed instruction

Table 2.94 (1/3) Nonmetal materials – plastic, elastomer, ceramic, and composite materials (reference only)

	Mechanical properties			Corrosion resistance [concentration, wt%], Temp.°C ( ): *see Notes.*															Others
No	Hardness[10]	Abrasion resistance	T.S Kg/mm^2	Oxi. resist	UV[1] resist	Strong acids	Weak acids	Caustics	Aliphatic solvents	Aromatic solvents	Halogenated solvents	Alcohols	Ketones	Deionized water	Amines	Calcium hydroxide	HF acid	Nitric acid	Standards, ASTM unless otherwise specified
1						E	E	E[50]		P		E	P	E	P		E [50] *(2)*	G/E	ASTM D2239/ D3035/ D2737
2																	*(2)*		
3																	*(2)*		
4			0.06–0.17			P	E	E[50]	E	E	E			E			*(2)*	P	
5			0.2–0.37			P	E	E[50]	E	E	E			E			*(2)*	P	
6			~0.17			P	E	E[50]	E	E	E						*(2)*		ASTM F714
7																	*(2)*		ASTM F714
8			0.21–0.34		P	E	E	E[50]		P		E	G	E	G		P(50)	VP/P	ASTM D4101/ D5857
9			0.21–0.34			E	E	E[50]		VP		E	P	E	P		E[50]	G/E	ASTM D4101/ D5857
10			0.21–0.34																ASTM D4101/ D5857
11			5.5–6.5			G	E	P		VP		E	VP		VP		G[50]	VP/P	ASTM D2564, AWWA C900, API 15LP
12			5.2–6.2			G	E	G		G				E					ASTM D2846/ F493, API 15LP
13			1.7–3.2																
14			5																
15	A75		2.46–4.36			E	E	E[50]		E		E	P	E	G		E[50]	E	
16	A75		2.46–4.36																
17	A50–65		1.41–4.57			E	E	E[50]		E				E				E	
18	A55		1.90–2.18			E	E	E[50]		E				E				E	
19	A64		2.81–3.16																
20																			
21	A75		4.64–5.48																
22	A75		2.81–4.22																

Table 2.94 (2/3) Nonmetal materials – plastic, elastomer, ceramic, and composite materials (reference only)

	Mechanical properties			Corrosion resistance [concentration, wt%], Temp.°C *( ): see Notes.*															Others
No	Hardness(10)	Abrasion resistance	T.S Kg/mm^2	Oxi. resist	UV(1) resist	Strong acids	Weak acids	Caustics	Aliphatic solvents	Aromatic solvents	Halogenated solvents	Alcohols	Ketones	Deionized water	Amines	Calcium hydroxide	HF acid	Nitric acid	Standards, ASTM unless otherwise specified
22	A75		2.81–4.22																
23	A75		4.5–4.8																
24						P	E	VP		P		E	VP	E	VP	VP	P/E		
25			0.35–0.57			P	E	E[50]						E/P,90					ASTM D2235
26	C108		0.83			VP	VP	E[50]		E		E	E	E/P,90	E		VP	P/E	
27			0.83			VP	VP							E/P,90				VP	ASTM D3835/ F2026
28			0.28–0.90			P	E	E(50)		E	P	E	P	E			E [50]	P/E	
29			3.4–7.6			E	E	E(50)		E				E				E	
30			2.8–6.9			P	G~P	G~P	P	P	P			E			G~P		
31			5.5–13.8			P	G~P	G~P	P	P	P			E			G~P		
32			17.2–34.5			P	G~P	G~P	P	P	P			E			G~P		
33							G	G-E											
34																			
35	A30–95		~0.69			VP	P	P		E	P			E					
36																			ASTM D3517/3754/ 2310(12) ASTM C581 for corrosion resistance test
37																			
38																			
39	A30–50	E		P		E	G	G	P	P	P								ASTM D1418
40	A50–90	G		G			G	G	G	P	P								ASTM D1418
41	>A90	P	0.4–0.6	G			G	G	G	P	P								ASTM D1418
42	A40–95	G	0.4–0.6	G			G	G	F	P	P	G	VP		VP		P	VP/P	ASTM D1418
43	A40–95	G		G			G	G	G	P	P	G	VP		VP		P	VP/P	ASTM D1418
44	A40–95	G	2–2.7				E	E	G	P	P								ASTM D1418
45						VP	P	G[50]		VP		E	G		G		G [50]	G/P	ASTM D1418
46	A50–60	E		G			G	G	P	P	P								ASTM D1418

Table 2.94 (3/3) Nonmetal materials – plastic, elastomer, ceramic, and composite materials (reference only)

	Mechanical properties			Corrosion resistance [concentration, wt%], Temp.°C *( ): see Notes.*															Others
No	Hardness[(10)]	Abrasion resistance	T.S Kg/mm^2	Oxi. resist	UV[(1)] resist	Strong acids	Weak acids	Caustics	Aliphatic solvents	Aromatic solvents	Halogenated solvents	Alcohols	Ketones	Deionized water	Amines	Calcium hydroxide	HF acid	Nitric acid	Standards, ASTM unless otherwise specified
47	A65–90	G		E	E	P	E	P	E	E	G	G	VP	G	VP		E [50]	E	ASTM D1418
48	A30–90	P		E			G	G	P	P	P								ASTM D1418
49						VP	P	G[50]		G		G	VP		VP		G [50]	VP/P	ASTM D1418
50	A30–95																		ASTM D1418
51	A30–90	G		E	E	G	E	G	VP	P	VP	P		E					
52	A45–95	E		E	G	E	E	E	G	P	P	P		G					
53	A80–90	F		E			E	E	E	E	E								
54																			
55																			
56	A40–70	P			G	G	E	G	E	E				E					
57	A30–95	G				G	G	G	E	G	G	G		G					
58																			
59			0.3–1.0																
60			1.8																ASTM D0662
61																			
62			0.35–0.41			VP	P	E	E	E	E	P	E						
63			0.41			P	E	E	E	E	E			E				P	
64							E	E	E	E	E								
65							E	E	E	E	E								

Notes

(1) Generally Gelcoating (Mixed or Coating type) on FRP is used to protect UV
(2) PE may be damaged by SCC in HF Service
(3) Up to 870 °C in no-oxidizing environment
(4) Carbon Graphite for wear parts (API 610)
– Resin-Impregnated: −50 to 285 °C
– Babbit-Impregnated: −100 to 150 °C
– Nickel-Impregnated: −195 to 400 °C
– Copper-Impregnated: −100 to 200 °C
(5) Gasket material is not recommended in seawater/concentrated brine because the flange material can be rapidly corroded due to galvanic corrosion
(6) Hardness: A: Duromer A, B: Durometer B, C: Rockwell R/Application Code: ASTM D2240
(7) The strength of Elastomer are based on the reinforced condition
(8) The permeability of O_2 & H_2O for plastic materials is specified on ASTM D1434 & E96
(9) For noncorrosive or nonfatigue service; and for short-term exposure. To narrow the temperature range for continuous exposure and/or high pressure
(10) See Sect. 5.4.1.3 for more details on non-metal hardness test.
(11) See ASME Sec.X, RG-112 for FRP Pressure Vessels
(12) ASTM D3517 Pressure Pipe, ASTM D3754 Sewer & Industrial Pressure Pipe, ASTM D2310 Machine Made Pipe
(13) Glasses: See API 579-1/ASME FFS-1, Table 11-16 Properties of Commercial Glasses

Table 2.95 Typical thermoplastic properties-ASME RTP-1[1]

Properties	HDPE	PP		PVC	CPVC	PVDF		ECTFE	ETFE	FEP	TFE	MFA	PFA
		Homopolymer	Copolymer (unfilled)			Homopolymer	Copolymer						
Density, g/cm^3	0.95–0.97	0.91	0.88–0.91	1.38	1.5	1.75–1.79	1.76–1.79	1.68	1.70	2.12–2.17	2.2–2.3	2.12–2.17	2.12–2.17
Mechanical properties[2]													
Tensile break strength (ASTM D638), MPa	22.1–31.1	31–41	27.6–38.0	41–52	47–62	31–48	24–41	46–54	45	19–21	14–19	28–36	28–31
Tensile break strength (ASTM D638), ksi	3.2–4.5	4.5–6.0	4.0–5.5	6.0–7.5	–	4.5–7.0	3.5–6.0	6.6–7.8	6.5	2.7–3.1	2.0–2.7	3.5–4.42	4.0–4.5
Tensile Modulus (ASTM D638). MPa	1070–1090	1139–1553	897–1242	2415–4140	2353–3278	1380–5520	–	1656	828	345	400–552	440	483
Tensile Modulus (ASTM D638). ksi	155–158	165–225	130–180	350–600	341–475	200–800	–	240	120	50	58–80	64	70
Elongation (ASTM D638), %	10–1200	100–600	200–500	40–80	4–100	12–600	–	200–300	100–400	250–330	200–400	300–600	300
Yield strength (ASTM D638), MPa	26.2–33.1	31–37	20.7–29.7	41–45	41–55	20–57	20–38	31–34	49	–	12	–	14
Yield strength (ASTM D638), ksi	3.8–4.8	4.5–5.4	3.0–4.3	5.9–6.5	6–8	2.9–8.3	2.9–5.5	4.5–4.9	7.1	–	1.7	–	2.1
Thermal properties													
HDT at 0.46 MPa (ASTM D648),°C	79–91	107–121	54–60	57	102–119	132–150	93–110	90	104	70	221	63	75
HDT at 66 psi (ASTM D648),°F	175–196	225–250	130–140	158	215–247	270–300	200–230	194	220	158	250	145	166
Linear coefficient of expansion (ASTM D696) per °C × 10^{-5}	10.6–19.8	14.6–18.0	12.2–17.1	5.0–10.0	11.2–14.0	12.6–25.6	–	14.4	10.6	8–11	12.6–22	12–16	25–38
Linear coefficient of expansion (ASTM D 696) per °F × 10^{-5}	5.9–11.0	8.1–10	6.8–9.5	2.7–5.6	6.2–7.8	7.0–14.2	–	8.0	5.9	–	2.0–12	–	14–21
Thermal conductivity (ASTM C177), W/m. K	0.39–0.43	0.1	0.16	0.16–0.18	0.12	0.09–0.11	0.16	0.14	0.20	0.21	0.21	0.20	0.21
Thermal conductivity (ASTM C177), Btu / ft^2-hr-°F/in.	76–83	0.7	1.1	1.1–1.23	0.81	0.59–0.76	1.11	0.97	1.40	1.48	1.48	1.41	1.48

General Notes: Properties are at room temperature unless otherwise stated. Properties are typical values and are not to be used for design purpose

Abbreviations: HDPE (High-Density Polyethylene), PP (Polypropylene), PVC (Polyvinyl Chloride), CPVC (Chlorinate Polyvinyl Chloride), PVDF (Polyvinylidene Fluoride), ECTFE (Ethylene-Chlorotrifluoroethylene), ETFE (Ethylemetetrafluoroethlene), FEP (Fluorinated Ethylene Propylene), TFE (Tetrafluoroethylene), MFA (MFA®), PFA (Perfluoroalkoxy), HDT (Heat Deflection Temperature)

Commentary Notes:

(1)All designated properties are for reference, and based on the room temperature unless otherwise specified. Contact with the supplier for the guaranteed property

(2)Lower level may be indicated for corrosive, or fatigue service; and for continuous exposure

Table 2.96 (1/2) Nonmetallic material and product standards – ASME B31.1 and B31.9

Nonmetallic materials and products	Standard No.
Nonmetallic fittings	
Acrylonitrile-butadiene-styrene ABS plastic pipe fittings, schedule 40	ASTM D2468
Butt heat fusion polyethylene (PE) plastic fittings for polyethylene (PE) plastic pipe and tubing	ASTM D3261
Chlorinated poly(vinyl chloride) CPVC plastic hot and cold water distribution systems	ASTM D2846
Electrofusion type polyethylene fittings for outside diameter controlled polyethylene pipe and tubing	ASTM F1055
Plastic insert fittings for polyethylene (PE) plastic pipe	ASTM D2609
Polybutylene (PB) plastic hot/cold water distribution systems	ASTM D3309
PVC plastic pipe fittings, schedule 40	ASTM D2466
Reinforced epoxy resin gas pressure pipe and fittings	ASTM D2517
Reinforced thermosetting resin (RTR) flanges	ASTM D4024
Socket-type chlorinated poly(vinyl chloride) (CPVC) plastic pipe fittings, schedule 40	ASTM F438
Socket-type chlorinated poly(vinyl chloride) (CPVC) plastic pipe fittings, schedule 80	ASTM F439
Socket-type polyethylene fittings for outside diameter-controlled polyethylene pipe and tubing	ASTM D2683
Socket-type poly(vinyl chloride) (PVC) plastic pipe fittings, schedule 80	ASTM D2467
Solvent cement for ABS plastic pipe and fittings	ASTM D2235
Solvent cements for CPVC plastic pipe and fittings	ASTM F493
Solvent cements for PVC plastic pipe and fittings	ASTM D2564
Specification for reinforced plastic mortar pipe fittings for nonpressure applications	ASTM D3840
Standard specification for cold-expansion fittings with metal compression sleeves for PEX pipe	ASTM F2080
Threaded poly(vinyl chloride) (PVC) plastic pipe fittings, schedule 80	ASTM D2464
Thermoplastic gas pressure pipe, tubing, and fittings	ASTM D2513
Threaded chlorinated poly(vinyl chloride) (CPVC) plastic pipe fittings, schedule 80	ASTM F437
Threaded poly(vinyl chloride) (PVC) plastic pipe fittings, schedule 80	ASTM D2464
Threads (60-deg. stud) for glass RTR pipe	ASTM D1694
Nonmetallic pipe and tube products	
ABS plastic pipe fittings, schedule 40	ASTM D2468
ABS plastic pipe (SDR-PR)	ASTM D2282
Acrylonitrile-butadiene-styrene (ABS) plastic pipe, schedules 40 and 80	ASTM D1527
Acrylonitrile-butadiene-styrene (ABS) plastic pipe (SDR-PR)	ASTM D2282
AWWA standard for glass-fiber-reinforced thermosetting-resin pressure pipe	*AWWA C 950
Biaxially oriented PE (PEO) plastic pipe (SDR-PR) based on controlled outside diameter	ASTM D3287
Centrifugally cast glass fiber RTR pipe	ASTM D2997
Centrifugally cast reinforced thermosetting resin pipe	ASTM D2997
Joints for IPS PVC pipe using solvent cement	ASTM D2672
Chlorinated poly(vinyl chloride) (CPVC) plastic hot and cold water distribution system	ASTM D2846
Chlorinated poly(vinyl chloride) (CPVC) plastic pipe, schedules 40 and 80	ASTM F441
Chlorinated poly(vinyl chloride) (CPVC) plastic pipe, (SDR-PR)	ASTM F442
Classification for machine-made RTR pipe	ASTM D2310
Concrete sewer, storm drain, and culvert pipe	ASTM C14
CPVC plastic pipe, schedules 40 and 80	ASTM F441
CPVC plastic pipe (SDR-PR)	ASTM F442
Filament-wound “fiberglass” (glass-fiber reinforced thermosetting-resin) pipe	ASTM D2996
Filament-wound RTR pipe	ASTM D2996
Low-pressure fiberglass line pipe	API 15LR
Machine-made reinforced thermosetting-resin pipe	ASTM D2310
Plastic-lined ferrous metal pipe, fittings, and flanges [Note (3)]	ASTM F1545
PB plastic hot-water distribution systems	ASTM D3309
Polybutylene (PB) plastic tubing	ASTM D2666
Polybutylene (PB) plastic pipe (SDR-PR) based on outside diameter	ASTM D3000
Polybutylene (PB) plastic pipe (SIDR-PR) based on controlled inside diameter	ASTM D2662
Polyethylene (PE) line pipe	API 15LE
Polyethylene (PE) plastic pipe, schedule 40	ASTM D2104
Polyethylene (PE) plastic pipe, schedules 40 and 80, based on outside diameter	ASTM D2447
PE plastic pipe (SDR-PR), based on controlled outside diameter	ASTM D3035
PE plastic pipe, schedules 40 and 80 based on outside diameter	ASTM D2447
Plastic insert fittings for PE plastic pipe	ASTM D2609

Table 2.96 (2/2) Nonmetallic material and product standards – ASME B31.1 and B31.9

Nonmetallic materials and products	Standard no.
Nonmetallic pipe and tube products – cont'd	
Polyethylene (PE) plastic pipe (SIDR-PR) based on controlled inside diameter	ASTM D2239
Polyethylene (PE) plastic pipe (SDR-PR) based on controlled outside diameter	ASTM D3035
Polyethylene (PE) plastic tubing	ASTM D2737
Polyvinyl chloride) (PVC) pressure-rated pipe (SDR series)	ASTM D2241
Polyvinyl chloride) (PVC) plastic pipe, schedules 40, 80, and 120	ASTM D1785
PVC pressure pipe, 4 in. through 12 in., for water	ANSI/AWWA C900
PVC pressure pipe, 4-inch through 12 in., for water	*AWWA C 900
Thermoplastic line pipe (PVC and CPVC)	API 15LP
Prestressed concrete pressure pipe, steel cylinder type, for water and other liquids	ANSI/AWWA C301
Reinforced concrete low-head pressure pipe	ASTM C361
Reinforced concrete pressure pipe, noncylinder type, for water and other liquids	ANSI/AWWA C302
Reinforced concrete pressure pipe, steel cylinder type, for water and other liquids	ANSI/AWWA C300
Reinforced epoxy resin gas pressure pipe and fittings	ASTM D2517
Socket-type PE fittings for outside diameter-controlled PE pipe and tubing	ASTM B2683
Solvent cement for ABS plastic pipe and fittings	ASTM D2235
Solvent cements for CPVC plastic pipe and fittings	ASTM F493
Solvent cements for PVC plastic pipe and fittings	ASTM D2564
Specification for "fiberglass" (glass-Fiber-reinforced-thermosetting resin) pressure pipe	ASTM D3517
Specification for fiberglass sewer and industries pressure pipe	ASTM D3754
Standard specification for polyethylene (PE) plastic pipe (SDR-PR) based on outside diameter	ASTM F714
Standard specification for crosslinked polyethylene/aluminum/crosslinked PE (PEX-AL-PEX) pressure pipe	ASTM F1281
Standard specification for crosslinked polyethylene (PEX) tubing	ASTM F876
Standard specification for polyethylene/aluminum/polyethylene (PE-AL-PE) composite pressure pipe	ASTM F1282
Standard specification for pressure-rated composite pipe for elevated temperature	ASTM F1335
Thermoplastic gas pressure pipe, tubing, and fittings	ASTM D2513
Miscellaneous	
Contact-molded reinforced thermosetting plastic (RTP) laminates for corrosion-resistant equipment	ASTM C582
CPVC plastic hot and cold water distribution systems	ASTM D2846
Design and construction of nonmetallic enveloped gaskets for corrosive service	ASTM F336
Electrofusion joining polyolefin pipe and fitting	ASTM F1290
External loading properties of plastic pipe by parallel-plate loading	ASTM D2412
Heat-joining polyolefin pipe and fitting	ASTM D2657
Joints for IPS PVC using solvent cement	ASTM D2672
Joints for plastic pressure pipes using flexible elastometric seals	ASTM D3139
Joints for plastic pressure pipes using flexible elastomeric seals	ASTM D3139
Making solvent-cemented joints with poly (vinyl chloride) (PVC) pipe and fittings	ASTM D2855
Obtaining hydrostatic design basis for thermoplastic pipe materials	ASTM D2837
Obtaining hydrostatic or pressure design basis for "fiberglass" (glass-Fiber-reinforced thermosetting-resin) pipe and fittings	*ASTM D2992
Plastic pipe institute (PPI) technical report thermal expansion and contraction of plastic pipe	PPI TR-21
Socket-type PE fittings for outside diameter-controlled PE pipe and tubing	ASTM B2683
Socket-type PVC plastic pipe fittings, schedule 80	ASTM D2467
Solvent cements for acrylonitrile-butadiene-styrene (ABS) plastic pipe and fittings	ASTM D2235
Solvent cements for chlorinated poly(vinyl chloride) (CPVC) plastic pipe and fittings	ASTM F493
Solvent cements for poly(vinyl chloride) (PVC) plastic pipe and fittings	ASTM D2564
Solvent cements for transition joints between ABS and PVC nonpressure piping components	ASTM D3138
Standard abbreviations of terms relating to plastics	ASTM D1600
Standard definitions of terms relating to plastics	ASTM D297
Standard methods of testing vitrified clay pipe	ASTM C301
Standard specification for crosslinked polyethylene (PEX) plastic hot and cold water distribution systems	ASTM F877
Standard test method for external pressure resistance of reinforced thermosetting resin pipe	ASTM D2924
Threads 60° (stub) for "fiberglass" (glass-Fiber-reinforced thermosetting-resin) pipe	*ASTM D1694
Underground installation of "fiberglass" (glass-fiber-reinforced thermosetting resin) pipe	ASTM D3839

Note: An asterisk (*) preceding the designation indicates that the standard has been approved as an American National Standard by the American National Standards Institute

1. The fluids contacted, including cleaning and other incidental fluids
2. Operating conditions, including the residual and operational stresses and the exposure temperature

(c) Thickness: The lining will be thick enough so that permeation will be low to minimize chemical exposure to the RTP (reinforced thermoset plastic) structure. However, the lining will not be so thick that anticipated forming processes during fabrication would cause damaging stresses and possible failure.
(d) Temperature – creep limitations for the bonding resin. The guideline limit is that the HDT (heat deflection temperature at 0.46 MPa/66 psi) of the bonding resin be at least 20 °C (36 °F) greater than the maximum design temperature of the vessel.
(e) The need for stress relief in the case of high residual stresses from forming or welding, which could cause cracking or other failure mode in service.
(f) Residual stresses in the received sheet and the need for stress relief prior to fabrication.

2.1.10 P-No.-Gr. No./S-No./F-No./A-No./SFA No./AWS Class-UNS No.

2.1.10.1 P-No. and Group No. [P = Parent]

P-Numbers (P-No.) have been developed for optimization of welding control by ASME Sec. IX for ASME BPVC and AWS B2.1 for metal structures, especially to reduce the number of required PQR. The base metals (**P**arent material) have been assigned P-Number that are based essentially on comparable base metal characteristics, such as composition, weldability, brazeability, and mechanical properties, where this can be locally done. P-Numbers have subnumbers, group numbers, to consider other properties such as impact test, tensile strength (TS), heat treatment, etc.

Because P No. system is for weldable materials, non-weldable materials, such as bolting or some casting materials are not designated and controlled by P No. system. Therefore, P No. 2 which was for casting materials (wrought iron) in the past is not existed any more even though the repair welding is commonly applied.

Table 2.97 shows the group of P-numbers of metals for welding and brazing. Table 2.98 shows the Group No. of carbon steels (P No. 1).

Table 2.99 shows the characteristics for classes of P-Numbers in accordance with API RP582. Table 2.100 shows the ASTM materials in accordance with P-Numbers and products. See the following standards for P No. for ASTM materials for more details:

Table 2.97 Groups of P no. of metals

Base metals	Welding (<100)	Brazing (>100)
Steel and steel alloys	1–15F	101–103
Aluminum and its alloys	21–25	104–105
Copper and its alloys	31–35	107–108
Nickel and its alloys	41–47	110–112
Titanium and its alloys	51–54	115
Zirconium and its alloys	61 and 62	117

Notes: source: ASME Sec.IX, API RP582, ASM Metal Handbook, Vol.1

Table 2.98 Group no. of CS (P No. 1)

Group no	Characteristics (typical) 1) 2)
1	T.S < 49.2 kg/mm^2 (70 ksi)
2	T.S ≥ 49.2 kg/mm^2 (70 ksi)
3 3)	T.S ≥ 56.2 kg/mm^2 (80 ksi) and/or Q-T steel
4 4)	T.S ≥ 56.2 or 63.3 kg/mm^2 (80 or 90 ksi) and/or Q-T steel

Notes: source: ASME Sec.IX, API RP582, ASM Metal Handbook, Vol.1
1) Actual data may be slightly different
2) T.S = specified minimum tensile strength Table 2.98 Notes (continued)
3) Group No. 3: e.g., ASTM A299-Gr.B/A333-Gr.10/A513-Gr.1026CW/A537-Cl.2 & 3/A633-Gr.E/A668-Cl.Fa & Fb/A656-Type 3, Gr.70 & Type 7. Gr.70/A671-CD80/A672-D80/A691-CMSH-80/A694-Gr.F70/A737-Gr.C/A738-Gr.B & C/A765-Gr.IV/A841-Gr.B, Cl.2/API 5L-Gr.X70/MSS SP-75-Gr. WPHY-70
4) Group No. 4: e.g., ASTM A656-Type 3 or 7, Gr.80 & higher/A724-Gr.A/B/C, API 5L-Gr.X80

Table 2.99 (1/2) Classes of P-numbers of metals – Note 1

P no.	Base metal description (strength-SMTS and chemistry)	P no.	Base metal description (strength-SMTS and chemistry)
1	CS max.: 0.030% C, 0.060% Si, 1.70% Mn	15C	74 ksi (510 MPa) ≤ SMTS 2.25% Cr, Mo, W, Cu
2	Wrought iron – deleted	15D	Open – not used yet
3	Low-alloy steel (LAS)	15E	85 ksi (585 MPa) ≤ SMTS (9% Cr, 1% Mo, V)
4	1.25% Cr-0.5% Mo nominal	15F	90 ksi (620 MPa) ≤ SMTS (11% Cr, 2% W, 0.5% Mo)
5	Cr-Mo steel – deleted	21	8 ksi (55 MPa) to 14 ksi (97 MPa) Al-unalloyed (Al, 1.0% Mn to 1.5% Mn, Cu)
5A	2.25% to 3% Cr, 1% Mo steel	22	22 ksi (150 MPa) to 31 ksi (215 MPa) (Al, 0.8–3.9% Mg, 0.2–1.5% Mn)
5B	5% to 10% Cr, 1% Mo steel	23	17 ksi (115 MPa) to 24 ksi (165 MPa) (Al, Mg, Si, Cu)
5C	Quench and tempered 2.25 to 3Cr-1Mo-V steel	24	Not used
6	MSS – e.g.,12% Cr	25	36 ksi (240 MPa) to 41 ksi (285 MPa) (Al, 3.5–5.1% Mg, 0.4–1.0% Mn)
7	FSS – 11% to 18% Cr	26	Castings
8	ASS (18% Cr, 8% Ni nominal) – note 2	31	30 ksi (205 MPa) to 38 ksi (260 MPa) copper – unalloyed (Cu, Ag, As, P, Fe)
9A	2% nickel alloy steels	32	40 ksi (275 MPa) to 72 ksi (495 MPa) bronze and brass (60–85% Cu, 20–40% Zn, 2% Al, 1%Sn, Sb, As, Ag, P)
9B	3.5% nickel alloy steels	33	40 ksi (275 MPa) to 85 ksi (585 MPa) (Cu, 1.6% Si to 3.5% Si)
9C	4.5% nickel alloy steels	34	34 38 ksi (260 MPa) to 63 ksi (435 MPa) copper nickel (66–90% Cu, 10–30% Ni, 2% Fe, 2% Mn)

Table 2.99 (2/2) Classes of P-numbers of metals – Note 1

P no.	Base metal description (strength-SMTS and chemistry)	P no.	Base metal description (strength-SMTS and chemistry)
10A	75 ksi (515 MPa) to 105 ksi (725 MPa) (Mn, V)	35	50 ksi (345 MPa) to 90 ksi (620 MPa) aluminum bronze (8–95% Cu, 5–11% Al, 5% Ni, 3–4% Fe)
10B	60 ksi (415 MPa) ≤ SMTS (1% Cr, V steel)	41	50 ksi (345 MPa) to 70 ksi (485 MPa) nickel – unalloyed
10C	81 ksi (560 MPa) to 83 ksi (570 MPa) (C, Mn, Si steel)	42	70 ksi (485 MPa) ≤ SMTS monel – (67% Cu, 30% Ni)
10D	Not used (20% Cr-1%Cu tubes)	43	105 ksi (725 MPa) to 120 ksi (825 MPa) NiCrFe alloys (47–72% Ni, 15–29% Cr, 8–16% Mo, 5–18% Fe, 14% W, 13 Co, 3.5% Cb, Cu)
10E	Not used	44	65 ksi (450 MPa) to 110 ksi (760 MPa) NiMo, NiMoCr alloys (62–70% Ni, 16–29.5% Mo, 1.3–7% Cr, 25% Fe, 13% Co, 3.5% Cb, Cu, Al, W)
10F	Not used (former Mn-Mo-V, Mn-Cr, Mo-V alloys)	45	65 ksi (450 MPa) to 109 ksi (750 MPa) NiFeCr alloys (21–49% Ni, 15–46% Fe, 20–33% Cr, 1.5–7% Mo, 18% Co, 3% W, 2.3–3% Cu, Cb, Al, Ti, N)
10G	Not used (36%Ni)		
10H	87 ksi (600 MPa) to 110 ksi (760 MPa) 18–29% Cr, 1.5–4.5% Mo, 3–8% Ni – DSS)	46	70 ksi (485 MPa) to 90 ksi (620 MPa) NiCrSi alloys (35–37% Ni, 19–28% Cr, 1.25–2.7% Si, 30% Co)
10I	60 ksi (415 MPa) to 90 ksi (620 MPa) (26% Cr to 27% Cr, 1% Mo – super ferritic)	47	Deleted
10 J	70 ksi (485 MPa) to 80 ksi (550 MPa) (29% Cr, 4% Mo – super ferritic)	49	120 ksi (825 MPa) ≤ SMTS cobalt alloys (Co, 26% Cr, 9% Ni, 5% Mo, 3% Fe, 2% W)
10 K	70 ksi (485 MPa) to 85 ksi (585 MPa) (26–29% Cr, 3–4% Mo, 2–2.5% Ni – super ferritic)	51	35 ksi (240 MPa) to 50 ksi (345 MPa) titanium – unalloyed (alpha) (Ti, Pd, Ru)
11A	LAS – quench and tempered: 9Ni (for cryogenic service)	52	65 ksi (450 MPa) to 70 ksi (485 MPa) titanium – unalloyed and alloyed (alpha) (Ti, 0.3% Mo, 0.8% Ni)
11B	LAS – quench and tempered, 105 ksi (725 MPa) ≤ SMTS	53	90 ksi (620 MPa) ≤ SMTS titanium alloyed (alpha-beta) (Ti, 3% Al, 2.5% V)
11C	LAS-normalized and precipitation heat-treated, providing a minimum SMYS of 55 ksi [380 MPa] and SMTS of 65 ksi [450 MPa: ASTM A859-A]	54	70 ksi (620 MPa) ≤ SMTS titanium – alloyed (alpha) (Ti, 0.3% Mo, 0.8% Ni) previous P-52
		61	55 ksi (380 MPa) ≤ SMTS zirconium – unalloyed
12	Deleted	62	80 ksi (550 MPa) ≤ SMTS zirconium – alloyed (Zr, 2.5% Cb)
15A 15B	Open – not used yet		

Source: API RP582
Notes: Missing number are not used.
1. For more details on P-numbers and ASME materials, see ASME Sec. IX, Nonmandatory Appendix D, P-number Listing
2. Group 1 – Grades 304, 316, 317, 347
   Group 2 – Grades 308x, 309x, 310x (others), F10, S30815, S30908, S30909, J92802, J93400, J93401, J93402, J94202, J94203, J94204
   Group 3 – High Manganese Grades (S20100, S20153, S20200, S20400, S20910, S21600, S21603, S21800, S21904, S21910, S24000, J93790)
   Group 4 – High Molybdenum Grades 317LM, 317LMN (S20910, S21904, S31254, S31725, S31726, S32053, S32654, S34565, S34956, J93254)

Table 2.100 (1/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/ Strip	Pipe (s/w/f/c)	Tubes (s/w)	Forgings	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Cast irons			A74, A888			A48, A126, A159, A278, A319, A667, A748, A823, A942	A74, A126, A888	
(Austenitic) ductile irons/ malleable irons			A377, A716, A746			A47, A197, A220, A395, A439, A476, A536, A571, A602, A842, A874, A897	A861	
High-silicon irons (Si > 14%)			A861 (Duriron)			A518 (Duriron)	A861 (Duriron)	
Abrasion-resistant cast irons						A532		
Carbon steels	1	A283 A285	A53(s/w), A134(w) A135(w), A139(w) A381(w), A587(w) A671(w)-CA55 A672(w)-A45 to A55 API 5L(s/w)	A179 (s) A192 (s) A214 (w) A519 (s-mechanical, Note 9)	A105 A181 A266	A216-WCA, WCB & WCC	A234- WPB	A36, A242, A572, A573, A675, A992, A500 (structural tubes-s/w) A322 (Note 9)

Table 2.100 (2/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f/c)	Tubes (s/w)	Forgings	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Carbon steels (low temp., −46 °C)	1	A516, A537, A662	A333/334-1, 6	A334(s/w)-1, 6	A350-LF2-Cl.1 A765-Gr.II, V	A352-LCB, LCC	A420- WPL6	
Killed carbon steels	1	A299 A515 A516	A106(s)-A&B(s) A333(s/w)-1/6 API 5L(s/w)-PSL2 A524 A672(w)-B55 to 70 A672(w)-C55 to 70	A210 (s)	A350			
Quenched-tempered carbon steels	1	A537-2 & 3 A678	A333(s/w)-1/6 A672 (Note 9)		A508 (Note 9) A541 (Note 9)	A352 (Note 9)	A592-Gr.A	A322 (Note 9)
C-½ Mo	3	A204-A, B, & C	A335(s)-P1 A691(w)-CM65~75	A209(s)- T1 A519 (s-mechanical, Note 9)	A182-F1 A336-F1	A217-WC1	A234-WP1	
Mn-½ Mo	3	A302-B			A350-LF5/6 A592-Gr.F		A592-Gr.F	
Mn-½ Mo-Ni	3	A302-B			A350-LF5 A592-Gr.F		A592-Gr.F	
Mn-½ Mo-3/4 Ni	3	A533-C-Cl.1						
1 Cr-½ Mo	4/1	A387-12	A335(s)-P12 A369(f)-FP12 A691(w)-1Cr	A213(s)-T12 A519 (s-mechanical, Note 9)	A182-F12 A336-F12	A487-9	A234-WP 12	
1 ¼Cr-½ Mo	4/1	A387-11	A335(s)-P11 A369(f)-FP11 A426(c)-CP11 (J12072) A691(w)-1-¼Cr	A213(s)-T11 A519 (s-mechanical, Note 9)	A182-F11 A336-F11 A541-Gr.11-Cl.4	A217-WC6	A234-WP 11 A592-Gr.E	
2 ¼Cr-1 Mo	5A/1	A387-22	A335(s)-P22 A369(f)-FP22 A426(c)-CP22 (J21890) A691(w)-2-¼Cr	A213(s)-T22	A182-F22 A336-F22 A541-Gr.22-Cl.3/4/5 and A541-Gr.22V	A217-WC9 A487-8	A234-WP 22	
2 ¼Cr-1 Mo-V (Q-T)	5C/1				A182-F22V			
3 Cr-1 Mo	5A/1	A387-21	A335(s)-P21 A369(f)-FP21 A691(w)-3 Cr	A213(s)-T21	A182-WP21 A336-F21 A541-Gr.3V			
3Cr-1 Mo-V (Q-T)	5C/1				A182-F3V, F3VCb			
5 Cr-½ Mo	5B/1	A387-5	A335(s)-P5 A369(f)-FP5 A691(w)-5 Cr	A213(s)-T5	A182-F5 A336-F5	A217-C5	A234-WP5	
9 Cr-1 Mo	5B/1	A387-9	A335(s)-P9 A369(f)-FP9 A426(c)-CP9 (J82090) A691(w)-9 Cr	A213(s)-T9	A182-F9 A336-F9	A217-C12	A234-WP9	
9 Cr-1 Mo-V-Cb (modified)	15E/1	A387-91, Cl.2	A335(s)-P91 A369(f)-FP91 A691(w)-91	A213(s)-T91	A182-F91 A336-F91	A217-C12A	A234-WP91	
2.25 Ni	9A/1	A203-A & B	A333(s/w)-7	A334(s/w)-7	A350-LF9	A352-LC2		
3.5 Ni	9B/1	A203-D, E & F	A333(s/w)-3	A334(s/w)-3	A350-LF3 A765-Gr.III	A352-LC3	A420-WPL3	
8Ni	11A/1	A553- II			A522-Type II			

Table 2.100 (3/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f/c)	Tubes (s/w)	Forgings	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
9Ni	11A/1	A353 A553- I A844 EN10028-4, X8Ni9/ X7Ni9	A333(s/w)-8	A334(s/w)-8	A522-Type I		A420-WPL8	
5Ni–0.25Mo	11A/2	A645-A						
0.5Ni–0.5Cr–0.25Mo–V	11A/3					A487-4, Cl.B/E		
Mn–0.5Mo-(0.25-0.75Ni)	11A/4	A533-Type A/B/C/D, Cl.3	A672(w)-J100					
2.75–3.5Ni–1.5–1.75Cr–0.5Mo – (V)	11A/5	A543-B/C, Cl.1			A508-4N/5, Cl.1	A352-LC2-1		
0.5Cr–0.25Mo–Si	11B/1	A517-A			A592-A			
1.75Cr–0.5Mo–Cu	11B/2	A514-E A517-E			A592-E			
0.75Ni–0.5Cr–0.5Mo–V	11B/3	A517-F			A592-F			
0.5Cr–0.2Mo–V	11B/4	A517-B						
1.25Ni–1Cr–0.5Mo	11B/8	A514-P A517-P						
1.3Ni–1.3Cr–0.5Mo–V	11B/9	A514-Q A517-Q						
3.5Ni–1.75Cr–0.5Mo–V	11B/10	A543-B/C, Cl.2			A508-4N/5, Cl.2			
409 SS (11 Cr) (S40900)	7	A240-409		A268(s/w)/ A803(s/w)-TP409				
405 SS (12 Cr-Al) (S40500)	7	A240-405		A268(s/w)-TP405 A511(s)-MT405	A473-405			A276-405
410 SS (13 Cr) (S41000)	6	A240-410 A276-410	A426(c)-CPCA15 (J91150)	A268(s/w)-TP410 A511(s)-MT410	A182-F6a A336-F6 A473-410	(J91150) A217, A487, A717, A743-CA15	A815-*WP*410	A276-410
410S SS (13 Cr-Low C) (S41008)	7	A240-410S			A473-410S			
420 SS (13Cr-0.15C min.) (S42000)	6	A176-420			A473-420	(J91153) A743-CA40	A276-420	
430 SS (17 Cr)(S43000)	7	A240-430		A268(s/w)-TP430 A511(s), A554(w)-MT430	A182-F430 A473-430		A276-430 A815-*WP*430	
444 SS (18-2) (18 Cr) (S44400)	7	A240-444		A554(w)-S44400 A803(s/w) Gr.18-2			A276-444	
13Cr-4Ni (CA6NM) (J91540)	6					(J91540) A352, A356, A487, A743-CA6NM A757-E3N		

Table 2.100 (4/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f/c)	Tubes (s/w)	Forgings	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
E-BRITE 26-1 (26Cr-1Mo) (S44627)	7	A240-XM-27		A268-TP XM-27				
304 SS (18Cr-8Ni) (S30400)	8/1	A240-304	A312(s/w)-TP304 A376(s)-TP304 A358(w)-304 A409(w)-TP304 A451(c)-CPF8A	A213(s), A249(w), A269(s/w), A511(s), A554(w)-MT304 A632(s/w)-TP304 A688(w)-TP304	A182, A965-F304 A473-304	(J92600) A351, A743, A744-CF8, CF8A	A403-*WP*304	A276-304 A479-304
304L SS (18Cr-8 Ni-Low C) (S30403)	8/1	A240-304L	A312(s/w)-TP304L A358(w)-304L A409(w)-TP304L A451(c)-CPF3/CPF3A	A213(s), A249(w), A269(s/w), A511(s), A554(w)-MT304L A632(s/w)-TP304L A688(w)-TP304L	A182, A965-F304L A473-304L	(J92500) A351, A743, A744-CF3	A403-*WP*304L	A276-304L A479-304L
304H SS (18Cr-8 Ni -High C) (S30409)	8/1	A240-304H	A312(s/w)-TP304H A376(s)-TP304H A358(w)-304H	A213(s)-TP304H A249(w)-TP304H	A182, A965-F304H	(J92590) A351-CF10	A403-*WP*304H	A479-304H
304LN SS (S30453)	8/1	A240-304LN	A312(s/w)-TP304LN A358(w)-304LN	A213(s), A249(w), A269(s/w), A688 (w)-TP304LN	A182-F304LN		A403-*WP*3LN	A276-304LN A479-304LN
316 SS (16 Cr-12 Ni-2 Mo) (S31600)	8/1	A240-316	A312(s/w)-TP316 A376(s)-TP316 A358(w)-316 A409(w)-TP316 A451(c)-CPF8M	A213(s), A249(w), A269(s/w), A688 (w)-TP316 A511(s), A554(w)-MT316 A632(s/w)-TP316	A182, A965-F316 A473-316	(J92900) A351, A743, A744-CF8M	A403-*WP*316	A276-316 A479-316
316L SS (16 Cr-12 Ni-2 Mo -Low C) (S31603)	8/1	A240-316L	A312(s/w)-TP316L A358(w)-316L A409(w)-TP316L A451(c)-CPF3M	A213(s), A249(w), A269(s/w), A688 (w)-TP316L A511(s), A554(w)-MT316L A632(s/w)-TP316L	A182, A965-F316L A473-316L	(J92800) A351, A743, A744-CF3M	A403-*WP*316L	A276-316L A479-316L
316H SS (16 Cr-12 Ni-2 Mo-High C) (S31609)	8/1	A240-316H	A312(s/w)-TP316H A376(s)-TP316H A358(w)-316H A451(c)-CPF10MC	A213(s)-TP316H A249(w)-TP316H	A182, A965-F316H	(J92901) A351-CF10M	A403-*WP*316H	A479-316H
316LN SS (S31653)	8/1	A240-316LN	A312(s/w)-TP316LN A376(s)-TP316LN A358(w)-316LN A451(c)-CPE20N	A213(s), A249(w), A269(s/w), A688 (w)-TP316LN	A182-F316LN	(J92804) A351, A743-CF3MN	A403-*WP*316LN	A276-316LN A479-316LN

Table 2.100 (5/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tubes (s/w)	Forgings	Castings (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
316Ti SS (S31635)	8/1	A240-316Ti	A312(s/w)-TP316Ti	A213(s)-TP316Ti	A182-F316Ti			A276-316Ti A479-316Ti
316Cb SS (S31640)	8/1	A240-316Cb				(J92971) A351-CF10MC		A276-316Cb A479-316Cb
317 SS (19Cr-14Ni-3Mo) (S31700)	8/1	A240-317	A312(s/w)-TP317 A358(w)-317 A409(w)-TP317	A213(s), A249(w), A269(s/w)-TP317 A511(s), A554(w)-MT317 A632(s/w)-TP317	A182-F317 A473-317	(J93000) A351, A743, A744-CG8M	A403-*WP*317	A276-317 A479-317
317L SS (19Cr-14Ni-3Mo-Low C) (S31703)	8/1	A240-317L	A312(s/w)-TP317L A358(w)-317L	A213(s)-TP317L A249(w)-TP317L	A182-F317L	(J92999) A351, A743, A744-CG3M	A403-*WP*317L	
317LM SS (19 Cr-14Ni-4Mo-Low C) (S31725)	8/1	A240-317LM	A312(s/w)-S31725 A376(s)-S31725 A409(w)-S31725	A213(s)-TP317LM A249(w)-S31725				A276-S31725 A479-S31725
317LMN SS (19 Cr-15Ni-4Mo-0.1N-Low C) (S31726)	8/1	A240-317LMN	A312(s)-S31726 A376(s)-S31726 A409(w)-S31726	A213(s)-TP317LMN A249(w)-S31725				A276-S31726 A479-S31726
317LN SS (S31753)	8/1	A240-317LN						
321 SS (18 Cr-10 Ni-Ti) (S32100)	8/1	A240- 321	A312(s/w)-TP321 A376(s)-TP321 A358(w)-321 A409(w)-TP321	A213(s), A249(w), A269(s/w)-TP321 A511(s), A554(w)-MT321 A632(s/w)-TP321	A182, A965-F321 A473-321		A403-*WP*321	A276-321 A479-321
321H SS (18 Cr-10 Ni-Ti-High C) (S32109)	8/1	A240-321H	A312(s/w)-TP321H A376(s)-TP321H A358(w)-321H	A213(s)-TP321H A249(w)-TP321H	A182, A965-F321H		A403-*WP*321H	A479-321H
347 SS (18 Cr-10 Ni-Cb) (S34700)	8/1	A240-347	A312(s/w)-TP347 A376(s)-TP347 A358(w)-347 A409(w)-TP347 A451(c)-CPF8C	A213(s), A249(w), A269(s/w)-TP347 A511(s), A554(w)-MT347 A632(s/w)-TP347	A182, A965-F347 A473-347	(J92710) A351,743,744-CF8C	A403-*WP*347	A276-347 A479-347
347H SS (18 Cr-10 Ni-Cb-High C) (S34709)	8/1	A240-347H	A312(s/w)-TP347H A376-TP347H A358(w)-347H	A213(s)-TP347H A249(w)-TP347H	A182, A965-F347H		A403-*WP*347H	A479-347H
347LN SS (S34751)	8/1	A240-347LN	A312(s/w)-TP347LN	A213(s)-TP347LN	A182-F347LN			

Table 2.100 (6/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tubes (s/w)	Forgings	Castings (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
348 SS (S34800)	8/1		A312(s/w)-TP348 A376(s)-TP348 A409(w)-TP348	A213(s), A249 (w), A269(s/w)-TP348 A632(s/w)-TP348	A182-F348 A473-348			A276-348 A479-348
348H SS (S34809)	8/1		A312(s/w)-TP348H A376(s)-TP348H	A213(s)-TP348H A249(w)-TP348H	A182-F348H			A479-348H
309 SS (23 Cr-12 Ni) (S30900)	8/2	A240-309 A167-309	A358(w)-309	A213(s)-TP309	A473-309	(J93402/J93503) A351-CH20	A403-*WP*309	A276-309
309S SS (S30908)	8/2		A312(s/w)-TP309S A358(w)-309S A409(w)-TP309S	A213(s)-TP309S A249(w)-TP309S A511(s), A554 (w)-MT309S	A473-309S			A276-309S A479-309S
309H SS (S30909)	8/2		A312(s/w)-TP309H	A213(s)-TP309H A249(w)-TP309H	A182- F309H			A479-309H
310 SS (25Cr-20 Ni) (S31000)	8/2	A240-310 A167-310	A312(s/w)-TP310 A451(c)-CPK20	A213(s)-TP310 A249(w)-TP310 A632(s/w)-TP310	A182, A965-F310 A473-310	(J94202/J94224) A351-CK20	A403- *WP*310	A276-310
310S SS (S31008)	8/2		A312(s/w)-TP310S A358(w)-310S A409(w)-TP310S	A213(s)-TP310S A249(w)-TP310S A511(s)-MT310S	A473-310S			A276-310S A479-310S
310H SS (S31009)	8/2		A312(s/w)-TP310H	A213(s)-TP310H A249(w)-TP310H	A182- F310H			A479-310H
310MoLN SS (S31050)	8/2		A312(s/w)-TP310HCb	A213(s)-TP310MoLN	A182-F310MoLN			
XM-15 (18Cr–18Ni–2Si) (S38100)	8/1	A240-XM-15	A312(s/w)-TPXM-15	A269(s/w)-TPXM-15	A182-F316			
Mn-V-Ni steel	10A/1	A225-C (K12525)						
1Cr-V	10B/1			A213-T17 (K12047)				
High strength steel	10C/1	A612 (K02900)						
2205 DSS (22Cr-3Mo-5.5Ni) (S31803/S32205)	10H/1	A240 – S31803/S32205	A790(s/w)-S31803/S32205	A789(s/w)-S31803/S32205	A182-S31803/S32205 (or F51/60)	(J92205) A995/A890-4A (CD3MN)	A815-*WP*S31803/*WP*S32205	A276, A479-S31802/32205
2304 DSS (23Cr-4Ni-2.5Mo) (S32304)	10H/1	A240-S32304	A790(s/w)-S32304	A789(s/w)-S32304	A182-F44			A276-S32304
2507 DSS (25Cr-7Ni-4Mo-N) (S32750)	10H/1	A240-S32750	A790(s/w)-S32750	A789(s/w)-S32750	A182-F53	(J93404) A995/A890-5A (CE3MN)	A815-*WP*S32750	A276-S32750 A479-S32750
3RE60 (18Cr–5Ni–3Mo–N) (S31500)	10H/1		A790(s/w)-S31500	A789(s/w)-S31500				

Table 2.100 (7/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tubes	Forgings	Castings (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Zeron 100 (24Cr-6Ni-3Mo-0.5W-0.5Cu-0.2N) (S32760)	10H/1	A240-S32760	A790(s/w)-S32760	A789(s/w)-S32760	A182-F55 A473-S32760	(J93380) A890/A995-6A (CD3MWCuN)	A815-*WP*S32760	A276-S32760 A479-S32760
XM-33 (26Cr-1Mo-0.6Ti) (S44626)	10I/1	A240-XM-33 (S44626)		A268-TPXM-33 A803(s/w)TP XM-33				
XM-27 (E-Brite 26-1) (26Cr-1Mo-0.1Cb) (S44627)	10I/1	A240-XM-27 (S44627)		A182 FXM-27Cb A268 TPXM-27 A479-XM-27 A803(s/w)TP XM-27				A276-S44627
Monit (25-4-4) 25Cr-4Ni-4Mo (S44635)	10I/1	A240-S44635		A268 Gr. 25-4-4 A803(s/w)Gr. 25-4-4		A890-CD6MN (3A) (J93371)		
26Cr-3Ni-3Mo (FSS)	10 K/1	A731-S44660				A890-CD6MN (3A) (J93371)		
17-4 PHSS (17Cr–4Ni–4Cu) (S17400)		A564/A693 - Type 630			A705-630 A579-61	(J92110) A747-CB7Cu-1		
17-7 PHSS (17Cr–7Ni–1Al) (S17700)		A564/A693 - Type 631			A705-631 A579-62			
Alloy 450 (14Cr–5Ni–1.3Cu-0.5Mo) (S45000)		A693 -Type XM-25			A705 -Type XM-25			A564 -Type XM-25
Austenitic Ductile Iron (Low Temp.) (22Ni-4Mn-2Si-2.4C)						A571		
Alloy 254 SMO (20Cr-18Ni-6Mo) (S31254)	8/4	A240	A312(s/w),A409(w), A813(w), A358(w), A814(w)- S31254	A249(w), A269(s/w)-S31254	A182-S31254	(J93254) A351,743,744-CK3MCuN	A403-S31254	A479-S31254,
Alloy 654 SMO (24Cr-22Ni-7Mo-3Mn)(S32654)-Note 4	45	A240,A480, A276,A479-S32654	A312(s/w),A358(w)-S32654	A249(w), A269 (s/w)-S32654				
Alloy 926 1925hMo (25Ni-20Cr-6Mo-1Cu-N) (N08926)	45	B625-N08926	B673(w) B677(s) -N08926	B674(w) B677(s) -N08926	ASME Code Case N455-2120.		B366-*WP*1925N	B625/B649 -N08926
AL-6XN (24Ni–21Cr–6Mo–Cu–N) (N08367)	45	A240/B688-N08367	A312(s/w), A358(w), A409(w), A813(w), A814(w), B675(w)-N08367 B690(s)	A249(w), A688 (w), B676(w), A269(s/w) -N08367 B690(s)	A182, B462, B564-N08367	(J94651) A351, A743, A744-CN3MN	B462-N08367 B366-*WP*6XN	A479-N08367
Alloy 904L (44Fe–25Ni–21Cr–4.5Mo) (N08904)	45	B625-N08904	A312(s/w)- N08904	A269(s/w)-N08904	A182-F904L		A403- N08904	A276-904L
Ni-Resist (12~32Ni-< 5.5Cr-1~6Si-< 3C-Mn) (F41000-41010)						A436-Type 1~6 A439-D-2~5S		

Table 2.100 (8/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tubes	Forgings	Castings (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Monel 400 (67Ni-30Cu) (N04400)	42	B127	B165(s) B474(w), B725(w)-400	B165(s) B163(s)-N04400	B564-N04400	A494-M35-1 (N24135) or A494-M30-C (N24130) A296-M35	B366-*WP*NC	B164 (bar)
Monel K500 (64Ni-30Cu-3Al) (N05500)	42	BS3072NA18 DIN 17750	BS3072NA18 DIN 17751	DIN 17751	DIN 17754			
Inconel 600 (72Ni–15Cr–8Fe) (N06600)	43	B168-N06600	B167(s)-N06600 B474(w)-600 B517(w)-N06600	B163(s)-N06600 B167(s)-N06600 B516(w)-N06600	B564-N06600	A494- CY40 (N06040)	B366-*WP*NCI	B166 (rod) B472 (bar)
Inconel 601 (60Ni–23Cr–12Fe–Al) (N06601)	43	B168-N06601	B474(w)-601 B167(s)-N06601	B163(s)-N06601 B167(s)-N06601	DIN 17750			B166 (rod)
Inconel 625 (60Ni–22Cr–9Mo–3.5Cb) (N06625)	43	B443- N06625	B444(s)-N06625 B705(w)-N06625 B474(w)-625-1/2	B444 (s) -N06625 B704(w)-N06625	B564-N06625	A494-CW6MC (N26625)	B366-*WP*NCMC	B166 (rod) B446 (rod) B472 (bar)
Alloy 686 (58Ni-21Cr-16Mo-4W) (N06686)	43	B575- N06686	B622(s)-N06686 B619(w)-N06686	B163(s)-N06686 B622(s)-N06686 B626 (w)-N06686	B462-N06686 B564-N06686		B366-*WP*IN686 B462-N06686	B574 (rod)
Incoloy 800/800H /800HT (33Ni–42Fe–21Cr) (N08800/ N08810/ N08811)	45	B409-N08800/ N08810/ N08011	B407(s)-N08800, N08810, N08011 B514(w)-N08800, N08810	B163(s), B407 (s), B515-N08800/ N08810/ N08811	B564- N08800/ N08810/ N08811		B366-*WP*NIC/ *WP*NIC10/ *WP*NIC11	B408 (rod)
Incoloy 825 (42Ni–21.5Cr–3Mo–2.3Cu) (N08825)	45	B424-N08825	B423(s) – N08825 B474(w)-825 B705(w)-N08825	B163(s) – N08825 B423(s) – N08825 B704(w)-N06625	B564-N08825	A494-CU5MCuC (N08826)	B366-*WP*NICMC	B425(rod/bar)
Alloy 20Cb3 (35Ni–35Fe–20Cr–Cb) (N08020)	45	B463-N08020	B729(s)-N08020 B464(w)-N08020 B474(w)-Alloy20	B468 (w)-N08020 B729(s)-N08020	B462-N08020	A351-CN7M (N08007)	B366 – *WP*20CB B462-N08020	B472 (bar) B473 (bar)
Alloy 20Mo6 (35Ni–30Fe–24Cr–6Mo–3Cu) (N08026)	45	B463-N08026	B729(s)-N08026 B464(w)-N08026 B474(w)-N08026	B468 (w)-N08026 B729(s)-N08026	B462-N08026		B462-N08026	B472 (bar) B473 (bar)
Alloy 925 (42Ni-21Cr- min. 22Fe-3Mo-2Cu-2Ti) (N09925)	45			ASME Code Case 2218	ASME Code Case 2218			ASME Code Case 2218
Alloy 718 (52Ni-18Cr-5 (Nb + Ta) -0.8Ti-0.5Al) (N07718)	Close to 43	B670 B906 AMS 5596/ 5597/5950	AMS 5589/ 5590 ASME Code Case N-253		B637 ASME Code Case 2206, 2222		ASME Code case N-62	B637 ASME Code Case 1993, 2206

Table 2.100 (9/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tube (s/w)	Forging	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Hastelloy B (62Ni–28Mo–5Fe) (N10001)	44	B333-N10001	B622(s)-N10001 B619(w)-N10001	B622(s)-N10001 B626 (w)-N10001		A494-N12MV (N30012)	B366-*WP*HB	B335 (rod)
Hastelloy B-2 (65Ni–28Mo–2Fe) (N10665)	44	B333-N10665	B622(s)-N10665 B474(w)-B2 B619(w)-N10665	B622(s)-N10665 B626 (w)-N10665	B564-N10665 B462-N10665	A494-N12MV (N30012)	B366-*WP*HB-2 B462-N10665	B335 (rod) B472 (bar)
Hastelloy B-3 (65Ni–29.5Mo–2Fe–2Cr) (N10675)	44	B333-N10675	B622(s)-N10675 B474(w)-B3 B619(w)-N10675	B622(s)-N10675 B626 (w)-N10675	B564-N10675 B462-N10675	A494-N12MV (N30012)	B366-*WP*HB-3 B462-N10675	B335 (rod) B472 (bar)
Hastelloy C276 (54Ni-15Cr-16Mo) (N10276)	43	B575-N10276	B622(s)-N10276 B474(w)-C276 B619(w)-N10276	B622(s)-N10276 B626 (w)-N10276	B564-N10276 B462-N10276	A494-CW12MW (N30002)	B366-*WP*HC276 B462-N06022	B574 (rod) B472 (bar)
Hastelloy C4 (61Ni–15Mo–16Cr-Low C) (N06455)	43	B575-N06455	B622(s)-N06455 B619(w)-N06455	B622(s)-N06455 B626 (w)-N06455		A494-CW12MW (N30002)	B366-*WP*HC4	B574 (rod)
Hastelloy C22 (59Ni-22Cr-14Mo) (N06022)	43	B575-N06022	B474(w)-C22 B622(s)-N06022 B619(w)-N06022	B622(s)-N06022 B626 (w)-N06022	B564-N06022 B462-N06022	A494-CX2MW (N26022)	B366-*WP*HC22 B462-N06022	B472 (bar) B574 (rod)
Hastelloy G3 (47Ni–22Cr–20Fe–7Mo) (N06985)	45	B582-N06985	B622(s)-N06985 B619(w)-N06985 B474(w)-G3	B622(s)-N06985 B626 (w)-N06985			B366-*WP*HG3	B581(rod)-N06985
Hastelloy X (47Ni–22Cr–18Fe–9Mo-Low C) (N06002)	43	B435-N06002	B622(s)-N06002 B474(w)-X B619(w)-N06002	B622(s)-N06002 B626 (w)-N06002				B472 (bar) B572 (rod)
Alloy 59 (59Ni–23Cr–16Mo-Low C) (N06059)	43	B575-N06059	B619(w)-N06059 B622(s)-N06059	B622(s)-N06059 B626 (w)-N06059	B564-N06059 B462-N06059	A494-CX2M (N06059)	B366-*WP*5923 B462-N06059	B472 (bar) B574 (rod)
Alloy X-750 (min.70 (Ni + Co)-15Cr-8Fe-2.5Ti-1 (Nb + Ta)-0.6Al) (N07750)		AMS 5542/5598		AMS (s) 5582/5583	B637-N07750 AMS 5667/5671/5747			AMS 5667/5671/5747
Nickel 200/201 (99.0Ni) (N02200/N02201)	41	B162	B161(s), B725(w)-N02200/N02201 B474(w)-200/201	B161(s), B163 (s)-N02200, N02201	B160-N02200, N02201 B564-N02200	A494-CZ100 (N02201)	B366-*WP*N/*WP*NL	B160-N02200/N02201
Copper (C1xxxx)	31	B152	B42(s) B302 (s-threadless)	B68(s), B75(s), B88(s), B111 (s), B280(s), B359(s) B395(s-U tube), B306-C12200 (for drainage) B543(w)	B283	B61, B62, B66, B176, B271, B427, B505, B584, B763, B806-C83xxx to C99xxx (Note 10)		B2 (wire) B152 B187

Table 2.100 (10/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tube (s/w)	Forging	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Admiralty Brass (71Cu-1Sn-bal Zn) (C44300-incl. As) (C44400-incl. Sb) (C44500-incl.P)	32	B171-C44300, C44400, C44500		B111(s), B359(s), B543(w)- C44300, C44400, C44500 B135(s)-C44300 B395(s-U tube)-C44300, C44400, C44500				
Naval Brass (69Cu-30Zn-1Sn) (C46400)	32	B171-C46400			B283-C46400			B21, B124-C46400
Aluminum Brass Incl As (0.02–0.06%) (77Cu-2Al-bal Zn) (C68700)	32			B111(s), B359(s), B395(s-U tube), B543 (w)- C68700				
Tungum (84Cu-1.1Ni-1.1Si-1Al-13Zn) (C69100)	32		B706(s)	B706(s)				
90-10 Cu-Ni (C70600)	34	B171-C70600	B466(s)-C70600 B467(w)-C70600/ C70620	B111(s), B359(s), B395(s-U tube), B466(s), B543(w)-C70600		B369-C96200		
80–20 Cu-Ni (C71000)	34		B466(s)-C71000	B111(s), B395(s-U tube), B466(s), B543(w)-C71000				
70–30 Cu-Ni (C71500)	34	B171-C71500	B466(s)-C71500 B467(w)-C71500/ C71520	B111(s), B395(s-U tube), B466(s), B543(w)-C71500		B369-C96400		
Aluminum bronze (7%Al-2.5%Fe-bal Cu) (C61300/ C61400)	35	B169, B171-C61300/ C61400	B608(w)-C61300, C61400	B111(s)-C61300, C61400		B148-C95700 B806-C95300		B150, B169-C61300/ C61400
Aluminum 3003 (98%Al, 1.2% Mn) (A93003)	21	B209(Note 7)- 3003	B241(s), B345 (s), B491(s)-3003	B234(s), B210(s), B241(s), B313(w), B345(s), B404(s), B547(w)- 3003	B247-3003	B26 sand castings B85 die castings B108 permanent mold castings B179 ingot B686 high strength castings B618 investment castings	B361(w)-WP3003	B211, B221, B316- 3003
Aluminum 5083 (93%Al, 4.5% Mg) (A95083)	25	B209(Note 7)- 5083		B210(s), B547(w)-5083	B247-5083		B361(w)-WP5083	B221-5083
Aluminum 5086 (94%Al, 4%Mg) (A95086)	25	B209(Note 7)- 5086		B210(s), B313(w), B547(w)-5086			B361(w)-WP5086	B221, B316-5086
Aluminum 6061 (98%Al, 1%Mg) (A96061)	25	B209(Note 7)- 6061	B241(s), B345 (s) - 6061	B210(s), B241(s), B234(s), B313(w), B345(s), B547(w)-6061	B247-6061		B361(w)-WP6061	B211, B221, B316- 6061
Titanium Gr.2 Ti (R50400)	51	B265	B861(s)-2 B862(w)-2	B338(s/w)-2	B381-F2	B367-C2	B363(s/w)-WPT2	B348 (bar)

Table 2.100 (11/11) ASTM no. for the most common materials and products (Note 2, 3, 6, and 11)

Material (Note 15)	P no. (/Gr No)	Plate/Strip	Pipe (s/w/f)	Tube (s/w)	Forging	Casting (Note 12)	Wrought Fitting (Note 5)	Bar/Shape (Note 8 & 12)
Titanium Gr.7 (Ti-0.2% Pd) (R52400)	51	B265	B861(s)-7 B862(w)-7	B338(s/w)-7	B381-F7	B367-C7	B363(s/w)-WPT7	B348 (bar)
Titanium Gr.12 (Ti-0.3%Mo – 0.8%Ni) (R53400)	52	B265	B861(s)-12 B862(w)-12	B338(s/w)-12	B381-F12	B367-C12	B363(s/w)-WPT12	B348 (bar)
Zirconium and its alloys (Note 14)	61 62	B551-R60700/ R60702/ R60704/ R60705/ R60706	B658(s/w)-R60702/ R60704/ R60705	B523(s/w)-R60702/ R60704	B493-R60702/ R60704/ R60705	B752-702C/ 704C/705C	B653-R60702 (PZ2)/ R60704 (PZ4)/ R60705 (PZ5)	B550-R60702/ R60704/ R60705
Tantalum and its alloys		B708 R05200 R05400 R05252 R05255 R05240	B521 (s/w)-R05200 R05400 R05252 R05255 R05240	B521 (s/w)-R05200 R05400 R05252 R05255 R05240				B365-R05200 R05400 R05252 R05255 R05240

Legend
(s) seamless, *(w)* welded, *(f)* forged or bored, *(c)* centrifugally casted, *(bal)* balance
General Notes: See ASME Sec. IX (for Pressure Containing Components) and AWS B2.1 (for Structures) for P-Numbers
Notes
1. See Table 2.30 for More Detail Classification of Cr-Mo Steels (P *No*. 3~5B & 15E, Enhanced and Advanced)
2. UNS No. to be affixed to the end of Code No. for nonferrous and newly developed metals. (e.g., B409-*N08800*)
3. Specifications for General or Common Requirements per Material Group
   – See ASTM A6 for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling
   – See ASTM A20 for Steel Plates for Pressure Vessels
   – See ASTM A29 for Steel Bars, Carbon and Alloy, Hot-Wrought
   – See ASTM A450 for Carbon and Low Alloy Steel Tubes
   – See ASTM A480 for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip
   – See ASTM A484 for Stainless Steel Bars, Billets, and Forgings
   – See ASTM A505 for Steel, Sheet and Strip, Alloy, Hot-Rolled and Cold-Rolled (for ASTM A506, A507, and A873)
   – See ASTM A510 for Wire Rods and Coarse Round Wire, Carbon Steel
   – See ASTM A530 for Specialized Carbon and Alloys Steel Pipe
   – See ASTM A555 for Stainless Steel Wire and Wire Rods
   – See ASTM A568 for Steel, Sheet, Carbon, Structural, and High-Strength, Low-Alloy, Hot-Rolled and Cold-Rolled
   – See ASTM A682 for Steel, Strip, High-Carbon, Cold-Rolled, Spring Quality
   – See ASTM A703 for Steel Castings, General Requirements, for Pressure-Containing Parts
   – See ASTM A749 for Steel, Strip, Carbon and High-Strength, Low-Alloy, Hot-Rolled
   – See ASTM A752 for Wire Rods and Coarse Round Wire, Alloy Steel
   – See ASTM A781 for Castings, Steel and Alloy-General Industrial Use
   – See ASTM A788 for Steel Forgings
   – See ASTM A834 for Iron Casting-General Industrial Use
   – See ASTM A924 for Steel Sheet, Metallic-Coated by the Hop-Dip Process
   – See ASTM A957 for Investment Castings, Steel, Alloy for General Industrial Use
   – See ASTM A960 for Wrought Steel Piping Fittings
   – See ASTM A961 for Steel Flanges, Forged Fittings, Valves, and Parts for Piping Applications
   – See ASTM A962 for Steel Fasteners or Fastener Materials, or Both, Intended for Use at Any Temperature from Cryogenic to the Creep Range
   – See ASTM A985 for Steel Investment Castings-Pressure Containing Parts
   – See ASTM A999 for Alloy and Stainless Steel Pipe
   – See ASTM A1016 for Ferritic Alloy Steel, Austenitic Alloy Steel, and Stainless Steel Tubes
   – See ASTM B248 for Wrought Copper and Copper-Alloy Plate, Sheet, Strip and Rolled Bar
   – See ASTM B249 for Wrought Copper and Copper-Alloy Rod, Bar, Shapes and Forgings
   – See ASTM B250 for Wrought Copper Alloy Wire
   – See ASTM B251 for Wrought Seamless Copper and Copper-Alloy Tube
   – See ASTM B476 for Wrought Precious Metal Electrical Contact Materials
   – See ASTM B584 for Copper Alloy Sand Castings
   – See ASTM B751 for Nickel and Nickel Alloys Welded Tube
   – See ASTM B775 for Nickel and Nickel Alloys Welded Pipe
   – See ASTM B824 for Copper Alloy Castings
   – See ASTM B829 for Nickel and Nickel Alloys Seamless Pipe and Tube
   – See ASTM B880 for Chemical Check Analysis Limits for Nickel, Nickel Alloys, and Cobalt Alloys
   – See ASTM B906 Flat-Rolled Nickel and Nickel Alloys Plate, Sheet, and Strip

4. See ASME code case 2195-1
5. Wrought Fittings: underlined *WP* or *WPS*; For Pressure Fittings
   CR or CRS; for Corrosion-Resistant Fittings ("*WP"* and "*WPS*" is to be "*CR" a*nd "*CRS*" for corrosion resistance)
6. Clad Plates
   – See ASTM A263 for Stainless Chromium Steel-Clad Plate
   – See ASTM A264 for Stainless Chromium-Nickel Steel-Clad Plate
   – See ASTM A265 for Nickel and Nickel-based Alloy-Clad Steel Plate
   – See ASTM B432 for Copper and Copper Alloy Steel Plate
7. The ultrasonic inspection of aluminum alloy plates for pressure vessels shall comply with ASTM B548
8. See Sect. 2.6.2.6 for Bolting Materials (i.e., ASTM A193, A194, A307, A320, A325, A354, A437, A563, etc.)
   See the following ASTM standard materials for ferritic steel wires
   – A82 (for concrete reinforcement)
   – A111 (Zn coated/galvanized iron telephone wire)
   – A116 (Metallic coated fence fabric)
   – A121 (Metallic coated CS)
   – A185 (Welded wire reinforcement for concrete)
   – A227 (Cold-drawn mechanical springs)
   – A228 (Music spring)
   – A229 (Q-T mechanical spring)
   – A230 (Oil-tempered mechanical spring)
   – A231 (Cr-V alloy steel spring)
   – A232 (Cr-V alloy steel valve spring)
   – A363 (Zn coated/galvanized overhead ground wire strand)
   – A401 (Cr-Si alloy steel)
   – A407 (Cold drawn coiled type springs)
   – A411 (Zn coated/galvanized Armor wire)
   – A416 (for prestressed concrete)
   – A421 (Stress relieved for prestressed concrete)
   – A460 (Cu clad)
   – A474 (Al coated)
   – A475 (Zn coated)
   – A496 (for concrete reinforcement)
   – A586 (Zn-coated parallel and helical structural strand)
   – A641 (Zn-coated/galvanized)
   – A648 (hard-drawn for prestressed concrete pipe)
   – A679 (High strength, cold drawn)
   – A713 (High carbon spring for heat treated components)
   – A740 (Hardware cloth)
   – A764 (Metallic coated mechanical springs)
   – A779 (Compacted steel strand for prestressed concrete)
   – A805 (flat wire, cold rolled)
   – A809 (Aluminized)
   – A817 (Metallic coated chain-link fence fabric)
   – A818 (Coppered CS)
   – A821 (Hard drawn for prestressed concrete tanks)
   – A824 (Metallic-Coated Steel Marcelled Tension Wire for Use With Chain Link Fence)
   – A853 (for general use)
   – A854 ((Metallic-coated, smooth high-TS fence))
   – A855 (Zn-5% Al Mischmetal-coated alloy steel wire strand)
   – A856 (Zn-5% Al Mischmetal-coated alloy steel)
   – A877 (for general use)
   – A878 (Modified Cr-V valve springs)
   – A881 (Intended, low-relaxation wire for prestressed concrete railroad ties)
   – A882 (Filled epoxy coated 7-wire prestressing strand)
   – A884 (Epoxy coated and welded reinforcement)
   – A886 (Steel strand intended, 7-wire stress-relieved for prestressed concrete)
   – A899 (Epoxy coated)
   – A905 (Pressure vessel winding)
   – A933 (Vinyl-Coated Steel Wire and Welded Wire Reinforcement)
   – A951 (for masonry joint reinforcement)
   – A925 (Zn-5% Al Mischmetal-coated alloy steel wire for overhead ground strand)
   – A975 (Metallic coated with PVC coating)
   – A1000 (Steel and alloy specialty quality)
   – A1007 (Rope)
   – A1023 (Stranded CS rope)
   – A1060 (Zn Coated (Galvanized) Steel Welded Wire Reinforcement, Plain and Deformed, for Concrete)
   – A1064 (welded wire reinforcement, plain and deformed for concrete)

See the following ASTM standard materials for SS and alloy wires
- A580 (SS)
- A313 (SS Springs)
- A368 (SS wire strand)
- A478 (Cr-Ni SS weaving and knitting)
- A492 (SS rope)
- A493 (SS wire for cold heading/forging)
- A581 (Free-machining SS)
- A1022 (Deformed and plain SS for concrete reinforcement)
- B107 (Mg alloys)
- B164 (Ni-Cu Alloys),
- B267 (for wire-wound resistors)
- B316 (Al alloys, cold heading wire)
- B351 (Zr alloys)
- B365 (Ta alloys)
- B392 (Nb alloys)
- B387 (Mo alloys)
- B473 (Ni alloys – N08020, N08024, and N08026)
- B475 (Ni alloys round weaving wire – N08020, N08024, and N08026)
- B550 (Zr alloys)
- B649 (Ni-Fe-Cr-Mo-Cu-N Low-Carbon alloys – N08925, N08031, N08354, N08926, R20033, and N08936)
- B655 (Nb-Hf alloys)
- B672 (Ni-Fe-Cr-Mo-Cb stabilized alloy – N08700)
- B691 (Fe-Ni-Cr-Mo alloys – N08366 and N08067)
- B737 (Hf)
- B805 (Precipitation Hardening Nickel Alloys)
- B833 (Zn alloys for thermal spray-metallizing)
- B863 (Ti alloys)
- B865 (Precipitation Hardening Ni-Cu-Al alloys – N05500)
- B943 (Zn and Sn alloy wire for thermal spraying for electronic applications)

9. See the grade, class, and heat treatment in each ASTM standard for more details on application
10. ASTM numbers of Cast Copper Based Alloys (Table 2.100a)

Table 2.100a Cast copper-based alloys

Cast copper-based alloys	UNS/CDA no.	ASTM no.
Red brass, leaded, SAE 40	C83600	B271, B505, B584
Manganese bronze, SAE 430A	C86200	B271, B505, B584
Manganese bronze, SAE 430B	C86300	B22, B271, B505, B584
Manganese bronze, SAE 43	C86500	B271, B505, B584
Tin bronze, “navy G”	C90300	B271, B505, B584
Tin bronze, “gun metal”	C90500	B271, B505, B584
Leaded tin bronze, “navy M”	C92200	B271, B61, B584, B505
High Lead tin bronze, SAE 660	C93200	B271, B505, B584
High Lead tin bronze, MOD.SAE 64	C93600	B271, B505, B584
High Lead tin bronze, SAE 64	C93700	B22, B271, B505, B584
Aluminum bronze	C95400	B148, B271, B505
Aluminum nickel bronze	C95500	B148, B271, B505
Aluminum nickel bronze	C95510	B148, B271, B505
Aluminum nickel bronze	C95520	B148, B271, B505
Aluminum bronze	C95800	B148, B271, B505
Aluminum bronze	C95900	B148, B271, B505

11. For more details on P-numbers and ASME materials, see ASME Sec. IX, Nonmandatory Appendix D, P-number Listing
12. Some of these materials may not be controlled by P-Numbers
13. Standard test methods and/or definitions
    - See ASTM A255 standard test methods for determining hardenability of steel
    - See ASTM A370 standard test methods and/or definitions for mechanical testing of steel products
    - See ASTM A751 standard test methods, practices, and terminology for chemical analysis of steel products
    - See ASTM A923 standard test methods for detecting detrimental intermetallic phase in duplex/austenitic/ferritic stainless steels
    - See ASTM D512 standard test methods for chloride ion in water
    - See ASTM E18 test methods for rockwell hardness and rockwell superficial hardness of metallic materials
    - See ASTM E112 test methods for determining average grain size
    - See ASTM E527 standard practice for numbering metals and alloys (UNS)
    - See ASTM G48 standard test methods for pitting and crevice corrosion resistance of stainless steels and related alloys by use of ferric chloride solution
14. See ASTM B898 standard specification for reactive and refractory metal clad plate
15. See ASTM A959 for standard guide for specifying harmonized standard grade (chemical) compositions for wrought stainless steels

- ASME Sec. II-Part D Stress Values
- ASME Sec. IX Welding and Brazing
- ASME B31.3 Process Piping
- ASME B31.1 Power Piping
- AWS B2.1 Welding Procedure and Performance Qualification (*See below)
- BS PD 5500 Unfired, Fusion Welded Pressure Vessels
- PED Pressure Equipment Directive
- EN 13445 Unfired Pressure Vessels

*** M-Number in AWS/AISI Structural Steels**

AWS B2.1 states Material Number (M-Number) instead of P-Number. Base metal has been divided into general categories, e.g., Material Numbers (M-numbers) 1, 1A, 3, 3A, 4, 4A, etc., and further divided into groups within each general category.

The category grouping does not imply that base metals may be substituted for other base metals within the same Material Number (M-Number) without consideration for weldability.

M numbers are similar to P-numbers, but include materials (including some MSS/CSA/AS/NZS/ISO/ABS standard materials) that are not approved for ASME codes. The base metals listed in each AWS group (M-number) are more extensive than the ASME P-number groups, but it doesn't mean they can be substituted one for another due to differences in processing and the resulting mechanical properties.

The British Standard (BS) PD 5500, PED, and EN13445 have a slightly different numbering system shown in Table 2.101. See PD 5500, Table 2.1-2 for more details on material group covered by BS EN Materials standards.

2.1.10.2 S-Numbers (ASME SEC IX QW-420.2/QW/QB-422 – Nonmandatory)

S-Numbers are a group of materials other than ASME materials that are accepted for use as equivalent of P No. series. (e.g., API materials). [S = *S*upplementary].

2.1.10.3 F-Numbers (ASME SEC IX QW-430/432) [F = *F*iller] – Table 2.102

F-Numbers are a group of materials which are for classification of electrodes and welding rods. The numbers are based on the usability characteristics which fundamentally determine the ability of welders to make satisfactory welds with a given filler metals. For example, E6010 welding electrodes have F-No. 3 while E7018 (low hydrogen) welding electrodes have F-No. 4, because different welder abilities are required for each of these filler metals.

2.1.10.4 A-Numbers (ASME Sec. IX QW-442) [A = *A*lloyed] – Table 2.103

A-Numbers are a group of materials which are classified by chemical composition of weld metals for PQ of ferrous metals. For example, A-No. 1 is for mild CS filler metal, A-No. 2 is for C-Mo steel, A-No. 3 is for low Cr-Mo steel, etc.

2.1.10.5 SFA Numbers (ASME Sec. II, Part C) – Table 2.104

Specification for each electrodes/rods/fluxes/cutting per materials and welding process in ASME.

2.1.10.6 AWS Class-UNS Numbers – Table 2.105

Table 2.101 (1/2) Steel materials group (PD 5500, Table 2.1-1)

Group	Subgroup	Types of steel
1	Steels with a specified minimum yield strength *R*eH ≤ 460 N/mm^2 and with analysis in %: C ≤ 0.25, Si ≤ 0.60, Mn ≤ 1.70, Mo ≤ 0.70[b], S ≤ 0.045, P ≤ 0.045, Cu ≤ 0.40[b], Ni ≤ 0.5[b] Cr ≤ 0.3 (0.4 for castings)[b], Nb ≤ 0.05, V ≤ 0.12[b], Ti ≤ 0.05	
	1.1	Steels with a specified minimum yield strength *R*eH ≤ 275 N/mm^2
	1.2	Steels with a specified minimum yield strength 275 N/mm^2 < *R*eH ≤ 360 N/mm^2
	1.3	Normalized fine grain steels with a specified minimum yield strength *R*eH > 360 N/mm^2
	1.4	Steels with improved atmospheric corrosion resistance whose analysis may exceed the requirements for the single elements as indicated in group 1
2	Thermomechanically treated fine grain steels and cast steels with a specified minimum yield strength *R*eH > 360 N/mm^2	
	2.1	Thermomechanically treated fine grain steels and cast steels with a specified minimum yield strength 360 N/mm^2 < *R*eH ≤ 460 N/mm^2
	2.2	Thermomechanically treated fine grain steels and cast steels with a specified minimum yield strength *R*eH > 460 N/mm^2
3	Quenched and tempered steels and precipitation hardened steels, except stainless steels, with a specified minimum yield strength *R*eH > 360 N/mm^2	
	3.1	Quenched and tempered steels with a specified minimum yield strength 360 N/mm^2 < *R*eH ≤ 690 N/mm^2
	3.2	Quenched and tempered steels with a specified minimum yield strength *R*eH > 690 N/mm^2
	3.3	Precipitation hardened steels except stainless steels
4	Low vanadium alloyed Cr-Mo-(Ni) steels with Mo ≤ 0.7% and *V* ≤ 0.1%	
	4.1	Steels with Cr ≤ 0.3% and Ni ≤ 0.7%
	4.2	Steels with Cr ≤ 0.7% and Ni ≤ 1.5%

Table 2.101 (2/2) Steel materials group (PD 5500, Table 2.1-1)

Group	Subgroup	Types of steel
5	Cr-Mo steels free of vanadium with $C \leq 0.35\%$c	
	5.1	Steels with 0.75% ≤ Cr ≤ 1.5% and Mo ≤ 0.7%
	5.2	Steels with 1.5% < Cr ≤ 3.5% and 0.7% < Mo ≤ 1.2%
	5.3	Steels with 3.5% < Cr ≤ 7.0% and 0.4% < Mo ≤ 0.7%
	5.4	Steels with 7.0% < Cr ≤ 10.0% and 0.7% < Mo ≤ 1.2%
6	High vanadium alloyed Cr-Mo-(Ni) steels	
	6.1	Steels with 0.3% ≤ Cr ≤ 0.75%, Mo ≤ 0.7% and $V \leq 0.35\%$
	6.2	Steels with 0.75% < Cr ≤ 3.5%, 0.7% < Mo ≤ 1.2% and V ≤ 0.35%
	6.3	Steels with 3.5% < Cr ≤ 7.0%, Mo ≤ 0.7% and 0.45% ≤ $V \leq 0.55\%$
	6.4	Steels with 7.0% < Cr ≤ 12.5%, 0.7% < Mo ≤ 1.2% and $V \leq 0.35\%$
7	Ferritic, martensitic or precipitation hardened stainless steels with $C \leq 0.35\%$ and 10.5% ≤ Cr ≤ 30%	
	7.1	Ferritic stainless steels (FSS)
	7.2	Martensitic stainless steels (MSS)
	7.3	Precipitation hardened stainless steels (PHSS)
8	Austenitic stainless steels (ASS)	
	8.1	ASS with Cr ≤ 19%
	8.2	ASS with Cr > 19%
	8.3	Manganese austenitic stainless steels with 4.0% < Mn ≤ 12.0%
9	Nickel alloy steels with Ni ≤ 10.0%	
	9.1	Nickel alloy steels with Ni ≤ 3.0%
	9.2	Nickel alloy steels with 3.0% < Ni ≤ 8.0%
	9.3	Nickel alloy steels with 8.0% < Ni ≤ 10.0%
10	Austenitic ferritic stainless steels (duplex)	
	10.1	Austenitic ferritic stainless steels with Cr ≤ 24.0%
	10.2	Austenitic ferritic stainless steels with Cr > 24.0%
11	Steels covered by group 1d except $0.25\% < C \leq 0.5\%$	
	11.1	Steels as indicated under 11 with $0.25\% < C \leq 0.35\%$
	11.2	Steels as indicated under 11 with $0.35\% < C \leq 0.5\%$

Notes
[a] In accordance with the specification of the steel product standards, ReH may be replaced by $Rp_{0.2}$ or $Rt_{0.5}$
[b] A higher value is accepted provided that Cr + Mo + Ni + Cu + V ≤ 0.75%
[c] "Free of vanadium" means not deliberately added to the material.
[d] A higher value is accepted provided that Cr + Mo + Ni + Cu + V ≤ 1%

Table 2.102 (1/3) F-numbers – ASME Sec. IX, QW-432 & AWS (Grouping of electrodes and welding rods for qualification)

Materials group	F-no.	ASME (SF-)/AWS specification no.	Applicable AWS classification no. [UNS no.]
Steel and steel alloys	1	A-5.1 & 5.5	EXX20, EXX 22, EXX 24, EXX 27, EXX 28
	1	A-5.4	EXXX(X) 26
	1	A-5.5	EXX20-X, EXX27-X
	2	A-5	EXX 12, EXX 13, EXX 14, EXX 19
	2	A-5.5	E(X)XX13-X
	3	A-5.1	EXX 10, EXX 11
	3	A-5.5	E(X)XX10-X, E(X)XX11-X
	4	A-5.1	EXX 15, EXX 16, EXX 18, EXX 18 M, EXX 48
	4	A-5.4 other than ASS and DSS	EXX(X) 15, EXX(X) 16, EXX(X) 17,
	4	A-5.5	E(X)XX15-X, E(X)XX16-X, E(X)XX18-X, E(X)XX18M, E(X)XX18M1, E(X)XX45
	5	A-5.4 (ASS and DSS)	EXX 15, EXX 16, EXX 17
	6	A-5.2	All classifications
	6	A-5.9	All classifications
	6	A-5.17	All classifications
	6	A-5.18	All classifications
	6	A-5.20	All classifications
	6	A-5.22	All classifications
	6	A-5.23	All classifications
	6	A-5.25	All classifications
	6	A-5.26	All classifications
	6	A-5.28	All classifications
	6	A-5.29	All classifications
	6	A-5.30	IN 3XX(X), IN 5XX, IN Ms-X
	6	A-5.36	All classifications

Table 2.102 (2/3) F-numbers – ASME Sec. IX, QW-432 & AWS (Grouping of electrodes and welding rods for qualification)

Materials group	F-no.	ASME (SF-)/AWS specification no.	Applicable AWS classification no. [UNS no.]
Aluminum and aluminum-based alloys	21	A-5.3	E1100 [A91100], E3003 [A93003]
	21	A-5.10	ER1070 [A91070], ER1080A [A91080], ER1100 [A91100], ER1188 [A91188], ER1200 [A91200], ER1450 [A91450], ER3103 [A93103], R1070 [A91070], R1080A [A91080], R1100 [A91100], R1188 [A91188], R1200 [A91200], R1450 [A91450], R3101 [A93103]
	22	A-5.10	ER5087 [A95087], ER5183 [A95183], ER5183A [A95183], ER5187 [A95187], ER5249 [A95249], ER5356 [A95356], ER5356A [A95356], ER5554 [A95554], ER5556 [A95556], ER5556A [A95556], ER5556B [A95556], ER5556C [A95556], ER5654 [A95654], ER5654A [A95654], ER5754 [A95754], R5087 [A95087], R5183 [A95183], R5183A [A95183], R5187 [A95187], R5249 [A95249], R5356 [A95356], R5356A [A95356], R5554 [A95554], R5556 [A95556], R5556A [A95556], R5556B [A95556], R5556C [A95556], R5654 [A95654], R5654A [A95654], R5754 [A95754]
	23	A-5.10	E4043 [A94043], ER4010 [A94010], ER4018 [A94018], ER4043 [A94043], ER4043A [A94043], ER4046 [A94046], ER4047 [A94047], ER4047A [A94047], ER4643 [A94643], ER4943 [A94943], R4010 [A94010], R4011 [A94011], R4018 [A94018], R-A356.0 [A13560], R357.0 [A03570], R-A357.0 [A13570], R4043 [A94043], R4043A [A94043], R4046 [A94046], R4047A [A94047], R4047 [A94047], R4643 [A94643], R4943 [A94943]
	25	A-5.10	ER2319 [A92319], R2319 [A92319], R206.0 [A02060]
	26	A-5.10	ER4009 [A94009], ER4145 [A94145], R4009 [A94009], R4145 [A94145], R-C355.0 [A33550]
Copper and copper-based alloys	31	A-5.6	ECu [W60189]
	31	A-5.7	ERCu [C18980]
	32	A-5.6	ECuSi [W60656]
	32	A-5.7	ERCuSi-A [C65600]
	33	A-5.6	ECuSn-A [W60518], ECuSn-C [W60521]
	33	A-5.7	ERCuSn-A [C51800], ERCuSn-C [C52100]
	34	A-5.6	ECuNi [W60715]
	34	A-5.7	ERCuNi [C71580]
	34	A-5.30	IN 67 [C71581]
	35	A-5.8	RBCuZn-A [C47000], RBCuZn-B [C68000], RBCuZn-C [C68100], RBCuZn-D [C77300]
	36	A-5.6	ECuAl-A2 [W60614]
	36	A-5.6	ECuAl-B [W60619]
	36	A-5.7	ERCuAl-A1 [C61000], ERCuAl-A2 [C61800], ERCuAl-A3 [C62400]
	37	A-5.6	ECuMnNiAl [C60633], ECuNiAl [C60632]
	37	A-5.7	ERCuMnNiAl [C63380], ERCuNiAl [C63280]
Nickel and nickel-based alloys	41	A-5.11	ENi-1 [W82141]
	41	A-5.14	ERNi-1 [N02061]
	41	A-5.30	IN 61 [N02061]
	42	A-5.11	ENiCu-7 [W84190]
	42	A-5.14	ERNiCu-7 [N04060], ERNiCu-8 [N05504]
	42	A-5.30	IN 60 [N04060]
	43	A-5.11	ENiCr-4 [W86172], ENiCrCoMo-1 [W86117], ENiCrFe-1 [W86132], ENiCrFe-2 [W86132], ENiCrFe-3 [W86182], ENiCrFe-4 [W86134], ENiCrFe-7 [W86152], ENiCrFe-9 [W86094], ENiCrFe-10 [W86095], ENiCrFe-12 [W86025], ENiCrMo-2 [W86002], ENiCrMo-3 [W86112], ENiCrMo-4 [W80276], ENiCrMo-5 [W80002], ENiCrMo-6 [W86620], ENiCrMo-7 [W86455], ENiCrMo-10 [W86022], ENiCrMo-12 [W86032], ENiCrMo-13 [W86059], ENiCrMo-14 [W86026], ENiCrMo-17 [W86200], ENiCrMo-18 [W86650], ENiCrMo-19 [W86058], ENiCrWMo-1 [W86231]
	43	A-5.14	ERNiCr-3 [N06082], ERNiCr-4 [N06072], ERNiCr-6 [N06076], ERNiCr-7 [N06073], ERNiCrCoMo-1 [N06617], ERNiCrFe-5 [N06062], ERNiCrFe-6 [N07092], ERNiCrFe-7 [N06052], ERNiCrFe7A [N06054], ERNiCrFe-8 [N07069], ERNiCrFe−11 [N06601], ERNiCrFe-12 [N06025], ERNiCrFe-13 [N06055], ERNiCrFe-14 [N06043], ERNiCrFeAl-1 [N06693], ERNiCrMo-2 [N06002], ERNiCrMo-3 [N06625], ERNiCrMo-4 [N10276], ERNiCrMo-7 [N06455], ERNiCrMo-10 [N06022], ERNiCrMo-13 [N06059], ERNiCrMo-14 [N06686], ERNiCrMo-16 [N06057], ERNiCrMo-17 [N06200], ERNiCrMo-18 [N06650], ERNiCrMo-19 [N06058], ERNiCrMo-20 [N06660], ERNiCrMo-21 [N06205], ERNiCrMo-22 [N06035], ERNiCrWMo-1 [N06231]
	43	A-5.30	IN 52 [N06052], IN 62 [N06062], IN 6A [N07092], IN 82 [N06082]
	43	A-5.34	All classifications
	44	A-5.11	ENiMo-1 [W80001], ENiMo-3 [W80003], ENiMo-7 [W80665], ENiMo-8 [W80008], ENiMo-9 [W80009], ENiMo-10 [W80675], ENiMo-11 [W80675]
	44	A-5.14	ERNiMo-1 [N10001], ERNiMo-2 [N10003], ERNiMo-3 [N10004], ERNiMo-7 (alloy B-2) [N10665], ERNiMo-8 [N10008], ERNiMo-9 [N10009], ERNiMo-10 [N10675], ERNiMo- [N10629], ERNiMo-12 [N10242]
	45	A-5.11	ENiCrMo-1 [W86007], ENiCrMo-9 [W86985], ENiCrMo-11 [W86030]
	45	A-5.14	ERNiCrMo-1 [N06007], ERNiCrMo-8 [N06975], ERNiCrMo-9 [N06985], ERNiCrMo-11 [N06030], ERNiFeCr-1 [N08065]
	46	A-5.11	ENiCrFeSi-1 [W86045]
	46	A-5.14	ERNiCrFeSi-1 [N06045], ERNiCoCrSi-1 [N12160]

Table 2.102 (3/3) F-numbers – ASME Sec. IX, QW-432 & AWS (grouping of electrodes and welding rods for qualification)

Materials group	F-no.	ASME (SF-)/AWS specification no.	Applicable AWS classification no. [UNS no.]
Titanium and titanium-based alloys	51	A-5.16	ERTi-1 [R50100], ERTi-11 [R52251], ERTi-13 [R53423], ERTi-17 [R52253], ERTi-27 [R52255], ERTi-2 [R50120], ERTi-7 [R52401], ERTi-14 [R53424], ERTi-16 [R52403], ERTi-26 [R52405], ERTi-30 [R53531], ERTi-33 [R53443], ERTi-3 [R50125], ERTi-15A [R53416], ERTi-31 [R53533], ERTi-34 [R53444]
	52	A-5.16	ERTi-4 [R50130]
	53	A-5.16	ERTi-9 [R56320], ERTi-9ELI [R56321], ERTi-18 [R56326], ERTi-28 [R56324]
	54	A-5.16	ERTi-12 [R53400]
	55	A-5.16	ERTi-5 [R56400], ERTi-23 [R56408], ERTi-24 [R56415], ERTi-25 [R56413], ERTi−29 [R56414], ERTi-38 [R54251]
	56	A-5.16	ERTi-32 [R55112]
Zirconium and zirconium-based alloys	61	A-5.24	ERZr2 [R60702], ERZr3 [R60704], ERZr4 [R60705]
Hardfacing weld metal overlay	71	SFA-5.13	ECoCr-A [W73006], ECoCr-B [W73012], ECoCr-C [W73001], ECoCr-E [W73021], ECuAl-A2 [W60617], ECuAl-B [W60619], ECuAl-C [W60625], ECuAl-D [W61625], ECuAl-E [W62625], ECuMnNiAl [W60633], ECuNi [W60715], ECuNiAl [W60632], ECuSi [W60656], ECuSn-A [W60518], ECuSn-C [W60521], EFe1 [W74001], EFe2 [W74002], EFe3 [W74003], EFe4 [W74004], EFe5 [W75110], EFe6 [W77510], EFe7 [W77610], EFeCr-A1A [W74011], EFeCr-A2 [W74012], EFeCr-A3 [W74013], EFeCr-A4 [W74014], EFeCr-A5 [W74015], EFeCr-A6 [W74016], EFeCr-A7 [W74017], EFeCr-A8 [W74018], EFeCr-E1 [W74211], EFeCr-E2 [W74212], EFeCr-E3 [W74123], EFeCr-E4 [W74214], EFeMn-A [W79110], EFeMn-B [W79310], EFeMn-C [W79210], EFeMn-D [W79410], EFeMn-E [W79510], EFeMn-F [W79610], EFeMnCr [W79710], ENiCr-C [W89606], ENiCrFeCo [W83002], ENiCrMo-5A [W80002], EWCX-12/30 [-], EWCX-30/40 [-], EWCX-40 [-],EWCX-40/120 [-]
	72	SFA-5.21	ERCCoCr-A [W73036], ERCCoCr-B [W73042], ERCCoCr-C [W73031], ERCCoCr-E [W73041], ERCCoCr-G [W73032], ERCCuAl-A2 [W60618], ERCCuAl-A3 [W60624], ERCCuAl-C [W60626], ERCCuAl-D [W61626], ERCCuAl-E [W62626], ERCCuSi-A [W60657], ERCCuSn-A [W60518], ERCCuSn-D [W60524], ERCFe-1 [W74030], ERCFe-1A [W74031], ERCFe-2 [W74032], ERCFe-3 [W74033], ERCFe-5 [W74035], ERCFe-6 [W77530], ERCFe-8 [W77538], ERCFeCr-A [W74531], ERCFeCr-A1A [W74530], ERCFeCr-A3A [W74533], ERCFeCr-A4 [W74534], ERCFeCr-A5 [W74535], ERCFeCr-A9 [W74539], ERCFeCr-A10 [W74540], ERCFeMn-C [W79230], ERCFeMn-F [W79630], ERCFeMn-G [W79231], ERCFeMn-H [W79232], ERCFeMnCr [W79730], ERCNiCr-A [W89634], ERCNiCr-B [W89635], ERCNiCr-C [W89636], ERCNiCrFeCo [W83032], ERCNiCrMo-5A [W80036], ERCoCr-A [R30006], ERCoCr-B [R30012], ERCoCr-C [R30001], ERCoCr-E [R30021], ERCoCr-F [R30002], ERCoCr-G [R30014], ERCuAl-A2 [C61800], ERCuAl-A3 [C62400], ERCuAl-C [C62580], ERCuAl-D [C62581], ERCuAl-E [C62582], ERCuSi-A [C65600], ERCuSn-A [-], ERCuSn-D [C52400], ERFe-1 [T74000], ERFe-1A [T74001], ERFe-2 [T74002], ERFe-3 [T74003], ERFe-5 [T74005], ERFe-6 [T74006], ERFe-8 [T74008], ERFeCr-A [-], ERFeCr-A1A [-], ERFeCr-A3A [-], ERFeCr-A4 [-], ERFeCr-A5 [-], ERFeCr-A9 [-], ERFeCr-A10 [-], ERFeMn-C [-], ERFeMn-F [-], ERFeMn-G [-], ERFeMn-H [-], ERFeMnCr [-], ERNiCr-A [N99644], ERNiCr-B [N99645], ERNiCr-C [N99646], ERNiCr-D [N99647], ERNiCr-E [N99648], ERNiCrFeCo [F46100], ERNiCrMo-5A [N10006], ERWCX-20/30 [-], ERWCX-30/40 [-], ERWCX-40 [-], ERWCX-40/120 [-], RWCX-20/30 [-], RWCX-30/30 [-], RWCX-40 [-], RWCX-40/120 [-]

Table 2.103 A-numbers – classification of ferrous weld metal analysis for PQ – ASME Sec. IX, QW-442-2004

A-no.	Types of weld deposit	Analysis, wt% [Note (1)]					
		C	Cr	Mo	Ni	Mn	Si
1	Mid steel	0.15	–	–	–	1.60	1.00
2	C-Mo	0.15	0.50	0.40–0.65	–	1.60	1.00
3	Cr (0.4–2%)-Mo	0.15	0.40–2.00	0.40–0.65	–	1.60	1.00
4	Cr (2–6%)-Mo	0.15	2.00–6.00	0.40–1.50	–	1.60	2.00
5	Cr (6–10.5%)-Mo	0.15	6.00–10.50	0.40–1.50	–	1.20	2.00
6	Cr-Martensitic	0.15	11.00–15.00	0.70	–	2.00	1.00
7	Cr-Ferritic	0.15	11.00–30.00	1.00	–	1.00	3.00
8	Cr-Ni	0.15	14.50–30.00	4.00	7.50–15.00	2.50	1.00
9	Cr-Ni	0.30	25.00–30.00	4.00	15.00–37.00	2.50	1.00
10	Ni to 4%	0.15	–	0.55	0.80–37.00	1.70	1.00
11	Mn-Mo	0.17	–	0.25–0.75	0.85	1.25–2.25	1.00
12	Ni-Cr-Mo	0.15	1.50	0.25–0.80	1.25–2.80	0.75–2.25	1.00

Note: (1) Single values shown above are maximum

Table 2.104 SFA-numbers (specification for electrodes/rods/fluxes)-ASME Sec. II, Part C

SFA no.	Description
SFA-5.01(M)	Welding consumables – procurement of filler materials and fluxes
SFA-5.02(M)	Filler metal standard sizes, packaging, and physical attributes
SFA-5.1(M)	CS electrodes for SMAW
SFA-5.2(M)	CS and LAS rods for OGW
SFA-5.3(M)	Al/Al alloy electrodes for SMAW
SFA-5.4(M)	SS electrodes for SMAW
SFA-5.5(M)	LAS electrodes for SMAW
SFA-5.6(M)	Covered Cu/Cu alloy arc welding electrodes
SFA-5.7(M)	Cu/Cu alloy bare welding rods and electrodes
SFA-5.8(M)	Brazing filler metal
SFA-5.9(M)	Bare SS welding electrodes and rods
SFA-5.10(M)	Bare Al/Al alloy welding electrodes and rods
SFA-5.11(M)	Ni/Ni alloy welding electrodes for SMAW
SFA-5.12(M)	Tungsten and tungsten alloy electrodes for arc welding and cutting
SFA-5.13(M)	Surfacing electrodes for SMAW
SFA-5.14(M)	Ni/Ni alloy bare welding electrodes and rods
SFA-5.16(M)	Ti/Ti alloy bare welding rods and electrodes
SFA-5.17(M)	CS electrodes and fluxes for SAW
SFA-5.18(M)	CS electrodes and fluxes for gas shield arc welding (GTAW, GMAW-MIG)
SFA-5.20(M)	CS electrodes for FCAW
SFA-5.21(M)	Bare electrodes and rods for surfacing
SFA-5.22(M)	SS electrodes for FCAW and SS flux core rods for GTAW
SFA-5.23(M)	LAS electrodes and fluxes for SAW
SFA-5.24(M)	Zr/Zr alloy welding electrodes and rods
SFA-5.25(M)	CS and LAS electrodes and fluxes for ESW
SFA-5.26(M)	CS and LAS electrodes and fluxes for EGW
SFA-5.28(M)	LAS electrodes and rods for gas shield arc welding (GTAW, GMAW-MIG)
SFA-5.29(M)	LAS electrodes for FCAW
SFA-5.30(M)	Consumable inserts
SFA-5.31(M)	Fluxes for brazing and braze welding
SFA-5.32(M)	Welding shield gases
SFA-5.34(M)	Ni alloy electrodes for FCAW
SFA-5.36(M)	CS and LAS- flux cored electrodes for FCAW and metal cored electrodes for GMAW

See Table 4.4 for ASME/AWS Filler Metal Specifications per Material and Welding Process.

See Table 2.105 for the conversion of AWS Specification/Class Numbers-UNS Numbers. UNS Wxxxxx series are for weld metal/cored metal and other UNS numbers are for electrodes/filler-solid metals.

Table 2.105 (1/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
A5.1 CS Welding Electrodes for SMAW		A5.4 (E316/316H)	W31610	A5.5 (E8015-B7)	W50315
		A5.4 (E316L)	W31613	A5.5 (E8015-B7L)	W50305
A5.1 (E6010)	W06010	A5.4 (E317)	W31710	A5.5 (E8015-B8)	W50415
A5.1 (E6011)	W06011	A5.4 (E317L)	W31713	A5.5 (E8015-B8L)	W50405
A5.1 (E6012)	W06012	A5.4 (E318)	W31910	A5.5 (E8016-B1)	W51016
A5.1 (E6013)	W06013	A5.4 (E320)	W88021	A5.5 (E8016-B2)	W52016
A5.1 (E6018)	W06018	A5.4 (E320LR)	W88022	A5.5 (E8016-B5)	W51316
A5.1 (E6019)	W06019	A5.4 (E330)	W88331	A5.5 (E8016-B6)	W50216
A5.1 (E6020)	W06020	A5.4 (E330H)	W88335	A5.5 (E8016-B6L)	W50206
A5.1 (E6022)	W06022	A5.4 (E347)	W34710	A5.5 (E8016-B6L)	W50206
A5.1 (E6027)	W06027	A5.4 (E383)	W88028	A5.5 (E8016-B6L)	W50206
A5.1 (E7014)	W07014	A5.4 (E349)	W34910	A5.5 (E8016-B6L)	W50206
A5.1 (E7015)	W07015	A5.4 (E385)	W88904	A5.5 (E8016-B6L)	W50206
A5.1 (E7016)	W07016	A5.4 (E409Nb)	W40910	A5.5 (E8016-C1)	W22016
A5.1 (E7018)	W07118	A5.4 (E410)	W41010	A5.5 (E8016-C2)	W23016
A5.1 (E7018M)	W07018	A5.4 (E410NiMo)	W41016	A5.5 (E8016-C3)	W21016
A5.1 (E7024)	W07024	A5.4 (E430)	W43010	A5.5 (E8016-C4)	W21916
A5.1 (E7027)	W07027	A5.4 (E430Nb)	W43011	A5.5 (E8016-D3)	W18016
A5.1 (E7028)	W07028	A5.4 (E630)	W37410	A5.5 (E8018-B1)	W51018
A5.1 (E7048)	W07048	A5.4 (E2209)	W39209	A5.5 (E8018-B2)	W52018
		A5.4 (E2307)	S32871	A5.5 (E8018-B3L)	W53118
A5.2 CS & LAS Oxyfuel Gas Welding Rods		A5.4 (E2553)	W39553	A5.5 (E8018-B6)	W50218
		A5.4 (E2593)	W39593	A5.5 (E8018-B6L)	W50208
A5.2 (R45)	K00045	A5.4 (E2594)	W39594	A5.5 (E8018-B7)	W50318
A5.2 (R60)	K00060	A5.4 (E2595)	W39595	A5.5 (E8018-B7L)	W50308
A5.2 (R65)	K00065	A5.4 (E3155)	W73155	A5.5 (E8018-B8)	W50418
A5.2 (R100)	K12147	A5.4 (E33–31)	W33310	A5.5 (E8018-B8L)	W50408
				A5.5 (E8018-C1)	W22018
A5.3 Al and Al Alloy Welding Electrodes for SMAW		**A5.5 LAS Welding Electrodes for SMAW**		A5.5 (E8018-C2)	W23018
				A5.5 (E8018-C3)	W21018
A5.3 (E1100)	A91100	A5.5 (E7010-A1)	W17010	A5.5 (E8018-C4)	W21918
A5.3 (E3003)	A93003	A5.5 (E7010-P1)	W17110	A5.5 (E8018-D1)	W18118
A5.3 (E4043)	A93043	A5.5 (E7011-A1)	W17011	A5.5 (E8018-D3)	W18016
		A5.5 (E7015-A1)	W17015	A5.5 (E8018-NM1)	W21118
A5.4 Stainless Steel Welding Electrodes for SMAW		A5.5 (E7015-B2L)	W52115	A5.5 (E8018-P2)	W18218
		A5.5 (E7015-C1L)	W22115	A5.5 (E8018-W2)	W20118
A5.4 (E16–8-2)	W36810	A5.5 (E7015-C2L)	W23115	A5.5 (E8045-P2)	W18245
A5.4 (E209)	W32210	A5.5 (E7016-A1)	W17016	A5.5 (E9010-P1)	W19110
A5.4 (E219)	W32310	A5.5 (E7016-B2L)	W52116	A5.5 (E9015/6/8-B23)	K20857
A5.4 (E240)	W32410	A5.5 (E7016-C1L)	W22116	A5.5 (E9015/6/8-B24)	K20885
A5.4 (E307)	W30710	A5.5 (E7016-C2L)	W23116	A5.5 (E9015-C5L)	W25018
A5.4 (E308/308H)	W30810	A5.5 (E7018-A1)	W17018	A5.5 (E9015-D1)	W19015
A5.4 (E308L)	W30813	A5.5 (E7018-B2L)	W52118	A5.5 (E9018-D1)	W19018
A5.4 (E308Mo)	W30820	A5.5 (E7018-C1L)	W22118	A5.5 (E9018-D3)	W19118
A5.4 (E308LMo)	W30823	A5.5 (E7018-C2L)	W23118	A5.5 (E9018-NM1)	W21119
A5.4 (E309/309H)	W30910	A5.5 (E7018-C3L)	W20918	A5.5 (E9018M)	W21218
A5.4 (E309L)	W30913	A5.5 (E7018-W1)	W20018	A5.5 (E10015-D2)	W10015
A5.4 (E309Nb)	W30917	A5.5 (E7020-A1)	W17020	A5.5 (E10016-D2)	W10016
A5.4 (E309Mo)	W30920	A5.5 (E7027-A1)	W17027	A5.5 (E10018-D2)	W10018
A5.4 (E309LMo)	W30923	A5.5 (E8010-P1)	W18110	A5.5 (E10018-M)	W21318
A5.4 (E310)	W31010	A5.5 (E8015-B2)	W52015	A5.5 (E10045-P2)	W10245
A5.4 (E310H)	W31015	A5.5 (E8015-B3L)	W53115	A5.5 (E12018M)	W22218
A5.4 (E310Nb)	W31017	A5.5 (E8015-B4L)	W53415	A5.5 (E12018M1)	W23218
A5.4 (E310Mo)	W31020	A5.5 (E8015-B6)	W50215		
A5.4 (E312)	W31310	A5.5 (E8015-B6L)	W50205		

Table 2.105 (2/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
A5.6 Cu and Cu Alloy Electrodes for SMAW		A5.8 (BAg-36)	P07454	A5.8 (BVAu-2)	P00807
		A5.8 (BAg-37)	P07253	A5.8 (BVAu-2)	P00807
A5.6 (ECu)	W60189	A5.8 (BAlSi-2)	A94343	A5.8 (BVAu-4)	P00827
A5.6 (ECuSi)	W60656	A5.8 (BAlSi-3)	A94145	A5.8 (BVAu-7)	P00507
A5.6 (ECuSn-A)	W60518	A5.8 (BAlSi-4)	A94047	A5.8 (BVAu-8)	P00927
A5.6 (ECuSn-C)	W60521	A5.8 (BAlSi-5)	A94045	A5.8 (BVAu-9)	P00354
A5.6 (ECuNi)	W60715	A5.8 (BAlSi-7)	A94004	A5.8 (BVAu-10)	P00503
A5.6 (ECuAl-A2)	W60614	A5.8 (BAlSi-9)	A94147	A5.8 (BVPd-1)	P03657
A5.6 (ECuAl-B)	W60619	A5.8 (BAlSi-11)	A94104		
A5.6 (ECuNiAl)	W60632	A5.8 (BAu-1)	P00375	**A5.9 Bare Stainless Steel Welding Electrodes and rods**	
A5.6 (ECuMnNiAl)	W60633	A5.8 (BAu-2)	P00800		
		A5.8 (BAu-3)	P00350	A5.9 (ER209)	S20980
A5.7 Cu and Cu Alloy Bare Welding Electrodes and Rods		A5.8 (BAu-4)	P00820	A5.9 (ER218)	S21880
		A5.8 (BAu-5)	P00300	A5.9 (ER219)	S21980
A5.7 (ERCu)	C18980	A5.8 (BAu-6)	P00700	A5.9 (ER240)	S23980
A5.7 (ERCuSi-A)	C65600	A5.8 (RBCuZn-A)	C47000	A5.9 (ER307)	S30780
A5.7 (ERCuSn-A)	C51800	A5.8 (RBCuZn-B)	C68000	A5.9 (ER308/308H)	S30880
A5.7 (ERCuSn-C)	C52100	A5.8 (RBCuZn-C)	C68100	A5.9 (ER308Si)	S30881
A5.7 (ERCuNi)	C71581	A5.8 (RBCuZn-D)	C77300	A5.9 (ER308L)	S30883
A5.7 (ERCuAl-A1)	C61000	A5.8 (BCo-1)	R39001	A5.9 (ER308LSi)	S30888
A5.7 (ERCuAl-A2)	C61800	A5.8 (BCu-1)	C14180	A5.9 (ER308LMo)	S30886
A5.7 (ERCuAl-A3)	C62400	A5.8 (BCu-1b)	C11000	A5.9 (ER308Mo)	S30882
A5.7 (ERCuNiAl)	C63280	A5.8 (BCu-3)	C10200	A5.9 (ER309)	S30980
A5.7 (ERCuMnNiAl)	C63380	A5.8 (BCuP-2)	C55181	A5.9 (ER309Si)	S30981
		A5.8 (BCuP-3)	C55281	A5.9 (ER309L)	S30983
A5.8 Brazing Filler Metal		A5.8 (BCuP-4)	C55283	A5.9 (ER309LSi)	S30988
A5.8 (BAg-1)	P07450	A5.8 (BCuP-5)	C55284	A5.9 (ER309LMo)	S30986
A5.8 (BAg-1a)	P07500	A5.8 (BCuP-6)	C55280	A5.9 (ER309Mo)	S30982
A5.8 (BAg-2)	P07350	A5.8 (BCuP-7)	C55282	A5.9 (ER310)	S31080
A5.8 (BAg-2a)	P07300	A5.8 (BCuP-8)	C55285	A5.9 (ER312)	S31380
A5.8 (BAg-3)	P07501	A5.8 (BCuP-9)	C55385	A5.9 (ER316/316H)	S31680
A5.8 (BAg-4)	P07400	A5.8 (BCuP-10)	C55386	A5.9 (ER316Si)	S31681
A5.8 (BAg-5)	P07453	A5.8 (BCuZn-A)	C47000	A5.9 (ER316L)	S31683
A5.8 (BAg-6)	P07503	A5.8 (BCuZn-B)	C68000	A5.9 (ER316LSi)	S31688
A5.8 (BAg-7)	P07563	A5.8 (BCuZn-C)	C68100	A5.9 (ER316LMn)	S31682
A5.8 (BAg-8)	P07720	A5.8 (BCuZn-D)	C77300	A5.9 (ER317)	S31780
A5.8 (BAg-8a)	P07723	A5.8 (BMg-1)	A19001	A5.9 (ER317L)	S31783
A5.8 (BAg-9)	P07650	A5.8 (BNi-1)	N99600	A5.9 (ER318)	S31980
A5.8 (BAg-10)	P07700	A5.8 (BNi-1a)	N99610	A5.9 (ER320)	N08321
A5.8 (BAg-13)	P07540	A5.8 (BNi-2)	N99620	A5.9 (ER320LR)	N08022
A5.8 (BAg-13a)	P07560	A5.8 (BNi-3)	N99630	A5.9 (ER321)	S32180
A5.8 (BAg-18)	P07600	A5.8 (BNi-4)	N99640	A5.9 (ER330)	N08331
A5.8 (BAg-19)	P07925	A5.8 (BNi-5)	N99650	A5.9 (ER347)	S34780
A5.8 (BAg-20)	P07301	A5.8 (BNi-5a)	N99651	A5.9 (ER347Si)	S34788
A5.8 (BAg-21)	P07630	A5.8 (BNi-5b)	N99652	A5.9 (ER383)	N08028
A5.8 (BAg-22)	P07490	A5.8 (BNi-6)	N99700	A5.9 (ER385)	N08904
A5.8 (BAg-23)	P07850	A5.8 (BNi-7)	N99710	A5.9 (ER409)	S40900
A5.8 (BAg-24)	P07505	A5.8 (BNi-8)	N99800	A5.9 (ER318)	S31980
A5.8 (BAg-26)	P07250	A5.8 (BNi-9)	N99612	A5.9 (ER409Nb)	S40940
A5.8 (BAg-27)	P07251	A5.8 (BNi-10)	N99622	A5.9 (ER410)	S41080
A5.8 (BAg-28)	P07401	A5.8 (BNi-11)	N99624	A5.9 (ER410NiMo)	S41086
A5.8 (BAg-33)	P07252	A5.8 (BNi-12)	N99720	A5.9 (ER420)	S42080
A5.8 (BAg-34)	P07380	A5.8 (BNi-13)	N99810	A5.9 (ER430)	S43080
A5.8 (BAg-35)	P07351	A5.8 (BNi-14)	N99660	A5.9 (ER439)	S43035

Table 2.105 (3/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
A5.9 Bare Stainless Steel Welding Electrodes and Rods (cont'd)		**A5.11 Ni and Ni Alloy Welding Electrodes for SMAW**		**A5.13 Surfacing Electrodes for SMAW**	
				A5.13 (ECoCr-A)	W73006
A5.9 (ER446LR)	S44687	A5.11 (ENi-1)	W82141	A5.13 (ECoCr-B)	W73012
A5.9 (ER630)	S17480	A5.11 (ENiCr-4)	W86172	A5.13 (ECoCr-C)	W73001
A5.9 (ER19–10H)	S30480	A5.11 (ENiCrCoMo-1)	W86117	A5.13 (ECoCr-E)	W73021
A5.9 (ER16–8-2)	S16880	A5.11 (ENiCrFe-1)	W86132	A5.13 (ECuAl-A2)	W60617
A5.9 (ER2209)	S39209	A5.11 (ENiCrFe-2)	W86133	A5.13 (ECuAl-B)	W60619
A5.9 (ER2307)	S82371	A5.11 (ENiCrFe-3)	W86182	A5.13 (ECuAl-C)	W60625
A5.9 (ER2553)	S32550	A5.11 (ENiCrFe-4)	W86134	A5.13 (ECuAl-D)	W61625
A5.9 (ER2594)	S32750	A5.11 (ENiCrFe-7)	W86152	A5.13 (ECuAl-E)	W62625
A5.9 (ER33–31)	S20033	A5.11 (ENiCrFe-9)	W86094	A5.13 (ECuMnNiAl)	W60633
A5.9 (ER3556)	R30556	A5.11 (ENiCrFe-10)	W86095	A5.13 (ECuNi)	W60715
		A5.11 (ENiCrFe-12)	W86025	A5.13 (ECuNiAl)	W60632
A5.10 Bare Al and Al Alloy Bare Welding Electrodes and Rods		A5.11 (ENiCrFe-13)	W86155	A5.13 (ECuSi)	W60656
		A5.11 (ENiCrFeSi-1)	W86045	A5.13 (ECuSn-A)	W60518
A5.10 (ER/R1070)	A91070	A5.11 (ENiCrMo-1)	W86007	A5.13 (ECuSn-C)	W60521
A5.10 (ER/R1080A)	R91080	A5.11 (ENiCrMo-2)	W86002	A5.13 (EFe1)	W74001
A5.10 (ER/R1100)	A91100	A5.11 (ENiCrMo-3)	W86112	A5.13 (EFe2)	W74002
A5.10 (ER/R1188)	A91188	A5.11 (ENiCrMo-4)	W80276	A5.13 (EFe3)	W74003
A5.10 (ER/R1200)	A91200	A5.11 (ENiCrMo-5)	W80002	A5.13 (EFe4)	W74004
A5.10 (ER/R1450)	A91450	A5.11 (ENiCrMo-6)	W86620	A5.13 (EFe5)	W75110
A5.10 (ER/R2319)	A92319	A5.11 (ENiCrMo-7)	W86455	A5.13 (EFe6)	W77510
A5.10 (R-206.0)	A02060	A5.11 (ENiCrMo-9)	W86985	A5.13 (EFe7)	W77610
A5.10 (ER/R3103)	A93103	A5.11 (ENiCrMo-10)	W86022	A5.13 (EFeCr-A1A)	W74011
A5.10 (R-C355.0)	A03550	A5.11 (ENiCrMo-11)	W86030	A5.13 (EFeCr-A2)	W74012
A5.10 (R-A356.0)	A03560	A5.11 (ENiCrMo-12)	W86032	A5.13 (EFeCr-A3)	W74013
A5.10 (R-357.0.0)	A03570	A5.11 (ENiCrMo-13)	W86059	A5.13 (EFeCr-A4)	W74014
A5.10 (R-A357.0)	A03570	A5.11 (ENiCrMo-14)	W86686	A5.13 (EFeCr-A5)	W74015
A5.10 ER/R4009	A94009	A5.11 (ENiCrMo-17)	W86200	A5.13 (EFeCr-A6)	W74016
A5.10 ER/R4010	A94010	A5.11 (ENiCrMo-18)	W86650	A5.13 (EFeCr-A7)	W74017
A5.10 R4011	A94011	A5.11 (ENiCrMo-19)	W86058	A5.13 (EFeCr-A8)	W74018
A5.10 ER/R4018	A94018	A5.11 (ENiCrMo-22)	W86035	A5.13 (EFeCr-E1)	W74211
A5.10 ER/R4043	A94043	A5.11 (ENiCrWMo-1)	W86231	A5.13 (EFeCr-E2)	W74212
A5.10 ER/R4043A	A94043	A5.11 (ENiCu-7)	W84190	A5.13 (EFeCr-E3)	W74213
A5.10 ER/R4046	A94046	A5.11 (ENiMo-1)	W80001	A5.13 (EFeCr-E4)	W74214
A5.10 ER/R4047	A94147	A5.11 (ENiMo-3)	W80004	A5.13 (EFeMn-A)	W79110
A5.10 ER/R4047A	A94147	A5.11 (ENiMo-7)	W80665	A5.13 (EFeMn-B)	W79310
A5.10 (ER/R4145)	A94145	A5.11 (ENiMo-8)	W80008	A5.13 (EFeMn-C)	W79210
A5.10 (ER/R4643)	A94643	A5.11 (ENiMo-9)	W80009	A5.13 (EFeMn-D)	W79410
A5.10 (ER/R4943)	A94943	A5.11 (ENiMo-10)	W80675	A5.13 (EFeMn-E)	W79510
A5.10 (ER/R5087)	A95087	A5.11 (ENiMo-11)	W80629	A5.13 (EFeMn-F)	W79610
A5.10 (ER/R5183)	A95183			A5.13 (EFeMnCr)	W79710
A5.10 (ER/R5183A)	A95183	**A5.12 Tungsten (W) and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting** (Note 1)		A5.13 (ENiCr-C)	W89606
A5.10 (ER/R5187)	A95187			A5.13 (ENiCrFeCo)	N83002
A5.10 (ER/R5249)	A95249			A5.13 (ENiCrMo-5A)	N80002
A5.10 (ER/R5356)	A95356	A5.12 (EWP)	R07900		
A5.10 (ER/R5556A)	A95556	A5.12 (EWCe-2)	R07932		
A5.10 (ER/R5554)	A95554	A5.12 (EWLa-1)	R07941		
A5.10 (ER/R5556/A)	A95556	A5.12 (EWLa-1.5)			
A5.10 (ER/R5556B)	A95556	A5.12 (EWLa-2)			
A5.10 (ER/R5556A)	A95556	A5.12 (EWTh-1)	R07911		
A5.10 (ER/R5556C)	A95556	A5.12 (EWTh-1)	R07912		
A5.10 (ER/R5654)	A95654	A5.12 (EWZr-1)	R07920		
A5.10 (ER/R5654A)	A95654	A5.12 (EWZr-8)			
A5.10 (ER/R5754)	A95754	A5.12 (EWG)			

Table 2.105 (4/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
A5.14 Ni and Ni Alloy Bare Welding Electrodes and Rods		**A5.15 Welding Electrodes and Rods for Cast Iron**		**5.17 CS Electrodes and Fluxes for SAW**	
				A5.17 (EC1)	W06041
A5.14 (ERNi-1)	N02061	A5.15 (ENi-CI)	W82001	A5.17 (EH10 K)	K01210
A5.14 (ERNiCoCrSi-1)	N12160	A5.15 (ENi-CI-A)	W82003	A5.17 (EH11K)	K11140
A5.14 (ERNiCrCoMo-1)	N06617	A5.15 (ENiFe-CI)	W82002	A5.17 (EH11K)	K01213
A5.14 (ERNiCrWMo-1)	N06231	A5.15 (ENiFe-CI-A	W82004	A5.17 (EH14)	K11585
A5.14 (ERNiCu-7)	N04060	A5.15 (ENiFeMn-CI)	W82006	A5.17 (EL8)	K01008
A5.14 (ERNiCu-8)	N05504	A5.15 (ENiCu-A)	W84001	A5.17 (EL8K)	K01009
A5.14 (ERNiCr-3)	N06082	A5.15 (ENiCu-B)	W84002	A5.17 (EL12)	K01012
A5.14 (ERNiCr-4)	N06072	A5.15 (ENiFeT3-CI)	W82032	A5.17 (EM11K)	K01111
A5.14 (ERNiCr-6)	N06076	A5.15 (Est)	K01520	A5.17 (EM12)	K01112
A5.14 (ERNiCr-7)	N06073	A5.15 (RCI)	F10090	A5.17 (EM12K)	K01113
A5.14 (ERNiCrFe-5)	N06062	A5.15 (RCI-A)	F10091	A5.17 (EM13K)	K01313
A5.14 (ERNiCrFe-6)	N07092	A5.15 (RCI-B)	F10092	A5.17 (EM14K)	K01314
A5.14 (ERNiCrFe-7)	N06052	A5.15 (ERNi-CI)	N02215	A5.17 (EM15K)	K01515
A5.14 (ERNiCrFe-7A)	N06054	A5.15 (ERNiFeMn-CI)	N02216		
A5.14 (ERNiCrFe-8)	N07069			**5.18 CS Electrodes and Rods for Gas Shielded Arc Welding**	
A5.14 (ERNiCrFe-11)	N06601	**A5.16 Ti and Ti Alloy Bare Welding Electrodes and Rods**			
A5.14 (ERNiCrFe-12)	N06025			A5.18 (ER70S-2)	K10726
A5.14 (ERNiCrFe-13)	N06055	A5.16 (ERTi-1)	R50100	A5.18 (ER70S-3)	K11022
A5.14 (ERNiCrFe-14)	N06043	A5.16 (ERTi-2)	R50120	A5.18 (ER70S-4)	K11132
A5.14 (ERNiCrFeSi-1)	N06045	A5.16 (ERTi-3)	R50125	A5.18 (ER70S-6)	K11140
A5.14 (ERNiCrFeAl-1)	N06693	A5.16 (ERTi-4)	R50130	A5.18 (ER70S-7)	K11125
A5.14 (ERNiFeCr-2)	N07718	A5.16 (ERTi-5)	R56402	A5.18 (ER70C-3X)	W07703
A5.14 (ERNiCrMo-1)	N06007	A5.16 (ERTi-7)	R52401	A5.18 (ER70C-6X)	W07706
A5.14 (ERNiCrMo-2)	N06002	A5.16 (ERTi-9)	R52321		
A5.14 (ERNiCrMo-3)	N06625	A5.16 (ERTi-11)	R52251	**A5.20 CS Electrodes for FCAW**	
A5.14 (ERNiCrMo-4)	N10276	A5.16 (ERTi-12)	R53401	A5.20 (ExxT-1C, -1M, -4,	K02600
A5.14 (ERNiCrMo-7)	N06455	A5.16 (ERTi-13)	R53423	-5C, -5M, -6, -7, -8, -9C, -9M,	K02801
A5.14 (ERNiCrMo-8)	N06975	A5.16 (ERTi-14)	R53424	-11, -12C, -12M, G, -2C,	K03101
A5.14 (ERNiCrMo-9)	N06985	A5.16 (ERTi-15A)	R53416	-2M, -3, -10, -13, -14, -GS)	K02700
A5.14 (ERNiCrMo-11)	N06030	A5.16 (ERTi-16)	R52403		G10150
A5.14 (ERNiCrMo-13)	N06059	A5.16 (ERTi-17)	R52253		G10180
A5.14 (ERNiCrMo-14)	N06686	A5.16 (ERTi-18)	R56326		G10200
A5.14 (ERNiCrMo-15)	N06725	A5.16 (ERTi-19)	R58641		
A5.14 (ERNiCrMo-16)	N06057	A5.16 (ERTi-20)	R58646	**A5.21 Bare Electrodes and Rods for Surfacing**	
A5.14 (ERNiCrMo-17)	N06200	A5.16 (ERTi-21)	R58211		
A5.14 (ERNiCrMo-18)	N06650	A5.16 (ERTi-23)	R56408	A5.21 (ERCoCr-A)	R30006
A5.14 (ERNiCrMo-19)	N06058	A5.16 (ERTi-24)	R56415	A5.21 (ERCoCr-B)	R30012
A5.14 (ERNiCrMo-20)	N06660	A5.16 (ERTi-25)	R56413	A5.21 (ERCoCr-C)	R30001
A5.14 (ERNiCrMo-21)	N06205	A5.16 (ERTi-26)	R52405	A5.21 (ERCoCr-E)	R30021
A5.14 (ERNiCrMo-22)	N06035	A5.16 (ERTi-27)	R52255	A5.21 (ERCoCr-F)	R30002
A5.14 (ERNiFeCr-1)	N08065	A5.16 (ERTi-28)	R56324	A5.21 (ERCoCr-G)	R30014
A5.14 (ERNiMo-1)	N10001	A5.16 (ERTi-29)	R56414	A5.21 (ERCuAl-A2)	C61800
A5.14 (ERNiMo-2)	N10003	A5.16 (ERTi-30)	R53531	A5.21 (ERCuAl-A3)	C62400
A5.14 (ERNiMo-3)	N10004	A5.16 (ERTi-31)	R53533	A5.21 (ERCuAl-C)	C62580
A5.14 (ERNiMo-7)	N10665	A5.16 (ERTi-32)	R55112	A5.21 (ERCuAl-D)	C62581
A5.14 (ERNiMo-8)	N10008	A5.16 (ERTi-33)	R53443	A5.21 (ERCuAl-E)	C62582
A5.14 (ERNiMo-9)	N10009	A5.16 (ERTi-34)	R53444	A5.21 (ERCuSi-A)	C65600
A5.14 (ERNiMo-10)	N10675	A5.16 (ERTi-36)	R58451	A5.21 (ERCuSn-A)	C51800
A5.14 (ERNiMo-11)	N10629	A5.16 (ERTi-38)	R54251	A5.21 (ERCuSn-D)	C53400
A5.14 (ERNiMo-12)	N10242			A5.21 (ERFe-1)	T74000
				A5.21 (ERFe-1A)	T74001

Table 2.105 (5/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
A5.21 Bare Electrodes and Rods for Surfacing – cont'd		A5.22 (E2209 T-3)	W39239	A5.22 (EC317L)	S31783
		A5.22 (E2207 T-3)	S82371	A5.22 (EC318)	S31980
A5.21 (ERFe-2)	T74002	A5.22 (E2553 T-3)	W39533	A5.22 (EC320)	S08021
A5.21 (ERFe-3)	T74003	A5.22 (E2594 T-3)	W39594	A5.22 (EC320LR)	N08022
A5.21 (ERFe-5)	T74005	A5.22 (E307T0–3)	W30733	A5.22 (EC321)	S32180
A5.21 (ERFe-6)	T74006	A5.22 (E308T0–3/E308HT0–3)	W30833	A5.22 (EC330)	N08331
A5.21 (ERFe-8)	T74008	A5.22 (E308LT0–3)	W30837	A5.22 (EC347)	S34780
A5.21 (ERFeCr-A)	W74531	A5.22 (E308LMoT0–3)	W30838	A5.22 (EC347Si)	S34788
A5.21 (ERFeCr-A1A)	W74530	A5.22 (E308HMoT0–3)	W30830	A5.22 (EC383)	N08028
A5.21 (ERFeCr-A3A)	W74533	A5.22 (E308MoT0–3)	W30839	A5.22 (EC385)	N08904
A5.21 (RFeCr-A4)	W74534	A5.22 (E309T0–3)	W30933	A5.22 (EC409)	S40900
A5.21 (RFeCr-A5)	W74535	A5.22 (E309LT0–3)	W30937	A5.22 (EC409Nb)	S40940
A5.21 (RFeCr-A9)	W74539	A5.22 (E309LMoT0–3)	W30938	A5.22 (EC410)	S41080
A5.21 (ERFeCr-A10)	W74540	A5.22 (E309LNbT0–3)	W30934	A5.22 (EC410NiMo)	S41086
A5.21 (ERFeMn-C)	W79230	A5.22 (E310T0–3)	W31031	A5.22 (EC420)	S42080
A5.21 (ERFeMn-F)	W79630	A5.22 (E312T0–3)	W31231	A5.22 (EC430)	S43080
A5.21 (ERFeMn-G)	W79231	A5.22 (E316T0–3)	W31633	A5.22 (EC439)	S43035
A5.21 (ERFeMn-H)	W79232	A5.22 (E316LT0–3)	W31637	A5.22 (EC439Nb)	S43035
A5.21 (ERFeMnCr)	W79730	A5.22 (E316LKT0–3)	W31630	A5.22 (EC446LMo)	S44687
A5.21 (ERNiCr-A)	W99644	A5.22 (E317LT0–3)	W31737	A5.22 (EC630)	S17480
A5.21 (ERNiCr-B)	W99645	A5.22 (E347LT0–3)	W34733	A5.22 (EC19–10H)	S30480
A5.21 (ERNiCr-C)	W99646	A5.22 (E409T0–3)	W40931	A5.22 (EC16–8-2)	S16880
A5.21 (ERNiCr-D)	W99647	A5.22 (E410T0–3)	W41031	A5.22 (EC2209)	S39209
A5.21 (ERNiCr-E)	W99648	A5.22 (E410NiMoT0–3)	W41036	A5.22 (EC2553)	S39553
A5.21 (ERNiCrFeCo)	F46100	A5.22 (E430T0–3)	W43031	A5.22 (EC2594)	S32750
A5.21 (ERNiCrMo-5A)	N10006	A5.22 (E2209 T-3)	W39239	A5.22 (EC33–31)	R20033
		A5.22 (E2307 T-3)	S82371	A5.22 (EC3556)	R30556
A5.22 Stainless Steel Flux Cored and Metal Cored Welding Electrodes and Rods		A5.22 (E2553 T-3)	W39533	A5.22 (R308LTi-5)	W30835
		A5.22 (E2594 T-3)	W39594	A5.22 (R309LTi-5)	W30935
		A5.22 (EC209)	S20980	A5.22 (R316LTi-5)	W31635
A5.22 (E307Tx- x)	W30731	A5.22 (EC218)	S21880	A5.22 (R347Ti-5)	W34731
A5.22 (E308Tx- x/E308HTx- x)	W30831	A5.22 (EC219)	S21980		
A5.22 (E308LTx- x)	W30835	A5.22 (EC240)	S24080	**5.23 LAS Electrodes and Fluxes for SAW**	
A5.22 (E308LMoTx- x)	W30838	A5.22 (EC307)	S30780		
A5.22 (E308MoTx- x)	W30832	A5.22 (EC308/EC308H)	S30880	A5.23 (A1)	W17041
A5.22 (E309T- x/E309HTx- x)	W30931	A5.22 (EC308L)	S30883	A5.23 (A2)	W17042
A5.22 (E309LTx- x)	W30935	A5.22 (EC308LSi)	S30888	A5.23 (A3)	W17043
A5.22 (E309LMoTx- x)	W30938	A5.22 (EC308LMo)	S30886	A5.23 (A4)	W17044
A5.22 (E309MoTx- x)	W30939	A5.22 (EC308Mo)	S30882	A5.23 (B1)	W51040
A5.22 (E309LNiMoTx- x)	W30936	A5.22 (EC308Si)	S30881	A5.23 (B2)	W52040
A5.22 (E309LNbTx- x)	W30932	A5.22 (EC309)	S30980	A5.23 (B2H)	W52240
A5.22 (E310Tx- x)	W31031	A5.22 (EC309L)	S30903	A5.23 (B3)	W53040
A5.22 (E312Tx- x)	W31331	A5.22 (EC309LSi)	S30988	A5.23 (B4)	W53340
A5.22 (E316Tx- x/E316HTx- x)	W31631	A5.22 (EC309LMo)	S30986	A5.23 (B5)	W51340
A5.22 (E316LTx- x)	W31635	A5.22 (EC309Mo)	S30982	A5.23 (B6)	W50240
A5.22 (E317LTx- x)	W31735	A5.22 (EC309Si)	S30981	A5.23 (B6H)	W50140
A5.22 (E347Tx- x/E347HTx- x)	W34731	A5.22 (EC310)	S31080	A5.23 (B8)	W50440
A5.22 (E409Tx-x)	W40931	A5.22 (EC312)	S31380	A5.23 (B23)	K20857
A5.22 (E409NbTx-x)	W40957	A5.22 (EC316/EC316H)	S31680	A5.23 (B24)	K20885
A5.22 (E410Tx-x)	W41031	A5.22 (EC316L)	S31683	A5.23 (B91)	W50442
A5.22 (E410NiMoTx-x)	W41036	A5.22 (EC316LMn)	S31682	A5.23 (F1)	W21150
A5.22 (E430Tx-x)	W43031	A5.22 (EC316LSi)	S31688	A5.23 (F2)	W20240
A5.22 (E430NbTx-x)	W43057	A5.22 (EC316Si)	S31681	A5.23 (F3)	W21140
		A5.22 (EC317)	S31780	F4	W20440

Table 2.105 (6/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
5.23 LAS Electrodes and Fluxes for SAW		A5.23 (EM14K)	K01314	A5.28 (E70S-B2L)	K20500
		A5.23 (EM15K)	K01515	A5.28 (E80C-B3L)	W53130
A5.23 (F5)	W22540	A5.23 (ENi1)	K11040	A5.28 (E80C-Ni1)	W21030
A5.23 (F6)	W22640	A5.23 (ENi1K)	K11058	A5.28 (E80C-Ni2)	W22030
A5.23 (M1)	W21240	A5.23 (ENi2)	K21010	A5.28 (E80C-Ni3)	W23030
A5.23 (M2)	W21340	A5.23 (ENi3)	K31310	A5.28 (ER80S-B2)	K20900
A5.23 (M3)	W22240	A5.23 (ENi4)	K11485	A5.28 (ER80S-B3L)	K30560
A5.23 (M4)	W22440	A5.23 (ENi5/ENi6)	K11240	A5.28 (ER80S-B6)	S50280
A5.23 (M5)	W21345	A5.23 (EW)	K11245	A5.28 (ER80S-B8)	S50480
A5.23 (M6)	W21346			A5.28 (ER80S-B9)	S50482
A5.23 (Ni1)	W21040	**5.24 Zr and Zr-Alloy Welding Electrodes and Rods**		A5.28 (ER80S-D2)	K10945
A5.23 (Ni2)	W22040			A5.28 (ER80S-Ni1)	K11260
A5.23 (Ni3)	W23040	A5.24 (ERZr2)	R60702	A5.28 (ER80S-Ni2)	K21240
A5.23 (Ni4)	W21250	A5.24 (ERZr3)	R60704	A5.28 (ER80S-Ni3)	K31240
A5.23 (Ni5/N6)	W21042	A5.24 (ERZr4)	R60707	A5.28 (E90C-B3)	W53030
A5.23 (W)	W20140			A5.28 (E90C-D2)	W19230
A5.23 (EA1)	K11222	**5.25 CS and LAS Electrodes and Fluxes for ESW**		A5.28 (ER90S-B3)	K30960
A5.23 (EA1TiB)	K11020			A5.28 (ER90S-B9)	S50482
A5.23 (EA1TiB)	K11126	A5.25 (EA3K-EW)	K10945	A5.28 (ER90S-D2)	K10945
A5.23 (EA2)	K11223	A5.25 (EH10 K-EW)	K01010	A5.28 (ER100S-1)	K10882
A5.23 (EA3)	K11423	A5.25 (EH11K-EW)	K11140	A5.28 (ER110S-1)	K21015
A5.23 (EA3K)	K21451	A5.25 (EH14-EW)	K11585	A5.28 (ER120S-1)	K21030
A5.23 (EA4)	K11424	A5.25 (EM5K-EW)	K10726		
A5.23 (EB1)	K11043	A5.25 (EM12-EW)	K01112	**5.29 LAS Electrodes for FCAW**	
A5.23 (EB2)	K11172	A5.25 (EM12K-EW)	K01113	A5.29 (A1)	W1703x
A5.23 (EB2H)	K23016	A5.25 (EM13K-EW)	K01313	A5.29 (B1)	W5103x
A5.23 (EB3)	K31115	A5.25 (EM15K-EW)	K01515	A5.29 (B1L)	W5113x
A5.23 (EB5)	K12187	A5.25 (EWS-EW)	K11245	A5.29 (B2)	W5203x
A5.23 (EB6)	S50280	A5.25 (EWT1)	W06040	A5.29 (B2L)	W5203x
A5.23 (EB6H)	S50180	A5.25 (EWT2)	W20140	A5.29 (B2H)	W5223x
A5.23 (EB8)	S50480	A5.25 (EWT3)	W22340	A5.29 (B3)	W5303x
A5.23 (EB23)	K20857			A5.29 (B6)	W50231
A5.23 (EB24)	K20885	**5.26 CS and LAS Electrodes for ESW**		A5.29 (B6L)	W50230
A5.23 (EB91)	S50482	A5.26 (EGxxS-1)	K01313	A5.29 (B8)	W50431
A5.23 (EF1)	K11160	A5.26 (EGxxS-2)	K10726	A5.29 (B8L)	W50430
A5.23 (EF2)	K21450	A5.26 (EGxxS-3)	K11022	A5.29 (B9)	W50531
A5.23 (EF3)	K21485	A5.26 (EGxxS-5)	K11357	A5.29 (Ni1)	W2103x
A5.23 (EF4)	K12048	A5.26 (EGxxS-6)	K11140	A5.29 (Ni2)	W2203x
A5.23 (EF5)	K41370	A5.26 (EGxxS-D2)	K10945	A5.29 (Ni3)	W2303x
A5.23 (EF6)	K21135	A5.26 (EG6xT1)	W06301	A5.29 (D1)	W1913x
A5.23 (EH10 K)	K01210	A5.26 (EG6xT2)	W06302	A5.29 (D2)	W1923x
A5.23 (EH11K)	K11140	A5.26 (EG7xT1)	W07301	A5.29 (D3)	W1933x
A5.23 (EH12K)	K01213	A5.26 (EG7xT2)	W07302	A5.29 (K1)	W2113x
A5.23 (EH14)	K11585	A5.26 (EGxxT-Ni1)	W21033	A5.29 (K2)	W2123x
A5.23 (EL8)	K01008	A5.26 (EGxxT-NM1)	W22334	A5.29 (K3)	W2133x
A5.23 (EL8K)	K01009	A5.26 (EGxxT-NM2)	W22333	A5.29 (K4)	W2223x
A5.23 (EL12)	K01012	A5.26 (EGxxT-W)	W20131	A5.29 (K5)	W2162x
A5.23 (EM2)	K10882			A5.29 (K6)	W2104x
A5.23 (EM3)	K21015	**5.28 LAS Electrodes and Rods for Gas Shielded Arc Welding**		A5.29 (K7)	W2205x
A5.23 (EM4)	K21030			A5.29 (K8)	W2143x
A5.23 (EM11K)	K01111	A5.28 (E70C-B2L)	W52130	A5.29 (K9)	W23230
A5.23 (EM12K)	K01113	A5.28 (E70C-Ni2)	W22030	A5.29 (W2)	W2013x
A5.23 (EM13K)	K01313	A5.28 (E70S-A1)	K11235		

Table 2.105 (7/7) AWS spec-UNS numbers (unit and classes: US customary and AWS traditional)

AWS spec/class no.	UNS no.	AWS spec/class no.	UNS no.
5.30 Consumable Inserts		**5.36 Carbon and Low-Alloy Steel Flux Cored Electrodes for FCAW and Metal Cored Electrodes for GMAW**	
A5.30 (IN6A)	N07092		
A5.30 (IN52)	N06052		
A5.30 (IN60)	N04060	A5.36 (A1)	W1703x
A5.30 (IN61)	N02061	A5.36 (B1)	W5103x
A5.30 (IN62)	N06062	A5.36 (B1L)	W5113x
A5.30 (IN67)	C71581	A5.36 (B2)	W5203x
A5.30 (IN82)	N06082	A5.36 (B2L)	W5213x
A5.30 (IN308)	S30880	A5.36 (B2H)	W5223x
A5.30 (IN308L)	S30883	A5.36 (B3)	W5303x
A5.30 (IN309)	S30980	A5.36 (B3L)	W5313x
A5.30 (IN309L)	S30983	A5.36 (B3H)	W5323x
A5.30 (IN310)	S31080	A5.36 (B6)	W50231
A5.30 (IN312)	S31380	A5.36 (B6L)	W50230
A5.30 (IN316)	S31680	A5.36 (B8)	W50431
A5.30 (IN347)	S34780	A5.36 (B8L)	W50430
A5.30 (IN348)	S34780	A5.36 (B91)	W50531
A5.30 (IN502)	S50280	A5.36 (Ni1)	W2103x
A5.30 (IN504)	S50482	A5.36 (Ni2)	W2203x
A5.30 (IN515)	K20900	A5.36 (Ni3)	W2303x
A5.30 (IN521)	K30960	A5.36 (D1)	W1913x
A5.30 (INMs1)	K10726	A5.36 (D2)	W1923x
A5.30 (INMs2)	K01313	A5.36 (D3)	W1933x
A5.30 (INMs3)	K11140	A5.36 (K1)	W2113x
		A5.36 (K2)	W2123x
		A5.36 (K3)	W2133x
5.34 Ni-Alloy Electrodes for FCAW		A5.36 (K4)	W2223x
A5.34 (ENiCr3Tx-y)	W86082	A5.36 (K5)	W2162x
A5.34 (ENiCrFe1Tx-y)	W86132	A5.36 (K6)	W2104x
A5.34 (ENiCrFe2Tx-y)	W86133	A5.36 (K7)	W2205x
A5.34 (ENiCrFe3Tx-y)	W86182	A5.36 (K8)	W2143x
A5.34 (ENiMo13Tx-y)	N10300	A5.36 (K9)	W23230
A5.34(ENiCrMo2Tx-y)	W86002	A5.36 (W2)	W2013x
A5.34(ENiCrMo3Tx-y)	W86625		
A5.34(ENiCrMo4Tx-y)	W80276		
A5.34(ENiCrMo10Tx-y)	W80022		
A5.34(ENiCrCoMo1Tx-y)	W86117		

General notes
x & *y*: various numbers (0–9)
Notes

1. AWS color ID	Color
EWP (WP)	Green
EWCe-2 (WCe20)	Grey
EWLa-1 (WLa10)	Black
EWLa-1.5 (WLa15)	Gold
EWLa-2 (WLa20)	Blue
EWTh-1 (WTh10)	Yellow
EWTh-2 (WTh20)	Red
EWZr-1 (WZr3)	Brown
EWZr-8 (WZr8)	White

2.1.11 ISO/TR 15608 (Welding-Guidelines for a Metallic Materials Grouping System) and EN 13445

ASME Sec.VIII, Div.2, Part 7 (Inspection and Examination Requirements) is based on the ISO/TR 15608 Material Group below.

Steel (Group 1–11)

Group 1: Steels with C $\leq$ 0.25%, Si $\leq$0.60%, Mn $\leq$ 1.7%, Mo $\leq$ 0.70%[b], S $\leq$ 0.045%, P $\leq$ 0.045%, Cu $\leq$ 0.40%[b], Ni $\leq$ 0.5%[b], Cr $\leq$ 0.3% (0.4% for castings)[b], Nb $\leq$ 0.05%, V $\leq$ 0.12%[b], Ti $\leq$ 0.05% with SMYS $\leq$460 N/mm^2 as below:
- Gr. 1.1: SMYS $\leq$275 N/mm^2
- Gr. 1.2: 275 N/mm^2 $\leq$ SMYS $\leq$360 N/mm^2
- Gr. 1.3: Normalized fine grain steels with SMYS >360 N/mm^2
- Gr. 1.4: Steels with improved atmospheric corrosion resistance, with analysis which may exceed the above specification.

Group 2: Thermomechanically treated fine grain steels and cast steels:
- Gr. 2.1: 360 N/mm^2 < SMYS $\leq$460 N/mm^2
- Gr. 2.2: SMYS >460 N/mm^2

Group 3: Quenched-tempered and precipitation hardened fine grain steels (except stainless steels) with SMYS >360 N/mm^2
- Gr. 3.1: 360 N/mm^2 < SMYS $\leq$690 N/mm^2
- Gr. 3.2: SMYS >690 N/mm^2
- Gr. 3.3: Precipitation hardened steels except stainless steels

Group 4: Low vanadium alloyed Cr-Mo-(Ni) steels with Mo $\leq$ 0.7% and V $\leq$ 0.1%
- Gr. 4.1: Steels with Cr $\leq$ 0.3% and Ni $\leq$ 0.7%
- Gr. 4.2: Steels with Cr $\leq$ 0.7% and Ni $\leq$ 1.5%

Group 5: Cr-Mo steels free of vanadium and C $\leq$ 0.35%
- Gr. 5.1: Steels with 0.75% $\leq$ Cr $\leq$ 1.5% and Mo $\leq$ 0.7%
- Gr. 5.2: Steels with 1.5% < Cr $\leq$ 3.5% and 0.7% < Mo $\leq$ 1.2%
- Gr. 5.3: Steels with 3.5% < Cr $\leq$ 7.0% and 0.4% < Mo $\leq$ 0.7%
- Gr. 5.4: Steels with 7.0% < Cr $\leq$ 10% and 0.7% < Mo $\leq$ 1.2%

Group 6: High vanadium alloyed Cr-Mo-(Ni) steels
- Gr. 6.1: Steels with 0.3% $\leq$ Cr $\leq$ 0.75%, Mo $\leq$ 0.7%, and V $\leq$ 0.35%
- Gr. 6.2: Steels with 0.75% < Cr $\leq$ 3.5%, 0.7% < Mo $\leq$ 1.2%, and V $\leq$ 0.35%
- Gr. 6.3: Steels with 3.5% < Cr $\leq$ 7.0%, Mo $\leq$ 0.7%, and 0.45% < V $\leq$ 0.35%
- Gr. 6.4: Steels with 7.0% < Cr $\leq$ 12.5%, 0.7% < Mo $\leq$ 1.2%, and V $\leq$ 0.35%

Group 7: Ferritic, martensitic, or precipitation-hardened stainless steels with C $\leq$ 0.35% and 10.5% $\leq$ Cr $\leq$ 30%
- Gr. 7.1: FSS
- Gr. 7.2: MSS
- Gr. 7.3: PHSS

Group 8: ASS, Ni $\leq$ 31%
- Gr. 8.1: ASS with Cr $\leq$ 19%
- Gr. 8.2: ASS with Cr > 19%
- Gr. 8.3: Manganese ASS with 4% < Mn $\leq$ 12%

Group 9: Nickel alloy steels, Ni $\leq$ 10%
- Gr. 9.1: Nickel alloy steels with Ni $\leq$ 3.0%
- Gr. 9.2: Nickel alloy steels with 3.0% < Ni $\leq$ 8.0%
- Gr. 9.3: Nickel alloy steels with 8.0% < Ni $\leq$ 10%

Group 10: Austenitic – Ferritic stainless steels (DSS)
- Gr. 10.1: DSS with Cr $\leq$ 24%
- Gr. 10.2: DSS with Cr > 24%

Group 11: Steels covered by Group 1 with 0.25% $\leq$ C $\leq$ 0.5%
- Gr. 11.1: Steels as indicated under 11 with 0.25% < Ni $\leq$ 0.35%
- Gr. 11.2: Steels as indicated under 11 with 0.35% < Ni $\leq$ 0.5%

Aluminum and Aluminum Alloys (Group 22–26)

Group 21: Pure aluminum with $\leq$1% impurities or alloy content
Group 22: Non-heat treatable Al alloys (Al-Mn & Al-Mg alloys)
Group 23: Heat treatable Al alloys (Al-–Mg-Si, Al-Zn-Mg alloys)
Group 24: Al-Si alloys
Group 25: Al-Si-Cu alloys
Group 26: Al-–Cu alloys

Copper and Copper Alloys (Group 31–38)

Group 31: Copper with $\leq$6% Ag and $\leq$ 3% Fe
Group 32: Cu-Zn alloys
Group 33: Cu-Sn alloys
Group 34: Cu-Ni alloys
Group 35: Cu-Al alloys
Group 36: Cu-Ni-Zn alloys
Group 37: Copper alloys, low alloyed
Group 38: Other Copper alloys

Nickel and Nickel Alloys (Group 41–48)

Group 41: Pure nickel
Group 42: Ni-Cu alloys
Group 43: Ni-Cr alloys
Group 44: Ni-Mo alloys
Group 45: Ni-Fe-Cr alloys

Group 46: Ni-Cr-Co alloys
Group 47: Ni-Fe-Cr-Cu alloys
Group 48: Ni-Fe-Co alloys

Titanium and Titanium Alloys (Group 51–54)
Group 51: Pure titanium
Group 52: Alpha alloys
Group 53: Alpha – beta alloys
Group 54: Near beta and beta alloys

Zirconium and Zirconium Alloys (Group 61–62)
Group 61: Pure zirconium
Group 62: Zirconium with 2.5% Nb

Cast Iron (Group 71–76)
Group 71: Gray cast iron
Group 72: Spheroidal graphitic cast iron
Group 73: Malleable cast iron
Group 74: Austempered ductile cast iron
Group 75: Austenitic cast iron
Group 76: Cast irons excepting groups 71–75

Notes
[a] In accordance with the specification of the steel product standards, *R*eH may be replaced by *R*p0.2 or *R*p0.5
[b] A higher value is accepted provided that Cr + Mo + Ni + Cu + V $\leq$ 0.75%
[c] "Free of vanadium" means not deliberately added to the material.
[d] A higher value is accepted provided that Cr + Mo + Ni + Cu + V $\leq$ 1%

2.1.12 API Materials Classes for Pumps and Valves

2.1.12.1 Pumps

Tables 2.106 and 2.107 show the standard classes of material combination of several components for API centrifugal pumps.

Table 2.106 Materials classes in API 610 centrifugal pumps (modified) (See Table H.1 in API 610 for more detail)

Part	Materials classes (See Table 2.107)													
	I-1	I-2	S-1	S-3	S-4	S-5	S-6	S-8	S-9	C-6	A-7	A-8	D-1	D-2
Pressure casing	CI	CI	CS	CS	CS	CS	CS	CS	CS	12%Cr	ASS	316 SS	DSS	SDSS
Impeller	CI	Bronze	CI	Ni-resist	CS	CS	12%Cr	316 SS	Ni-Cu	12%Cr	ASS	316 SS	DSS	SDSS
Shaft	CS	CS	CS	CS	CS	AISI 4140	AISI 4140	316 SS	Ni-Cu	12%Cr	ASS	316 SS	DSS	SDSS

General Notes
1. CI = cast iron; CS = cast steel; ASS = austenitic stainless steel; (S)DSS = (super) duplex stainless steel
2. CI: CI casing should be used at 1725 kPa.g (17.25 bar.g/250 psig) and below. The raised face (RF) of CI casing flange should be used at 1725 kPa.g (17.25 bar.g/250 psig) and below
3. Alternative materials recommended for the service by the vendor, including material that can improve life and performance in service, may also be included in the proposal and listed on the final data sheets
4. Threaded piping joints may be used only on seal glands, instrumentation connections, and for pumps of cast iron construction

Commentary General Notes
a. CI: The raised face (RF) of CI flange should be used at 690 kPa.g (6.9 bar.g/100 psig) and below
b. CI: CI casing should not be used for hydrocarbon, flammable, and lethal services. Repair welding should be minimized.
c. The material class S-8 or A-8 should be used for amine service
d. 12%Cr steel: CA6NM (12Cr-4Ni) instead of 12%Cr should be used for heavy duty or erosion circuit
e. All repair-welded parts of CI or CS casing in EAC (Environmentally Assisted Cracking) and hydrogen services should be post weld heat treated per code and project specification
f. ASS: 304 SS (typical no Mo contained.)
g. DSS & SDSS: See Sect. 2.1.5.5(e) for more detail.

Table 2.107 (1/2) Materials class selection guidance for Table 2.106 (API 610, Table G.1 – modified)

Service	Temperature range		Pressure range	Materials class	Ref. note
	°C	°F			
Fresh water, condensate, cooling tower water	<100	<212	All	1–1 or 1–2	—
Boiling water and process water	<120	<250	All	1–1 or 1–2	a
	120–175	250–350	All	S-5	a
	>175	>350	All	S-6, C-6	a
Boiler feed water – Axially split	>95	>200	All	C-6	—
Boiler feed water – Double- casing (barrel)	>95	>200	All	S-6	—
Boiler circulator	>95	>200	All	C-6	—
Foul water, reflux. Drum water, water draw, and hydrocarbons containing these waters, including reflux streams	<175	<350	All	S-3 or S-6	b
	>175	>350	All	C-6	—

Table 2.107 (2/2) Materials class selection guidance for Table 2.106 (API 610, Table G.1 – modified)

Service	Temperature range		Pressure range	Materials class	Ref. note
	°C	°F			
Propane, butane, liquefied petroleum gas, ammonia, ethylene, low-temperature services (minimum metal temperature)	<230	<450	All	S-1	—
	> −46	> −50	All	S-1 (LCB)	h
	> −73	> −100	All	S-1 (LC2)	h
	> −100	> −150	All	S-1 (LC3)	h, i
	> −196	> −320	All	A-7 or A-8	h, i
Diesel oil, gasoline, naphtha, kerosene, gas oils, light, medium and heavy lubricating oils, fuel oil, residuum, crude oil, asphalt, synthetic crude bottoms	<230	<450	All	S-1	—
	230–370	450–700	All	S-6	b, c
	>370	>700	All	C-6	b
Non-corrosive hydrocarbons, e.g., catalytic reformate, isomaxate, desulfurized oils	230–370	450–700	All	S-4	c
Xylene, toluene, acetone, benzene, furfural, MEK, cumene	<230	<450	All	S-1	—
Sodium carbonate	<175	<350	All	1-1	—
Caustic (NaOH), concentration < 20%	<100	<212	All	S-1	d
	>100	>212	All	—	e
Seawater	<95	<200	All	—	f, k
Sour water	<260	<470	All	D -1	L
Produced water, formation water, and brine	All	All	All	D-1 or D-2	f
Sulfur (liquid state)	All	All	All	S-1	—
Refinery FCC slurry	<370	<700	All	C-6	—
Potassium carbonate	<175	<350	All	C-6	—
	<370	<700	All	A-8	—
MEA, DEA, TEA stock solutions	<120	<250	All	S -1	—
DEA, TEA – lean solutions	<120	<250	All	S-1 or S-8	d, g
MEA – lean solution (CO_2 only)	80–150	175–300	All	S-9	d
MEA – lean solution (CO_2 and H_2S)	80–150	175–300	All	S-8	d, g
MEA-, DEA-, TEA-rich solutions	<80	<175	All	S-1 to S-8	d
Sulfuric acid concentration > 85%	<38	<100	All	S-1	b
85% to <1%	<230	<450	All	A-8	b, j
Hydrofluoric acid concentration > 96%	<38	<100	All	S-9	b

General Notes;
1. The materials for pump parts for each material class are given in Annex H in API 610
2. Specific material recommendations should be obtained for services not clearly identified by the service descriptions listed in this table
3. Cast iron castings (6.12.1.6), if recommended for chemical services, are for nonhazardous locations only. Steel casings should be used for pumps in services located near process plants or in any location where released vapor from a failure can create a hazardous situation or where pumps can be subjected to hydraulic shock, e.g., in loading services

Notes:
a Oxygen content and buffering of water should be considered in material selection
b The corrosiveness of foul waters, hydrocarbons over 230 °C (450 °F), acids, and acid sludges can vary widely. Material recommendations should be obtained for each service. The material class indicated above is satisfactory for many of these services, but shall be verified. S-8 materials may also be considered for operating temperatures below 95 °C (200 °F)
c If product corrosivity is low, class S-4 materials may be used for services at 231–370 °C (451–700 °F). Specific material recommendations should be obtained in each instance
d All welds shall be stress-relieved.
e UNS N08007 or Ni-Cu alloy pump material should be used.
f For seawater, produced water, formation water, and brine services, the purchaser and the vendor should agree on the construction materials that best suit the intended use
g The vendor shall consider the effects of differential material expansion between casing and rotor and confirm suitability if operating temperatures can exceed 95 °C (200 °F)
h Materials selected for low-temperature services shall meet the requirements of API 610, 6.12.1.6, and 6.12.4. Casting alloy grades LCB, LC2, and LC3 are shown only for reference. Grades LCB, LC2, and LC3 refer to ISO 4991. C23-45BL, C43E2aL, and C43L are equivalent to ASTM A352/A352M, grades LCB, LC2, and LC3. Use equivalent materials for wrought alloys
i Alloy materials based on aluminum, bronze, aluminum bronze, and nickel may also be considered for temperatures as low as −196 °C (−320 °F)
Commentary Notes:
j Class, A-8 is normally used at 54 °C (130 °F) and below. For above 54 °C (130 °F), Alloy 825, Alloy 20, and Alloy 904L, and others are considered [References; (1) MTI MS-1, NiDI Publication #1318 or #10057, API RP571, etc.]
k Seawater: See Tables 2.76, 2.188, and 2.189, Figs. 2.93, 2.145, 2.146, 2.147, 2.180, 2.191, Sect. 5.5.5.6, and Table 2.124 Note b
L Sour water: See Table 2.124(2) for Alkaline Sour Water Corrosion and Table 2.124(3) for Acidic Sour Water Corrosion

2.1.12.2 Valves

The following are the most common industrial standards for valves:

- ***API SPEC 6D/ISO 14313***: Specification for Pipeline Valves
  It is for Petroleum and Natural Gas Industries, Pipeline Transportation Systems, Pipeline Valves. This International Standard specifies requirements and gives recommendations for the design, manufacturing, testing, and documentation of ball, check, gate, and plug valves for application in pipeline systems.
- ***API 526***: Flanged Steel Pressure Relief Valves
  The standard is a purchase specification for flanged steel pressure relief valves. Basic requirements are given for direct spring-loaded pressure relief valves and pilot-operated pressure relief valves as follows: orifice designation and area; valve size and pressure rating, inlet and outlet; materials; pressure-temperature limits; and center-to-face dimensions, inlet and outlet.
- ***API 527***: Seat Tightness of Pressure Relief Valves
  Describes methods of determining the seat tightness of metal- and soft-seated pressure relief valves, including those of conventional, bellows, and pilot-operated designs.
- ***API 594***: Check Valves: Flanged, Lug, Wafer, and Butt-Welding
  It covers design, material, face-to-face dimensions, pressure-temperature ratings, and examination, inspection, and test requirements for two types of check valves.
- ***API 598***: Valve Inspection and Testing
  It covers inspection, supplementary examination, and pressure test requirements for both resilient-seated and metal-to-metal seated gate, globe, plug, ball, check, and butterfly valves. Pertains to inspection by the purchaser and to any supplementary examinations the purchaser may require at the valve manufacturer's plant.
- ***API 599***: Metal Plug Valves – Flanged, Threaded, and Welding Ends
  A purchase specification that covers requirements for metal plug valves with flanged or butt-welding ends, and ductile iron plug valves with flanged ends, in sizes NPS 1 through NPS 24, which correspond to nominal pipe sizes in ASME B36.10 M. Valve bodies conforming to ASME B16.34 may have flanged end and one butt-welding end. It also covers both lubricated and nonlubricated valves that have two-way coaxial ports, and includes requirements for valves fitted with internal body, plug, or port linings or applied hardfacings on the body, body ports, plug, or plug port.
- ***API 600/ISO 10434***: Steel Gate Valves, Flanged and Butt-Welding Ends, Bolted Bonnets
  Bolted Bonnet Steel Gate Valves for Petroleum and Natural Gas Industries.
- ***API 602***: Steel Gate, Globe, and Check Valves for Sizes NPS 4 (DN 100) and Smaller for the Petroleum and Natural Gas Industries
  The standard covers threaded-end, socket-welding-end, butt-welding-end, and flanged-end compact carbon steel gate valves in sizes NPS4 and smaller.
- ***API 603***: Corrosion-Resistant, Bolted Bonnet Gate Valves – Flanged and Butt-Welding Ends
  The standard covers corrosion-resistant bolted bonnet gate valves with flanged or butt-weld ends in sizes NPS 1/2 through 24, corresponding to nominal pipe sizes in ASME B36.10 M, and Classes 150, 300, and, 600, as specified in ASME B16.34.
- ***API 607***: Fire Test for Quarter Turn Valves and Valves Equipped with Nonmetallic Seats
  It covers the requirements for testing and evaluating the performance of straightway, soft-seated quarter-turn valves when the valves are exposed to certain fire conditions defined in this standard. The procedures described in this standard apply to all classes and sizes of such valves that are made of materials listed in ASME B16.34.
- ***API 608***: Metal Ball Valves – Flanged and Butt-Welding Ends
  It covers Class 150 and Class 300 metal ball valves that have either butt-welding or flanged ends and are for use in on-off service.
- ***API 609***: Butterfly Valves: Double Flanged, Lug and Wafer Types
  It covers design, materials, face-to-face dimensions, pressure-temperature ratings, and examination, inspection, and test requirements for gray iron, ductile iron, bronze, steel, nickel-based alloy, or special alloy butterfly valves that provide tight shutoff in the closed position and are suitable for flow regulation.
- ***API 6FA***: API Specification for Fire Test for End Connections
  It covers the requirements for testing and evaluating the performance of API Spec 6A and Spec 6D valves when exposed to specifically defined fire conditions.
- ***API 6FC***: Specification for Fire Test for Valve with Automatic Backseats
  It covers the requirements for testing and evaluating the performance of API Spec 6A and Spec 6D valves with automatic backseats when exposed to specifically defined fire conditions.
- ***API 6RS***: Referenced Standards for Committee 6, Standardization of Valves and Wellhead Equipment.
- ***API 11V6***: Design of Continuous Flow Gas Lift Installations Using Injection Pressure Operated Valves
  The standard sets guidelines for continuous flow gas lift installation designs using injection pressure operated valves.
- ***API RP 11V7***: Recommended Practice for Repair, Testing, and Setting Gas Lift Valves
  The standard applies to repair, testing, and setting gas lift valves and reverse flow (check) valves.
- ***API RP520***-Part I: Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries – Sizing and Selection
  It applies to the sizing and selection of pressure relief devices used in refineries and related industries for equipment that has a maximum allowable working pressure of 15 psig (1.03 bar g or 103 kPa g) or greater.
- ***API RP520***-Part II: Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries – Installation
  It covers methods of installation for pressure-relief devices for equipment that have a maximum allowable working pressure of 15 psig (1.03 bar g or 103 kPa g) or greater. It covers gas, vapor, steam, two-phase, and incompressible fluid service.

- ***API RP574***: Inspection Practices for Piping System Components
  It covers the inspection of piping, tubing, valves (other than control valves) and fittings used in petroleum refineries.
- ***API RP576***: Inspection of Pressure-Relieving Devices
  It describes the inspection and repair practices for automatic pressure-relieving devices commonly used in the oil and petrochemical industries.
- ***ASME B16.34***: Valves – Flanged, Threaded, and Welding End.
- ***ASME Section VIII, Div.1***, UG-126/127/128/131/136/137, UW-60, UF-115, UB-55, UCS-115, UNF-115, UHA-60, UCI-115, UCL-55, UCD-115, UHT-115, ULW-115, UIG-115, and Appendix M: Pressure Vessels-Pressure Relief Devices.
- ***ASME PTC 25***: Pressure Relief Devices.
- ***MSS SP-6***: Standard Finishes for Contact Faces of Pipe Flanges and Connecting and End Flanges of Valves and Fittings.
- ***MSS SP-25***: Standard Marking System for Valves, Fittings, Flanges, and Unions.
- ***MSS SP-42***: Class 150 Corrosion Resistant Gate, Globe, Angle, and Check Valves with Flanged and Butt-Weld Ends.
- ***MSS SP-53***: Quality Standard for Steel Castings and Forgings for Valves, Flanges, and Fittings and Other Piping Components – Magnetic Particle Exam Method.
- ***MSS SP-54***: Quality Standard for Steel Castings for Valves, Flanges and Fittings, and Other Piping Components – Radiographic Examination Method.
- ***MSS SP-55***: Quality Standard for Steel Castings for Valves, Flanges and Fittings and Other Piping Components – Visual Method for Evaluation of Surface Irregularities.
- ***MSS SP-60***: Connecting Flange Joint Between Tapping Sleeves and Tapping Valves.
- ***MSS SP-61***: Pressure Testing of Valves.
- ***MSS SP-67***: Butterfly Valves.
- ***MSS SP-68***: High-Pressure Butterfly Valves with Offset Design.
- ***MSS SP-70***: Cast Iron Gate Valves, Flanged and Threaded Ends.
- ***MSS SP-71***: Cast Iron Swing Check Valves, Flanged and Threaded Ends.
- ***MSS SP-72***: Ball valves with Flanged or Butt-Welding Ends for General Service.
- ***MSS SP-78***: Cast Iron Plug Valves.
- ***MSS SP-80***: Bronze Gate, Globe Angle and Check Valves.
- ***MSS SP-81***: Stainless Steel, Bonnetless, Flanged Knife Gate Valves.
- ***MSS SP-82***: Valve Pressure Testing Methods (withdrawn, replaced by MSS SP-01).
- ***MSS SP-85***: Cast Iron Globe and Angle Valves, Flanged and Threaded Ends.
- ***MSS SP-86***: Guidelines for Metric Data in Standards for Valves, Flanges, Fittings, and Actuators.
- ***MSS SP-88***: Diaphragm Valves.
- ***MSS SP-91***: Guidelines for Manual Operation of Valves.
- ***MSS SP-92***: MSS Valve User Guide.
- ***MSS SP-93***: Quality Standard for Steel Castings and Forgings for Valves, Flanges, and Fittings and Other Piping Components – Liquid Penetrant Exam Method.
- ***MSS SP-94***: Quality Standard for Ferritic and Martensitic Steel Castings for Valves, Flanges, Fittings, and Other Piping Components – Ultrasonic Examination Method.
- ***MSS SP-96***: Guidelines on Terminology for Valves and Fittings.
- ***MSS SP-98***: Protective Coatings for the Interior of Valves, Hydrants, and Fittings.
- ***MSS SP-99***: Instrument Valves.
- ***MSS SP-100***: Qualification Requirements for Elastomer Diaphragms for Nuclear Service Diaphragm Type Valves.
- ***MSS SP-101***: Part-Turn Valve Actuator Attachment – Flange and Driving Component Dimensions and Performance Characteristics.
- ***MSS SP-102***: Multi-Turn Valve Actuator Attachment – Flange and Driving Component Dimensions and Performance Characteristics.
- ***MSS SP-105***: Instrument Valves for Code Applications.
- ***MSS SP-108***: Resilient-Seated Cast Iron-Eccentric Plug Valves.
- ***MSS SP-110***: Ball Valves Threaded, Socket-Welding, Solder Joint, Grooved and Flared Ends.
- ***MSS SP-113***: Connecting Joint between Tapping Machines and Tapping Valves.
- ***MSS SP-115***: Excess Flow Valves, 1 1/4 NPS and Smaller, for Natural Gas Service.
- ***MSS SP-116***: Service Line Valves and Fittings for Drinking Water Systems.
- ***MSS SP-117***: Bellows Seals for Globe and Gate Valves.
- ***MSS SP-118***: Compact Steel Globe & Check Valves – Flanged, Flangeless, Threaded & Welding Ends (Chemical & Petroleum Refinery Service).
- ***MSS SP-120***: Flexible Graphite Packing System for Rising Stem Steel Valves – Design Requirements.
- ***MSS SP-121***: Qualification Testing Methods for Stem Packing for Rising Stem Steel Valves.
- ***MSS SP-122***: Plastic Industrial Ball Valves.
- ***MSS SP-125***: Grey Iron and Ductile Iron In-Line, Spring-Loaded, Center-Guided Check Valves.
- ***MSS SP-126***: Steel In-Line Spring-Assisted Center Guided Check Valves.
- ***MSS SP-128***: Ductile Iron Gate Valves.
- ***MSS SP-130***: Bellows Seals for Instrument Valves.
- ***MSS SP-131***: Metallic Manually Operated Gas Distribution Valves.
- ***MSS SP-132***: Compression Packing Systems for Instrument Valves.

- ***MSS SP-133***: Excess Flow Valves for Low-Pressure Fuel Gas Appliances.
- ***MSS SP-134***: Valves for Cryogenic Service, Including Requirements for Body/Bonnet Extensions.
- ***MSS SP-135***: High-Pressure Steel Knife Gate Valves.
- ***MSS SP-136***: Ductile Iron Swing Check Valves.
- ***MSS SP-137***: Quality Standard for Positive Material Identification of Metal Valves, Flanges, Fittings, and Other Piping Components.
- ***MSS SP-138***: Quality Standard Practice for Oxygen Cleaning of Valves and Fittings.
- ***MSS SP-139***: Copper Alloy Gate, Globe, Angle, and Check Valves for Low-Pressure/Low-Temperature Plumbing Applications.
- ***EEMUA Publication 192***: Guide for the Procurement of Valves for Low-Temperature (Noncryogenic) Service.
- ***ISO 5208***: Industrial Valves – Pressure Testing of Valves.

Figure 2.109 shows the Identification of Gate Valve Terms. The trim is comprised of the following:

(a) Stem.
(b) Body seating surface.
(c) Gate seating surface.
(d) Bushing, or a deposited weld, for the backseat and stem hole guide.
(e) Small internal parts that normally contact the service fluid, excluding the pin that is used to make a stem-to-gate connection (this pin shall be made of an austenitic stainless steel material).

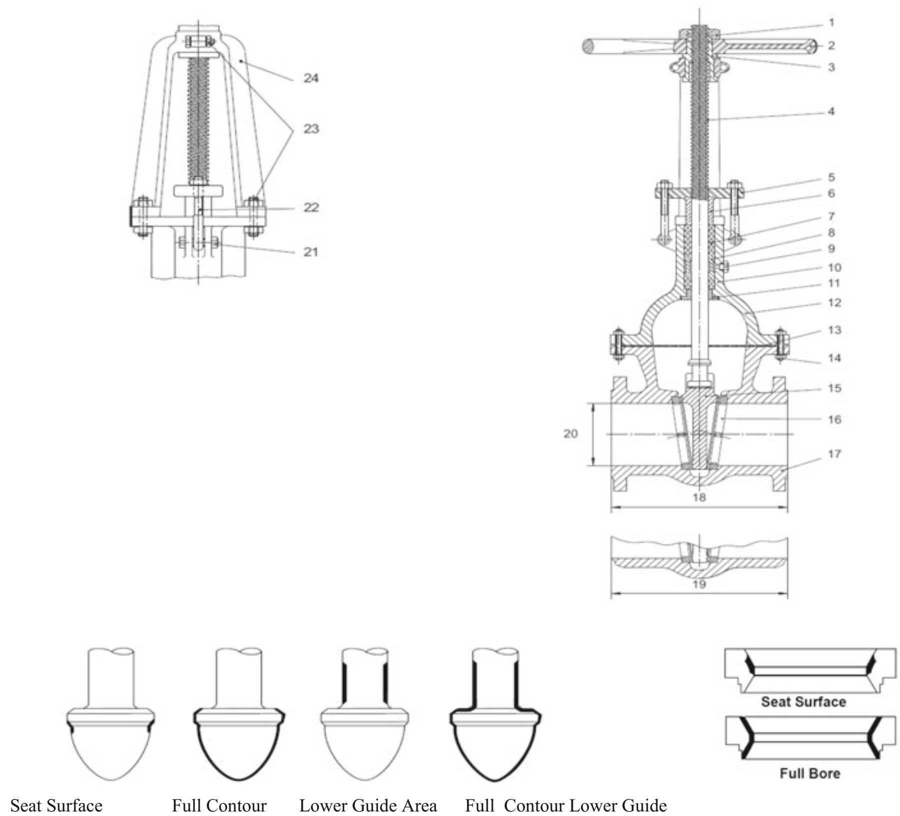


Figure 2.109 Identification of gate valve terms (Source: API 600). *Keys*. (1) Handwheel nut. (2) Handwheel. (3) Stem nut. (4) **Stem**. (5) Gland flange. (6) Gland. (7) Stem packing. (8) Lantern ring. (9) Plug. (10) Wiper packing. (11) **Backseat bushing**. (12) Bonnet. (13) Bonnet gasket. (14) Bonnet bolts and nuts. (15) **Gate**. (16) **Seat ring**. (17) Body. (18) Raised face. (19) Butt-welding end. (20) Valve port. (21) Gland lug bolts and nuts. (22) Gland bolts or gland eyebolts and nuts. (23) Yoke bolting. (24) Yoke. Note-Critical leakage parts are underlined

Table 2.108 (1/2) Valve trim materials classes (API 600/ISO 10434-2006 old version, Table 13)

Valve part	Combination number (API material class)[2)]	Materials description	Brinell hardness
Stem[1)]	1, 4 through 8A	13Cr	200 ~ 275 HB
	2	18Cr-8Ni	[3)]
	3	25Cr-20Ni	[3)]
	9 or 11	Ni-Cu alloy	[3)]
	10 or 12	18Cr-8Ni-Mo	[3)]
	13 or 14	19Cr-29Ni	[3)]

Table 2.108 Valve trim materials classes (API 600/ISO 10434-2006 old version, Table 13)

Valve part	Combination number (API material class)2)	Materials description	Brinell hardness
Seating surfaces	1	13Cr	250 HB min.
	2	18Cr-8Ni	3)
	3	15Cr – 20Ni	3)
	4	13Cr	750 HB min.
	5 or 5A	HF	350 HB min.
	6	13Cr/Cu-Ni	250 HB min/175 HB min.
	7	13Cr/13Cr	250 HB min/750 HB min.
	8 or 8A	13Cr/HF	250 HB min/350 HB min.
	9	Ni-Cu alloy	3)
	10	18Cr-8Ni-Mo	3)
	11 or 11A	NI-Cu alloy/HF	350 HB min.3)
	12 or 12A	18Cr-8Ni-Mo/HF	350 HB min.3)
	13	19Cr-29Ni	3)
	14 or 14A	19Cr-29Ni/HF	350 HB min.3)

General Notes
1. Cr = chromium; Ni = Nickel; Co = cobalt; Mo = Molybdenum
2. HF = Hard Facing using CoCr or NiCr welding alloy. The suffix A applies to NiCr
3. Free machining grades of 13 Cr shall not be used.
4. For Combination Number (CN) 1, a differential hardness of at least 50 Brinell points is required between mating surfaces
5. When two materials are separated by a slash this denotes two separate materials, one for the seat ring seating surface and the other for the gate seating surface without implying a preference for which is to be applied.

Notes
1) Stems shall be wrought material.
2) Backseat surfaces for CN 1 and 4 through 8A shall have a minimum hardness of 250 HB
3) Not specified.

Table 2.108 shows the valve trim material classes in API 600/ISO 10434 (old editions-up to 2006) gate valves.

Table 2.109 shows the nominal seating surfaces, stem, and backseat bushing or weld-deposit materials and hardness per trim code number for steel gate valves: flanged and butt-welding ends, bolted bonnets in API 600/ISO 10434 (current Edition) gate valves. See Sect. 2.4.5.3 for several hardfacing processes.

Table 2.109 (1/2) Nominal seating surfaces, stem and backseat bushing or weld-deposit materials and hardness per trim code number

Trim #	Nominal trim material	Seat surface material(3)	Seat surface hardness, min. HBW	Stem/bushing material(3)	Stem hardness range, HBW	Backseat/bushing hardness, min. HBW	Remark
1	F6 (410 SS)	–	–	–	–	–	#1 is obsolete.
2	304 SS	–	–	–	–	–	#2 is obsolete.
3	F310 SS	25Cr-20Ni	(4)	25Cr-20Ni	(4)	(4)	
4	Hard F6 (410 SS)	Hard 13Cr	750(7)	13Cr	200–275	250	
5	Hardfaced	Stellite(1)	350(7)	13Cr	200–275	250	
5A	Hardfaced	Ni-Cr	350(7)	13Cr	200–275	250	
6	F6 (410 SS) and Cu-Ni	13Cr	250(6)	13Cr	200–275	250	
		Cu-Ni	175(6)	13Cr	200–275	250	
7	F6 (410 SS) and Hard F6	13Cr	250(6)	13Cr	200–275	250	
		Hard 13Cr	750(6)	13Cr	200–275	250	
8	F6 (410 SS) and Hardfaced	13Cr	250(6)	13Cr	200–275	250	
		Stellite(1)	350(6)	13Cr	200–275	250	
8A	F6 (410 SS) and Hardfaced	13Cr	250	13Cr	200–275	250	
		Ni-Cr	350	13Cr	200–275	250	
9	Monel (Ni-Cu)	Ni-Cu	(4)	Ni-Cu	(4)	(4)	
10	316 SS	18Cr-8Ni-Mo	(4)	18Cr-8Ni-Mo	(4)	(4)	
11	Monel (Ni-Cu) and Hardfaced	Ni-Cu	(4)	Ni-Cu	(4)	(4)	
		Stellite(1)	350(6)	Ni-Cu	(4)	(4)	
		Ni-Cr	350(6)	Ni-Cu	(4)	(4)	

Table 2.109 (2/2) Nominal seating surfaces, stem and backseat bushing or weld-deposit materials and hardness per trim code number

Trim #	Nominal trim material	Seat surface material(3)	Seat surface hardness, min. HBW	Stem/bushing material(3)	Stem hardness range, HBW	Backseat/bushing hardness, min. HBW	Remark
12	316 SS and Hardfaced	18Cr-8Ni-Mo	(4)	18Cr-8Ni-Mo	(4)	(4)	
		Stellite(1)	350(6)	18Cr-8Ni-Mo	(4)	(4)	
		Ni-Cr	350(6)	18Cr-8Ni-Mo	(4)	(4)	
13	Alloy 20 (19Cr-29Ni)	19Cr-29Ni	(4)	19Cr-29Ni	(4)	(4)	
14	Alloy 20 (19Cr-29Ni) and Hardfaced	19Cr-29Ni	(4)	19Cr-29Ni	(4)	(4)	
		Stellite(1)	350(6)	Stellite(1)	(4)	(4)	
		Ni-Cr	350(6)	Ni-Cr	(4)	(4)	
15	304 SS and Hardfaced	Stellite(1)	350(7)	18Cr-8Ni	(4)	(5)	
16	316 SS and Hardfaced	Stellite(1)	350(7)	18Cr-8Ni-Mo	(4)	(5)	
17	347 SS and Hardfaced	Stellite(1)	350(7)	18Cr-8Ni-Nb	(4)	(5)	
18	Alloy 20 and Hardfaced	Stellite(1)	350(7)	19Cr-29Ni	(4)	(5)	
19	Nickel(2)	Ni alloy	(4)	Ni alloy	(4)	(5)	
19A	Alloy 625	Alloy 625	(4)	Alloy 625	(4)	(5)	
19B	Alloy C276	Alloy C276	(4)	Alloy C276	(4)	(5)	
19C	Alloy 825	Alloy 825	(4)	Alloy 825	(4)	(5)	
20	Nickel(2) and Hardfaced	Ni alloy	(4)	Ni alloy	(4)	(5)	
		Stellite(1)	350	Ni alloy	(4)	(5)	
20A	Alloy 625 and Hardfaced	Alloy 625	(4)	Alloy 625	(4)	(5)	
		Stellite(1)	350(6)	Alloy 625	(4)	(5)	
20B	Alloy C276 and Hardfaced	Alloy C276	(4)	Alloy C276	(4)	(5)	
		Stellite(1)	350(6)	Alloy C276	(4)	(5)	
20C	Alloy 825 and Hardfaced	Alloy 825	(4)	Alloy 825	(4)	(5)	
		Stellite(1)	350(6)	Alloy 825	(4)	(5)	
21	Hardfaced(2)	Stellite(1)	350(7)	Ni alloy	(4)	(5)	

Source: API 600 Steel Gate Valves, Table 8 modified

Notes

(1) AWS A5.13 ECoCr-A or AWS A5.21 ERCoCr-A: This classification includes such trademark materials as Stellite 6™, * Stoody 6™, * and Wallex 6™.* For the Plasma Transfer Arc Welding (PTAW) process, powder with a metallurgy equivalent to UNS R30006 can also be used. CoCr-E (Stellite 21™ * or equal) may be used only with purchaser approval, and typical CoCr-E alloys include AWS A5.13 ECoCr-E or AWS A5.21 ERCoCr-E

(2) Trim materials, including stem and base material for HF (hard faced) trim items, shall have a corrosion resistance and temperature limit at least equal to the valve body's corrosion resistance and pressure temperature rating

(3) Free machining grades of 13Cr are prohibited.

(4) Manufacturer's standard hardness

(5) Per manufacturer's standard if not hardfaced, 250 HBW minimum if hardfaced.

(6) Hardness differential between the body and disc seat surfaces shall be the manufacturer's standard.

(7) Differential hardness between the body and disc seat surfaces is not required.

Table 2.110 shows the seating surface nominal trim material of check valves (API 594).

Table 2.110 (1/2) Seating surface nominal trim material (API RP594, Table 4)

Trim no.	Nominal trim	Material type	Typical specification (grade)		
			Cast	Forged	Welded
1	F6	13Cr	ASTMA A217 (CA15)	ASTM A182 (F6)	AWS A5.9 (ER410)
2	304 SS	18Cr-8Ni	ASTMA A351 (CF8)	ASTM A182 (F304)	AWS A5.9 (ER308)
5	Hardfaced	Co-Cr-A	N/A	N/A	AWS A5.13 (E or R Co-Cr-A)
5A	Hardfaced	Ni-Cr	N/A	N/A	Manufacturer's standard
8	F6 and Hardfaced	13Cr Co-Cr-A	ASTM A217 (CA15) N/A	ASTM A182 (F6) N/A	AWS A5.9 (ER410) AWS A5.13 (E or R Co-Cr-A)

Table 2.110 (2/2) Seating surface nominal trim material (API RP594, Table 4)

Trim no.	Nominal trim	Material type	Typical specification (grade)		
			Cast	Forged	Welded
9	Monel	Ni-Cu alloy	ASTM A494 (M-35-1)	ASTM B564 (UNS N04400)	AWS A5.9 (ER410) AWS A5.13 (E or R Co-Cr-A)
10	316 SS	18Cr-8Ni-Mo	ASTM A351 (CF8M)	ASTM A182 (F316)	AWS A5.9 (ER316)
12	316 SS and Hardfaced	18Cr-8Ni-Mo Trim 5 or 5A	ASTM A351 (CF8M)	ASTM A182 (F316)	AWS A5.9 (ER316) Trim 5 or 5A
13	Alloy 20	19Cr-29Ni	ASRM A351 (CN7M)	ASTM B473	AWS A5.9 (ER320)
14	Alloy 20 and Hardfaced	19Cr-29Ni Trim 5 or 5A	ASRM A351 (CN7M)	ASTM B473	AWS A5.9 (ER320) Trim 5 or 5A
AA	Bronze	Bronze	Manufacturer's standard	Manufacturer's standard	—

Tables 2.111, 2.112, 2.113, and 2.114 shows the ASTM material specification list per materials group in ASME B16.34 (Valves-Flanged, Threaded, and Welding End).

Table 2.111 (1/2) Group 1 – materials specification of valve materials (ASME B16.34, Table 1 modified)

Group no ASME B16.34	Material		Temperature(A)		Product form				
	Commercial name (C & low alloy steel)	Main composition	°C	°F	Forging	Casting	Plate	Bars	Tubular
1.1	CS	C-Si	−29 to 538	−20 to 1000	A105(1),(2)	A216-WCB(1)	A515-70(1)	A105(1),(2)	
	Low Temp. CS	C-Mn-Si	−46 to 538	−50 to 1000	A350-LF2-Cl.1(1)		A516-70(1),(4)	A350-LF2-Cl.1(1)	A672-C70 (A51670)(1)
							A537-Cl.1(3)	A696-C(3)	A672-B70 (A515-70)(1)
	Low temp. CS	C-Mn-Si-V-N	−50 to 260	−60 to 500	A350-LF6-Cl.1(5)			A350-LF6-Cl.1(5)	
	Cryogenic Ni St.	3.5Ni	−101 to 345	−150 to 650	A350-LF3(6)			A350-LF3(6)	
1.2	CS	C-Si	−29 to 538	−20 to 1000					A106-C(1)
	CS	C-Mn-Si	−29 to 538	−20 to 1000		A216-WCC(2)			
	Low temp. CS	C-Mn-Si	−46 to 345	−50 to 650		A352-LCC(4)			
	Low temp. CS	C-Mn-Si-V-N	−50 to 260	−60 to 500	A350-LF6-Cl.2(3)			A350-LF6-Cl.2(3)	
	Low temp. Ni St.	2.25Ni	−73 to 345	−100 to 650		A352-LC2(4)	A203-B(2)(B)		
	Cryogenic.Ni St.	3.5Ni	−101 to 345	−150 to 650		A352-LC3(4)	A203-E(2)		
1.3	CS	C	−29 to 538	−20 to 1000				A675-70(1),(4),(5)	
		C-Si	−29 to 538	−20 to 1000		A352-LCB(2)	A515-65(1)		A672-B65(A515-65)(1)
		C-Mn-Si	−29 to 538	−20 to 1000			A516-65(1),(3)		A672-C65(A516-65)(1)
	LAS	C-0.5Mo	−29 to 538	−20 to1000		A217-WC1(6),(7),(8)			
	Low temp. LAS		−59 to 345	−75 to 650		A352-LC1(2)			
	Low temp. Ni St.	2.25Ni	−68 to 538	−90 to 1000			A203-A(1)		
	Cryogenic.Ni St.	3.5Ni	−101 to 538	−150 to 1000			A203-D(1)		
1.4	CS	C	−29 to 538	−20 to 1000				A675-60(1),(2),(3)	
								A675-65(1),(3),(4)	
		C-Si	−29 to 538	−20 to 1000			A515-60(1),(2)		A106-B(1) A672-B60(A515-60)(1)
		C-Mn-Si	−29 to 538	−20 to 1000	A350-LF1, Cl.1(1)		A516-60(1),(2)	A350-LF1, Cl.1 (1) A696-B(5)	A672-C60 (A516-60)(1)
1.5	High temp. LAS	C-0.5Mo	−29 to 538	−20 to 1000	A182-F1(1)		A204-A/B(1)	A182-F1(1)	A691-CM70(1)
1.6	High temp. LAS	0.5Cr-0.5Mo	−29 to 538	−20 to 1000			A387-2 Cl.1 & 2		A691-0.5Cr
1.7	High temp. LAS	C-0.5Mo	−29 to 575(4)	−20 to 1050					A691-CM75
		0.5Cr-0.5Mo	−29 to 538	−20 to 1000	A182-F2(1)			A182-F2(1)	
		0.5Cr-0.5Mo-1Ni	−29 to 538	−20 to 1000		A217-WC4(1),(2),(3)			
		3/4Cr-1Mo-3/4Ni	−29 to 575(4)	−20 to 1050		A217-WC5(2)			

Table 2.111 (2/2) Group 1 – materials specification of valve materials (ASME B16.34, Table 1 modified)

Group no ASME B16.34	Material		Temperature(A)		Product form				
	Commercial name (C & low alloy steel)	Main composition	°C	°F	Forging	Casting	Plate	Bars	Tubular
1.8(a)	High temp. LAS	1Cr-0.5Mo	−29 to 650	−20 to 1200			A387-12 Cl.2(1)		
		1.25Cr-0.5Mo-Si	−29 to 650	−20 to 1200			A387-11 Cl.1(1)		A691-1.25Cr(1)
		2.25Cr-1Mo	−29 to 650	−20 to 1200			A387-22 Cl.1(1)		A691-2.25Cr(1) A335-P22(1) A335-P22(1) A369-FP22(1)
1.9(a)	High temp. LAS	1.25Cr-0.5Mo-Si	−29 to 650	−20 to 1200	A182-F11, Cl.2(1),(2)		A387-11 Cl.2(2)	A182-F11, Cl.2(1),(2)	
		1.25Cr-0.5Mo	−29 to 650	−20 to 1200		A217-WC6(1),(3),(4)		A739-B11(2)	
1.10(a)	High temp. LAS	2.25Cr-1Mo	−29 to 650	−20 to 1200	A182-F22 Cl.3(1)	A217-WC9(2),(3),(4)	A387-22 Cl.2(1)	A182-F22 Cl.3(1) A739-B22(2)	
1.11(a)	High temp. LAS	3Cr-1Mo	−29 to 650	−20 to 1200	A182-F21(1)		A387-21 Cl.2(1)	A182-F21(1)	
		Mn-0.5Mo	−29 to 650	−20 to 1200			A302-A&B(2)		
		Mn-0.5Mo-0.5Ni	−29 to 650	−20 to 1200			A302-C(2)		
		Mn-0.5Mo-3/4Ni	−29 to 650	−20 to 1200			A302-D(2)		
		C-Mn-Si	−29 to 370	−20 to 700			A537-Cl.2(3)		
		C-0.5Mo	−29 to 650	−20 to 1200			A204-C(4)		
1.12(a)	High temp. LAS	5Cr-0.5Mo	−29 to 650	−20 to 1200			A387-5Cl.1 & 2		A691-5Cr A335-P5 A369-FP5
		5Cr-0.5Mo-Si	−29 to 650	−20 to 1200					A335-P5b
1.13(a)	High temp. LAS	5Cr-0.5Mo	−29 to 650	−20 to 1200	A182-F5a	A217-C5(1),(2)		A182-F5a	
1.14(a)	High temp. LAS	9Cr-1Mo	−29 to 650	−20 to 1200	A182-F9	A217-C12(1),(2)		A182-F9	
1.15(a)	9Cr-1Mo-V	9Cr-1Mo-V	−29 to 650	−20 to 1200	A182-F91	A217-C12A(1)	A387-91 Cl.2	A182-F91	A335-P91
1.16(a)	C-0.5Mo	C-0.5Mo	−29 to 650	−20 to 1200					A335-P1(1),(2) A369-FP1(1),(2)
	1Cr-0.5Mo	1Cr-0.5Mo	−29 to 650	−20 to 1200			A387-12 Cl.1(3)		A691-1Cr(3),(4) A335-P12(3) A369-FP12(3)
	1.25Cr-0.5Mo-Si	1.25Cr-0.5Mo-Si	−29 to 650	−20 to 1200					A335-P11(3) A369-FP11(3)
1.17(a)	1Cr-0.5Mo	1Cr-0.5Mo	−29 to 650	−20 to 1200	A182-F12 Cl.2(1),(2)			A182-F12 Cl.2(1),(2)	
	5Cr-0.5Mo	5Cr-0.5Mo	−29 to 650	−20 to 1200	A182-F5			A182-F5	
1.18(2)	9Cr-2W-V	9Cr-2W-V	−29 to 650	−20 to 1200	A182-F92(1)			A182-F92(1)	A335-P92(1) A369-FP92(1)

Notes: (a) Flanged-end valve ratings terminate at 538°C (1000°F).

[Group 1.1]

(1) Upon prolonged exposure to temperatures above 425 °C (800 °F), the carbide phase of steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 425 °C (800 °F).
(2) Only killed steel shall be used above 455 °C (850 °F).
(3) Not to be used over 370 °C (700 °F).
(4) Not to be used over 455 °C (850 °F).
(5) Not to be used over 260 °C (500 °F).
(6) Not to be used over 345 °C (650 °F).

[Group 1.2]

(1) Not to be used over 425 °C (800 °F).
(2) Upon prolonged exposure to temperatures above 425 °C (800 °F), the carbide phase of steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 425 °C (800 °F).
(3) Not to be used over 260 °C (500 °F).
(4) Not to be used over 345 °C (650 °F).

[Group 1.3]

(1) Upon prolonged exposure to temperatures above 425 °C (800 °F), the carbide phase of steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 425 °C (800 °F).
(2) Not to be used over 345 °C (650 °F).
(3) Not to be used over 455 °C (850 °F).
(4) Leaded grades shall not be used where welded or in any application above 260 °C (500 °F).
(5) For service temperatures above 455 °C (850 °F), it is recommended that killed steels containing not less than 0.10% residual silicon be used.
(6) Upon prolonged exposure to temperatures above 470 °C (875 °F), the carbide phase of steel of carbon-molybdenum steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 470 °C (875 °F).

(7) Use normalized and tempered (N-T) material only.
(8) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.

[Group 1.4]
(1) Upon prolonged exposure to temperatures above 425 °C (800 °F), the carbide phase of steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 425 °C (800 °F).
(2) Not to be used over 455 °C (850 °F).
(3) Leaded grades shall not be used where welded or in any application above 260 °C (500 °F).
(4) For service temperatures above 455 °C (850 °F), it is recommended that killed steels containing not less than 0.10% residual silicon be used.
(5) Not to be used over 370 °C (700 °F).

[Group 1.5]
(1) Upon prolonged exposure to temperatures above 470 °C (875 °F), the carbide phase of steel of carbon-molybdenum steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 470 °C (875 °F).

[Group 1.7]
(1) Not to be used over 538 °C (1000 °F).
(2) Use normalized and tempered material only.
(3) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.
(4) For welding-end valves only. Class 150 flanged-end valves terminate at 538 °C (1000 °F) for Standard Class.

[Group 1.8]
(1) Permissible, but not recommended for prolonged use above 595 °C (1100 °F).

[Group 1.9]
(1) Use normalized and tempered material only.
(2) Permissible, but not recommended for prolonged use above 595 °C (1100 °F).
(3) Not to be used over 595 °C (1100 °F).
(4) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.

[Group 1.10]
(1) Permissible, but not recommended for prolonged use above 595 °C (1100 °F).
(2) Use normalized and tempered material only.
(3) Not to be used over 595 °C (1100 °F).
(4) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.

[Group 1.11]
(1) Permissible, but not recommended for prolonged use above 595 °C (1100 °F).
(2) Upon prolonged exposure to temperatures above 470 °C (875 °F), the carbide phase of carbon-molybdenum steel may be converted to graphite. Permissible, but not recommended for prolonged use above 470 °C (875 °F).
(3) Not to be used over 370 °C (700 °F).
(4) Upon prolonged exposure to temperatures above 470 °C (875 °F), the carbide phase of steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 470 °C (875 °F).

[Group 1.13]
(1) Use normalized and tempered (N-T) material only.
(2) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.

[Group 1.14]
(1) Use normalized and tempered material only.
(2) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.

[Group 1.15]
(1) The deliberate addition of any element not listed in ASTM A217, Table 1 is prohibited, except that calcium (Ca) and manganese (Mn) may be added for deoxidation.

[Group 1.16]
(1) Upon prolonged exposure to temperatures above 470 °C (875 °F), the carbide phase of steel may be converted to graphite. Permissible, but not recommended for prolonged usage above 470 °C (875 °F).
(2) Not to be used over 538 °C (1000 °F).
(3) Permissible, but not recommended for prolonged use above 595 °C (1100 °F).
(4) Use normalized and tempered material only.

[Group 1.17]
(1) Use normalized and tempered material only.
(2) Permissible, but not recommended for prolonged use above 595 °C (1100 °F).

[Group 1.18]
(1) Application above 620 °C (1150 °F) is limited to tubing of maximum outside diameter of 88.9 mm (3.5 inch).
(2) For welding-end valves only. Flanged-end valve ratings terminate at 538 °C (1000 °F).

Commentary Notes:.

[A] *These maximum temperatures are based on ASME Sec.Vlll, Div.1 (See Table 2.15) under short term exposure and/or depressurized condition, but the maximum working pressure for valves shall not be used above the maximum design temperature permitted in ASME B16.34 in accordance with the selected material and flange rating. Some codes or regulations may require CVN impact testing for applications even where temperatures are higher than the minimum temperature.*

[B] *−68 °C (≤50 mm)/−59 °C (≤76 mm)*

Table 2.112 (1/2) Group 2 – valve body materials (ASME B16.34, Table 1 modified)[C]

Group no ASME B16.34	Material		Temperature[A]		Product form				
	Commercial name	Nominal designation	°C	°F	Forging	Casting	Plate	Bars	Tubular
2.1[a]	304 SS	18Cr-8Ni	−196 to 816	−320 to 1500	A182-F304[1] A182-F304H	A351-CF3[2] A351-CF8[1] A351-CF10	A240-304[1] A240-304H	A182-F304[1] A182-F304H A479-304[1] A479-304H	A312-TP304[1] A312-TP304H A358-304[1] A376-TP304[1] A376-TP304H A430-FP304[1] A430-FP304H
2.2[a]	316 SS	16Cr-12Ni-2Mo	−196 to 816	−320 to 1500	A182-F316[1] A182-F316H	A351-CF3M[3] A351-CF8M[1] A351-CF10M	A240-316[1] A240-316H	A182-F316[1] A182-F316H A479-316[1] A479-316H	A312-TP316[1] A358-316[1] A376-TP316[1] A430-FP316[1] A312-TP316H A430-FP316H
	304 SS	18Cr-8Ni	−196 to 345	−320 to 650		A351-CF3A[2] A351-CF8A[2]			
	317 SS	18Cr-13Ni-3Mo	−196 to 816	−320 to 1500	A182-F317[1]		A240-317[1]		A312-TP317[1]
	317 SS	19Cr-10Ni-3Mo	−196 to 538	−320 to 1000		A351-CG3M[3] A351-CG8M[4]			
2.3	Low carbon 304L SS	18Cr-8Ni	−196 to 425	−320 to 800	A182-F304L[1]		A240-304L[1]	A182-F304L[1] A479-304L[1]	A312-TP304L[1]
	Low carbon 316L SS	16Cr-12Ni-2Mo	−196 to 450[B]	−320 to 850	A182-F316L		A240-316L	A182-F316L A479-316L	A312-TP316L
	Low carbon 317L SS	18Cr-13Ni-3Mo	−196 to 450[B]	−320 to 850	A182-F317L			A182-F317L	
2.4 [a]	321 SS	18Cr-10Ni-Ti	−196 to 538	−320 to 1000	A182-F321[1]		A240-321[1]	A182-F321[1] A479-321[1]	A312-TP321[1] A376-TP321[1] A358-321[1] A430-FP321[1]
	321H SS	18Cr-10Ni-Ti	−196 to 816	−320 to 1500	A182-F321H[2]		A240-321H[2]	A182-F321H[2] A479-321H[2]	A312-TP321H[2] A376-TP321H[2] A430-FP321H[2]
2.5[a]	347(H) SS	18Cr–10Ni–Cb	−196 to 816	−320 to 1500	A182-F347[1] A182-F347H[2]		A240-347[1] A240-347H[2]	A182-F347[1] A182-F347H[2] A479-347[1] A479-347H	A312-TP347[1] A312-TP347H A358-347[1] A376-TP347[1] A376-TP347H A430-FP347[1] A430-FP347H
	348(H) SS	18Cr–10Ni–Cb-Co	−196 to 816	−320 to 1500	A182-F348[1] A182-F348H[2]		A240-348[1] A240-348H[2]	A182-F348[1] A182-F348H A479-348[1] A479-348H	A312-TP348[1] A312-TP348H A376-TP348[1] A376-TP348H[1]
2.6[a]	309(H) SS	23Cr–12Ni	−196 to 816	−320 to 1500			A240-309H		A312-TP309H A358-309H
2.7	310(H) SS	25Cr–20Ni	−196 to 816	−320 to 1500	A182-F310		A240-310H	A182-F310 A479-310H	A312-TP310H A358-310H
2.8	6%Mo SS	20Cr–18Ni–6Mo	−196 to 400	−320 to 750	A182-F44	A351-CK3MCuN	A240-S31254	A182-F44 A479-S31254	
	DSS	22Cr–5Ni–3Mo–N	−29 to 315	−20 to 600	A182-F51[1]	A995-4A (CD3MN)[1]	A240-S31803[1]	A182-F51 A479-S31803[1]	A789-S31803[1] A790-S31803[1]
	SDSS	25Cr–7Ni–4Mo–N	−29 to 315	−20 to 600	A182-F53[1]		A240-S32750[1]	A182-F53 A479-S32750[1]	A789-S32750[1] A790-S32750[1]
		24Cr–10Ni–4Mo –N	−29 to 315	−20 to 600		A995-2A (CE8MN)[1]			
		25Cr–5Ni–2Mo–3Cu-N	−29 to 315	−20 to 600		A995-1B (CD4MCuN)[1]			
		25Cr–7Ni–3.5Mo –W–N	−29 to 315	−20 to 600		A995-6A (CD3MWCuN)			
		25Cr–7.5Ni–3.5Mo–N–Cu–W	−29 to 315	−20 to 600	A182-F55		A240-S32760[1]	A479-S32760[1]	A789-S32760[1] A790-S32760[1]

Table 2.112 (2/2) Group 2 – valve body materials (ASME B16.34, Table 1 modified)

Group no ASME B16.34	Material		Temperature[(a)]		Product form				
	Commercial name	Nominal designation	°C	°F	Forging	Casting	Plate	Bars	Tubular
2.9[(a)] Low C	309S SS	23Cr–12Ni	−196 to 816	−320 to 1500			A240-309S[(1),(2),(3)]		
	310S SS	25Cr–20Ni	−196 to 816	−320 to 1500			A240-310S[(1),(2),(3)]	A479-310S[(1),(2),(3)]	
2.10[(a)]	UNS J93400	25Cr–12Ni	−196 to 816	−320 to 1500		A351-CH8[(1)]			
	UNS J93402	25Cr–12Ni	−196 to 816	−320 to 1500		A351-CH20[(1)]			
2.11[(a)]	UNS J92710	18Cr–10Ni–Cb	−196 to 816	−320 to 1500		A351-CF8C[(1)]			
2.12[(a)]	UNS J94202	25Cr–20Ni	−196 to 816	−320 to 1500		A351-CK20[(1)]			

Notes: [(a)] Flanged-end valve ratings terminate at 538 °C (1000 °F).
[Group 2.1]
(1) At temperatures above 538 °C (1000 °F), use only when the carbon content is 0.04% or higher.
(2) Not to be used over 425 °C (800 °F).
[Group 2.2]
(1) At temperatures above 538 °C (1000 °F), use only when the carbon content is 0.04% or higher.
(2) Not to be used over 345 °C (650 °F).
(3) Not to be used over 455 °C (850 °F).
(4) Not to be used over 538 °C (1000 °F).
[Group 2.3]
(1) Not to be used over 425 °C (800 °F).
[Group 2.4] and [Group 2.5]
(1) Not to be used over 538 °C (1000 °F).
(2) At temperatures above 538 °C (1000 °F), use only if the *production* material is *solution*-heat treated by heating to a minimum temperature of 1095 °C (2000 °F).
[Group 2.8]
(1) This steel may become brittle after service at moderately elevated temperatures. Not to be used over 315 °C (600 °F).
[Group 2.9]
(1) At temperatures above 538 °C (1000 °F), use only when the carbon content is 0.04% or higher.
(2) For temperatures above 538 °C (1000 °F), use only if the *production* material is solution heat treated to the minimum temperature specified in the material specification but not lower than 1040 °C (1900 °F) and quenching in water or rapidly cooling by other means.
(3) This material should be used for service temperatures 515 °C (960 °F) and above only when assurance is provided that grain size is not finer than ASTM 6 (*per ASTM E112*).
[Group 2.10], [Group 2.11], and [Group 2.12]
(1) At temperatures above 538 °C (1000 °F), use only when the carbon content is 0.04% or higher.
Commentary Notes: The underbars are for the commentary notes.
[(A)] *These maximum temperatures are based on ASME Sec.VIII, Div.1 (See Table 2.15) under short term exposure and/or depressurized condition, but the maximum working pressure for valves shall not be used above the maximum design temperature permitted in ASME B16.34 in accordance with the selected material and flange rating. Some codes or regulations may require CVN impact testing for applications even where temperatures are higher than the minimum temperature.*
[(B)] *Should be 455 °C (850 °F) with appropriate working pressures.*
[(C)] *Chemical cleaning per ASTM A380 or other applicable regulations/specifications should be considered for final production after heat treatment (if required).*

Table 2.113 (1/2) Group 3 – valve body materials (ASME B16.34, Table 1 modified)

Group no ASME B16.34	Material		Temperature[(A)]		Product form				
	Commercial name	Nominal designation	°C	°F	Forging	Casting	Plate	Bars	Tubular
3.1	Alloy 20	35Ni-35Fe-20Cr-Cb	−196 to 425	−320 to 800	B 462-N08020[(1)]		B463-N08020[(1)]	B462-N08020[(1)] B473-N08020[(1)]	B464-N08020[(1)] B468-N08020[(1)]
3.2	Nickel	99Ni	−198 to 325[(B)]	−325 to 600	B564-N02200[(1)]		B162-N02200[(1)]	B160-N02200[(1)]	B161-N02200[(1)] A163-N02200[(1)]
3.3 [(a)]	Nickel low C	99Ni-Low C	−198 to 650	−325 to 1200			B162-N02201[(1)]	B160-N02201[(1)]	
3.4	Monel 400	67Ni-30Cu	−198 to 475[(C)]	−325 to 900	B564-N04400[(1)]	A494-M35-1[(1)]	B127-N04400[(1)]	B164-N04400[(1)]	B163-N04400[(1)] B165-N04400[(1)]
		67Ni-30Cu-S				A494-M35-2[(1)]		B164-N04405[(1)]	
3.5[(a),(D)]	Alloy 600	72Ni-15Cr-8Fe	−198 to 650	−325 to 1200	B564-N06600[(1)]		B168-N06600[(1)]	B166-N06600[(1)]	B163-N06600[(1)]
3.6[(a)]	Alloy 800	33Ni-42Fe-21Cr	−196 to 816	−320 to 1500	B564-N08800[(1)]		B409-N08800[(1)]	B408-N08800[(1)]	B163-N08800[(1)]
3.7	Alloy B-2	65Ni-28Mo-2Fe	−198 to 425	−325 to 800	B462-N10665[(1)] B564-N10665[(1)]		B333-N10665[(1)]	B335-N10665[(1)] B462-N10665[(1)]	B622-N10665[(1)]
	Alloy B-3	64Ni-29.5Mo-2Cr-2Fe-Mn-W			B462-N10675[(1)] B564-N10675[(1)]		B333-N10675[(1)]	B335-N10675[(1)] B462-N10675[(1)]	B622-N10675[(1)]

Table 2.113 (2/2) Group 3 – valve body materials (ASME B16.34, Table 1 modified)

Group no ASME B16.34	Material		Temperature(A)		Product form				
	Commercial name	Nominal designation	°C	°F	Forging	Casting	Plate	Bars	Tubular
3.8(a)	Alloy C276	54Ni-16Mo-15Cr	−198 to 675	−325 to 1250	B462-N10276(1),(5) B564-N10276(1),(5)		B575-N10276(1),(5)	B462-N10276(1),(5) B574-N10276(1),(5)	B622-N10276(1),(5)
	Alloy 625	60Ni-22Cr-9Mo-3.5Cb	−198 to 700	−325 to 1300	B564-N06625(3),(4)		B443-N06625(3),(4)	B446-N06625(3),(4)	
	Alloy B	62Ni-28Mo-5Fe	−198 to 425	−325 to 800			B333-N10001(1),(2)	B335-N10001(1),(2)	B622-N10001(2),(3)
	Alloy N	70Ni-16Mo-7Cr-5Fe	−198 to 700	−325 to 1300			B434-N10003(3)	B573-N10003(3)	
	Alloy C-4	61Ni-16Mo-16Cr	−198 to 425	−325 to 800			B575-N06455(1),(2)	B574-N06455(1),(2)	B622-N06455(1),(2)
	Alloy 825	42Ni-21.5Cr-3Mo-2.3Cu	−198 to 538	−325 to 1000	B564-N08825(3),(6)		B424-N08825(3),(6)	B425-N08825(3),(6)	B423-N08825(3),(6)
	Alloy C-22	55Ni-21Cr-13.5Mo	−198 to 675	−325 to 1250	B462-N06022(1) B564-N06022(1)		B575-N06022(1),(5)	B462-N06022(1),(5) B564-N06022(1),(5) B574-N06022(1),(5)	B622-N06022(1),(5)
	Alloy C-2000	55Ni-23Cr-16Mo-1.6Cu	−198 to 425	−325 to 800	B462-N06200(1),(2) B564-N06200(1),(2)		B575-N06200(1),(2)	B564-N06200(1),(2) B574-N06200(1),(2)	B622-N06200(1),(2)
3.9(a)	Alloy X	47Ni-22Cr-9Mo-18Fe	−196 to 816	−320 to 1500			B435-N06002(1)	B572-N06002(1)	B622-N06002(1)
	Alloy 556	21Ni-22Cr-30Fe-18Co-3Mo-3W					B435-R30556(1)	B572- R30556(1)	B622- R30556(1)
3.10	JS-700	25Ni-21Cr-5Mo-47Fe	−196 to 350	−320 to 650			B599-N08700(1)	B672-N08700(1)	
3.11	904L	25Ni-21Cr-44Fe-Mo	−196 to 375	−320 to 700			B625-N08904(1)	B649- N08904(1)	B677-N08904(1)
3.12	Alloy 20MOD	26Ni-22Cr-5Mo-43Fe	−196 to 425	−320 to 800			B620-N08320(1)	B621-N08320(1)	B622-N08320(1)
	Alloy G3	47Ni-22Cr-7 Mo-20Fe					B582-N06985(1)	B581-N06985(1)	B622-N06985(1)
	AL-6XN	24Ni-21Cr-6Mo-46Fe-Cu-N	−196 to 425	−320 to 800	B462-N08367(1)	A351-CN3MN(1)	B688-N08367(1)	B462-N08367(1) B691-N08367(1),(2)	
	Alloy G-35	58Ni-33Cr-8Mo	−198 to 425	−325 to 800	B462-N06035(1),(2) B564-N06035(1),(2)		B575-N06035(1),(2)	B462-N06035(1),(2) B574-N06035(1),(2)	B622-N06035(1),(2)
3.13	Alloy G-2	49Ni-25Cr-18Fe-6Mo	−196 to 425	−320 to 800			B582-N06975(2)	B581-N06975(2)	B622-N06975(2)
	Alloy 31	31Ni-27Cr-7Mo-32Fe-1Cu			B564-N08031(1)		B625-N08031(1)	B649-N08031(1)	B622-N08031(1)
3.14	Alloy G	47Ni-22Cr-6Mo-19Fe	−196 to 538	−320 to 1000			B582-N06007(1)	B581-N06007(1)	B622-N06007(1)
	Alloy G-30	40Ni-29Cr-5Mo-15Fe	−196 to 425	−320 to 800	B462-N06030(1),(2)		B582-N06030(1),(2)	B462-N06030(1),(2) B581-N06030(1),(2)	B622-N06030(1),(2)
3.15(a)	Alloy 800H	42Ni-21Cr-2Fe	~816	~1500	B564-N08810(1)		B409-N08810(1)	B408-N08810(1)	B407-N08810(1)
	Ni-Mo cast	65Ni-28Mo-5Fe	−198 to 538	−325 to 1000		A494-N12MV(1),(2) (UNS N30012)			
	Ni-Cr cast	54Ni-16Cr-17Mo-6Fe-4W-V				A494-CW12MW(1),(2) (UNS N30002)			
3.16(a)	Alloy 330	35Ni-19Cr-1.25Si	−196 to 816	−320 to 1500			B536-N08330(1)	B511-N08330(1)	B535-N08330(1)
3.17	CN-7M	29Ni-20.5Cr-3.5Cu-2.5Mo	−196 to 325(b)	−320 to 600	A351-CN7M(1)				
3.18(a),(D)	Alloy 600	72Ni-15Cr-8Fe	−198 to 650	−325 to 1200					B167-N06600(1)
3.19(a)	Alloy 230	57Ni-22Cr-14W-2Mo-La	−198 to 816	−325 to 1500	B564-N06230(1)		B435-N06230(1)	B572-N06230(1)	B622-N06230(1)

Notes: (a) Flanged-end valve ratings terminate at 538 °C (1000 °F).

[Group 3.1], [Group 3.2], [Group 3.3], [Group 3.4], [Group 3.5], [Group 3.6] [Group 3.9], [Group 3.10], [Group 3.11], [Group 3.18], and [Group 3.19]
(1) Use annealed material only.

[Group 3.7], [Group 3.14], [Group 3.16] and [Group 3.17]
(1) Use solution-annealed material only.

[Group 3.8]
(1) Use solution-annealed material only.
(2) Not to be used over 425 °C (800 °F).
(3) Use annealed material only.

(4) Not to be used over 645 °C. Alloy N06625 in the annealed condition is subject to severe loss of impact strength at room temperatures after exposure in the range of 538 °C (1000 °F) to 760 °C (1400 °F).
(5) Not to be used over 675 °C (1250 °F).
(6) Not to be used over 538 °C (1000 °F).
[Group 3.12]
(1) Use annealed material only.
(2) Not to be used over 425 °C (800 °F).
[Group 3.13]
(1) Use annealed material only.
(2) Use solution-annealed material only.
[Group 3.15]
(1) Use solution-annealed material only.
(2) Not to be used over 538 °C (1000 °F).
Commentary Notes:
(A) These maximum temperatures are based on ASME Sec.VIII, Div.1 (See table 2.15) under short term exposure and/or depressurized condition, but the maximum working pressure for valves shall not be used above the maximum design temperature permitted in ASME B16.34 in accordance with the selected material and flange rating. Some codes or regulations may require CVN impact testing for applications even where temperatures are higher than the minimum temperature.
(B) Should be 315 °C (600 °F) with appropriate working pressures.
(C) Should be 480 °C (900 °F) with appropriate working pressures.
(D) The Group 3.5 and 3.18 have a different TS. YS, and allowable stress values even though they have a same material group.

Table 2.114 Group 4 – bolting materials (ASME B16.34, Table 1 modified)

ASTM no.	Grade	Note no.	Notes
A193		(2),(3)	General notes: (a) It's the user's responsibility to use the governing codes or regulations in the project and plant. (b) ASME Sec. II materials that also meet the requirements of the listed ASTM specification may also be used. (c) To apply the pressure-temperature tables, ASME B16.34, Table 2-1.1 through Table 2-3.19. Notes: (1) Repair welding of bolting material is not permitted. (2) Where austenitic bolting materials have been carbide-solution-treated but not strain-hardened, they are designated Class 1 or Class 1A in ASTM A193. ASTM A194 nuts of corresponding material are recommended. (3) Where austenitic bolting materials have been carbide-solution-treated and strain-hardened, they are designated Class 2, 2B, or 2C in ASTM A193. ASTM A194 nuts of corresponding material are recommended. (4) For limitations of usage and strength level, see ASME B16.34, 5.1.2. (5) Bolts with drilled or undersize heads shall not be used. (6) For ferritic bolting materials intended for service at low temperatures, ASTM A194-Gr. 7 nuts are recommended. (7) Acceptable nuts for use with Q-T steel bolts are ASTM A194 Grade 2 and 2H. (8) Mechanical property requirements for studs shall be the same as for bolts. (9) Bolting materials suitable for high-temperature service with ASS valve materials. (10) Nuts may be of the same material or may be of compatible grade of ASTM A194. (11) Forging quality not permitted unless the producer last heating or working these parts tests them as required for other permitted conditions in the same specification and certifies their final tensile, yield, and elongation properties to equal or exceed the requirements for one of the other permitted conditions. (12) Maximum operating temperature is arbitrarily set at 260 °C (500 °F), unless material has been annealed, solution-annealed, or hot-finished, because hard temper adversely affects design stress in the creep-rupture temper range.
A307	B	(4),(5)	
A320		(2),(3),(6)	
A354			
A449		(7),(8)	
A453	651, 660	(9)	
A540			
A564	630	(7)	
B164		(10),(11),(12)	
B166		(10,(11)	
B335	N10665	(10)	
B335	N10675	(10)	
B408		(10,(11),(12)	
B473		(10)	
B574	N10276	(10)	
B574	N06022	(10)	
B637	N07718	(10)	

2.2 Degradation and Requirements of Metals in Low Temperatures

The mechanical and metallurgical quality at low temperatures is greatly related to the toughness of the metal. The impact test at low temperatures is the most common test for the toughness, which is against brittle failure. See Sect. 5.2.3 for several fracture toughness tests and the applicable standards.

2.2.1 Characteristics of Materials in Low Temperatures

2.2.1.1 General Characteristics of Metals in Low Temperatures

Metallic microstructures are subject to toughness reduction in low temperatures. Generally, FCC (face-centered cubic structure) materials, such as ASS, austenitic nickel-based alloys, aluminum alloys, etc., which have closely packed planes (to allow more plastic deformation instead of cracking) have still good toughness in cryogenic services while BCC (body-centered cubic structure) and HCP (hexagonal close-packed structure) materials have very low toughness in low temperatures. Chary V-notch (CVN) impact test is commonly used for evaluation of brittle failure in low temperatures. CVN impact test is also used for the evaluation of the risk of temper embrittlement of Cr-Mo steels. See Sect. 5.2.3 for applicable standards of toughness tests and Sect. 1.3.4.6 for fracture toughness estimation from the result of the CVN impact test.

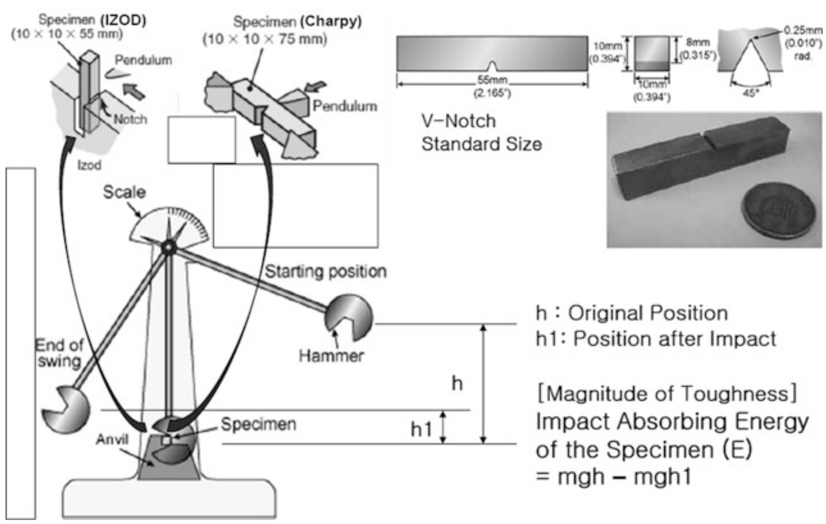


Figure 2.110 Theory of impact test to obtain the absorbed energy values

2.2.1.2 CVN Impact Test Absorbing Energy (IAE)

The resistant properties against Impact Test are evaluated from the absorbed energy values of the test specimen until fractured. Figure 2.110 shows the Chary V-notch impact test machines and theory.

The absorbed energy values of the test specimen are obtained from the differential potential energy value (= mgh – mgh1). Higher IAE material has better toughness. So, IAE is a magnitude of toughness.

This test method is normally very sensitive for the machining and sampling direction of the specimen.

Therefore, the three test specimens are typically used to evaluate the acceptance with required average and minimum values of the three specimens. ASME specifies that the minimum impact energy for one specimen shall not be less than 2/3 (67%) of the average energy required for the three specimens. However, ASTM/ASME material standards for impact test requires materials apply about 72–75% for this ratio.

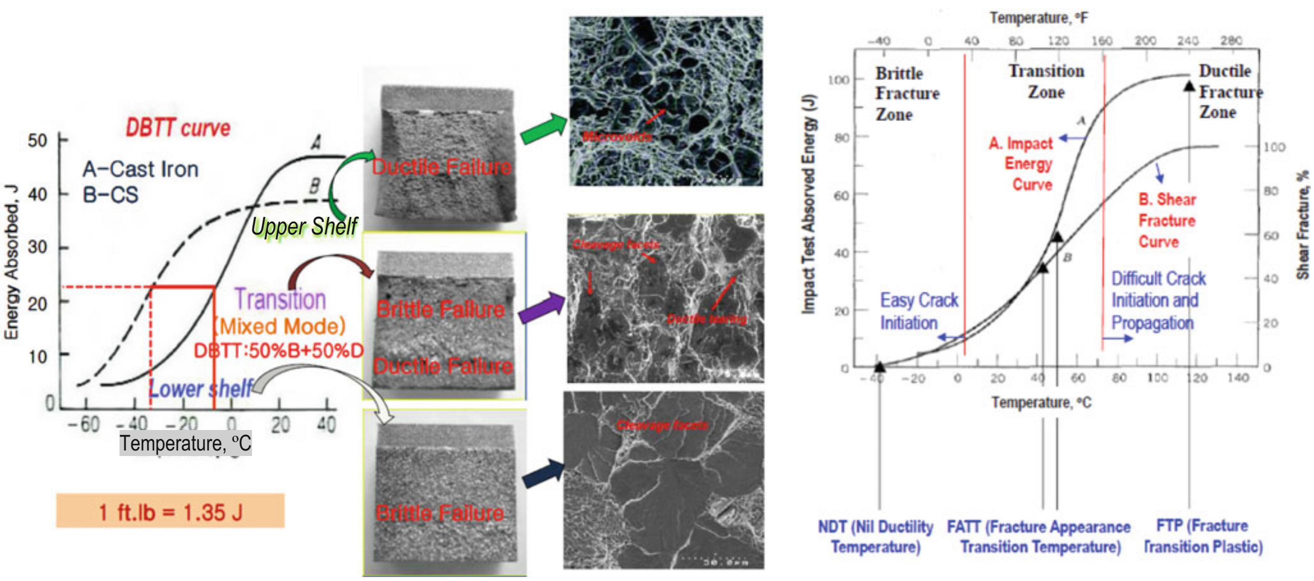


Figure 2.111 Typical impact test result curves, failure modes, and microstructures

The CVN impact test is mainly to proved the resistance of brittle failure of materials to be used in low temperatures. The materials with higher impact absorbing energy have lower ductile-brittle-transition temperature (DBTT), which has 50% ductile failure mode and 50% brittle failure mode. Figure 2.111 illustrates a typical DBTT curve, failure modes, and their microstructure. Ductile failure mode has high energy which is absorbed by micro void coalescence during ductile failure (high-energy fracture mode, less catastrophic) while brittle failure mode has low energy which is absorbed during transgranular cleavage fracture (low-energy fracture mode, more catastrophic).

The process of cleavage brittle fracture consists of the following three steps:

(i) Plastic deformation to produce dislocation pile-ups
(ii) Crack initiation
(iii) Crack propagation to failure

There are the following three typical definitions for toughness evaluation (See Fig. 2.111).

DBTT (Ductile Brittle Transition Temperature) or FATT (Fracture Appearance Transition Temperature)
The temperature is selected at the 50% ductile failure (fibrous) area and the 50% brittle failure (cleavage) area on fracture face as a result of impact test. This can alternatively be based upon the mean of the "upper" and "lower" shelf energies.

Nil Ductility Temperature (NDT)
It is the temperature below which the fracture is 100% cleavage/shear.

Fracture Transition Plastic (FTP)
It is the temperature above which the fracture is 100% fibrous/shear (0% cleavage/ductile). This is the most conservative estimate.

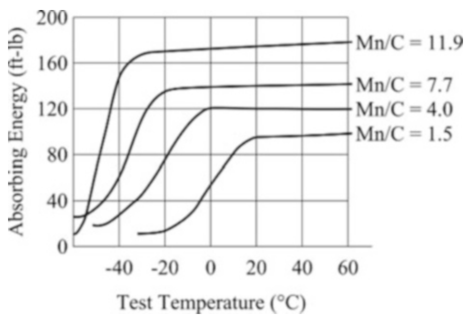


Figure 2.112 Mn/C effect for low-temperature toughness (CVN impact test of CS). (Source: ASM Metal Handbook, Vol.1)

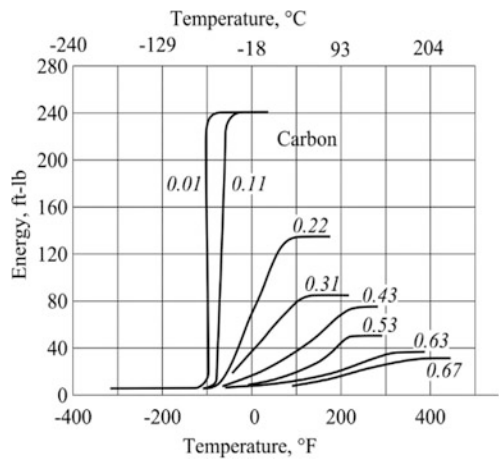


Figure 2.113 Carbon effect on low-temperature toughness (CVN impact test of CS austenizied 1600 °F/4 hours and slow cooled). (Source: ASM Metal Handbook, Vol.1)

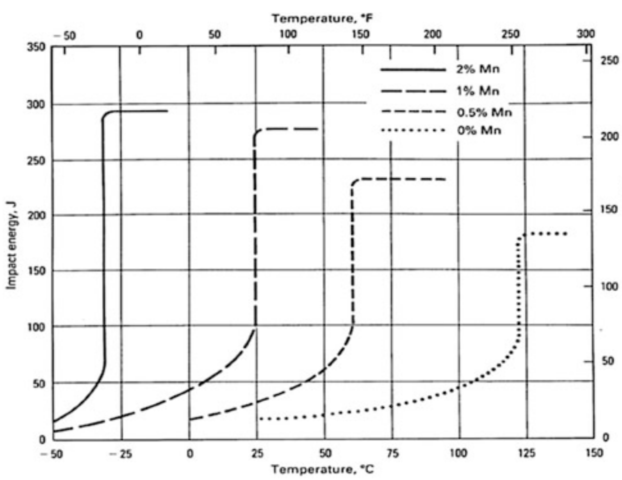


Figure 2.114 Manganese effect on low-temperature toughness (CVN impact test of CS with 0.03%C). (Source: ASM Metal Handbook, Vol.1)

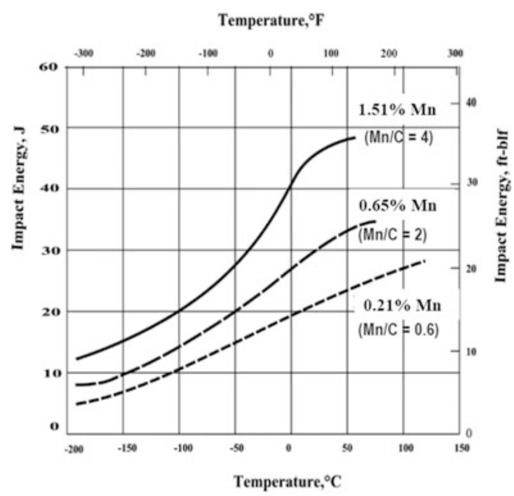


Figure 2.115 Manganese effect on low-temperature toughness (CVN impact test of CS with 0.35%C). (Source: ASM Metal Handbook, Vol.1)

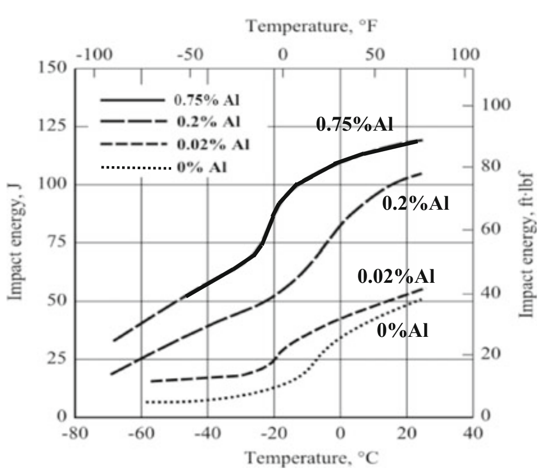


Figure 2.116 Aluminum effect on low-temperature toughness (CVN impact test of N-T steel (medium carbon). (Source: ASM Metal Handbook, Vol.1)

2.2.1.3 Chemical Composition Effect

Table 2.115 shows the effects of several elements for low-temperature toughness in ferritic steels.

Figures 2.112, 2.113, 2.114, 2.115, 2.116, 2.117, and 2.118 shows chemical element effects for low-temperature toughness. As the Mn/C ratio is increased and Ni in carbon steels and low-alloy steels, the IAE of the materials is improved.

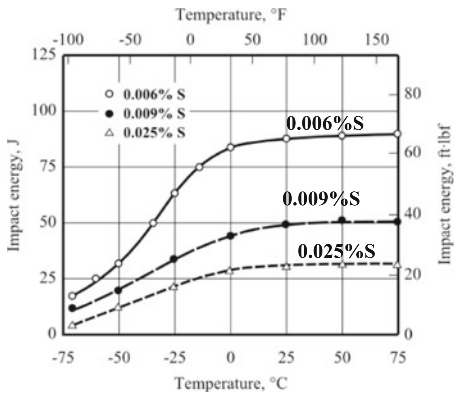


Figure 2.117 Sulfur effect on low-temperature toughness (CVN impact test of Si-Al killed HSLA steel -SMTS 450 MPa). (Source: ASM Metal Handbook, Vol.1)

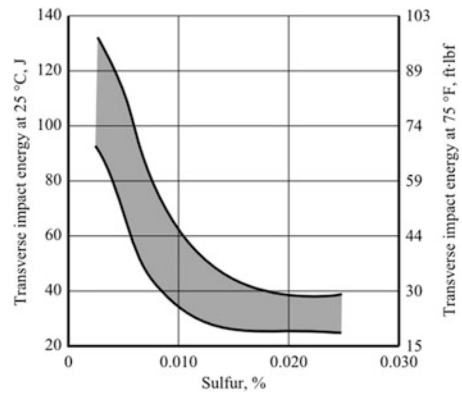


Figure 2.118 Sulfur effect on low-temperature toughness (CVN impact test of Si-AL Killed CS). (Source: ASM Metal Handbook, Vol.1)

Table 2.115 (1/2) Effects of several elements on low-temperature toughness in ferritic steels

Elements	Characteristics
Al (Aluminum)	Aluminum. The effect of Al on the notch toughness of a medium-carbon steel is illustrated in Fig. 2.116. Note that increasing the Al content above that needed for forming Al-nitrides (>> 0.075% Al) impairs notch toughness.
B (Boron)	For Q-T steels, a practical way of improving toughness without reducing strength is to use B-containing grade of steel with a lower C content. The effect of B shows a toughness improvement in Q-T steels, however, B reduces the toughness of as-rolled, as-annealed, and as-normalized steels.
C (Carbon)	Increasing C content increases transition temperature and decreases upper-shelf fracture energy primarily as a result of increased strength and hardness. These effects, measured by CVN impact tests, are shown in Figs. 2.112 and 2.113. C is one of the most potent alloying elements in its effect on notch toughness and strength. Consequently, for maximum toughness, C content should be kept as low as possible, consistent with strength requirements. Low carbon steels tend to have very steep transition curves.
Cr (Chromium)	Cr raises the transition temperature slightly. In steels having Cr contents in excess of 0.90%, it is very difficult to develop those microstructures and mechanical properties that are typical of plain CS; therefore, impact test results are not comparable. Cr is usually added to increase hardenability. The increase in hardenability is often sufficient to develop a martensitic microstructure, which provides high upper-shelf energy. Medium-carbon, straight Cr alloy steels, such as AISI 5140, are susceptible to embrittlement when quenched to martensite and tempered between 370 and 575 °C (700 and 1070 °F).
Cu (Copper)	Cu in steels that have not been subjected to precipitation hardening appears to be moderately beneficial to low-temperature notch toughness. However, Cu promotes precipitation hardening in steel and, as a result, may adversely affect notch toughness, particularly if the tempering temperature is between 400 and 565 °C (750 and 1050 °F).
Mn (Manganese)	Mn has a variety of effects on transition temperature. In low-carbon steels, it can substantially reduce the transition temperature, as shown in Fig. 2.114. In higher-carbon steels, Mn may be less beneficial. As illustrated in Fig. 2.115, increasing the ratio of Mn/C contents of a normalized medium-carbon steel lowered the ductile-to-brittle fracture transition temperature, probably because the additional Mn reduced the pearlite inter-lamellar spacing (the spacing between the alternating plates of ferrite and cementite in pearlite). Mn can make the steel susceptible to temper embrittlement, and it may cause the formation of less tough upper bainite (rather than fine pearlite) during normalizing.
Mo (Molybdenum)	Mo in typical quantities in alloy steels (up to about 0.40%) raises the 50% FATT. Mo is frequently used to increase hardenability, and it influences notch toughness primarily through its effect on microstructure. About 0.5–1.0% Mo can be added to alloy steels to reduce their susceptibility to temper embrittlement, but it is effective only for relatively short heating times at embrittling temperatures. Mo appears to delay rather than eliminate temper embrittlement, because steels containing small amounts of this element have become embrittled upon prolonged exposure within the embrittling temperature range.
N (Nitrogen)	N, by itself, lowers the upper-shelf energy and raises the transition temperature. However, most nitrogenized steels are deoxidized with Si and Al, both of which combine with N. Al-nitrides formed during deoxidation serve to stabilize grain size and thus improve the notch toughness of these steels.
Ni (Nickel)	Ni, like Mn, is useful for improving the notch toughness of steels at low temperatures. Ni is less effective in improving the toughness of medium-carbon steels than low-carbon steels. Some high-Ni alloy steels, such as maraging steels and ASS, do not exhibit the typical ductile-to-brittle transition (austenitic steels, being face-centered cubic, do not have a ductile-to-brittle transition). The high Ni content reduces upper-shelf fracture energy, but to a level that is still quite acceptable for most applications.

Table 2.115 (2/2) Effects of several elements on low-temperature toughness in ferritic steels

Elements	Characteristics
P (Phosphorus)	P has a strongly deleterious effect on the notch toughness of steel. It raises the 50% FATT about 7 °C (13 °F) for each 0.01% P and reduces upper-shelf energy. In addition, P increases the susceptibility of some steels to temper embrittlement.
S (Sulfur)	The effect of S on the notch toughness of steels is directly related to deoxidation practice. For rimmed, semikilled, and Si-killed steels, S in amounts up to about 0.04% has a negligible effect on notch toughness. S has a strong directional effect on Charpy V notch (CVN) impact test results depending on the inclusion types present (e.g., sulfides, oxides, and complex nonmetallics). CVN impact test taken perpendicular to the working or rolling direction have lower absorbed energies when manganese sulfide stringers are present. Steel ladle treatments, used to reduce S and to provide inclusion shape control, minimize CVN impact test directionality. For Si-Al killed steels, a reduction in S content can substantially increase upper-shelf energy, as shown in Fig. 2.117. This improvement in energy absorption results from a reduction in the number of sulfide stringers in the steel. Room-temperature CVN impact test results taken transverse to the rolling direction in plate steels show substantial improvement in energy absorbed only when S levels are reduced below about 0.010% (Fig. 2.118).
Si (Silicon)	Si used in amounts of 0.15–0.30% to deoxidize steels, generally lowers the ductile-to-brittle fracture transition and raises upper-shelf energy. Compared to rimmed or semikilled steels, silicon-killed steels are cleaner and have more uniform ferrite grains. These effects are probably caused by variations in steelmaking practice characteristic of the deoxidation methods used, rather than by the Si content.
Others	V, Nb, and Ti are most often used in steels that receive controlled thermomechanical treatment. Consequently, the toughness of steels containing these elements is largely a function of mill processing. When the steel is finished at temperatures below about 925 °C (1700 °F) (which is characteristic of certain HSLA steels), V, Nb, and Ti improve toughness primarily by refining the ferrite grain size. At higher finishing temperatures, these elements may be detrimental to toughness.
	Zr, Ti, Ca, and the rare earths can be used to control the shape of MnS inclusions, causing the inclusions to be spherical rather than elongated. Spherical inclusions raise upper-shelf energy and minimize the anisotropic nature of notch toughness; these effects are particularly useful in HSLA sheet and thin plate.
	Sb (Antimony), As (Arsenic), and Sn (Tin). In trace amounts, these elements reduce the notch toughness of steels and greatly Increase the susceptibility of Ni- and Cr-alloy steels to temper embrittlement.

Source: ASM Metal H/B, Vol.1

2.2.1.4 Oxygen Killing Effects

Higher deoxidized steel (as fully killed) has higher IAE (impact test absorbing energy) at the same condition (Fig. 2.119). Meanwhile, degassing (e.g., vacuum degassing) treatment may also promote low-temperature toughness. See Sect. 2.1.4.1(b) for killing treatment of steels.

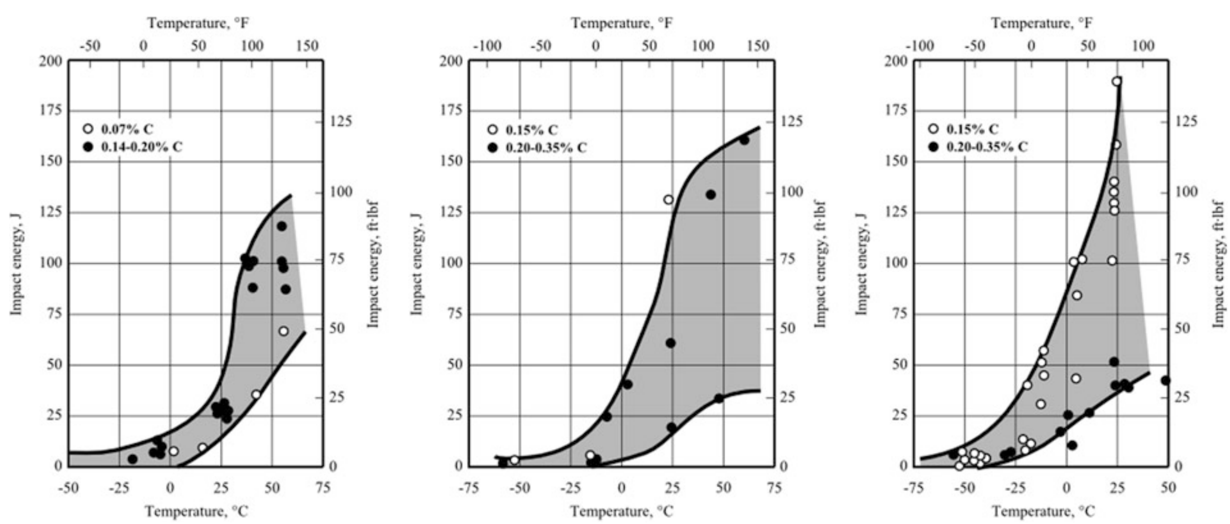


Figure 2.119 Deoxidization effect on low-temperature toughness. (Source: ASM Metal Handbook, Vol. 1). (**a**) Rimmed steel. (**b**) Semi-killed steel. (**c**) Killed steel

2.2.1.5 Grain Size Effects

Figure 2.120 shows the grain size effects for DBTT on notch toughness (0.11% carbon steel). Smaller grain size gives better toughness. Fine grain practice in ferritic steel is normally performed by chemical control or heat treatment (TMCP>Q-T>Normalizing), or both. Coarse grain practice in ferritic steel is normally performed by chemical control (Si) or heat treatment (longer holding time in austenitic structure) or both. See Sect. 1.1.10.2(*l*) for general characteristics of grain size, Table 2.20 for grain size control methods, Sect. 2.1.1.12 for general and measurements of grain size, Sect. 2.1.4.7 for grain size control of TMCP steel, and Sect. 2.1.4.8 for grain size control of NACT steel.

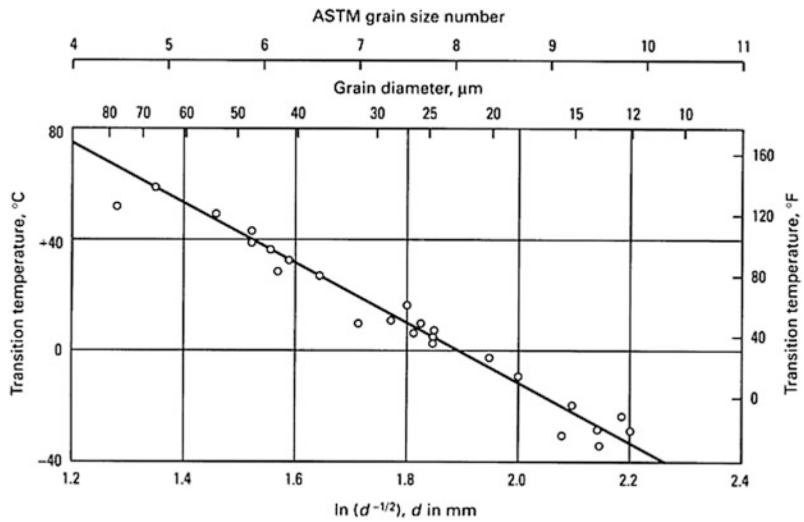


Figure 2.120 Grain size effects for DBTT on notch toughness (0.11% carbon steel). (Source: ASM Metal H/B Vol.1)

2.2.1.6 Thickness Effects

Table 2.116 Thickness effect on low-temperature toughness (ASTM A20), 1 $J = 0.7376$ ft.lbs.

Acceptance criteria CVN energy absorption			Material grade	Test temperature, °C for plate thickness (unless otherwise agreed upon)			
Class	Min. average for 3 specimen, J	Min. for 1 specimen, J		≤25 mm	>25 mm, ≤50 mm	>50 mm, ≤75 mm	>75 mm, ≤125 mm
IV	20	16	ASTM A516–70	−46	−40	−35	−29

Heavier thickness plate is subject to more brittle failure mode (lower DBTT). Figure 2.121 shows the fracture toughness modes per thickness. A very thin thickness is subject to plain stress which has high toughness. For this reason, the tube material in heat exchanger with low-temperature carbon steel should use plain carbon steel instead of low-temperature carbon steel (LTCS).

Table 2.116 shows the thickness effect on low-temperature toughness. In order to obtain the same absorbing energy value (20 J/15 ft-lb. for average) for A516-70, it is tested at −29 °C (−20 °F) for 75 mm (3 in.) and above while tested at −46 °C (−50 °F) for 25 mm (1 in.) and below.

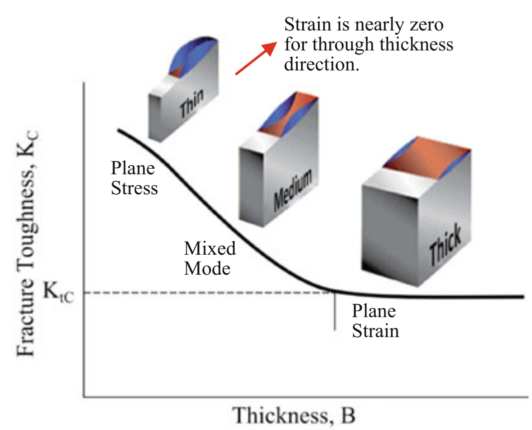


Figure 2.121 Fracture toughness modes per thickness

2.2.1.7 Tensile Strength (T.S) Effects

As the T.S is increased, the IAE of the materials will be decreased. [ASTM A20 Table A1.15 and ASME Sec. VIII, Div.1, Figure UCS-66 and Fig. 323.2.2A].

2.2.1.8 Yield Strength (Y.S) Effects

As the Y.S is increased, the IAE of the materials will be decreased. [ASME Sec. VIII, Div.1, Figure UG-84.1].

2.2.1.9 Test Direction of Specimen

The results of impact test as well as tensile strength are very sensitive per the test specimen direction as seen in Fig. 2.122. The through thickness direction shows the lowest toughness, and the next lowest toughness is from the transverse direction, and the result of longitudinal direction shows the highest toughness.

Codes, standards, and specification indicate to apply a certain direction of the test specimens. ASTM standards typically indicate "B" specimen for forging and "C" specimen for rolled plate unless otherwise specified by the purchaser. Typically, the TS/impact absorbing energy values per each direction will be shown as below.

$$Y \text{ (rolling) direction} > X \text{ (transverse of rolling) direction} > Z \text{ (through thickness) direction.}$$

Figure 2.123 shows the comparison of the requirements for direction of CVN specimens between ASTM A350 (forgings) and ASME Sec. VIII, Div.2.

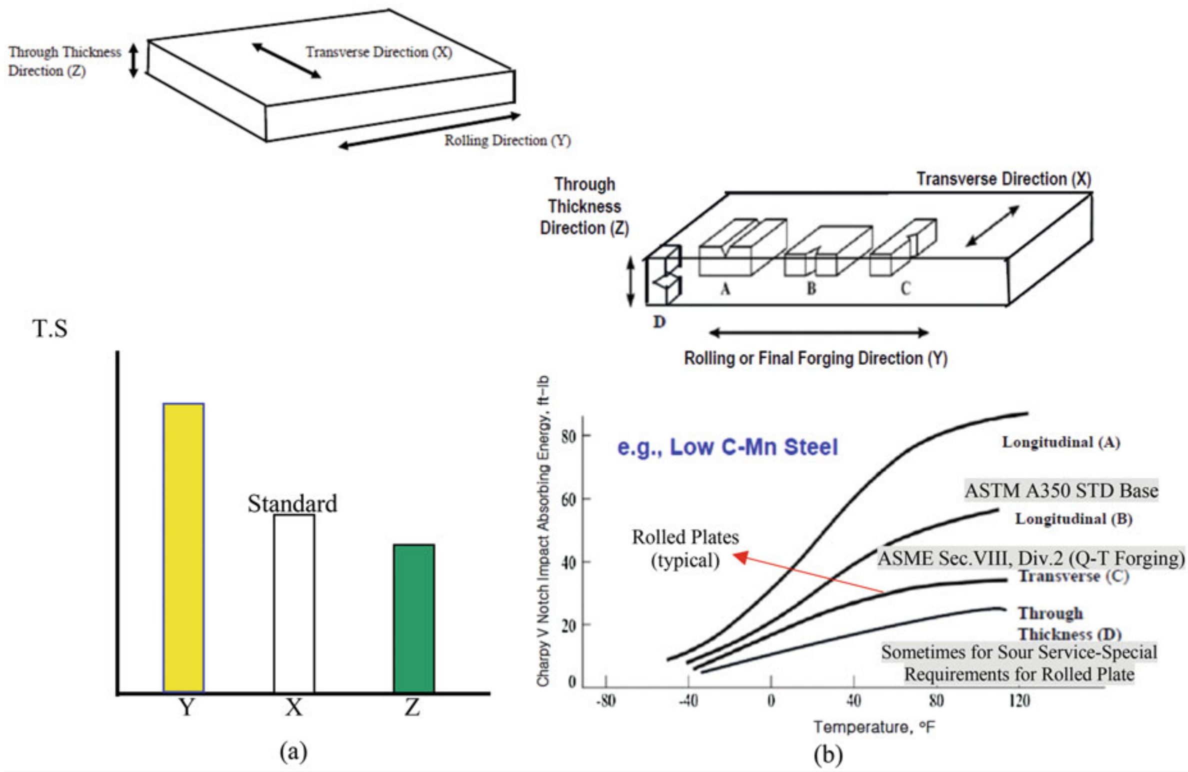


Figure 2.122 Mechanical properties per direction of specimen. (**a**) Tensile strength. (**b**) Impact absorbing energy (a case of C-Mn steel)

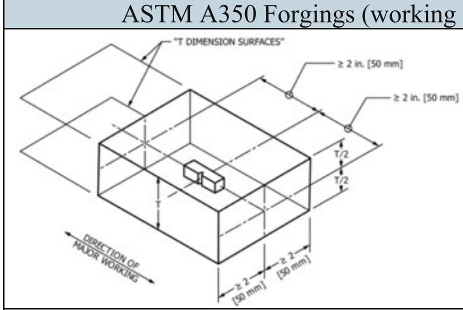
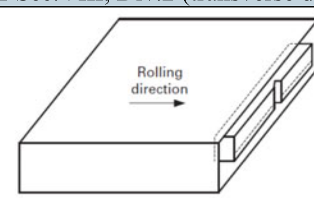
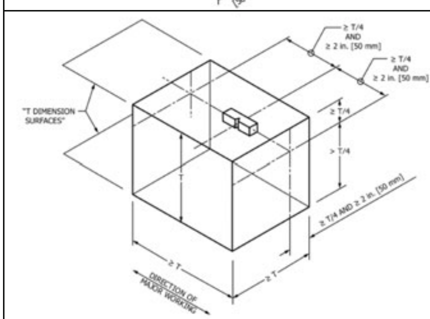
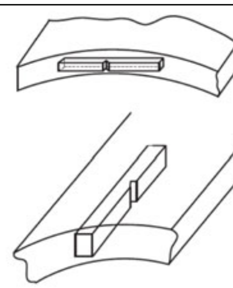
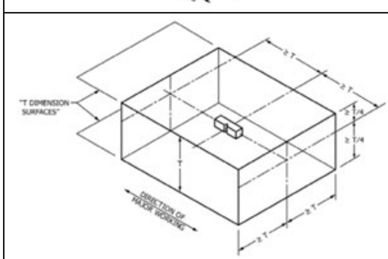
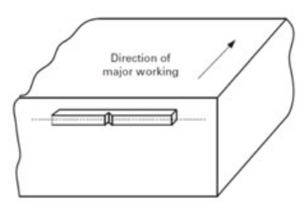
ASTM A350 Forgings (working direction)		ASME Sec.VIII, Div.2 (transverse direction)
	Separately Forged Test Bar for Forgings with T ≤ 2 in. [50 mm] and not Q-T	 (a) CVN Specimens From Plate
	Separately Forged Test Bar for Forgings with T > 2 in. [50 mm] and Not Q-T	 (b-1) (b-2) (b) CVN Specimens From Pipe
	Separately Forged Test Blank for Forgings with T > 2 in. [50 mm] and Q-T or Quenched and Precipitation-Heat Treated	 (c) CVN Specimens From Forgings

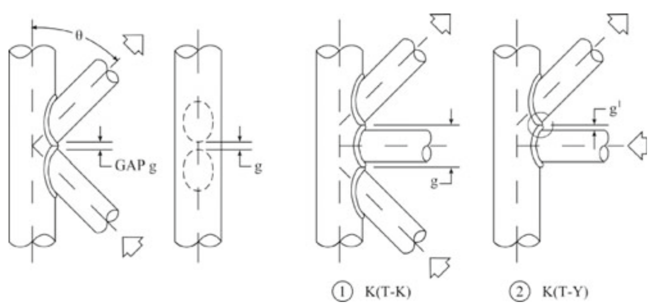
Figure 2.123 Requirements for direction of CVN specimen

2.2.1.10 Metallurgical and Physical Effects

Dissimilar welding parts with highly different thermal expansion coefficient (e.g., ASS to carbon steels) can show more reduced toughness compared to the lower toughness base metal due to fatigue stress.

2.2.1.11 Geometry-Notch Effects (Figs. 2.124, 2.125, and 2.126) – To Be Minimized.

(a) Severe Discontinuous Parts, e.g., butt joints
Discontinuous parts in pressure and/or loaded condition can be stress-concentrated. Also, the parts can be exposed to notch affect, which is readily able to initiate failure. Therefore, tapering with minimum 3:1 on thick parts is required at the butt weld with different thicknesses [ASME Sec. VIII, Div. 1, Fig. UW-13.1].
(b) Highly Restricted Parts due to welding and/or load, e.g., branch joints [AWS D1.1, Fig. 2.14 (F)]-see Fig. 2.124 in this book.
(c) Machined corner at pressure and/or loaded part can be exposed to stress concentration. A certain radius at the corner is required to avoid stress concentration. [ASME Sec. VIII, Div. 1, Fig. UW-13.3, UW-16-1, ULW-17.3, and Fig. 2.4 in Appendix 2]-see Fig. 2.125 in this book.
(d) To keep round corners (radius) for the components of pressure retaining parts (e.g., Flanges in ASME Sec. VIII, Div. 1, Fig. UW-13.3, 16-1 & ULW-17.3 and Appendix 2) – see Fig. 2.125 in this book.
(e) Chamfering for the joints with different thicknesses (e.g., min. 3:1 in ASME Sec. VIII, Div. 1, Fig. UW-13.1/B16.5, Fig. 10 through 14) -see Fig. 2.126 in this book.
(f) Weld reinforcement (on each side) (e.g., ASME Sec. VIII, Div. 1, Fig. UW-35/J.E. in regulation of Japan or Korea) – see Fig. 2.126 in this book.
(g) Thread Nozzle Connection (e.g., The thread should not be appeared outside of connections in low temperature or cyclic service) -see Fig. 2.126 in this book.
(h) Weld Joint of Shell to Skirt (e.g., flushing as concave type in clients' specifications) – See Fig. 2.126 in this book.
(i) Misalignment of butt joint (e.g., ASME Sec. VIII, Div. 1, Table UW-33/B31.3, Fig. 328.4.3 & Fig. K328.4.) – see Fig. 2.126 in this book.
(j) Full penetration welding is required in low-temperature and cyclic service (e.g., ASME Sec. VIII, Div. 1 UCS-68 & UW-2) – see Fig. 2.126 in this book.
(k) Full penetration and continuous welding is required in fatigue environment (e.g., AWS) – see Fig. 2.126 in this book.
(l) The maximum allowable offset (misalignment) and maximum reinforcement of weld joint and welds are to meet specifications in Tables 4.7 and 4.8, respectively in this book.



K-Connection K-Combination Connections

Figure 2.124 Highly restricted parts due to welding and/or load (ASW D1.1, Fig. 2.14)

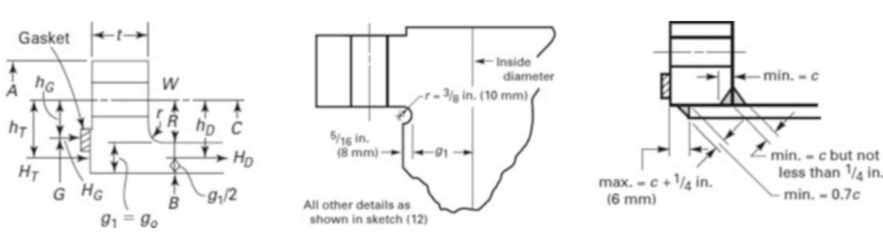


Figure 2.125 Corner design of machined parts to avoid stress concentration (notch effect)-ASME Sec. VIII, Div.1

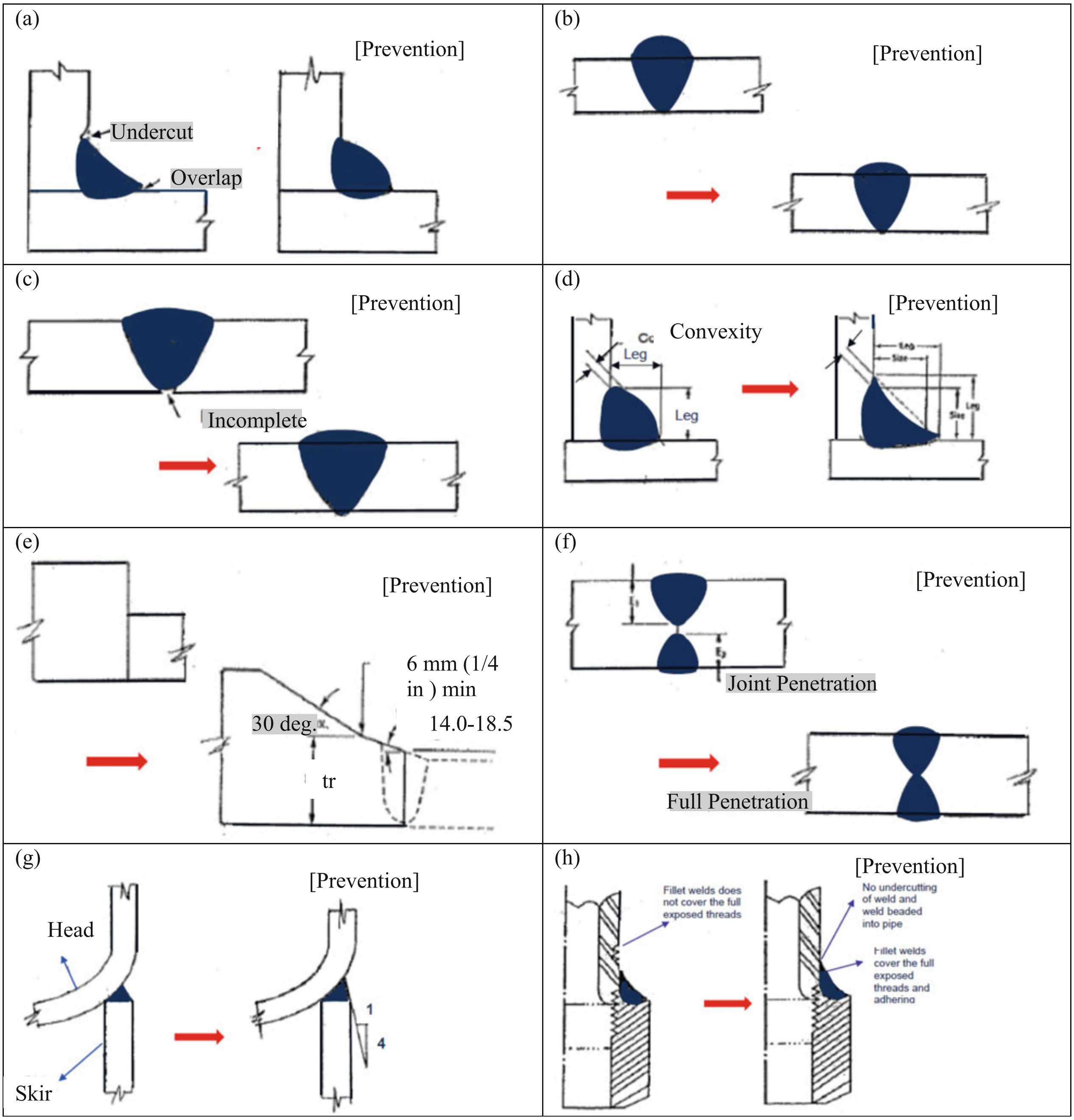
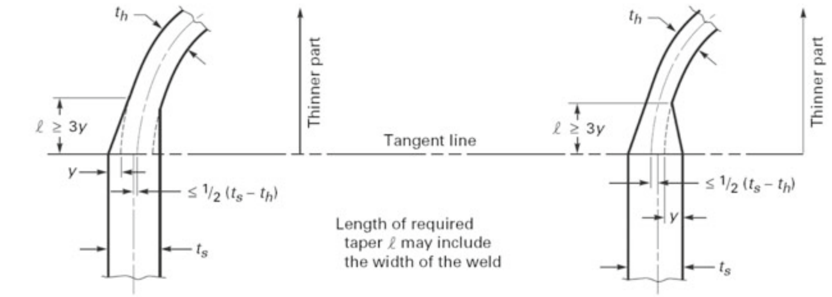
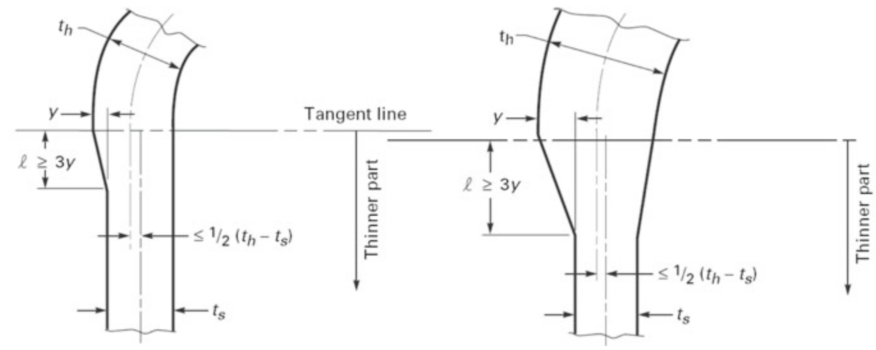


Figure 2.126 (1/3) Several types of notch effect and their prevention. (**a**) Undercut and overlap, (**b**) Overbead (convex), (**c**) Leak fusion, (**d**) Stress concentration parts, (**e**) Different thicknesses, (**f**) Partial welding in butt joint, (**g**) Chamfering, (**h**) Weld on threads



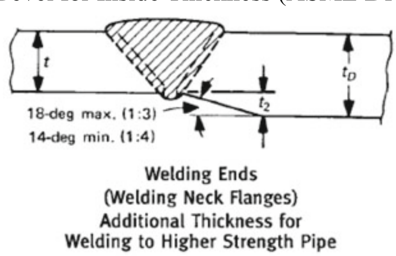
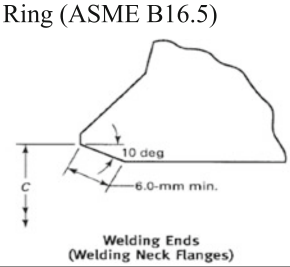
In all cases, the projected length of taper shall be not less than 3y. The shell plate centerline may be on either side of the head plate centerline.



In all cases shall be not less than 3y when th exceeds ts. Minimum length of skirt is 3th but need not exceed 1.5 in. (38 mm) except when necessary to provide required length of taper. When th is equal to or less than 1.25ts, length of skirt shall be sufficient for any required taper. Length of required taper may include the width of the weld. The shell plate centerline may be on either side of the head plate centerline.

ASME Sec. VIII, Div. 1, Fig. UW-13.1

Figure 2.126 (2/3) Several types of notch effect and their prevention

<table>
<tr>
<td>Bevel for Inside Thickness (ASME B16.5)

</td>
<td>Inside Contour for Use with Taper Backing Ring (ASME B16.5)

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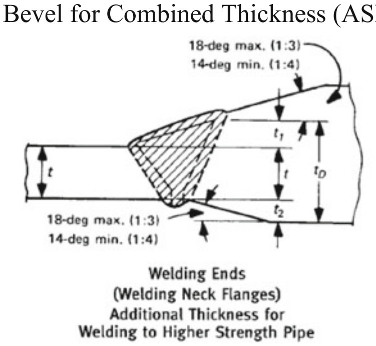
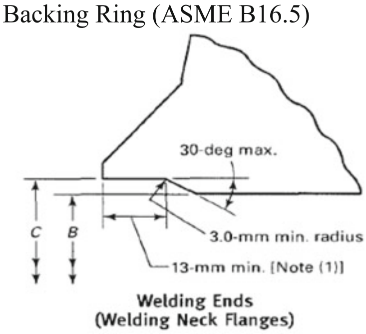
<tr>
<td>Bevel for Combined Thickness (ASME B16.5)

</td>
<td>Inside Contour for Use with Rectangular Backing Ring (ASME B16.5)

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</table>

Figure 2.126 (3/3) Several types of notch effect and their prevention

2.2.1.12 Heat Treatment Effects

Figure 2.127 shows the effect of several types of heat treatment on transverse CVN impact test. Toughness test of ASTM A516. Q-T steel has the highest toughness, and as-rolled steel shows the lowest toughness at the same thickness and same conditions (for base metal). Figures 2.128 and 2.129 illustrate the heavy PWHT (high LMP- high temperature & longer holding time) can degrade the toughness (impact test absorbed energy) for heavy wall ASTM A516-70 normalized steel [38 mm (1.5 in.) & 76 mm (3 in.) thickness]. See Sect. 1.3.3.1 for LMP (Larson-Miller Parameter) and HJP (Hollomon-Jaffe Parameter) calculation.

Figure 2.130 indicates the changes in mechanical properties of gray iron as a function of tempering temperature. The toughness at 400–500 °C (752–932 °F) of tempering shows highest values.

Figure 2.131 indicates the changes of hardness and notch toughness of AISI 4140 steel tempered for 1 hour at various temperatures. Higher tempering temperature from 350 °C (662 °F) shows higher toughness.

Figure 2.132 shows the variation in impact energy with tempering temperature for AISI 6150 steel-oil quenched from 885 °C (1625 °F) and tempered 2 hours at temperature. Higher tempering temperature up to 650 °C (1202 °F) shows higher toughness.

Figure 2.133 shows the impact toughness as a function of tempering temperature of hardened, low-alloy, medium-carbon steels. Lower carbon (≤ 0.4%C) steels have a great effect on tempering temperature while higher carbon steels (≥ 0.5%C) steels do not have remarkable effects on tempering temperature.

Figure 2.134 shows the effect of cooling rate on CVN impact toughness of two second-generation microalloy steels. Cooling rates ranged from 1.3 °C/s (2.4 °F/s) (bin cooling) to 2.7 °C/s (4.8 °F/s) (forced-air cooling). The Mo-containing steel is unaffected by cooling conditions.

Table 2.117 shows the effect of heat treatment (by environment cracking service or other purpose – no code requirement) for CVN impact test in ASME Sec. VIII, Div.1.

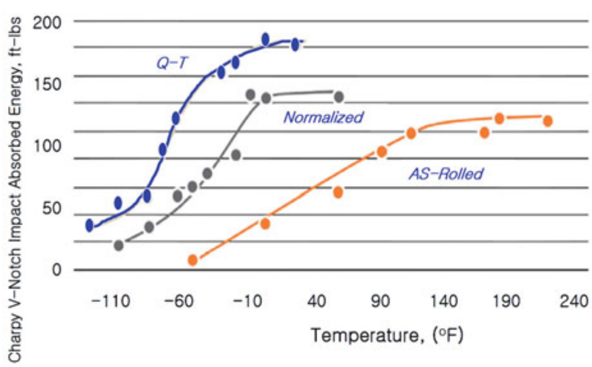


Figure 2.127 Effects of heat treatment on transverse CVN Impact toughness of ASTM A516. (Source: ArcelorMittal Lab Data, 2010)

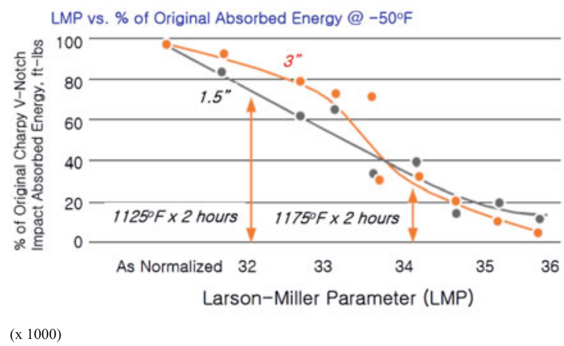


Figure 2.128 Effects of LMP by PWHT on transverse CVN Impact toughness of ASTM A516 heavy wall [38 mm (1.5 in.) & 76 mm (3 in.)]. (Source: ArcelorMittal Lab Data, 2010)

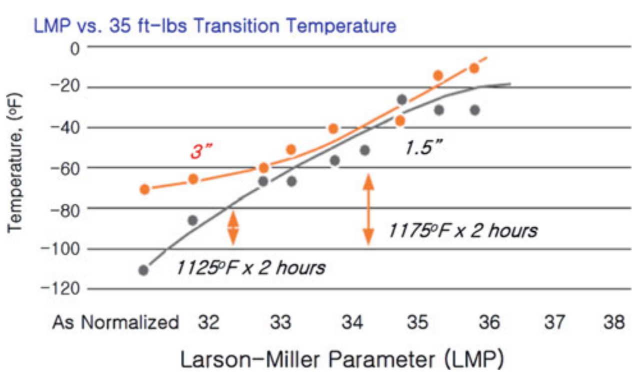


Figure 2.129 Effects of LMP by PWHT on transverse CVN Impact toughness of ASTM A516-heavy wall. (Source: ArcelorMittal Lab Data, 2010)

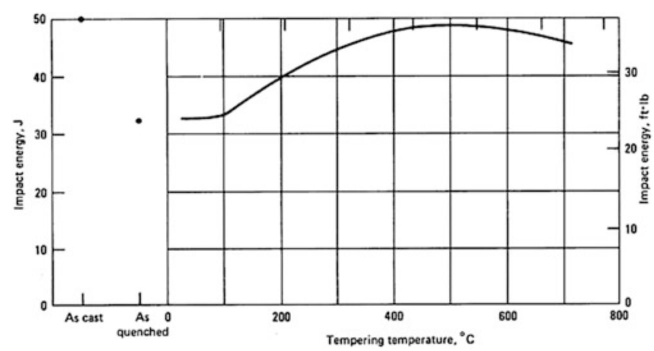


Figure 2.130 Changes in mechanical properties of gray iron as a function of tempering temperature. (Source: ASM Metal H/B, Vol.1)

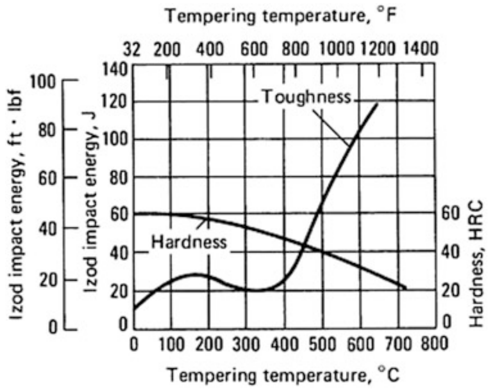


Figure 2.131 Hardness and notch toughness of AISI 4140 steel tempered for 1 h at various temperatures. (Source: ASM Metal H/B, Vol.1)

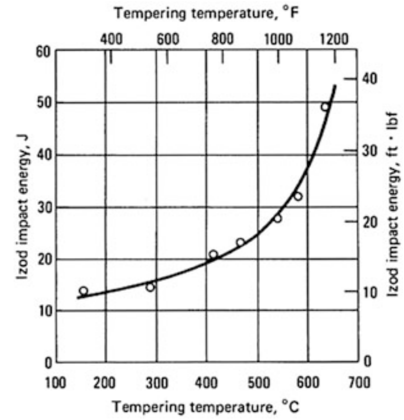


Figure 2.132 Variation in impact energy with tempering temperature for AISI 6150 steel. Specimens oil quenched from 885 °C (1625 °F) and tempered 2 h at temperature. (Source: ASM Metal H/B, Vol.1)

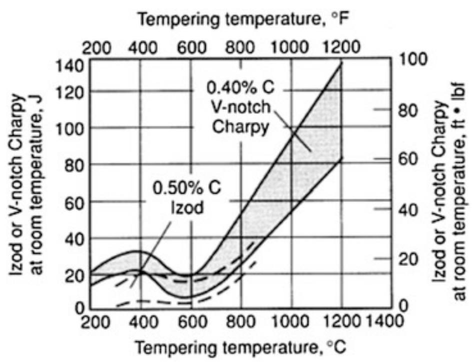


Figure 2.133 Impact toughness as a function of tempering temperature of hardened, low-alloy, medium-carbon steels. (Source: ASM Metal H/B, Vol.1)

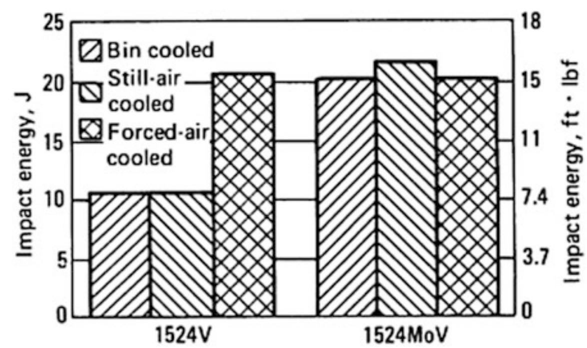


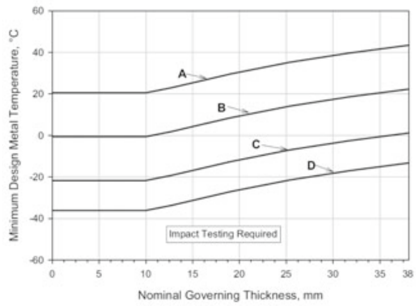
Figure 2.134 Effect of cooling rate on CVN impact toughness of two second-generation micro-alloy steels. Cooling rates ranged from 1.3 °C/s (2.4 °F/s) (bin cooling) to 2.7 °C/s (4.8 °F/s) (forced-air cooling). The Mo-containing steel is unaffected by cooling conditions. (Source: ASM Metal H/B, Vol.1)

Table 2.117 Compensation for impact test requirements by heat treatment- ASME Sec. VIII, Div.1

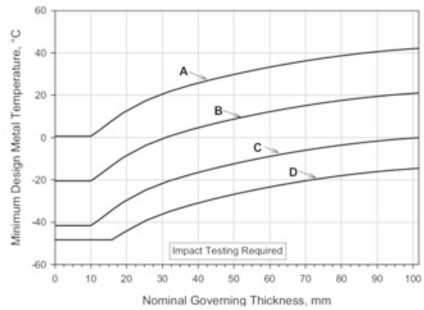
Item	ASME Sec. VIII Div. 1			ASME B31.3
1. PWHT (1)	UCS-68(c): If PWHT performs when it is not otherwise a requirement of this Division, a 17 °C (30 °F) reduction in IT exemption temperature may be given to the minimum permissible temperature from Figure UCS-66 for P No. 1 materials. The resulting exemption temperature may be colder than −48 °C (−55 °F).			–
2. Normalizing (N)	Figure UCS-66: If it is normalized, IT exemption temperature can be greatly decreased. e.g., IT exemption temperature for 25 mm (1 inch) thick			Already considered in ASME B31.3, table A-1
		Non-normalized	**Normalized**	
	SA516–60	−19 °C (−3 °F)	−34 °C (−30 °F)	
	SA516–65/70	−1 °C (30 °F)	−34 °C (−30 °F)	
3. Quenched & Tempered (Q-T) with fine grain practice	Reflected in Figure UCS-66.			Already considered in ASME B31.3, Figure 323.2.2A and Table A-1

Note:
(1) The reverse effect of PWHT will show toughness decrease if the PWHT is performed at higher temperatures at longer holding times (as high LMP zone-See Figs. 2.128 and 2.129). Especially the results of PWHT for heavy wall with cyclic times (i.e., 3–4 times) should be carefully evaluated at the design & material purchasing stage because the tensile strength and toughness can be greatly reduced.

Figure 2.135 shows the compensation of PWHT for CVN impact test (required energy from Full Size Specimen per SMTS of Carbon and Low Alloy Steels in ASME Sec. VIII, Div.2. The CVN impact test exemption curves in ASME Sec.VIII, Div.1, Fig. UCS-66, ASME Sec. VIII, Div.2, Fig. 3.7(M) & 3.8(M), ASME B31.3, Fig. 323.2.A, etc., are not applicable for impact-tested CS/LAS, such as LTCS. A/SA-105 is designated as Curve A for as-forged and Curve B for forging produced by fine grain practiced and N, N-T, or Q-T from ASME BPVC 2019 edition.



(a)



(b)

Figure 2.135 Compensation for impact test (required energy of CVN impact test from full size specimen per SMTS of CS and LAS by heat treatment (ASME Sec. VIII, Div.2, Figure 3.7M & 3.8M). (**a**) Parts without PWHT and nonwelded Part. (**b**) Parts with PWHT

Note: See Sects. 1.1.12 and 2.2.2.2 for governing thickness. The impact test for the materials at the locations above each curve is not required except as required by ASME Sec. VIII, Div.2, 3.11.8 for weld metal and HAZ.

Brief Categories; *N* = normalized, *T*-tempered, *Q* = quenched, LQ = liquid-quenched, WQ = water-quenched, and FGP = fine grain practice.

A: SA-216-WCB/WCC with N-T or WQ-T, SA-217-WC6 (t ≤ 50 mm) with FGP + water Q-T, *SA-105 forged flanges and all others than the listed materials in B, C, and D (SA105 since 2019 edition).*

B: SA-216-WCA with N-T or WQ-T, SA-216-WCB/WCC with N-T or WQ-T, SA-217-WC9 with N-T, SA-285-A/B, SA-299, SA-414-A, SA-515-60, SA-516-65/70, SA-662-B, SA/EN 10028–2-Gr. P355GH, SA-105 forged flanges with FGP + N or N-T or Q-T, and Pipe, Fittings, Forgings, and Tubes not listed in C & D *(SA-105 since 2019 edition)*,

C: SA-182-F21/F22 with N-T, SA-302-C/D, SA-336-F21/F22 with N-T or LQ-T, SA-387-21/22 with N-T or Q-T, SA-516-55/60, SA-533-B/C-Cl.1, SA-662-A, SA/EN 10082-2 Gr.10CrMo9-10 with N-T, and all materials listed in B with FGP + N, N-T, LQ-T except the materials listed in D.

D: SA-203, SA-299 with *N*, SA-508-1, SA-516 with *N*, SA-524-1/2, SA-537-1/2/3, SA-612 with *N* (except Cb increased per SA-20, Table 1, note), SA-662 with *N*, SA-738-A, SA-738-A with Cb and *V* deliberately controlled for ≥ −29 °C (−20 °F), SA-738-B for ≥ −29 °C (−20 °F), SA/EN 10082-2 Gr. P355GH with *N*. Castings not listed in curve A and B shall be CVN impact-tested

2.2.1.13 Thermal Shock During Cooling Down

A form of thermal fatigue cracking – thermal shock – can occur when high and nonuniform thermal stresses develop over a relatively short time in a piece of equipment due to differential expansion, contraction, or volume changes associated with sudden shifts in temperature. If the thermal expansion/contraction is restrained, stresses above the yield strength of the material can result. Thermal shock usually occurs when a colder liquid contacts a warmer metal surface. As a result, the material can crack during cooling down to low/cryogenic temperatures. Section 1.2.3.4 thermal stress as a secondary stress and Fig. 1.17 may be used for thermal shock analysis.

Maximum heating and cooling rates during heat treatment in ASME (or most facility codes and standards) are the most common requirements to prevent thermal shock. See Table 4.114 in this book for the maximum heating and cooling rates from several codes.

Figure 2.136 shows a crack on core-to-core weld in cold box H/EX due to cyclic thermal stress in cryogenic service. ALPEMA (Brazed Aluminum Plate-Fin H/EX), 4.9.3 states: The caution applicable to start-up, also applies to shutdown. In particular, to prevent thermal shock, warm-up should be accomplished slowly at no more than the recommended rate of 2 °C per minute measured at a suitable location on the H/EX. As with warm-up, the manufacturer should be consulted if this rate is likely to be exceeded.

(a) Start-up
 Prior to start-up, cool-down of the H/EX is only permitted using gas (i.e., no liquid phase present). Cool-down should be carefully controlled to avoid thermal shocking of the H/EX and the connected pipework. A rate of 2 °C (3.6 °F)/minute maximum is normally recommended to allow for gradual dimensional adjustments but the manufacturer should be consulted if this rate is likely to be exceeded. With the agreement of the manufacturer, rates in excess of 2 °C (3.6 °F)/minute have been approved for certain H/EX applications. The cooling medium (gas) should be introduced to all streams simultaneously to prevent local thermal stresses developing. The medium, when introduced to the system, should not have a temperature difference greater than 30 °C (54 °F) relative to the local metal temperature. A record of all relevant data should be kept for each individual start-up. This will be required in the event of problems developing later in the life of the H/EX.

(b) Shutdown
 The cautions applicable to start-up above also apply to shutdown. In particular, to prevent thermal shocking, warm-up should be accomplished slowly at no more than the recommended rate of 2 °C (3.6 °F)/minute measured at a suitable location on the H/EX. As with start-up, the manufacturer should be consulted if this rate is likely to be exceeded.

Meanwhile, see Sect. 2.3.10.2 for Thermal Shock at elevated temperatures.

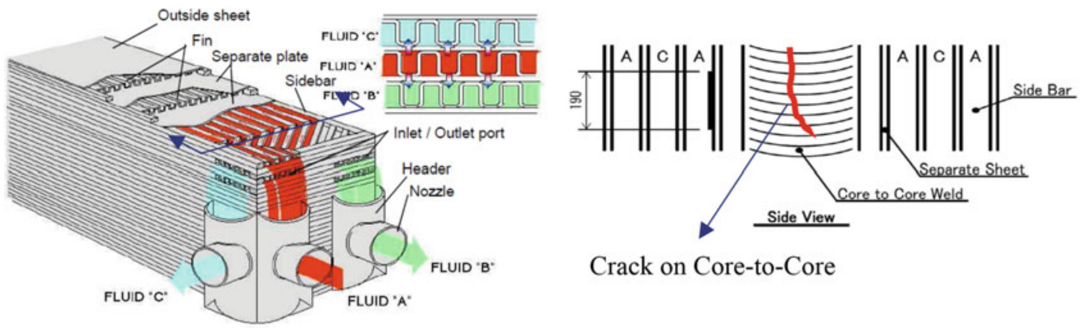


Figure 2.136 Crack on core-to-core weld in cold box

References for Thermal Shock Test

- MIL-STD-883/750/202
- ALPEMA

2.2.2 *Practical Requirements for Impact Test in Codes and Standards*

2.2.2.1 Minimum Required Absorbing Energy

The required absorbing energy depends on the material, YS, thickness, heat treatment (PWHT, N, or Q-T), etc. Minimum required absorbing energies are specified in the codes and standards, as below:

- ASME Sec.VIII, Div.1, Figure UG-84.1(M)
- ASME B31.3, Table 323.3.5
- ASTM A20, Table A1.15/A2.15 and A1.16/A2.16 for base metal of CS and LAS
- ASTM Materials Standards for LTCS and Cryogenic (A350, A333, A334, A420, A352, A203, A353, A553, A522, A765, etc.)
- API RP/TR 934 series (to evaluate the risk of temper embrittlement)
- API TR938-C for DSS

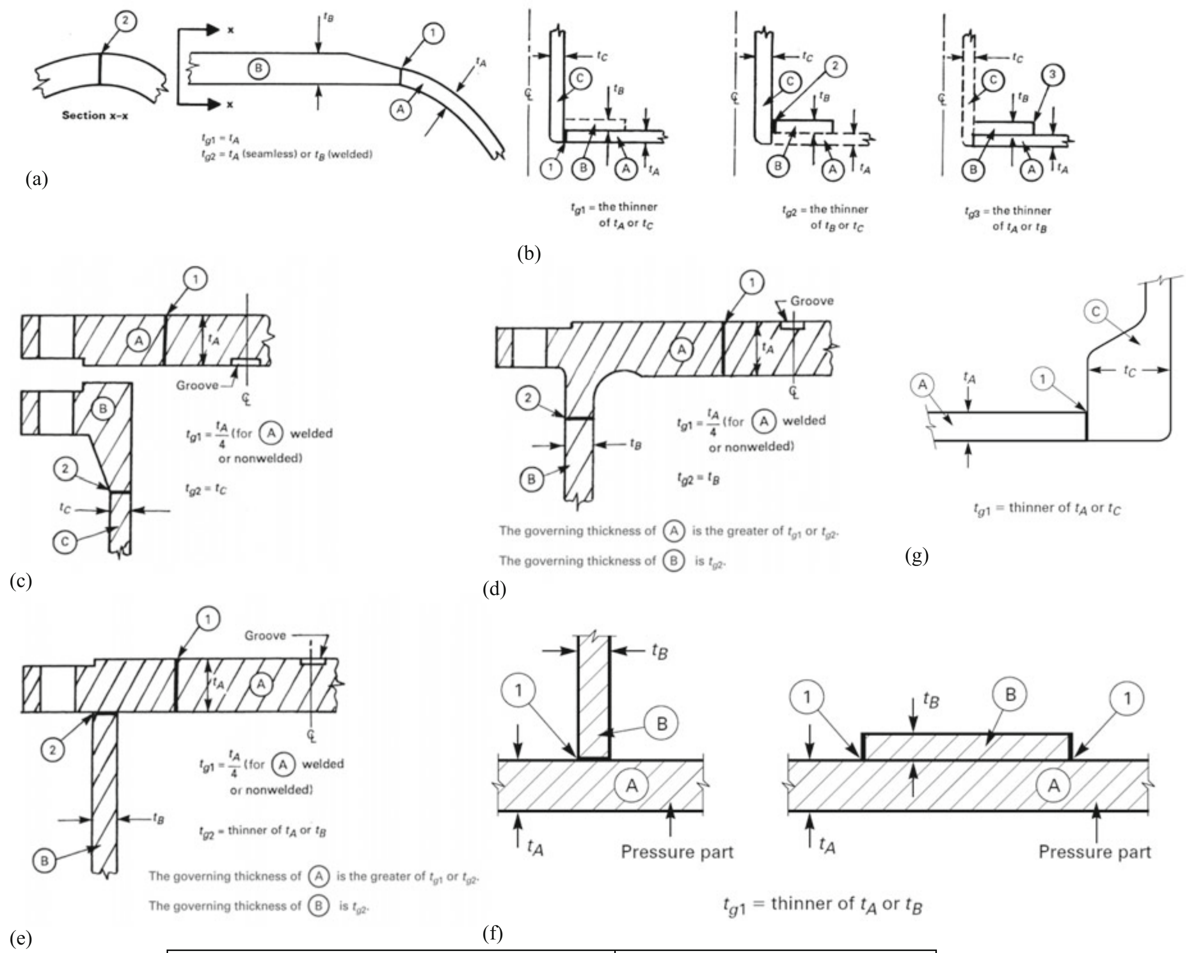
Normally, project specifications require more severe test conditions.

2.2.2.2 Governing Thickness (GT) to Define the Impact Test Requirements in Codes

ASME Sec. VIII, Div.1 & Div.2, define the GT as defined in (i) and (ii) above, and the MDMT.

(i) The following Governing Thickness (GT) definitions apply when using Fig. 2.137 in this book:
  (a) Excluding castings, the GT (tg) of a welded part is as follows:
    1. For butt joints except those in flat heads and tubesheets, the nominal thickness of the thickest welded joint [see Fig. 2.137a in this book].
    2. For corner, fillet, or lap-welded joints, including attachments as defined above, the thinner of the two parts joined.
    3. For flat heads or tubesheets, the larger of (−2) above or 25% flat component thickness
    4. For welded assemblies comprised of more than two components (e.g., nozzle-to-shell joint with reinforcing pad), the GT and permissible MDMT of each of the individual welded joints of the assembly shall be determined, and the warmest of the MDMT shall be used as the permissible MDMT of the welded assembly [See Fig. 2.137b in this book] – Sec. VIII, Div.1 only.
    5. If the GT at any welded joint exceeds 100 mm (4 in.) and the minimum design metal temperature is colder than 50 °C (120 °F), impact tested material shall be used – Sec. VIII, Div.1 only.
  (b) The GT of a casting shall be its largest nominal thickness.
  (c) The GT of flat nonwelded parts, such as bolted flanges, tubesheets, and flat heads, is 25% flat component thickness.
  (d) The GT of a nonwelded dished head [see Fig. 2.137c in this book] is the greater of 25% flat flange thickness or the minimum thickness of the dished portion.
  (e) If the GT of the nonwelded part exceeds 150 mm (6 in.) and the MDMT is colder than 50 °C (120 °F), impact-tested material shall be used.

(ii) Examples of the GT for some typical vessel details are shown in ASME Sec. VIII, Div.1, Fig. UCS-66.3.
  NOTE: The use of provisions in ASME Sec. VIII, Div.1, UCS-66 which waive the requirements for impact testing does not provide assurance that all test results for these materials would satisfy the impact energy requirements of ASME Sec. VIII, Div.1, UG-84 if tested.



Components	Governing Thickness (thinner of)
Nozzle Neck at Shell	tn or ts
Slip-on Flange and Nozzle Neck	tn or tf
Ring-type Flange and Nozzle Neck	tn or tf
Welding-neck flange and Nozzle Neck	tn
Long Welding-neck Flange	tn or ts
Non-welded Bolted Cover	¼ tc
Lap-type Joint Flange	tn or tf

Figure 2.137 Governing thickness to define the impact test requirements in ASME Sec. VIII, Div.1 & Div.2. (**a**) Butt welded components. (**b**) Welded connection with reinforcement plate added. (**c**) Bolted flat head or tubesheet and flange. (**d**) Integral flat head or tubesheet. (**g**) Integrally reinforced welded connection. (**e**) Flat head or tubesheet with a corner joint. (**f**) Welded attachments as defined in UCS-66(a)

API 650 (storage tanks) defines the GT for impact test requirements as seen in Fig. 2.138.

2.2.2.3 Subsize Specimen

Codes allow to use subsize specimen when the standard size (10 mm × 10 mm) is not available from the base metal. Figure 2.139 shows the subsize specimen for CVN impact test and general trend of the test curves. Tables 2.118 and 2.119 show the required energy values and CVN impact test reduction permitted in ASTM A333 pipe material. For subsize specimen, lower test temperature and lower absorbing energy are typically required compared to standard size. The standard subsizes of CVN impact test are somewhat different per code and standard, e.g., ASME BPV, ASME B31.3, ASTM A370, ASTM E23, ASTM E2248, etc. The number of CVN specimens in the cutting-map drawing should have some extra for small size tubular products because machining margin and thickness tolerance (especially seamless) should be considered.

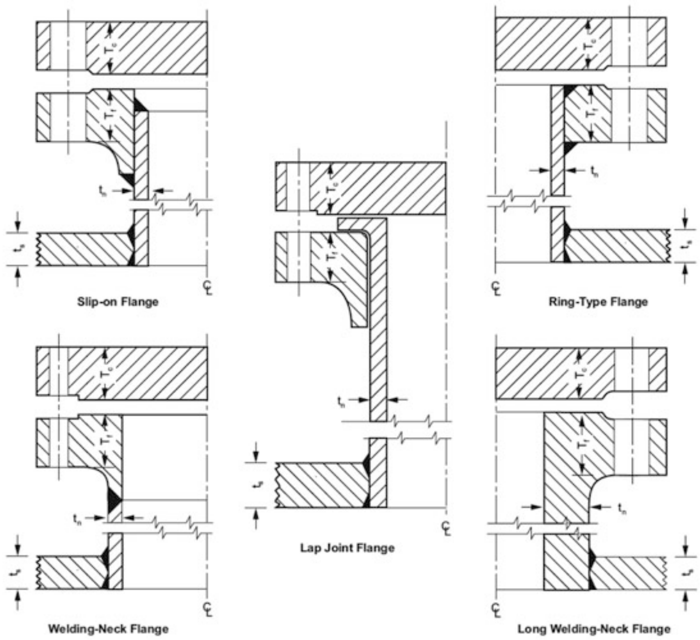


Figure 2.138 Governing thickness to define the impact test requirements in API 650 (storage tanks). Note 1. Shell reinforcing plate is not included in these illustrations. Note 2. ts = shell thickness; tn nozzle neck thickness, Tf flange thickness, Tc bolted cover thickness. Note 3. The governing thickness for each component shall be as follows (see above)

Components	Governing thickness (thinner of)
Nozzle neck at shell	tn or ts
Slip-on flange and nozzle neck	tn or Tf
Ring-type flange and nozzle neck	tn or Tf
Welding-neck flange and nozzle neck	tn
Long welding-neck flange	tn or ts
Nonwelded bolted cover	¼ Tc
Lap-type joint flange	tn or Tf

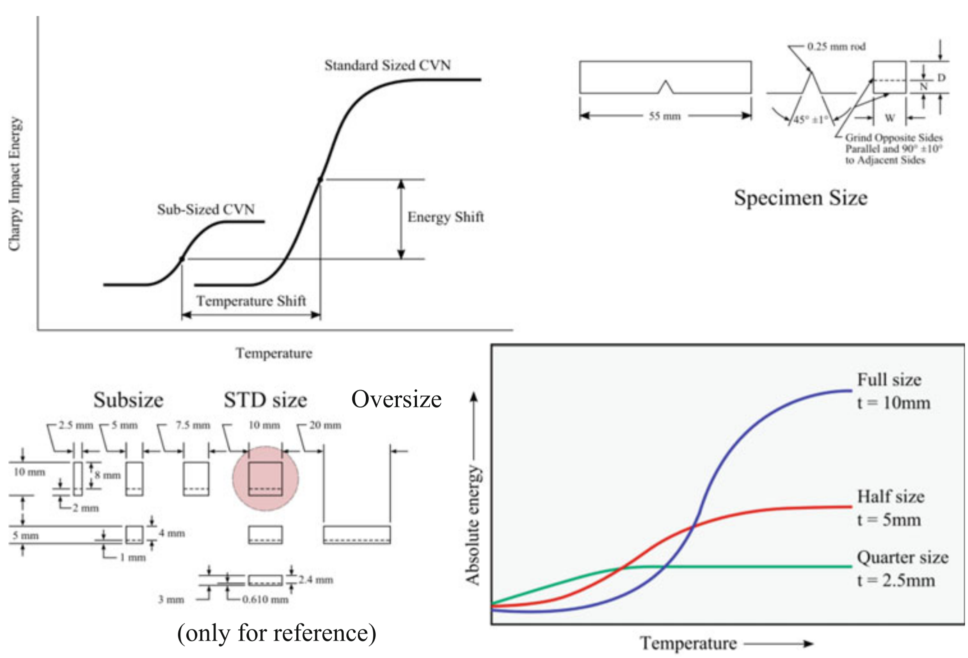


Figure 2.139 CVN impact test specimen and subsize. (Source: ASTM A370)

Table 2.118 Impact requirements for grades 1, 3, 4, 6, 7, 9, 10, and 11 of ASTM A333 for subsize specimen[3]

Size of specimen, mm	Min. average notched bar impact value of each set of 3 specimens[1]		Min. notched bar impact value of one specimen only of a set[1]	
	J	ft-lbf	J	ft-lbf
10 by 10	18	13	14	10
10 by 7.5	14	10	11	8
10 by 6.67	12	9	9	7
10 by 5	9	7	7	5
10 by 3.33	7	5	4	3
10 by 2.5	5	4	4	3

Notes for Tables 2.118 and 2.119
(1) Straight line interpolation for intermediate values is permitted.
(2) ASME B3.1.3 has decimal values in ( ) for °C
*ASME Sec.VIII, Div.1 states 6 °C
(3) Energy values in this table are for standard size specimens. For subsize specimens, these values shall be multiplied by the ratio of the actual specimen width to that of a full-size specimen, 10 mm (0.394 in.)
(4) ASME B3.1.3 states these temperature reduction criteria do not apply when lateral expansion for minimum required values specifies
(5) ASME Sec.VIII, Div.1:
The standard (10 mm × 10 mm) specimens, when obtainable, shall be used for nominal thicknesses of 11 mm (7/16 in.) or greater except below

For materials that normally have absorbed energy in excess of 240 J (180 ft-lbf) when tested using full size (10 mm × 10 mm) specimens at the specified testing temperature, subsize (10 mm × 6.7 mm) specimens may be used in lieu of full size specimens. However, when this option is used, the acceptance value shall be 100 J (75 ft-lbf) minimum for each specimen and the lateral expansion in mils (mm) shall be reported.

For material from which full size (10 mm × 10 mm) specimens cannot be obtained, either due to the material shape or thickness, the specimens shall be either the largest possible standard subsize specimens obtainable or specimens of full material nominal thickness which may be machined to remove surface irregularities

Where the largest possible test specimen has a width along the notch less than 8 mm (0.315 in.), the test shall be conducted at a temperature lower than the MDMT by the amount shown in Table 2.119 for that specimen width

Table 2.119 Impact temperature reduction for subsize specimen of ASTM A333/ASME B31.3/ASME Sec.VIII, Div.1[2][3][4][5]

Specimen width along notch or actual material thickness		Temperature reduction degrees colder[1]	
mm	inch	°C	°F
10 (standard size)	0.397	0	0
9	0.354	0	0
8	0.315	0	0
7.5 (3/4 standard size)	0.295	3 (2.8)	5
7	0.276	4 (4.4)	8
6.67 (2/3 standard size)	0.262	5* (5.6)	10
6	0.236	8 (8.3)	15
5 (1/2 standard size)	0.197	11 (11.1)	20
4	0.158	17 (16.7)	30
3.33 (1/3 standard size)	0.131	19 (19.4)	35
3	0.118	22 (22.2)	40
2.5 (1/4 standard size)	0.099	28 (27.8)	50

2.2.2.4 CVN Impact Test Exemption Curves

ASME Sec. VIII-Div.1, Figure UCS-66/66M, ASME Sec. VIII-Div.2, Figure 3.7/3.7M-see Fig. 2.135 in this book) & 3.8/3.8M, ASME B31.3, Fig. 323.2.2A allow to use the exemption curves of V-notch impact test requirements of CS or LAS in accordance with thin thickness, heat-treated steel (Q-T > N-T > N > PWHT: degree of more advantage of CVN impact test exemption), fine grain practiced, lower strength, killed, etc. These curves are not applied to the materials impact-tested mandatorily per the ASME/ASTM materials standards.

2.2.3 Material Classes in Low-Temperature and Cryogenic Services (Table 2.120)

Cryogenics is a broad field that encompasses several analogous disciplines as below:

– Cryonics: Cryonics is the cryopreservation of animals and humans with the goal of reviving them in the future.
– Cryosurgery: This is a branch of surgery in which cryogenic temperatures are used to kill unwanted or malignant tissues, such as cancer cells or moles.
– Cryoelectronics: This is the study of superconductivity, variable-range hopping, and other electronic phenomena at low temperatures. The practical application of cryoelectronics is called cryotronics.
– Cryobiology: This is the study of the effects of low temperatures on organisms, including the preservation of organisms, tissue, and genetic material using cryopreservation.

However, cryogenic service is used for extremely low temperatures by Liquefaction Temperatures of Gases.

2.2.4 Summary of Code Applications for Low Temperature (Table 2.121)

References for Low-Temperature Materials (Other than ASME)

– EEMUA Publ.192 for "Guide for The Procurement of Valves for Low Temperature, 0 to -50°C (32 to -58°F)"
– ASTM A320/A333/A334/A352/A420/A480/A522/A524/A571/A662/A671/A707/A736/A738/A757
– MSS SP134 Valves for Cryogenic Service Including Requirements for Body/Bonnet Extensions
– BS 6364 Valves for Cryogenic Service

Table 2.120 Liquefaction temperatures of gases and candidate materials(1)

Gas	Liquefaction temperature °C	Liquefaction temperature °F	Candidate materials
Ammonia (NH_3)	−33.4	−28.1	Carbon steels
Propane (LPG)	−42.1 to −45.5	−43.8 to −49.9	Fine grain Al-killed steel
Propylene (C_3H_6)	−47.7	−53.9	2 ¼ Ni Steel(1)
Carbon disulfide (CS_2)	−50.2	−58.4	
Hydrogen sulfide (H_2S)	−59.5	−75.1	3 ½ Ni Steel(2)
Carbon dioxide (CO_2)	−78.5	−109.3	
Acetylene (C_2H_2)	−84.0	−119.2	
Ethane (C_2H_6)	−88.4	−127.1	
Ethylene (C_2H_4)	−103.8	−154.8	5-9* Ni Steel(3) *9Ni: impact tested at −196℃
Krypton (Kr)	−151	−239.8	
Methane (LNG)	−163	−261.4	
Oxygen (O_2)	−182.9	−297.2	
Argon (Ar)	−185.9	−302.6	
Fluorine (F)	−188.1	−306.6	
Nitrogen (N_2)	−195.8	−320.4	Austenitic stainless steels (ASS)
Neon (Ne)	−246.1	−411.0	
Heavy hydrogen (nH_2)	−249.6	−417.3	Aluminum alloys
Hydrogen (H_2)	−252.8	−423.0	
Helium (He)	−268.9	−452.0	

Notes
(1) Definitions of Cryogenic Temperature/Fluid in Several Standards
; BS 6364 (Cryogenic Service Valves): ≤ −50 °C (−58 °F)
; NFPA 55 (Compressed Gasses and Cryogenic Fluids Code): ≤ −90 °C (−130 °F)
; MSS SP-134 (Valves for Cryogenic Service): ≤ −100 °C (−150 °F)
; EIGA and OIML (Gas Association): ≤ −153 °C (−243 °F)
; U.S. NIST (National Institute of Standards and Technology): ≤ −180 °C (−292 °F)
(2) Use of ASS is preferable because of easy brittle failure of 2–3.5 Ni steels
(3) Use of ASS except 9Ni steel for cryogenic storage tanks is preferable because of easy brittle failure of 5–9 Ni steels

Table 2.121 Paragraphs for impact test requirements in ASME Sec. VIII, Div. 1

Remarks	Code reference
Some materials and welds do not require impact test: See paragraphs in Code Subsection C to which material applies.	UG-20, UCS-66, UCS-67, UCS-68 Figure UCS-66, UCS-66.1 UHA-51, UCL-27
When impact tests are required, weld metal and HAZ must have impact tests.	UNF-65, UG-84, Appendix NF-6 UHT-5, Part UF
Low-temperature vessels.	Part ULT
Welded CS vessels must be postweld heat-treated unless exempted from impact tests.	UCS-66, UCS-68
All longitudinal and girth seams must be double-welded butt joints or the equivalent.	UW-2
Remove backing strip on long seams if possible.	Table UW-12
Vessels must be stamped according to Code requirements.	UG-116
ASS may not require impact tests, providing weld procedure specifications also included qualified impact test plates of the welding procedure.	UG-84, UHA-51, UHA-52
All joints of Category A must be Type 1 or 2 of Code Table UW-12.	UW-2(b), UW-3
All joints of Categories B must be Type 1 or 2 of Code Table UW-12.	UW-2(b)
All joints of Categories C and D must be full penetration welds.	UW-2(b)
Brazed vessels.	UB-22, UG-84
High-alloy vessels.	UHA-105
Nonferrous vessels.	UNF-65, NF-6

– EN 13458-1/2, Cryogenic Vessels
– ISO/TC 220 Standards (ISO 20421/21009/21029/21011/21012/21013/24490/21010/21028/21014/23208)– Cryogenic Facilities
– MIL-HDBK-5H, Metallic Materials and Elements for Aerospace Vehicle Structures
– Society of Automotive Engineers, Special Publication SP-61
– ALPEMA, The Standards of the Brazed Aluminum Plate-Fin H/EX Manufacturer's Association

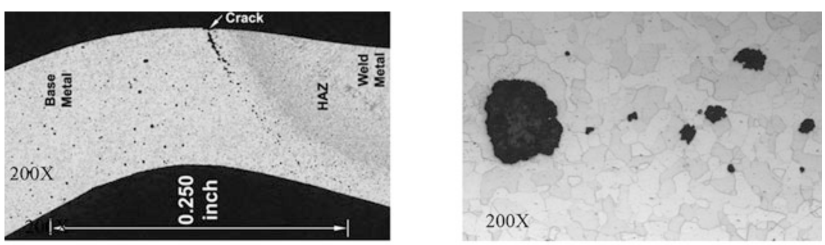
2.3 Metal Loss and Degradation of Metals in High Temperature

Most ferritic steels or alloys can be exposed to metal loss or strength degradation at >400–600 °C (750–1110 °F). See Sect. 2.4.3 for corrosion and prevention for high-temperature service. See Sect. 1.3.3 for Larson Miller parameter (LMP) and Hollomon (or Hollomon-Jaffe) parameter (HJP) for effects of high-temperature operation and various heat treatments.

2.3.1 Graphitization and Spheroidization from Operation in Elevated Temperature

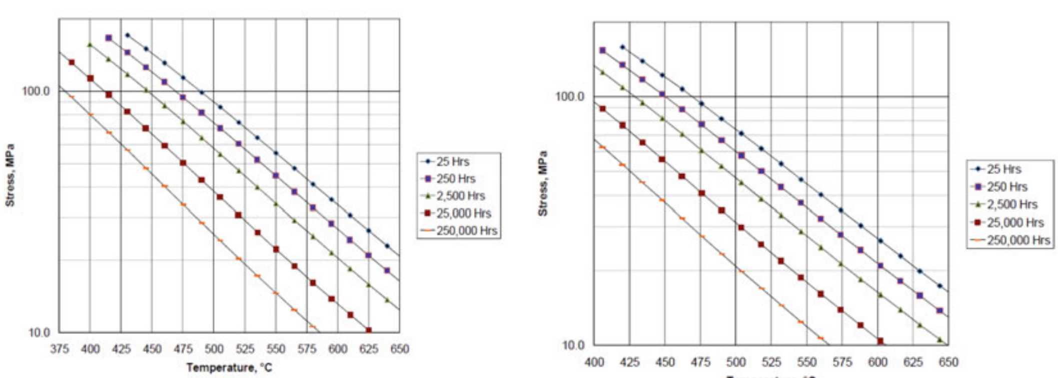
The carbon and low-alloy steels (LAS) resulting from long-term exposure to 425 °C (797 °F) and above can result in several kinds of microstructural deterioration; e.g., creep, carbide coarsening, spheroidization, and graphitization (Fig. 2.140). Although graphitization causes a moderate reduction of strength of the metal (Figs. 2.141 and 2.142), it can be a direct cause of premature (or catastrophic) failure in equipment and piping.

Graphitization is essentially confined to carbon steel, or CS (C–Mn, C–Si, and C–Mn–Si), and to C–1/2Mo steel exposed to service temperatures above about 425 °C and 470 °C (797 °F and 878 °F), respectively. Graphitization has been found in low-alloy C-Mo steels with up to 1% Mo and less than 0.7%Cr. Graphitization occurs when iron carbide (FeC) that is mainly in the pearlite phase (α + FeC) decomposes into the true equilibrium structure of ferrite (nearly pure Fe) and graphite (C) [$Fe_3C \rightarrow 3Fe + C$] as shown in Fig. 2.140. The formation of graphite particles or nodules, if dispersed throughout the metal, is not considered a problem, because there is no aligned plane of weakness. The carbon and low-alloy steels resulting from long-term exposure to 425 °C (797 °F) and above can result in several kinds of microstructural deterioration; e.g., creep, carbide coarsening, spheroidization, and graphitization. Graphite itself has very little strength (Figs. 2.141 and 2.142), and the linking together of graphite nodules and flakes into planes or chains causes embrittlement and a corresponding sharp decreases in ductility and toughness. Therefore, if they form in a continuous plane, graphitization can make a material susceptible to premature failure from mechanical and thermal shock. The two regions most prone to the unfavorable alignment are weld HAZ and cold-worked areas. During welding, decomposition of the pearlite phase tends to become unstable in the portion of the HAZ heated above the lower transformation temperature of approximately 725 °C (1337 °F), setting the stage for subsequent graphitization in a narrow aligned band. Cold work can occur in bends, in tubes straightened with a rotary straightener at the tube mill (spiral pattern of cold work), or from significant dings to the surface, again creating planes for formation of preferentially aligned graphite.



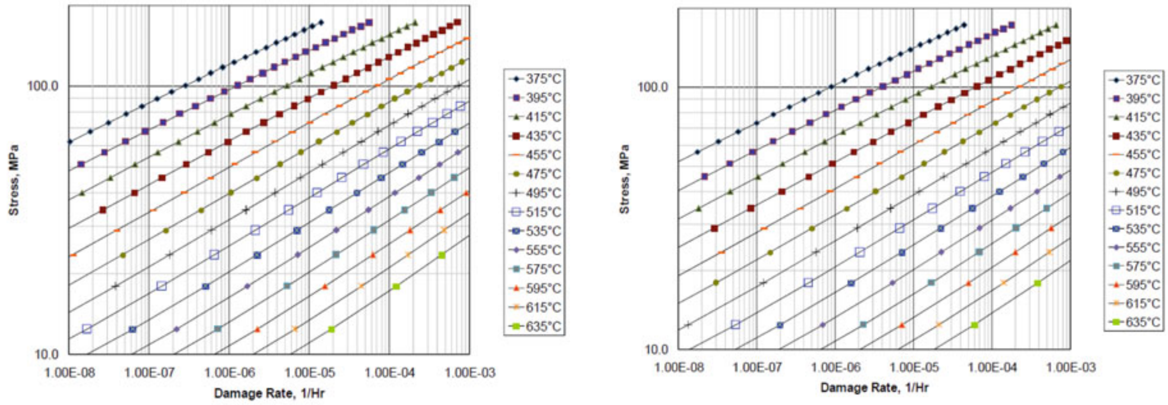
(a) (b)

Figure 2.140 Graphite microstructure. (Source: NACE Paper 05558 & 05559). (**a**) Crack-Initiated Graphites of CS Welds (5%Nital). (**b**) Typical Graphite Nodules of CS (3%Nital)



(Not Graphitized) (Graphitized)

Figure 2.141 Screening curves of level 1 Screening Criteria for CS (API 579–1/ASME FFS-1, Fig. 10.3 M/4 M)



(Not Graphitized) (Graphitized)

Figure 2.142 Damage curves of level 1 screening criteria for CS (API 579–1/ASME FFS-1)

Above approximately 552 °C (1025 °F), spheroidization will begin to occur before steel can become fully graphitized, while at temperatures below 552 °C (1025 °F), graphitization is the more dominant mechanism and is expected to develop earlier than spheroidization. At temperatures greater than 552 °C (1025 °F), carbides in carbon steels and C-0.5Mo may agglomerate or spheroidize, leading to reductions in strength of up to 30% and some increases in ductility. Spheroidization can also decrease a material's creep and stress-rupture life. Spheroidization is primarily a function of temperature, time, and the microstructure of the steel.

It was formerly believed that the deoxidation practice of either silicon (Si) or aluminum (Al) killing affected the propensity toward graphitization, with Al-killed steels being more vulnerable. The role of deoxidation practice is now thought to be of secondary importance.

Table 2.122 shows maximum metal temperatures (MMT) as given in ASME and API codes for carbon steel and C- ½ Mo steel to avoid graphitization.

Table 2.122 Maximum metal temperatures in ASME and API for CS and C-0.5Mo steel

Material	Codes & standards	Location of relative stress values	MMT-short term exposure, °C (°F)	MMT-long term exposure, °C (°F)	Remark
CS	ASME Sec. VIII, Div.1	ASME Sec. II-D, Table 1A	538 (1000)	427 (800)	(1)
CS	ASME B31.1	Table A-1	427 (800)	413 (775)	(2)
CS	ASME B31.3	Table A-1	593 (1100)	427 (800)	(3)
CS	ASME Sec. I	ASME Sec. II-D, Table 1A	538 (1000)	427 (800)	(1)
CS	ASME Sec. VIII, Div.2	ASME Sec. II-D, Table 2A	371 (700)	–	–
CS	API 530/ISO 13704	Figure F.2	538 (1000)	–	(4)
C-1/2Mo	ASME Sec. VIII, Div.1	ASME Sec. II-D, Table 1A	538 (1000)	468 (875)	(5)
C-1/2Mo	ASME B31.1	Table A-2	454 (850)	468 (875)	(6)
C-1/2Mo	ASME B31.3	Table A-1	593 (1100)	468 (875)	(7)
C-1/2Mo	ASME Sec. I	ASME Sec.II-D, Table 1A	538 (1000)	468 (875)	(5)
C-1/2Mo	ASME Sec.VIII, Div.2	ASME Sec.II-D, Table 2A	371 (700)	–	–
C-1/2Mo	API 530/ISO 13704	Figure F.3	538 (1000)	–	(4)

Notes

(1) ASME Sect. II-D, Table 1A, Note G10: Upon prolonged exposure to temperatures above 427 °C (800 °F), the carbide phase of CS may be converted to graphite. See Nonmandatory Appendix A, A–201 and A–202 in Sec. II-D

(2) ASME B31.1, Table A-1, Note (2): Upon prolonged exposure to temperatures above 427 °C (800 °F), the carbide phase of CS may be converted to graphite

(3) ASME B31.3, Table A-1, Note (57): Conversion of carbides to graphite may occur after prolonged exposure to temperatures over 427 °C (800 °F). See para. F323.4(b)(2) in B31.3

(4) API 53,0 Table 4 states that other considerations may require lower operating-temperature limits such as oxidation, graphitization, carburization, and hydrogen attack. These factors shall be considered when furnace tubes are designed

(5) ASME Sect. II-D, Table 1A, Note G11: Upon prolonged exposure to temperatures above 468 °C (875 °F), the carbide phase of C-Mo steel may be converted to graphite. See Nonmandatory Appendix A, A–201 and A–202 in Sec. II-D

(6) ASME B31.1, Table A-2, Note (2): Upon prolonged exposure to temperatures above 468 °C (875 °F), the carbide phase of C-Mo steel may be converted to graphite

(7) ASME B31.3, Table A-1, Note (58): Conversion of carbides to graphite may occur after prolonged exposure to temperatures over 468 °C (875 °F). See para. F323.4(b)(3)

References

- ASME Sec. II, Part D, A-201 (graphitization) and A-202 (spheroidization)
- API 579–1/ASME FFS-1, Fitness-For-Service
- API 530, Calculation of Heater Tube Thickness in Petroleum Refineries, American Petroleum Institute
- API RP571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry
- J.G. Wilson, *Graphitization of steel in petroleum refining equipment and the effect of graphitization of steel on stress-rupture properties, WRC Bulletin 32*, Jan.1957
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- NACE Paper 07380, 05999, 05558, 89248.

2.3.2 Temper Embrittlement from Operation in Elevated Temperatures

Temper embrittlement refers to the decrease in toughness due to a metallurgical change that can occur in some LAS as a result of long-term exposure in the temperature range of about 343–593 °C (650–1100 °F). This change causes an upward shift in the ductile-to-brittle transition temperature as measured by CVN impact testing. Although the loss of toughness is not evident at operating temperature, equipment that is temper embrittled may be susceptible to brittle fracture during startup and shutdown. See Sect. 2.1.4.2(c) for more details.

2.3.3 Sigma (σ) Phase Embrittlement from Operation in Elevated Temperature

Formation of a metallurgical phase known as sigma phase can result in a loss of fracture toughness and ductility in some SS as a result of high temperature exposure. Sigma phase is a nonmagnetic intermetallic phase composed mainly of Fe and Cr, which forms in FSS, ASS, and DSS during exposure at 538–1093 °C (1000–2000 °F). As a result, below 260 °C (500 °F) cracking could occur if the components were impact loaded or excessively stressed during maintenance work. See Sect. 2.1.6.5 for more details.

2.3.4 475 °C (885 °F) Embrittlement from Welding, Heat Treatment, and Operation in Elevated Temperature

It is a loss in toughness due to a metallurgical change that can occur in alloys containing a ferrite phase (FSS or DSS), as a result of exposure in the temperature range 316–540 °C (600–1000 °F). A primary consideration is operating time at temperature within the critical temperature range. Damage is cumulative and results from the precipitation of an embrittling intermetallic phase that occurs most readily at approximately 475 ± 70 °C (885 ± 126 °F). Additional time is required to reach maximum embrittlement at temperatures above or below 475 °C (885 °F) as increased the Cr content in FSS or DSS. For example, many thousands of hours may be required to cause embrittlement at 316 °C (600 °F). See Sect. 2.1.6.4 for more details.

2.3.5 Degradation by Hot Work

The hot work above Lower Critical Phase Transformation Temperature (LCPTT) for most commercial metals will provide the recrystallization and grain growth of the metallic structure. Also, hot work may create secondary precipitations which are prone to loose corrosion resistance, toughness, and strength. As a result, the mechanical, metallurgical, and/or physical properties cannot meet the design condition. See Sects. 3.1.4.2 and 4.2 for more details.

2.3.6 Liquid Metal Embrittlement (LME) from Welding and Operation

2.3.6.1 Phenomena

LME is a phenomenon of practical importance, where certain ductile metals experience drastic loss in tensile ductility or undergo brittle fracture when tested in the presence of specific liquid metals with low melting temperature. Typically, LME is a form of cracking that results when certain molten metals come in contact with specific alloys. Cracking can be very sudden and brittle in nature. The practical significance of liquid metal embrittlement is revealed by the observation that several steels experienced ductility losses and cracking during hot dip galvanizing or during subsequent fabrication. LME effects also can be observed even in solid state, when one of the metals is brought close to its melting point; e.g., cadmium-coated parts operating at high temperature.

Table 2.123 Some LME couples susceptible to embrittlement

Susceptible alloys	Molten metal	Exposure conditions
CS	Zinc, Copper, Cadmium,	Hip-Dip Galvanizing, Welding, Long-time Aging at high temperature
300 Series SS	Zinc, Copper, Cadmium, Lead	Welding in contamination with molten metals
Copper Alloys	Mercury	Operation under broken manometers/ thermometers. Under mercury salts
Alloy 400	Mercury	Operation, Welding
Aluminum Alloys	Mercury, Indium, Tin, Zinc, Gallium	Operation, Welding
High Strength Steels	Cadmium, Lead	Operation, Welding
Gr.91 Steel	Lead-Bismuth	Operation, Welding
Titanium Alloys	Cadmium, Mercury	Operation, Welding

ASM Metal Handbook, vol.13 series, API RP571 modified
Note: Nickel alloys are susceptible to a LME caused by the nickel-nickel sulfide eutectic that forms at 625°C (1157°F).

2.3.6.2 Affected Materials and Critical Factors

Carbon steel, low-alloy steels, high-strength steels, 300 Series SS, nickel alloys, copper alloys, aluminum alloys, and titanium alloys are susceptible to LME as shown in Table 2.123.

The following factors will be critical concerns for LME:

(a) LME occurs in very specific combinations of metals in contact with low-melting-point metals such as zinc (Zn), mercury (Hg), cadmium (Cd), lead (Pb), copper (Cu), and bismuth (Bi). Typical combinations of industrial significance are shown in Table 2.123.
(b) High tensile stress promotes cracking and its crack propagation rates; however, cracking can initiate simply through contacting the molten metal with the susceptible alloy. Very small quantities of the low-melting-point metal are sufficient to cause LME. Cracking under load can be extremely rapid such that cracks may pass through the wall within seconds of contact with the molten metal.
(c) Cracking can occur after long periods of time when contaminated surfaces are exposed to liquid metals.
(d) A susceptible metal in contact with a low melting metal at low temperature may crack later when the (temperature rises above the melting temperature of the low melting alloy or compounds.

2.3.6.3 Prevention and Mitigation

(a) LME can only be prevented by protecting metal substrates from coming into contact with the low melting metal. For example, galvanized steel components should not be welded to 300 Series SS. 300 Series SS should be protected to avoid contact with galvanized components and overspray from zinc and inorganic zinc coatings. A fully stress-relieved condition of the base metal before galvanizing is required to mitigate LME.
(b) Once cracking from LME has initiated, the material should not be used because grinding out the affected area is not an acceptable fix. Also, see Sect. 2.1.6.6 for more details of zinc embrittlement (LME) in austenitic stainless steels (ASS) and Sects. 2.1.7.3(c) and 4.11.9.3 mercury embrittlement in aluminum alloys.

References

- API RP571 & RP580
- ASME Sec. II, Part D, A-312
- WRC Bulletin 488, 489, 490 Damage Mechanisms Affecting Fixed Equipment in Several Industries
- ASM Metal Handbook, Vol.13 series and Stainless Steel Metal Handbook
- ALPEMA, 8.3.2
- NACE Paper 19-12700, 17-9192, 16-7556, 14-3993/4124, 13-2519, 11298, 10294, 04558, 03659, 99219, 99202, 99097, 98255, 97522, 94128, 89106
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- R. Coade et al., The interaction of mercury and aluminum in H/EXs in a natural gas plants. Int. J. Press. Vessels Piping. **83**, 336 (2006)

– N. Eckersley, Advanced mercury removal technologies. Hydrocarb. Proc. 29–35 (2010)
– See the references in Sect. 2.1.6.6 for Zinc Embrittlement (LME) in SS

2.3.7 Solidification Crack (Hot Crack or Liquation Crack) from Welding

Both solidification cracking and hot cracking (or liquation cracking) are to form shrinkage cracks during the solidification of fusion weld metal. Solidification cracks can appear in several locations and orientations, but most commonly appear as longitudinal centerline cracks. See Sects. 2.1.6.1 and 4.2.8 for more details on stainless steel, and Sect. 4.2.7 for more details on carbon steel.

2.3.8 Reheat Cracking (or Stress Relaxation Cracking-SRC)

Cracking of a metal due to stress relaxation during heat treatment (normally in field) or in service at elevated temperatures. It is most often observed in heavy wall sections which are exposed to 400 °C (750 °F) and above. Type of material (chemical composition and impurity elements of Cr-Mo steels; ASS H grades, i.e., 304H/316H; stabilized ASS, i.e., 321/347 SS; some nickel alloys, i.e., Alloy 800H/HT, Alloy 617, HP modified, etc.), grain size, residual stresses from fabrication (i.e., cold working, welding), section thickness (which controls restraint and stress state), notches and stress concentrators, weld metal and base metal strength, and welding and heat treating conditions are the critical factors of reheat cracking. Reheat cracking is also called stress relief cracking (SRC), creep embrittlement, low creep ductility cracking, and stress-induced/assisted cracking in accordance with the failure mode. See the following paragraphs in this book for more details.

– Cr-Mo Steels: Sect. 2.1.4.2(d)
– Stainless Steels: Sect. 2.1.6.9 and ASME Sec. II, Part D, A-206, and API TR942-B.

2.3.9 Creep and Rupture from Operation at Elevated Temperatures

As one of the aging effects, at high temperatures, metal components can slowly and continuously deform under load below the yield stress. This time-dependent deformation of stressed components is known as creep. As a result, early rupture can be reached. See Sect. 1.3.3, API RP571, API TR942-B, and API 530 for more details.

2.3.10 Thermal Fatigue/Shock from Operation in Elevated Temperature

2.3.10.1 Thermal Fatigue

Thermal fatigue is the result of cyclic stresses caused by variations in temperature (swing and frequency). There are two types of stresses: high cycle and low cycle. Damage is in the form of cracking that may occur anywhere in a metallic component where relative movement or differential expansion is constrained, particularly under repeated thermal cycling (i.e., coke drums in refinery delayed coker unit). See Sect. 1.3.2 for more details.

See Sect. 2.4.2.11 for Fatigue Corrosion.

2.3.10.2 Thermal Shock at Elevated Temperature

Typically, thermal shock occurs due to different amounts of thermal expansion in different parts (i.e., inside and outside). This differential expansion can be recognized as a stress or strain, equivalently. Once this stress exceeds the strength of the material, it will cause the material’s structure to fail.

Normally the following methods can reduce or minimize a thermal shock failure:

– Reducing the thermal gradient seen by the object, by changing its temperature more slowly or increasing the material’s thermal conductivity. Especially for thick walls, the temperature gradient between internal and external surfaces should be minimized.
– Reducing the material’s coefficient of thermal expansion (to avoid austenitic microstructure if possible).
– Increasing its strength (to make up for the loss of tensile strength).
– Introducing built-in compressive stress, e.g., in tempered glass.
– Decreasing its Young’s modulus (same theory as the method of fatigue stress reduction in Fig. 1.9).
– Increasing its toughness, by crack tip blunting (i.e., plasticity or phase transformation) or crack deflection (higher elongation, killed steel, normalized steel preferable).

See Sect. 2.2.1.13 for the details on thermal shock at low temperature.

2.4 Corrosion Types and Their Prevention

2.4.1 General/Localized Corrosion and Corrosion Allowance

2.4.1.1 Classes by Corrosion Mechanism

Figure 2.143 shows types of several corrosion mechanisms which have uniform, localized, and stress corrosion cracking (SCC) modes. Figure 2.144 indicates the typical rust grades on uncoated steel surfaces and on stored steel surfaces. See ASME Sec. II, Part D, A-702 and NACE SP0472 for Overall of Hydrogen Damage (e.g., Hydrogen Embrittlement-HE, Hydrogen-Induced Cracking-HIC, Cracking from The Precipitation of Internal Hydrogen, Hydrogen Attack, Cracking from Hydride Formation). See NACE SP0177 for AC (Alternating Current) corrosion for buried metallic facilities. Table 2.124 shows the mechanisms of several corrosion.

See ASTM G161 for Standard Guide-Corrosion Related Failure Analysis and API RP970 for Corrosion Control Documents.

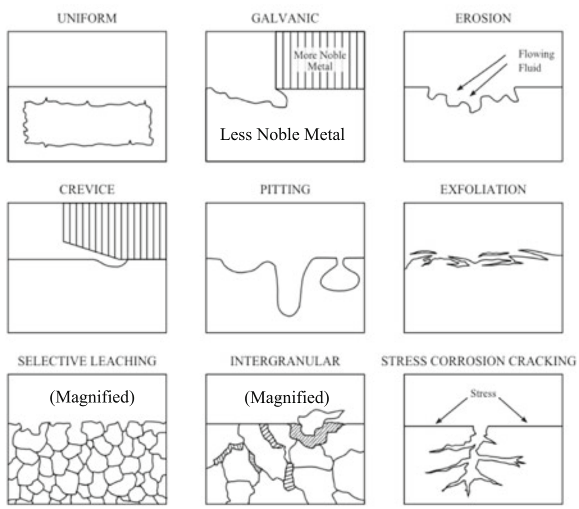
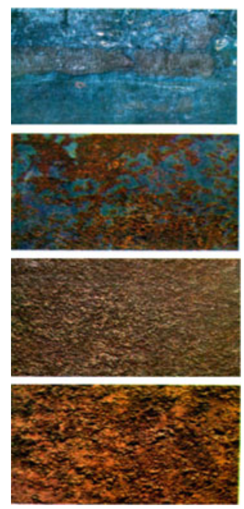


Figure 2.143 Common types of corrosion



; Steel surface largely covered with adhering mill scale but little, if any, rust.

; Steel surface which has begun to rust and from which the mill scale has begun to flake.

; Steel surface on which the mill scale has rusted away or from which it can be scraped, but with slight pitting visible under normal vision.

; Steel surface on which the mill scale has rusted away and on which general pitting is visible under normal vision.

Figure 2.144 Rust grades. (Source: ISO 8501)

Table 2.124 (1/3) Mechanisms and the comparison of general or localized corrosion

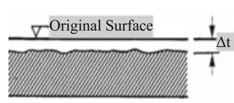
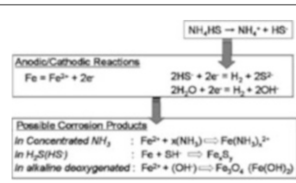
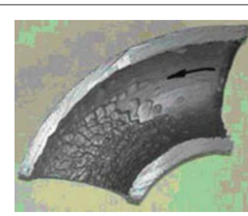
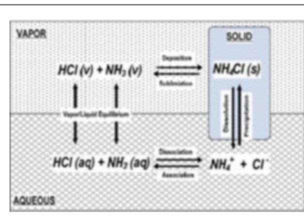
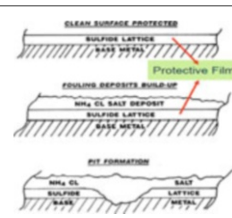
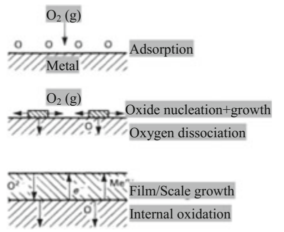
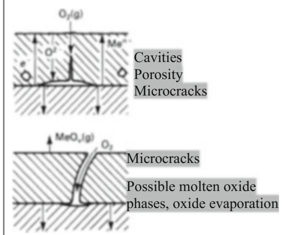
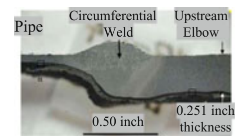
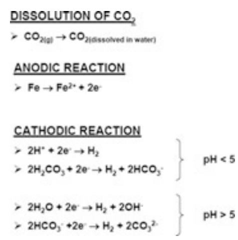
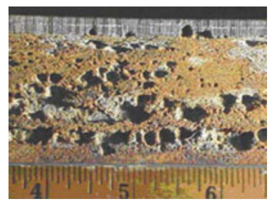
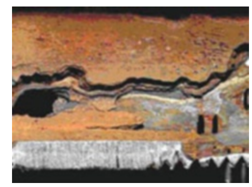
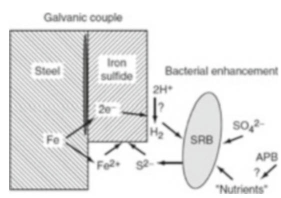
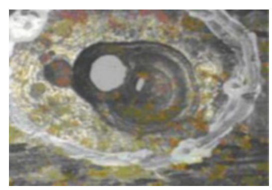
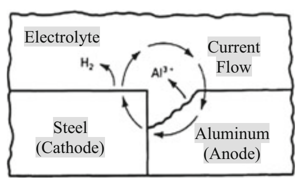
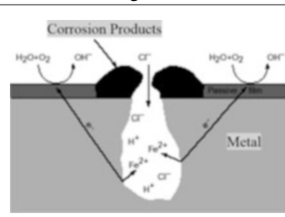
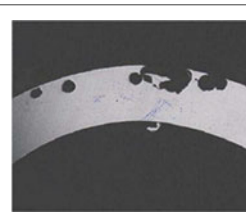
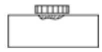
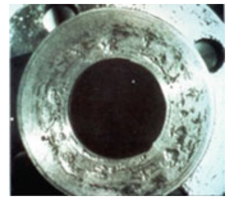
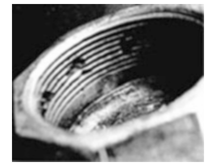
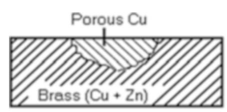
Classes	Factors of severity in ferritic steels	Corrosion mechanisms	Phenomena (photos)	
(1) Uniform corrosion	Service (concentration), pH, temperature, velocity, dissolved oxygen, chlorides, phase See Sect. 2.4.1.2 for more details			
(2) Alkaline sour water corrosion	pH, temperature, velocity, alkaline concentration (NH4HS, etc.) NACE Paper 00702/ 07576/ 10356 API RP571			
(3) Acidic sour water corrosion	pH, temperature, velocity, dissolved oxygen, chlorides (NH4Cl), phase NACE paper 10359/ 02477 API RP571			

Table 2.71 (2/3) Mechanisms and typical photos of general or localized corrosion

Classes	Factors of severity other than material	Corrosion mechanisms	Phenomena (photos)	
(4) High-temperature oxidation	Temperature, oxygen contents at 480 °C (900 °F) and above per material. See Sect. 2.4.3.1 for more detail information			
(5) High-temperature Sulfidation	Total sulfur, naphthenic acid at 232 °C (450 °F) and above per material (ferrous metal) See Sect. 2.4.3.5 for more detailed information	S and H_2S -H_2 free, or H_2S-H_2 Naphthenic acid can be synergy effect for corrosion.		
(6) Carbonic acid (wet CO_2) corrosion	CO_2 partial pressure, condensed water (carbonic acid), pH for ferrite steels at 150 °C (300 °F) and below See Sect. 2.4.1.5 for more detailed information			
(7) Micro-biological induced corrosion (MIC)	Sulfates, contaminated water, stagnant flow (velocity), temperature for mostly ferrite steel (but occasionally to ASS & DSS as well) at 20 °C (68 °F) to 40 °C (104 °F) mostly, but sometimes reported at 40–70 °C (104–158 °F) See Sect. 2.4.1.4 for more detailed information	 FeS corrosion cell created by the action of SRB		
(8) Galvanic corrosion-severe corrosion on low grade materials in dissimilar metal contact	Galvanic potential, solution, contact area ratio, CP at 150 °C (300 °F) and below See Sects. 2.4.1.3 general, 2.1.6.10 due to SS, and Table 2.138(4) H/EXs for more detailed information			
(9) Erosion/cavitation corrosion In high velocity (turbulent flow)	Flow pattern, impact velocity, impinging angle/pipe bend, wall shear stress-surface roughness/pipe diameter, hardness of target material, density of particle and fluid, flow rate of particle, phase of service, cavitation effect, corrosive components, service temperature, etc. See Sect. 2.4.5 for more detailed information	Typically, $Vc = 4.3.\ H^{2.5}.\ J^2.\ \rho$-0.5 at low particle velocity ($Vp < Vc$) ;Vc = critical velocity to keep Erosion resistance ; H = hardness of target material ; J = parameter of the elastic Modulus of target material ; P = density of impacting particle ; Vp = critical velocity to prevent plastic deformation/ cracking		 See Sect. 2.4.5 for more details
(10) Pitting corrosion in chloride solution, rich oxygen, wet CO2 environment, etc. Can be developed to SCC.	Passivation film, halides (e.g., chlorides), condensed water, more severe in crevice environment, pH, temperature, etc. see Sect. 2.4.2.4 and 2.4.2.5 alkaline, Sect. 2.4.2.6 PTASCC, Sect. 2.4.2.7 CLSCC, Sect. 2.1.6.2 ASS, Sect. 2.4.4.6 tests for more detail information.			

Other than Cracking Mode. (Sources: several API, NACE, MTI,, ASM H/B, etc.)

Table 2.124 (3/3) Mechanisms and typical photos of general or localized corrosion

Classes	Factors of severity other than material	Corrosion mechanisms	Phenomena (photos)	
(11) Crevice corrosion joint of tube to tubesheet, gasket contact face of flange, or bolting	 Crevice between two materials  Crevice between metal and deposit – See Sect. 2.1.6.2(b) for more details	 Tube to Tubesheet	 Flange gasket face	 Bolting inside – Seal welding and/or use CRA materials
(12) Exfoliation (lamellar or stratified rust layers)	Oxygen, wet-dry cycling service, material (e.g., leafing of rolled or extruded aluminum guardrail, 70-80Cu-30-20Ni alloys, etc.). Often found next to fasteners where an electrically insulating sealant or a sacrificial Cd plating has broken down, permitting a galvanic action between the dissimilar metals	 Initiation along planes parallel to the surface, generally at grain boundaries, giving rise to a layered appearance		– Appropriate coatings – Selecting a more exfoliation-resistant aluminum alloy (aluminum alloys are particularly susceptible to this type of corrosion) – Heat treatment to control precipitate distribution
(13) Selective leaching corrosion, e.g., dezincification of brass	[Mechanisms] 1. Zn has weaker atomic bonds than Cu. 2. Cu is more noble than Zn. 3. Zn more readily forms compounds than Cu. [Susceptible copper alloys] ; Brass (Zn > 15%) without inhibited elements (As, Sb, P)	 – See Fig. 2.95, Table 2.76, Table 2.79, Table 2.138 (15) for more detail.		

Other than Cracking Mode. (Sources: several API, NACE, MTI, ASM H/B, etc.)
General Notes:
a. See Tables 2.141 and 2.143 for more details on damage mechanisms and inspection and monitoring.
b. Deadleg corrosion:
Candidate areas: Blanked branches/Lines with normally closed block valves/Lines with one end blanked/Pressurized dummy support legs/Stagnant control valve bypass piping/Spare pump piping/Level bridles/Relief valve inlet and outlet header piping/Pump trim bypass lines/High-point vents/Sample points/Drains/Bleeders/Steam out connections/Instrument tappings/connections/Nozzles for thermowells on channel heads and piping/H/EX shell side
Solutions: to minimize deadlegs/to keep minimum velocity/ frequent cleaning
c. Seawater Corrosion: See Tables 2.76, 2.188, 2.189, Figs. 2.93, 2.145, 2.146, 2.147, 2.180, 2.191, Sect. 5.5.5.6
References for Seawater Corrosion:
– API/ Norsok/DNV/ABS standards and NiDI/OTC/Offshore/TWI/Valve World Reports/Papers for offshore, subsea, marine, and ships
– CDA Publ. 36, 37, 38, 118, 206 (Copper Alloys)
– NACE Seawater Corrosion Handbook
– NACE Papers, Corrosion, and MP (too many)
– CRA Materials Suppliers' Reports & Papers
d. References for Organic Acid/Alkaline Corrosion: NACE SP/TM/TR/Publications/MP and Papers, NIDI, MTI, ASM Metal Handbook-Vol.13 series, other corrosion books

2.4.1.2 Types, Corrosion Rate Calculation, and Corrosion Allowance in General/Uniform Corrosion

General corrosion usually appears in uniform corrosion mode. Normally the corrosion rate (CR) calculated by uniform corrosion is used for the corrosion allowance (CA) of internal and external surfaces of the metal as shown in Table 2.124(1) Uniform Corrosion. It shows extremely severe uniform corrosion in some corrosive environments and/or service velocity, e.g., atmosphere (industrial, marine, rural, and indoor), water (industrial, cooling, potable, etc.), seawater, wet CO_2, NH_4HS, high-temperature oxidation, sulfidation (with naphthenic acid), several acidic services (concentration, temperature, dissolved oxygen), velocity, etc. API RP581, Part 2 introduces corrosion rate calculation data in various general corrosion environments. Table 2.138(11) introduces dew point corrosion with general corrosion pattern and prevention. ASME STS-1, API 560, and ISO 13705 state flue gas dew point corrosion with severe general corrosion pattern and prevention guides.

Meanwhile, corrosion rate conversion for general/uniform weight loss from the lab test can be calculated by the following formula and Tables 2.125 and 2.126. This corrosion rate measurement is generally recognized as a uniform corrosion rate:

$$\text{mpy(mils/year)} = 0.0254\ \text{mm/y} = \text{C} \times \text{W} \times \text{k}/(\text{A} \times \text{t})$$

Table 2.125 C factors from several units for weight loss (NACE corrosion engineer's reference book)

Weight loss, W	Area, A	C factor per t (time)				
		Hour	Day	Week	Month	Year
Mg	cm^2	437	18.2	2.59	5.98×10^{-1}	4.98×10^{-2}
	dm^2	4.37	1.82×10^{-1}	2.59×10^{-2}	5.98×10^{-3}	4.98×10^{-4}
	m^2	0.0437	1.82×10^{-3}	2.59×10^{-4}	5.98×10^{-5}	4.98×10^{-6}
	in^2	67.7	2.82	0.402	0.0927	7.72×10^{-3}
	ft^2	0.470	1.96×10^{-2}	2.79×10^{-3}	6.44×10^{-4}	5.36×10^{-5}
g	cm^2	437×10^3	182×10^2	2590	598	49.8
	dm^2	4370	182	25.9	5.98	4.98×10^{-1}
	m^2	43.7	1.82	0.259	0.0598	4.98×10^{-3}
	in^2	677×10^2	2820	402	92.7	7.72
	ft^2	470	19.6	2.79	0.644	0.0536
Lb	cm^2	198×10^6	825×10^4	118×10^4	271×10^3	226×10^2
	dm^2	198×10^4	825×10^2	118×10^2	2710	226
	m^2	198×10^2	825	118	27.1	2.26
	in^2	307×10^5	128×10^4	182×10^3	420×10^2	3500
	ft^2	213×10^3	8880	1270	292	24.3

Notes: mdd = mg/(dm^2.day)

For example, for 0.52 mg/in^2.hr. on CS [W, weight loss = 130 mg at A (total surfaces of specimen) of 5.0 in^2 and during t = 50 hrs], C factor = 67.7 (from Table 2.125), *k* (density factor, CS's/Metal's) = 1.00 for CS from Table 2.126. Therefore, corrosion rate as mpy = 67.7 × 130 × 1.0/(5.0 × 50) = 35.2 and corrosion rate as mm/y = 35.2 × 0.0254 = 0.88

Table 2.126 (1/2) *k* values [density factor, CS's (7.86)/Metal's] of Common Alloys [1 lb./in^3 = 27.68 g/cm^3]

UNS	Common/brand name	Density g/cm^3	*k*	UNS	Common/brand name	Density g/cm^3	*k*
A91100	Al 1100	2.72	2.89	N06625	Alloy 625	8.44	0.93
A93003	Al 3003	2.74	2.87	N06686	Alloy 686	8.73	0.90
A95052	Al 5052	2.68	2.93	N06690	Alloy 690	8.11	0.97
A96061	Al 6061	2.70	2.91	N06975	Alloy G-2	8.17	0.96
A97075	Al 7075	2.80	2.81	N06985	Alloy G-3	8.31	0.95
C11000	ETP copper	8.94	0.88	N07001	Waspaloy (Ni-Cr PH)	8.19	0.96
C22000	Commercial bronze, 90%Cu	8.89	0.88	N07041	Rene 41 (Ni-Cr PH)	8.25	0.95
C23000	Red brass, 85%Cu	8.75	0.90	N07718	Alloy 718	8.19	0.96
C26000	Catridge brass, 70%Cu	8.53	0.92	N07750	Alloy X-750	8.28	0.95
C27000	Yellow brass, 65%Cu	8.39	0.94	N08020	20Cb-3	8.08	0.97
C28000	Muntz metal, 60%Cu	8.39	0.94	N08024	20Mo-4	8.11	0.97
C44300	Admiralty brass, 70%Cu, As	8.52	0.92	N08026	20Mo-6	8.13	0.97
C46500	Naval Brass, 60%Cu, As	8.41	0.93	N08028	Sanicro 28	8.00	0.98
C51000	Phosphor bronze (former A1)	8.86	0.89	N08031	Alloy 31	8.11	0.97
C52400	Phosphor bronze (former D)	8.78	0.90	N08330	RA-330	8.03	0.98
C61300	Al bronze, 7%Al	7.80	1.00	N08366	AL-6X	8.00	0.98
C61400	Al bronze D, 7%Al	7.78	1.01	N08367	AL-6XN	8.06	0.98
C63000	Ni-Al bronze	7.58	1.04	N08800/10/11	Alloy 800/800H/800HT	7.94	0.99
C65500	High Si bronze	8.52	0.92	N08825	Alloy 825	8.14	0.97
C67500	Mn bronze A	8.36	0.94	N08904	Alloy 904L	8.00	0.98
C68700	Aluminum brass, As	8.33	0.94	N08925	25-6Mo	8.10	0.97
C70600	90–10 Cu-Ni	8.94	0.88	N08926	Alloy 926	8.14	0.86
C71500	70–30 Cu-Ni	8.94	0.88	N09925	Alloy 925	8.05	0.98
C75200	Ni silver, 65%Cu + Ag, 18%Ni	8.73	0.90	N10001	Alloy B	9.16	0.86
C83600	Cast leaded red Brass, 85%cu	8.80	0.89	N10003	Alloy N	8.79	0.89
C86500	Cast Mn bronze, 57%Cu	8.30	0.95	N10004	Alloy W	9.03	0.87
C90500	Cast tin (gun) metal, 87%Cu	8.72	0.90	N10242	Alloy 242	9.05	0.87
C92200	Cast leaded tin (M) bronze	8.64	0.91	N10276	Alloy C-276	8.89	0.88
C95700	Cast Mn-Ni-Al bronze	7.53	1.04	N10629	Alloy B-4	9.19	0.86
C95800	Cast Ni-Al bronze	7.64	1.03	N10665/75	Alloy B-2/ B-3	9.22	0.85
F10005	Gray cast iron	7.20	1.09	N12160	HR-160	8.08	0.97
F20000	Malleable cast iron	7.27	1.08	R03600	Molybdenum	10.22	0.77

Table 2.126 (2/2) *k* values [density factor, CS's (7.86)/Metal's] of Common Alloys [1 lb./in^3 = 27.68 g/cm^3]

UNS	Common/brand name	Density g/cm^3	*k*	UNS	Common/brand name	Density g/cm^3	*k*
F32800	Ductile iron	7.10	1.11	R04210	Niobium	8.57	0.92
F41002	Ni-resist type 2	7.30	1.08	R05200	Tantalum alloy	16.60	0.47
F43006	Ductile Ni-resist, DS	7.68	1.02	R05240	Tantalum alloy	13.60	0.58
F47003	Duriron	7.00	1.12	R05252	Tantalum alloy	16.70	0.47
G10200	AISI 1020 carbon steel	7.86	1.00	R05255	Tantalum alloy	16.90	0.47
G41300	AISI 4130 Cr-Mo steel	7.86	1.00	R05400	Tantalum alloy	16.60	0.47
J91150	CA-15 cast SS	7.61	1.03	R30556	Cr-Ni-co alloy	8.23	0.96
J91151	CA-15 M cast SS	7.61	1.03	R50250	Titanium gr.1	4.54	1.73
J91540	CA-6NM cast SS	7.70	1.02	R50400	Titanium gr.2	4.54	1.73
J92600	CF-8 cast SS	7.75	1.01	R53400	Titanium gr.12	4.52	1.74
J92804	CF-3MN cast SS	7.75	1.01	R56400	Titanium gr.5	4.43	1.77
J92900	CF-8 M cast SS	7.75	1.01	R60702/04/05	Zr 702/704/705	6.53	1.20
J94204	HK-40 cast SS	7.75	1.01	S20100	201 SS	7.94	0.99
J95150	CN-7 M cast SS	8.00	0.98	S20200	202 SS	7.94	0.99
K11597	1 1/4Cr-1/2 Mo steel	7.85	1.00	S30400	304 SS	7.94	0.99
K81340	9Ni steel	7.86	1.00	S30403	304L SS	7.94	0.99
L51120	Chemical lead	11.30	0.70	S30900	309 SS	7.98	0.98
M11311	Magnesium AZ31B	1.77	4.44	S31000	310 SS	7.98	0.98
N02200	Nickel 200	8.89	0.88	S31254	254SMO (SASS)	8.00	0.98
N04400	Alloy 400	8.80	0.89	S31500	3RE60 (DSS)	7.75	1.01
N05500	Alloy K-500	8.44	0.93	S31600	316 SS	7.98	0.98
N06002	Alloy X	8.23	0.96	S31603	316L SS	7.98	0.98
N06007	Alloy G	8.31	0.95	S31700	317 SS	7.98	0.98
N06022	Alloy C-22	8.69	0.90	S32100	321 SS	7.94	0.99
N06030	Alloy G-30	8.22	0.96	S32550	Ferralium 255 (DSS)	7.81	1.01
N06045	Nicrofer 45	8.00	0.98	S32950	7Mo plus (DSS)	7.75	1.01
N06059	Alloy 59	8.80	0.89	S34700	347 SS	8.03	0.98
N06200	Alloy C-2000	8.50	0.92	S41000	410 SS	7.70	1.02
N06230	Alloy 230	8.97	0.88	S43000	430 SS	7.72	1.02
N06455	Alloy C-4	8.64	0.91	S44600	446 SS	7.65	1.03
N06600	Alloy 600	8.41		S50100	5Cr-1/2Mo steel	7.82	1.01
N06601	Alloy 601	8.11		S50400	9Cr-1Mo steel	7.67	1.02
N06617	Alloy 617	8.36					

Sources: ASME Sec.II, part D/ASTM G-28/NACE Corrosion Engineer's Reference Book/UNS System

The corrosion allowance is calculated by uniform (general) corrosion according to facility lifetime.

$$\mathrm{CA(mm)} = \mathrm{CR(mm/yr)} \times \text{design life(yr)of the facility.}$$

Table 2.127 shows the typical requirements for Corrosion Allowance in most company standards. Normally the remaining CA is reached to 50% initial CA, the sustainable/new project according to the maintenance plan may be executed. The CA is increased per the expected/calculated corrosion allowance in the given design life of the facility, but the maximum CA for CS and LAS should be 6.4 mm (1/4 in.) and 9.5 mm (3/8 in.) in onshore/offshore topside and offshore splash/subsea environment, respectively. The maximum CA for SS or nonferrous alloys may be considered up to 3.2 mm (1/8 in.) and 4.8 mm (3/16 in.) for onshore/offshore topside and offshore flash/subsea environment respectively. For bulk materials, such as piping, the purchased thickness may have some more extra corrosion allowance on the required CA because it will be selected by standard schedule.

The corrosion allowance for internals (nonpressure parts) may have a reduced CA because the components may be considered as consumable material and/or less severe components. Especially the corrosion allowance of tube materials for heat exchangers is not considered unless otherwise severe erosion or metal loss to be expected.

For the components with thick hub, such as pumps or valves, material upgrading instead of corrosion allowance should be considered in the severe erosion or metal loss environment. Normally the CA is not specified for these materials.

Tables 2.127, 2.128, and 2.129 list the typical application guidelines and recommendations for corrosion allowance.

Tables 2.130, 2.131, and 2.132 show the requirements for Corrosion Allowance in several codes and standards.

Table 2.133 shows corrosion allowance and the requirements for Body (Shells and Channels) for Shell & Tube type heat exchangers (H/EX) in TEMA.

Table 2.127 Typical application for CA grades (for reference)

CA grade (from company standards)		Application
Inch	Mm	
0	0	CRA, nonmetallic materials, CS (in fully dry phase as noncorrosive), exchanger tubes, rotating machineries (covered by MOC and thick casting)
	0.5	Minimum CA in noncorrosive service for SI/metric units, CRA
1/32	0.80	Minimum CA in very mild-corrosive service for US customary units, CRA
	1	Minimum CA in very mild-corrosive service for SI/metric units, CRA
1/16	1.5 (or 1.6)	Mild-corrosive service, minimum CA for CS/LAS in some companies, potable/treated water, noncorrosive dry gas with some moisture (e.g., air, N2, etc.), Steam line, fuel gas, etc.
1/8	3.0 (or 3.2)	Moderate-corrosive service, most CS pipelines, maximum CA for H/EX (shell section) and pipelines, optional
3/16	4.5 (or 4.8)	Severe-corrosive, sour water, rich amine, boots, feed/outlet nozzle (including erosion/turbulent circuit)
1/4	6.0 (or 6.4)	Very severe-corrosive, sour water, rich amine, boots, feed/outlet nozzle (including erosion/turbulent circuit)
>1/4	>6 (or 6.4)*	Upgrade the material, *for CA > 6 mm in offshore topside (optional) or oil sands pipelines (8–10 mm CA may be used)

Notes
- Noncorrosive service: total CR < 1 mpy (0.025 mm/yr) for 20 years Design Life
- Very mild-corrosive: total CR < 1.5 mpy (0.038 mm/yr) for 20 years Design Life
- Mild-corrosive: total CR < 3 mpy (0.075 mm/yr for 20 years Design Life
- Moderate-corrosive: total CR < 6 mpy (0.15 mm/yr) for 20 years Design Life
- Severe-corrosive: total CR < 10 mpy (0.25 mm/yr) for 20 years Design Life
- Very severe-corrosive: total CR < 12 mpy (0.30 mm/yr) for 20 years Design Life
- Minimum CA: normally not calculated

Table 2.128 Corrosion allowance and requirements (common engineering practice-onshore and offshore topside)

Materials	Facilities or parts	Minimum corrosion allowance, inch (mm)
Carbon steel & low alloy steel	Pressure vessels/heat exchanger – shell & heads	1/16 (1.5), 1/8 (3.0), 3/16 (4.5)(1), ¼ (6.0)(1)
	Pressure vessels – each side for fixed internals	½ × (corrosion allowance of body)(5)
	Pressure vessels – each side for removable internals	¼ × (corrosion allowance of body)(5)
	Heat exchangers – tubes(3)	0(4)
	Heaters/boilers – tubes	(1 mm, 2 mm, or 3 mm)
	Piping/Pipelines(2), Tanks	1/16 (1.5), 1/8 (3.0)
	Rotating machineries	By manufacturer
Stainless steel & nonferrous metal	(3)	Nil, 0.05 (1.3), 0.1 (2.5), 0.125 (3.2)

* *Notes*
(1) Normally not applicable for heat exchangers unless it is for low cost, short design lives, and severe fouling issues
(2) For offshore lines, the corrosion of both sides (internal and external) should be considered
(3) Normally the design life is 5–10 years for CS and LAS. For erosion circuit or design life of 15 years and higher, the minimum wall thickness of tubes should be 2.7 mm (0.1 in.) for CS and LAS and 1.65 mm (0.065 in.) for SS or CRA when CA is 0
(4) For severe corrosion and/or erosion environments, 0.25–1.00 mm (0.01–0.04 in.) CA per the design life of the bundle may be applied based on the end-user's decision
(5) Some end-users use the following guidance for minimum acceptable metal thickness and corrosion allowance (CA) of pressure vessel internal components (See Table 2.129 for reference)

2.4.1.3 Galvanic Corrosion

When dissimilar metals are in contact under the following conditions, galvanic corrosion, which is an electrochemical action of two dissimilar metals, can occur (Fig. 2.144). The following three conditions (all of them) are the essential requirements for galvanic corrosion:

(i) The presence of an electrolyte and an electron conductive path
(ii) A difference in potential between the metals to enable a significant galvanic current
(iii) A sustained cathodic reaction on the more noble of the two metals

Figure 2.145 shows the effect of Zn coating/galvanizing as a sacrificial anode. However, the potential levels of CS and Zn in seawater are switched at 66 °C (155 °F) and above. Eventually CS will be anode against Zn at ≥66 °C (155 °F), and so it is called "reversal galvanic corrosion." Therefore, a careful consideration is required when Zn-containing coating and galvanized steel are used. Figure 2.146 shows the typical galvanic potential series of various metals with saturated calomel half-cell reference electrode in seawater at 10 °C (50 °F). The typical galvanic potential series in Fig. 2.146 should not be used in the solution other than seawater. Figure 2.147 illustrates the comparison of galvanic series in flowing seawater and tap water. It shows some order change and potential level change per the solution. The galvanic

Table 2.129 Recommended minimum thickness and corrosion allowance used by several end-users

Part	Vessel materials		Minimum thickness (Total CA), mm			
			CA on Shell; or cladding thickness, mm			
	Shell or lining	Internal part	1.5 or 2.0	2.5 or 3.0	4.5	6.0
Tray decks, splash decks, pans, drawoff sumps, dist, troughs, downcomers, disc & donuts, integral minor beams	CS	CS	2.5 (1.0)	3.5 (1.5)	4.5 (3.0)	5.5 (4.0)
	CS	Alloy	2.0 (0.4)			
	Alloy	Alloy	2.0 (0.4)	3.5 (1.5)	–	–
Tray components: bubble caps, valves, weir, chimneys, baffkes	CS	CS	2.0 (0.4)	2.5 (1.0)	3.5 (1.5)	4.5 (3.0)
	CS	Alloy	0.060 (0.00)			
	Alloy	Alloy	2.0 (0.4)	2.5 (0.8)	–	–
Major beams, support rings, support brackets, nonintegral minor, beams, any load bearing part welded to vessel shell	CS	CS	9.5	13 (6.0)	16 (9.5)	19 (13)
	CS	Alloy	6.0 (0.0) ¼ (0.0)			
	Alloy	Alloy	13 (1.5)	9.5 (3.0)	–	–
Grating support plates packing plates	CS	CS	3.0 (1.5)	5.0 (3.0)	6.0 (4.5)	–
	CS	Alloy	3.0 (1.5) 1/8 (1/16)			
	Alloy	Alloy	3.0 (1.5)	6.0 (3.0)	–	–
Internal piping (nonpressure)	CS	CS	STD Wt. 1.5	STD Wt. 3.0	X-Stg. 4.5	X-Stg. 6.0
	CS	Alloy	Scheme 10S (0.0)			
	Alloy	Alloy	Scheme 10S (0.0)	Scheme 40S (0.0)	–	–

Notes: This table is only for reference
1. Numbers in parentheses indicate total required corrosion allowance
2. Minimum acceptance new thickness includes corrosion allowance. Thicknesses shall be increased as necessary to satisfy mechanical requirements specified in this standard
3. CS = carbon steel and alloys with less than 11 Cr
4. Alloy = stainless steel, nickel alloys, and copper alloys
5. CA for titanium, tantalum, zirconium: Consult with a responsible metallurgist

Table 2.130 Corrosion and corrosion allowance (CA) requirement in ASME Sec. VIII, Div. 1 (directly extracted from the code)

Item	Code reference
General requirements	Para. UG-16 & 25
Suggested good practice – nonmandatory	Appendix E
Vessels subjected to corrosion	Para. UG-25
Corrosion for brazed vessels	Para. UB-13
Thickness, including CA to define the PWHT requirements	Para. UCS-56 & UHA-32
Corrosion and CA for clad vessels – nonmandatory	Para. UCL-25, UG-26, Appendix F
Forging vessels	Para. UF-25
Ferritic steel vessels enhanced TS by heat treatment	Para. UHT-25
CA for limits of reinforcement	Para. UG-40
Vessels subject to corrosion, erosion, or mechanical abrasion must have inspection openings	Para. UG-46
MAWP	Para. UG-98 & 101

General Notes: All required thicknesses in the code exclude corrosion allowance

Table 2.131 Corrosion allowance and requirement in ASME Sec. VIII, Div. 2 (directly extracted from the code)

Item	Code reference
General requirements	Sect. 3.2.1.6
CA in design equations	Sects. 4.1.4 and 4.5.4
CA for internals	Sect. 4.13.7.4
Use of CS for stress and fatigue analysis – normative	Annex 5-F
CA for pressure testing requirements	Para. 8.1.1

General Notes: All required thicknesses in the code exclude corrosion allowance

Table 2.132 Requirement of corrosion allowance for tubes in TEMA, JIS, and API

Parts	Codes	Materials	Minimum corrosion allowance, mm (inch)
Tube for shell & tube type heat exchanger	TEMA	–	Not required
Tube for shell & tube type heat exchanger	API 660	–	Not required
Tube for air cooler	API 661	–	Not required
Tube for boiler for land use	JIS B8201 (withdrawn)	–	1.0 (0.04)
Tube for fired heater in oil refinery	API 560	C.S & C-1/2Mo	3.0 (1/8)
		½Cr-1/2Mo ~ 9Cr-1Mo	2.0 (0.080)
		Stainless steels	(0.04)

Table 2.133 Corrosion allowance and requirements in TEMA (for body for shell & tube type H/EX)

Parts	Class	Corrosion allowance, minimum, mm (inch)	
		Carbon steel & low alloy	Cast iron, high alloy & nonferrous metal
1. Pressure parts	R	3.2 (1/8)	Note 1
2. Pressure parts	C, B	1.6 (1/16)	
3. Internal floating head covers	R, C, B	Same as pressure parts (Note 3)	
4. Tubesheets	R, C, B	Same as pressure parts (Note 4)	
5. External covers	R, C, B	Same as pressure parts (Note 5)	
6. End flanges	R, C, B	Same as pressure parts (Note 6)	
7. Nonpressure parts (Note 2)	R, C, B	NR	
8. Partition plate, bolting, floating head backing devices	R, C, B	NR	

Notes: NR = not required

1. (1) High alloy & Nonferrous metal: NR
   (2) Cast Iron (R Class): 3.2 mm (1/8 in.)
   (3) Cast Iron (C & B Class): 1.6 mm (1/16 in.)
2. E.g., tie-rods, spacers, baffles, and support plates
3. On all wetted parts. Gasket seating surface: NR. Corrosion allowance on the outside of the flanged portion may be included in the recommended minimum edge distance
4. On each side with the provision that, on the grooved side of a grooved tubesheet, the depth of the gasketed groove may be considered as available for corrosion allowance
5. Where they are grooved, the depth of the gasketed groove may be considered as available for corrosion allowance
6. Applied only to the inside diameter of flanges where exposed to the fluids

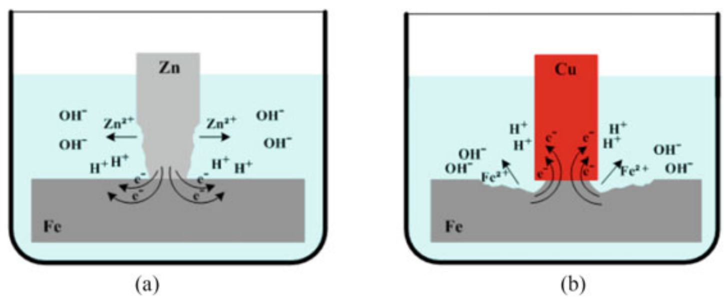


Figure 2.145 Typical circuits of galvanic corrosion in seawater. (**a**) Fe (CS) to Zn [<150 °F (66 °C)]. (**b**) Fe (CS) to Cu (or ASS)

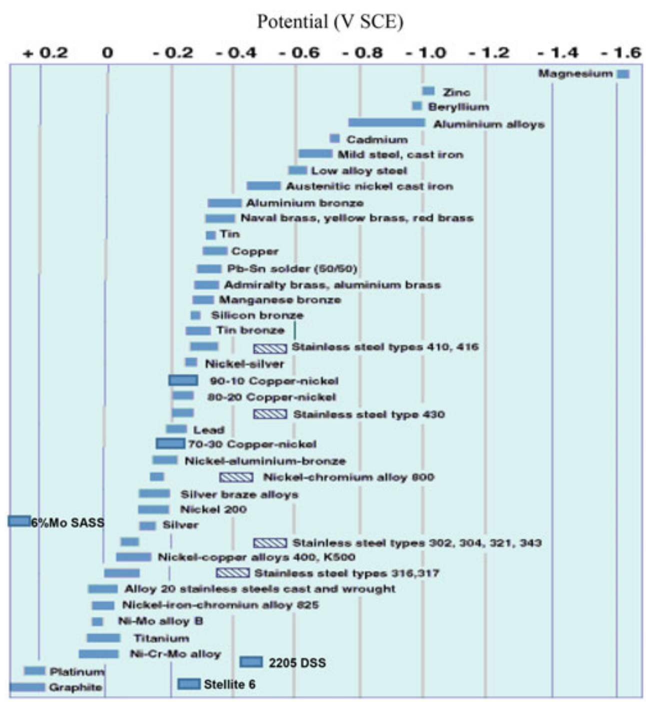


Figure 2.146 Galvanic potential series of various metals – saturated calomel half-cell reference electrode in seawater [hatched box] unpassivated (active) condition (stressed or heat tinted). The addition of chlorine to seawater may reduce or prevent galvanic corrosion attack, so this galvanic potential figure should not be used in chlorinated seawater

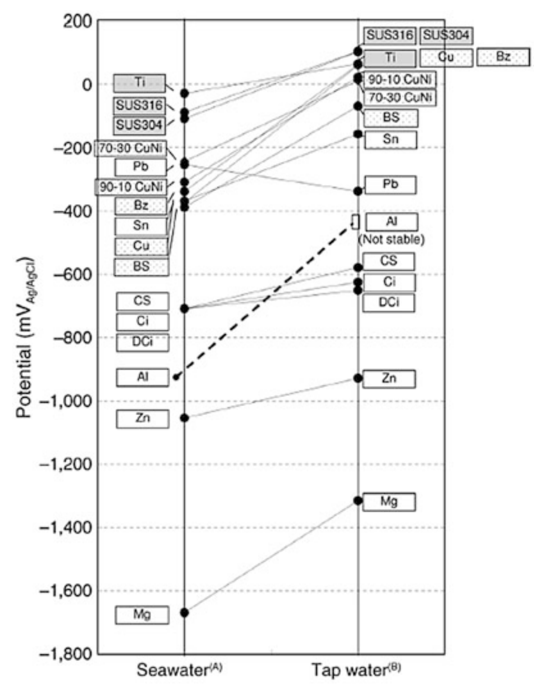


Figure 2.147 Comparison of galvanic series in flowing seawater and tap water at 10 °C (50 °F). (**a**) The mean value of the potential fluctuation band that had been shown in potential in seawater. (**b**) Potential in tap water plotted the value of the average in the stability region). (Source: Galvanic Series of Metals Used in Tap Water with or without Flow vs. in Seawater 2011. (Source: NACE Corrosion V67-No.12)

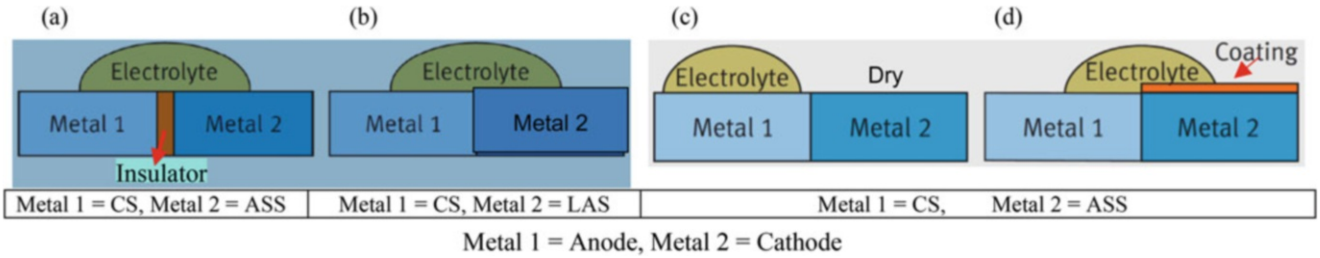


Figure 2.148 Typical circuits of No galvanic corrosion. (Source: euro inox report 2009-modified). (**a**) Without Electrically Conductive Joints due to Insulator. (**b**) Similar Metal Contact Without Remarkably Different Potential (No Insulator). (**c**) Without Connection in the Conductive Electrolyte (No Insulator). (**d**) Connection with Blocking from Coating in Conductive Electrolyte (No Insulator)

potential of each metal will be changed per the solution as seen in Fig. 2.147, so that the applicable solution should be preferentially confirmed for galvanic corrosion evaluation.

As a rule of thumb, in industries, the following guideline may be applicable. If the potential difference is less than 0.1 volt, then it is unlikely that galvanic corrosion will be significant.

- *Harsh environments*, such as outdoors, high humidity, and salt environments, fall into this category. Typically, there should be *not more than 0.15 V* difference. For example, Gold (0 V) to Silver (−0.15 V) in seawater would have a difference of 0.15 V, which is acceptable.
- *For normal environments*, such as storage in warehouses or non-temperature and non-humidity controlled environments. Typically, there should *not be more than 0.25~0.3 V*.
- *For controlled environments*, such as where temperature and humidity are controlled, *0.50 V* can be tolerated. Caution should be maintained when deciding for this application as humidity and temperature do vary between regions.

However, the electron path is blocked as seen in Fig. 2.148a, c, d, and no galvanic corrosion occurs.

The following factors for the severity of galvanic corrosion should be evaluated for material selection and construction.

$$\text{Corrosion Rate in Anode} = \text{CRB} \times F(s) \times F(p) \times F(a) \times F(d) \times F(o)$$

CRB = Basic corrosion rate in the solution
F(s) = Factor of environment-conductivity (e.g., harsh, normal, and controlled) at the target temperature
F(p) = Factor of potential difference between two contact metals
F(a) = Factor of contact area difference between two contact metals ("Larger area anode-Smaller area cathode" can reduce galvanic corrosion on the anode side.)
F(d) = Factor of distance between two contact metals
F(o) = Factor of dissolved oxygen content in the solution

Applicable Codes, Standards, or Reports

NiDI Publ. 1259/11003/12003/14027, CDA publication series, API RP571, ASTM G71/82/116, etc., MIL-STD-889B/C Dissimilar Metals, ASME Sec. VIII, Div.2, A-303 and ASM Metal Handbook, Vol. 3 & 11.

References: For More Detail and/or Use as Check List

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2.4.1.4 Microbiologically Induced Corrosion (MIC)

(a) Appearance and Phenomena

Microbiologically Induced Corrosion (MIC) is a significant degradation mechanism for materials in many industries, such as chemical processing, refineries, pulp and paper, oil and gas production and distribution, and utilities, including heating, ventilation, and air conditioning (HVAC). Essentially, all cooling water and process water applications may be susceptible to MIC. Furthermore, biological fouling, which is always a precursor to MIC, can reduce the efficiency of H-EXs and fluid distribution systems and can interfere with water-based processes. MIC and microbiological fouling can produce significant damage to plant components, resulting in increased downtime of equipment and increased operating costs.

Most common materials of construction include CS, LAS, 300 Series ASS, 400 Series FSS/MSS, aluminum, copper, and some Ni-based alloys. Fig. 2.149 shows a typical Growth process of MIC.

Figure 2.149 Typical occurrence and growth of MIC

(b) Organisms caused the most common MIC
1. *Sulfate-Reducing Bacteria (SRB)* are anaerobes that are sustained by organic nutrients. Generally, they require complete absence of O_2 and a highly reduced environment to function efficiently. The most common strains of SRB grow best at temperatures from 25~35 °C (77~95 °F). A few thermophilic strains capable of functioning efficiently at more than 60 °C (140 °F) have been reported. Although SRB are anaerobic, the availability of oxygen can increase corrosion in the presence of SRB (i.e., reported in a range of 0.0075–0.6 mm/yr. (0.3–24 mpy)).
2. *Sulfate-Reducing Archaea (SRA)* are like sulfide-reducing bacteria (SRB), obtaining their energy by oxidizing organic compounds or molecular hydrogen (H_2) while reducing sulfates to sulfides, especially to H_2S. SRA consist of the general archaeoglobus. Archaeoglobus grow at temperatures in the range of 60–95 °C (140–203 °F), with optimal growth at 83 °C (181 °F). SRA are known to cause corrosion of iron and steel in oil and gas processing systems by producing FeS.
3. *Acid Production Bacteria (APB)*: Organic acids are produced by both bacteria and fungi. This process is anaerobic for some microorganisms, and aerobic for other microorganisms and fungi. Most final products of APB are short-chain fatty acids (e.g., acetic, formic, lactic acids). The role of APB in MIC is controversial, being responsible for corrosion in the absence of SRB. The main role of APB is to provide the environment and nutrients for SRB growth. Other bacterial species can produce aggressive inorganic acids, such as H_2SO_4, in aerobic environments. Microorganisms can generate locally high concentrations of CO_2. The CO_2 dissolves in the water, producing carbonic acid (very corrosive to most ferritic steels)
4. *Methanogens* produce methane as a metabolic by-product in anoxic conditions. They are classified as *Archaea*, a group quite distinct from bacteria. Methanogens typically thrive in environments in which all electron acceptors other than CO_2 (such as oxygen, nitrate, sulfate, and trivalent iron, Fe^{3+}) have been depleted. They are common in wetlands, where they are responsible for marsh gas, and in the guts of animals such as ruminants and humans. Others are extremophiles, found in environments such as oilfield systems, hot springs, and submarine hydrothermal vents, as well as in the "solid" rock kilometers below the surface of the Earth's crust. Methanogens are common *Archaea* in oil production systems; however, they are normally not measured with current culturing techniques.

(c) Critical Factors for MIC
1. MIC is usually found in aqueous environments or services where water is always or sometimes present, especially where stagnant or low-flow conditions allow and/or promote the growth of microorganisms.
2. Because there are several types, organisms can survive and grow under severe conditions, including lack of oxygen, light or dark, high salinity, pH range of 0–12, and temperatures from −18 °C to 113 °C (0 °F to 235 °F).
3. Systems may become "inoculated" by the introduction of organisms that multiply and spread unless controlled.
4. Different organisms thrive on different nutrients, including inorganic (e.g., sulfur, ammonia, H_2S) and organic (e.g., hydrocarbons, organic acids) substances. In addition, all organisms require a source of carbon, nitrogen, and phosphorous for growth.
5. Inleakage of process contaminants such as hydrocarbons or H_2S may lead to a massive increase in biofouling and corrosion.

(d) Prevention and Mitigation of MIC
1. Microbes require water to thrive. Systems that contain water (cooling water, storage tanks, etc.) should be treated with biocides such as chlorine, bromine, ozone, ultraviolet light, or proprietary compounds.
2. Proper application of biocides will control but not eliminate microbes so that continued treatment is necessary.
3. Maintain flow velocities above minimum levels. Minimize low or stagnant flow [to be >0.5 m/s (1.6 fps)].
4. Systems that are not designed or intended for water containment should be kept clean and dry.
5. To use appropriate hydrotest water quality.
6. Empty hydrotest water as soon as possible. Blow dry and prevent moisture intrusion.
7. Wrapping and cathodically protecting underground structures have been effective in preventing MIC.
8. Effective mitigation of established organisms requires complete removal of deposits and organisms using a combination of pigging, blasting, chemical cleaning, and biocide treatment.
9. Add biocides to water phase, e.g., chlorine, bromine, chlorine dioxide, hypochlorite, ozone, nonoxidizing, ultraviolet light, or proprietary compounds.
10. Maintain coatings on the interior of storage tanks.

11. Remove heat tints after welding
12. Temporary CP or wrapping may be used during hydrotest.
13. Use high-pressure hydrolancing
14. Completely remove the deposits and organisms from pigging, blasting, chemical cleaning, and biocide treatment.
15. Use stainless steel scrapers (for hard to remove or heavy deposits).
16. Use higher alloy to be resistant to MIC (i.e., 304L → 316L → 2205 DSS → 6%Mo steel)

Applicable Codes, Standards, or Reports
; API RP571, NACE TM0194, NACE TM0212, NiDI Publ. 10,085, etc.

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2.4.1.5 Wet CO_2 (Carbonic Acid) Corrosion

Crude oil and gas contain CO_2 gas. The CO_2 gas in condensed water will form carbonic acid (H_2CO_3) which is highly corrosive while dry CO_2 gas is not corrosive (see Fig. 2.150). The higher CO_2 and H_2S service may require stainless steels or nickel alloys because of the high risk of mesa corrosion (due to low pH) and SSC.

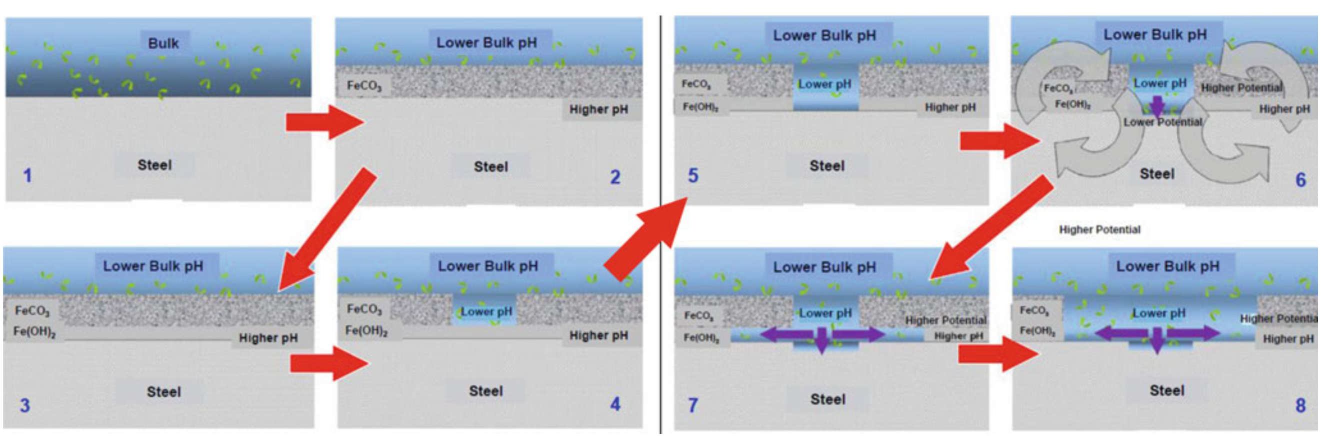

Figure 2.150 Typical mesa corrosion processes of wet CO_2 corrosion of CS. (Source: NACE paper 08332)

The severity of wet CO_2 corrosion depends on the following factors:

- CO_2 mol% (partial pressure) and fugacity of CO_2 (fCO_2, bar)
- H_2S mol% (partial pressure)
- Dissolved Oxygen
- Total pressure and operating temperature
- pH
- Liquid velocity
- Service phase and flow pattern
- Contaminations in the service (i.e., S, sands, particles, etc.)
- Water cut
- Line diameter
- Oil type (crude oil or gas condensate)
- Glycol concentration
- Water analysis data (Ca^{2+}, Bicarbonate-HCO_3, free organic (i.e., acetic, formic, propionic acid) acid, chlorides, etc.)
- Wall shear stress (S, Pa) and fraction factor
- Oil wetting
- High-temperature carbonate scaling
- Geometry (horizontal, vertical, bend angle, pipe size, etc.)
- Glycol or corrosion inhibition treatment
- Upset conditions

Many companies and laboratories have been developing wet CO_2 corrosion prediction models; however, the application scope and the functional weight of input data are somewhat different, making the results significantly different. Therefore, use of multiple models is recommended for the final decision (Table 2.134).

Table 2.134 (1/2) Several models for wet CO_2 corrosion calculation

Model name	Owner 2)	Initial 1)	Strong consideration 3)	Remark
API RP581 CO_2 model	API		Similar with Norsok M-506	Industrial standard
Cassandra	BP	CA	Acetic acid considered as major factor/no oil wetting See NACE Paper 05552 for more details.	Withdrawn-see mechanistic CO_2 corrosion model below
Cormed	Elf Aquitaine		Highly dependent of free acetic acid/no effect of oil wetting and flow velocity/give lower pH values than other models	Merged to Corplus model
Corplus	Total	CO	Organic acid, calcium, sour corrosion, liquid erosion, free acetic acid, considered corrosivity without any protection from corrosion films or oil wetting	A result of a merger of the Cormed tool (CM) developed by elf
CorPos	Force Technology	CP	For multiphase flow/lower CR than Norsok for pipelines. A probability of water wetting is calculated depending on water cut, flow regime, local phase velocities, and emulsion stability	Developed by CorrOcean (now part of force technology)
de Waard and Milliams model	Shell	DW	Basic Model (1975, 1991, 1993, 1995 Ed.) See NACE paper 90041, 91577, and 02235 for more details	Only for reference
Dream	Oklahoma State University		For downhole corrosion in annular flow	
ECE (electronic corrosion engineer)	Wood Group Intetech	EC	Strong effects of oil wetting. The oil wetting factor is dependent on the oil density, liquid flow velocity, and inclination of flow. For water cuts lower than the emulsion breakpoint, the water is believed to be present as a water-in-oil emulsion, and the predicted corrosion is low, but not zero. The critical flow velocity for water dropout is taken as 1 m/s for horizontal flow and lower for inclined flow.	The developer, Intetech was merged to Wood Group. See NACE Paper 05648
FreeCorp	Ohio University		For multiphase flow/highly dependent of pH/very low CR at pH < 5.	
Hydrocor	Shell	HY	Corrosion and flow combined/included top-of-line/scale factor, H_2S corrosion, organic acid/little dependence of pH. Oil wetting and no corrosion is assumed when the water cut is below 40% and the liquid velocity is above 1.5 m/s.	
KSC	IET	KS	Electrochemical model, bulk phase, and diffusion through porous $FeCO_3$ films, calculate corrosion rate without protective films, a corrosion rate with protective films, and a risk for mesa attack; lower CR at high temperature and high pH/no oil wetting.	Institute for Energy Technology, Kjeller, Norway

Source: NACE paper 02233 modified

Table 2.134 (2/2) Several models for wet CO_2 corrosion calculation

Model name	Owner [2)]	Initial [1)]	Strong consideration [3)]	Remark
Lipucorr	Total/elf/IFP		Little dependence of pH/strong effects of oil wetting. Merged to Corplus model.	
Mechanistic CO_2 corrosion model	BP		New BP model; modified Casandra.	
Multicorp	Ohio University	MU	Multiphase flow, iron carbonate films, oil wetting, crude oil chemistry, H2S, FeS precipitation, organic acids, corrosion inhibitors. See NACE Paper 12-1559, Electorchemica Acta-vol.56 1752-1760. And NACE Corrosion vol.65, No5-p291 for more detail	Very active researcher program
Norsok M-506	Norsok (Norway)	NO	Large amount effect of protective film/lower CR at high temperature and high pH/more sensitive to pH variation than de Waard (1998, 2005, 2017 Ed.) See NACE Paper 03623 and 05551for more details.	Developed by Statoil, Norsok Hydro and Saga Petroleum
OLI model		OL	Thermodynamic, formation & dissolution of Fe-carbonate & sulfide scale/no oil wetting. Protectiveness of corrosion films is modeled by assumption. The scale formation parameters have been calibrated against selected lab data.	
Predict	Honeywell	PR	Highly dependent on pH, shear stress, and protective film/lower CR at pH > 4.5. Low corrosion rates are typically predicted when the water cut is below 50% for highly persistent oils and 5% for not persistent oils.	Very active commercial program See NACE paper 96011
SPPS	University of Tulsa	TU	Two-phase/for sand containing fluids-solid erosion/strong effect of protective ($FeCO_3$) films/highly dependent on pH/erosion corrosion	
SweetCor	Shell	SW	Highly dependent on temperature & pCO_2/insufficient pH considered. Only a weak effect of protective corrosion films, and does not take effect of oil wetting into account.	
ULL	University of Louisiana at Lafayette	UL	For gas condensate wells/strong effects of oil wetting when hydrocarbon condensation occurs. Contains multiphase flow, phase equilibria, flow rates, and flow regime.	

Source: NACE paper 02233 modified

Notes

1) For Table 2.135

2) Most models developed in Universities and National Research Lab are based on the JIP (Joint Industry Projects). So, the users are greatly limited

3) Most models are typically based on the input data, such as the pH, temperature, CO_2 partial pressure (pCO_2), as a minimum, and applicable only for CS unless otherwise specified.

Table 2.135 Comparison of characteristics of several models for wet CO_2 corrosion calculation

Model	DW	NO	HY	CO	CA	KS	MU	EC	PR	TU	UL	CP	OL	SW
Lab data, *F*ield data model, *M*echanistic model	L	L	M	F	L	M	M	L	L	M	F	L	M	L
Scale effect formation water[(1)]	N	M	N	W	W	M	M	W	S	S		M	W	W
Scale effect condensed water[(1)]	W	M	W	W	W	M	M	W	S	S		M	M	W
Effect of pH on corrosion rate[(1)]	W	M	W	M	W	M	M	W	S	S	S	M	W	W
Risk for localized attack				Y		Y			Y		Y			
Oil wetting effect crude oil[(1)]	S	N	M	M	N	N	S	S	S	N	S	M	N	N
Oil wetting effect condensate[(1)]	N	N	N	M	N	N	M	M	M	N	S	M	N	N
$CaCO_3$ correction for pH				Y			Y						Y	
Effect of organic acid on corrosion			Y	Y	Y		Y	Y	Y		Y			
Top of line corrosion	Y		Y				Y	Y			Y			
Effect of H_2S on corrosion rate[(1)]	N	N	W	N	N	N	M	S	S	N	W	N	S	N
Multiphase flow calculation[(2)]	N	P	M	P	N	N	P	M	P	P	M	M	N	N
Max. temperature limit, °C	140	150	150	150	140	150	100	140		115		150	120	120
Max. CO_2 partial pressure, bar.a	10	10	20	20	10	20	20	20	70	17		10	20	
*O*pen, *C*ommercial, *P*roprietary	O	O	P	O	O	O	P	C	C	P	P	P	C	P

Source: NACE Paper 10,371 modified

Notes: Blank = No Data

Y: yes (considered)

(1) *S* strong effect, *M* moderate effect, *W* weak effect, *N* no effect

(2) *P* point calculation, *M* multiphase profile calculation, *N* no multiphase flow calculation

Applicable Codes, Standards, or Manuals

API RP571/RP581, NACE TM0194, NACE TM0106/0212, NiDI Publ. 10,085/46107, Norsok M-501, DNV-OS-F101, etc.

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- Other Reports- SPE, TWI, ISOPE, OTC, Carbon Capture, etc.

2.4.1.6 Key Corrosivity Factors for General Corrosion and Localized Corrosion

Table 2.136 shows the characteristics of major factors for major corrosion in energy industries.

Table 2.137 shows the most common combination of materials and environment for stress corrosion cracking (SCC) to occur.

2.4.1.7 Typical Corrosion and Prevention in Tube Bundle of H/EXs

Table 2.138 shows the typical corrosion phenomena and prevention methods in tube bundle of H/EXs.

Table 2.136 Characteristics of key corrosivity factors for major corrosion in oil & gas industries – see Note

Corrosivity factors in service	Characteristics and major environments
Temperature	Water, sulfidation, oxidation, nitriding, most acidic services, caustic, high-temperature hydrogen attack (HTHA), Pitting, Cl-SCC, etc. The maximum operating temperature may be used unless otherwise required.
pH	Most acidic services, sour services, alkaline SCC, brine/seawater, etc.
Concentration	Most acidic and alkaline services, units: weight %, mole %, partial pressure, etc.
Service velocity	Erosion, severe corrosion, flow pattern change. The limits of erosion velocity should be considered for all piping and pipeline systems.
Dew point	To be acidic or corrosive solution at the gas phase, e.g., overhead system, flue gas system, flare, etc. The dew point control with 5–15 °C (or 9–27 °F) margin is required to avoid dew point condensation. See Sect. 3.5.4.1) for dew point control of winterization and Appendix Table A-12 for dew point determination in atmosphere. Typically, pressure vessel overhead, cooling water system, and flue gas systems are prone to dew point condensation corrosion as noted in Table 2.138(11), 2.191-note (2), and Fig. 5.25.
Oxygen (O_2)	Originates in crude, aerated water, or packing gland leaks. Oxygen in the air used with fuel in surface combustion and FCC regeneration results in high-temperature environments, which cause oxidation and scaling of metal surfaces of under-alloyed materials. High corrosion rate at the splash zone in seawater. ASS is susceptible to SCC at high temperature in oxygen-chloride-containing solutions.
Sulfur (S)	Present in raw crude. It causes high-temperature sulfidation of metals, and combines with other elements to form aggressive compounds, such as various sulfides, sulfates, sulfurous, polythionic, and sulfuric acid.
Chlorides (Cl^-)	Present in the form of salts (such as magnesium chloride and calcium chloride) originating from crude oil, catalysts, and cooling water. Susceptible to pitting and SCC for ASS in high-chloride environments.
Carbon dioxide (CO_2)	Combines with moisture or water to form carbonic acids. Shows severe corrosion rate for CS and LAS especially in upstream and midstream oil and gas industries. Occurs in stream reforming of hydrocarbon in hydrogen plants, and to some extent in catalytic cracking.
Ammonia (NH_3)	Anhydrous ammonia may occur the CS cracking. Nitrogen in feedstocks combines with hydrogen to form ammonia-or ammonia is used for neutralization-which in turn may combine with other elements to form corrosive compounds, such as ammonium chloride.
Cyanides (CN^-)	Usually generated in the cracking of high-nitrogen feedstocks. When present, corrosion rates are likely to increase, especially in sour water service.
Hydrogen (H_2, H^+)	In itself not corrosive but can lead to blistering (HTHA) and embrittlement of steel. Delayed crack occurs after welding and limits minimum pressurizing temperature (MPT) curves for the equipment fabricated with Cr-Mo steel. In addition, it readily combines with other elements to produce corrosive compounds.
Phenols	Found primarily in sour water strippers.
Carbon (C)	Not corrosive but in high temperature results in carburization that causes embrittlement or reduced corrosion resistance in some alloys.
Debris, dissolved solids, salt deposits	Increase fouling corrosion under deposits, pitting, erosion, and local corrosion. May provoke turbulent flow of the service.

Note: See ASME Sec. II, part D, Nonmandatory Appendix A, API RP571, and API RP581 for more details of above corrosions and further corrosion mechanisms

Table 2.137 Common combination of materials and environment for SCC. (Source: ASM Metal H/B, Vol.13)

Materials	Environment known to cause SCC (as a necessary environment)
Aluminum alloys	Moist air, seawater, chloride, mercury, bromide and iodide solutions, etc.
Copper alloys	Ammonia solutions and vapors, amines, acetate solutions, citrate solutions, formates solutions, tartrates solutions, nitrates solutions, NaOH solutions, mercury, etc.
Nickel alloys	Hydro-oxide solutions (caustic), HF acid vapor, etc.
Titanium alloys	Chloride solutions, bromides solutions, iodides solutions, liquid N_2O_4 solutions, methanolic solutions, red fuming nitric acid (HNO_3), dry salts and elevated temperature, etc.
Ferritic steels (CS, LAS, and MSS, FSS, etc.)	Ammonia (anhydrous), amines (aqueous), hydroxide solutions (caustic), carbonates (aqueous), CO/CO_2/water mixtures, sulfides (aqueous, acidified), HF solutions, cyanides (aqueous, acidified), nitric acid solutions, nitrate solutions ($CaNO_3$, NH_4NO_3, $NaNO_3$), HCN, H_2S, NaOH-$NaSiO_3$, etc. (higher strength and hardness and/or higher residual stresses, more susceptible to SCC)
Austenitic stainless steels (ASS)	Chloride solutions, fluoride solutions, iodide solutions, bromide solutions, sulfate solutions (H_2S, NaOH-H_2S, etc.), NaCl-H_2O_2 solution, phosphate solutions, nitrates and polythionic acid solutions, etc.

Table 2.138 (1/3) Typical corrosion phenomena and prevention methods in tube bundle of H/EXs[(1),(2)]

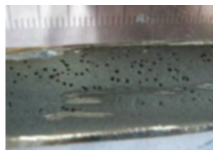
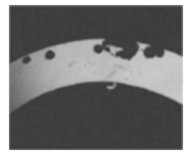
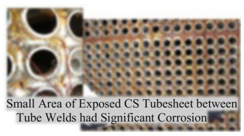
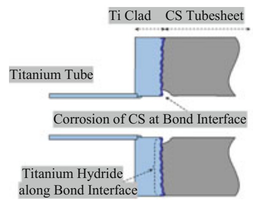
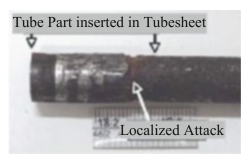
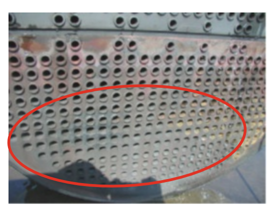
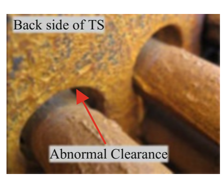
Damage type	Factors	Phenomena		Prevention
(1) Surface general corrosion	– Occurs evenly on the surface – Metal thinning evenly – See Sects. 2.4.1.1, 2.4.1.2, 2.4.1.3, 2.4.1.4, and 2.4.1.5.	– Surface corrosion occurs – From visual observation and metallographic test, the biggest depletion of the surface of the pipe and focus occurred in the shell inlet nozzle due to the high cross velocity		– Materials selection – CP – Inhibitor – Internal coating – Prompt drain/dry after hydrotest – Cooling water quality control – See Sects. 2.4.1.1, 2.4.1.2, 2.4.1.3, 2.4.1.4, and 2.4.1.5.
(2) Pitting corrosion	– Uneven gap occurs in the form of pits. – In environment containing chlorides and sulfides. – See Sect. 2.1.6.2.			– Materials selection – To consider the upset condition – Internal coating (i.e., slug catcher, separator, surge drum, etc.) – See Sect. 2.1.6.2.
(3) Corrosion crack (e.g., SCC, SSC, etc.)	– Occurs at the interstices. – Interstices between the metal surface and the scaling. – See Sect. 2.4.2.			– Materials selection – Stress relieving – To consider the upset condition – See Sect. 2.4.2.
(4) Galvanic corrosion	– Occurs when two different metals are interconnected in channel and shell section individually, Cooling water is the most common source. – See Sects. 2.4.1.5 general and 2.1.6.10 due to SS for more detailed information.	 – Tubes: 2205 DSS (cathode) – Tubesheet: CS (anode)		– Materials selection – CP (normally with sacrificial anode) – Internal coating or cladding (extend anode area) – See Sects. 2.1.6.10 and 2.4.1.3.
(5) Crevice corrosion	– Inadequate gap between tube to tubesheet hole – Inadequate tube rolling expansion – See Sect. 2.1.6.2(b) for more details.			– Full rolling expansion – Seal or strength welding – Close fit per codes
(6) Erosion-corrosion	– High velocity – Abrasive particles in fluids – High shear stress on the tube – Surfaces – Steam/water hammering – See Sect. 2.4.5 general and Sect. 2.1.7.2(d) copper alloys for more detail.			– Reduce the velocity – Minimum bending radius of U-tubes: 1.5 times the tube OD – Use higher thickness for inner tube row and U-bend – Install vacuum breaker vents – Properly size steam traps
(7) Fretting and/or abrasion by vibration	– Poor design of thermal rating – Galling on tubes under the baffles			– Use NTIW (no tubes in window) – Optimize tubes layout and baffle spaces – Velocity control

Table 2.138 (2/3) Typical corrosion phenomena and prevention methods in tube bundle of H/EXs(1),(2)

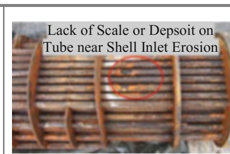
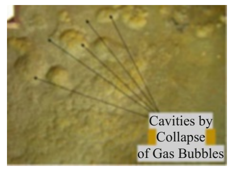
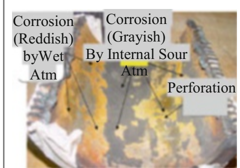
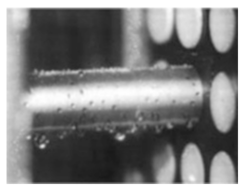
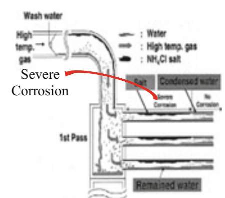
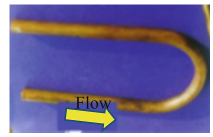
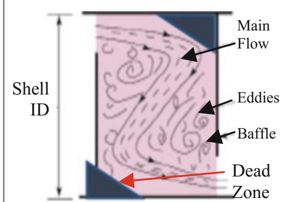
Damage type	Factors	Phenomena		Prevention
(8) Impingement & Turbulent Flow	– No impingement protection			– Install impingement plate (single/double) – Increase inlet nozzle size
(9) Cavitation (in reboilers)	– Liquid carrying gas bubbles – High pressure drop/high temperature – When these bubbles encounter a high-pressure zone, they collapse and cause explosive shocks on the surface			– Process control ($P_{absolute}$ to be below the liquid's vapor pressure/ reduce velocity/remove entrained air/DO) – Use erosion/wear resistant materials/coatings – Frequent internal cleaning
(10) Thermal fatigue corrosion	– Damage caused by combination of mechanical (fatigue) and the environment (corrosive) so the damage becomes faster – There is no indication of corrosion fatigue			– Use appropriate material with KDF
(11) Dew point corrosion	– Dew point is to close the operating temperature (higher contamination may increase the actual dew point) – Process system overhead, flue gas system followed by strong acidic or alkaline corrosion			– Process control (water washing location, phase control, etc.) – Appropriate dew point control considered the expected contamination – Use CRA material – NACE Publ. 34,109 – API RP932-B – See Table 2.174b and Sect. 3.5.4 for other facilities.
(12) Fouling	– Untreated fluids – No frequent cleaning – No adequate cleaning – Unexpected polymerization – Low service velocity – →Reduce the thermal conductivity, increase the pressure drop			– Process control (to avoid polymerization, high viscosity, etc.) – Appropriate tubes layout – See NACE paper 13-4152
(13) Under deposit/fouling corrosion	– Inadequate process design – No frequent cleaning – No adequate cleaning – Unexpected contamination			– See NACE paper 18-11055/17-9340/17-8973/ 17-9564/17-8889/ 16-7195/ 13-4152/13-2508/13-2225/11266/11265/11262/10331/ 06458/05643/04521/03426/ 97447/89193
(14) Deformation by differential pressure	– Inadequate mechanical design (not enough strength) for pass partition plates, baffles, tubesheets, and plate/spiral/ cold box type H/EXs.	– Differential pressure – Severe polymerization – Severe bending		– Consider the maximum differential pressure – Process control – Full corrosion allowance – Sound fabrication

Table 2.138 (3/3) Typical corrosion phenomena and prevention methods in tube bundle of H/EXs[(1),(2)]

Damage type	Factors	Phenomena		Prevention
(15) Selective leaching (dezincification)	– Cu-Zn (Zn > 15%) alloys – See Fig. 2.95, Table 2.76, Table 2.79, Table 2.124 (13) for more detail.	– Change in color (from yellow to brown in the case of brasses) – They give rise to plug and layered type of attack. – There can be a change in density in some cases.		– Materials selection (add Sn, As, Sb, and P in Cu-Zn alloys)
(16) Dead zone corrosion- deadleg/ stagnant flow corrosion	– Low velocity – Poor baffle arrangement – Poor drain and dry during shutdown or after hydrotest – High TDS (total dissolved solids) – Used untreated water	– Produce poor heat transfer and can lead ultimately to excessive fouling. Typically lead to excessive fouling. – Additional problem of potential damage to tubes as a result of flow induced vibration. – In the case of such damage, processes must often be interrupted or shutdown in order to perform costly and time-consuming repairs to the device.	– Under deposit/fouling corrosion – Salt deposit corrosion 	– Remove the affected factors – Increase the velocity – Frequent cleaning
(17) MIC (microbiologically induced corrosion)	– Bad cooling water – Contaminated fluid – Stagnant flow or long time hydrotest water/ service fluid holding			– Keep minimum velocity – Cooling water quality control – Avoid dead zone – Use appropriate inhibitor – See NACE paper 13–3795. – See Sect. 2.4.1.4

Notes:
[(1)] The following are not included in this table:
– Leakages due to incorrect gasket (wrong, old, reused) use, damage of machined surfaces, enforced tube bundle assembly, or poor welding/bolting.
– Malfunction due to pressure drop (excessive pressure, severe fouling/scaling, too many dummy tubing, etc.) and excessive heating due to loss of cooling water.
– Malfunction due to dirty condition/contamination (no frequent cleaning, inadequate filtering at upstream, etc.)
– Brittle failure due to improper drainage in winter shutdown, used inadequate antifreeze solution
– Fatigue failure due to thermal expansion in expansion joints and tubes
– Other corrosion mechanisms – typical pitting, SCC, condensate grooving (steam to water U-tubes), etc.
[(2)] See API RP586-Section 1 for H/EX Tubing Inspection

References for H/EX Failures and the Analysis
(1) M. Schwartz, 4 types of H/EX Failures, Technical Publishing, 1981,
(2) 5 troubleshooting tips for tubular H/EXs, Processing Insight, 2018,
(3) NACE Papers: 18-11320/11059, 17-9286, 16-7188, 14-4152/3795, 13-2368/2118, 08173, 99069, 98594, 98335, 98325, 98197, 98186, 97522, 97490, 97144, 93046, 92419, 92189, 90331, 89202, etc.

2.4.2 *Environmentally Assisted Cracking (EAC) Corrosion and Prevention in Moderate Temperature, <204 °C/(400 °F)*

Environmental cracking may be defined as a cracking process caused by synergistic effects of tensile stress and environment on a specific material. In general, three factors – tensile stress, aggressive environment, and susceptible material – are essential for environmental cracking to happen over a period of time. If the cracking has not initiated, the removal of one factor can negate cracking. Therefore, stress relieving and/or hardness control for carbon and low-alloy steels is the basic requirement to avoid cracking in these environments. Stress Corrosion Cracking (SCC), Sulfide Stress Corrosion Cracking (SSC), Hydrogen-Induced Cracking (HIC), Stress-Oriented HIC (SOHIC), and liquid embrittlement fall within the definition of environmental cracking. In some cases, corrosion fatigue can also be listed in this group. Environmental cracking is normally dependent on cold and ambient temperatures (<150–204 °C (300–400 °F)). So high-temperature hydrogen attack (HTHA) is not included in this category. In a broad sense, SCC, hydrogen embrittlement, and some corrosion fatigue on the external surfaces may be a part of EAC environments; however, EAC and prevention for external surfaces are not included in this book.

There are several different EAC mechanisms in oil and gas industries as below. See NACE SP0472 (Methods and Controls to Prevent Cracking of CS Weldments in Corrosive Petroleum Refining Environments) for more detailed requirements in petroleum industry.

Figure 2.151 shows various environment corrosion cracking mechanisms and their interrelationships.

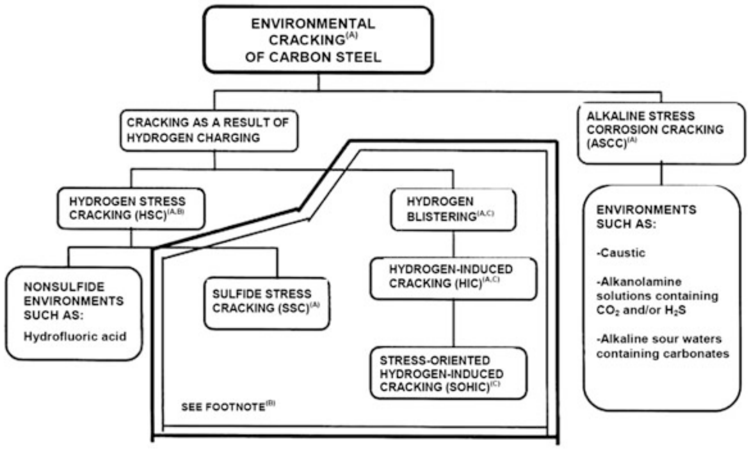


Figure 2.151 Interrelationships of the various cracking mechanisms. (Source: NACE SP0472). (**a**) Refer to the NACE Glossary of Corrosion-Related Terms for definitions (including SCC). (**b**) The forms of environmental cracking included within the double lines are commonly referred to as wet H_2S cracking when they occur in wet H_2S environments. (**c**) This form of environmental cracking can also occur in nonsulfide environments such as in hydrofluoric acid

2.4.2.1 Wet H_2S (Sour) Corrosion Cracking

H_2S in hydrocarbon fluids can be dissolved in free water as below:

$$; \quad Fe + 2(H_2S) + H_2O \rightarrow FeS + 2H^+ + S^- + H_2(gas) + H_2O$$

The atomic hydrogen will penetrate into the metal, and fom molecular hydrogen with multiple volume expansion within the stressed area or nonmetallic inclusions. This process continues until pressure buildup is sufficient to initiate fracture.

A number of factors such as pH, volume of hydrogen diffused, volume-fraction, and the shape of inclusions present, and the surrounding microstructure influence the process.

Atomic hydrogen (H^+) will concentrate near stress concentrators and may give rise to crack initiation at such points, leading to brittle fracture of the material.

As a result, the crack can occur rapidly and without warning. Because of its complexity, confirming SSC as the failure mechanism usually requires expert metallurgical analysis. The final fracture was a result of overload when the remaining ligament was insufficient to sustain the applied load.

The following failure types normally occur in wet H_2S (sour) service.

– Sulfide stress cracking (SSC)
– Hydrogen-induced cracking (HIC)
– Stepwise cracking (SWC) and hydrogen blistering.
– Stress-oriented hydrogen-induced cracking (SOHIC)

Figure 2.152 shows typical processes of hydrogen-induced cracking (HIC) and sulfide stress corrosion cracking (SSC).

The severity and susceptibility of SSC depend on the H_2S concentration in free water, H_2S partial pressure, pH of water, stress relieving (yes or no), hardness, Ni content of steel, etc., while the severity and susceptibility of HIC/SOHIC depend on the H_2S concentration in the free water, H_2S partial pressure, pH of water, HCN (cyanide) concentration of water, heat treatment of the base metal (N, N-T, Q-T), purity of steel (S & P), killed steel (semi or fully), degassing treatment, Ca treatment, Cu & Mn content of steel, etc.

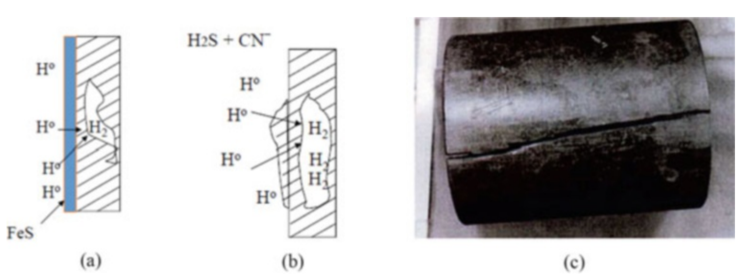


Figure 2.152 Typical processes of HIC and SSC. (**a**) Corrosion Layer of FeS Slows down Reaction and Blistering. (**b**) With Cyanides Present, FeS Dissolves and Corrosion/Hydrogen Blistering Continues. (**c**) SSC of A Well Casing Collar

Table 2.139 shows the characteristics of several H_2S corrosion types.

See Table 4.147 for PWHT requirements of CS in wet H_2S (sour) environments.

Applicable Codes, Standards, or Reports

ANSI/NACE MR0175/ISO 15156, ANSI/NACE MR0103/ISO 17945, NACE SP0296 (detection/repair/mitigation)/SP0472 (to prevent EAC), NACE TM0177/0284/0103, API RP581/571/55, NACE Publ. 8X194 & 8X294, NACE Publ. 1F192/939/939-B, BS EN ISO 21457, EFC Publ. 15 & 17, EEMUA 179, EUR 12959 EN

Table 2.139 (1/2) Simplified characteristics of several H_2S & hydrogen-assisted corrosion types [(1)(5)]

Item	HE (hydrogen embrittlement)	HTHA & surface decarburization	SSC (sulfide stress cracking)	HIC (blistering & stepwise wise cracking)	SOHIC (stress-oriented HIC)
Relative materials	CS, LAS, plated CS/LAS, Ni alloys, SS, Ti alloys, Al alloys (rarely)	CS, LAS	CI, CS, LAS, Ni alloys, SS, Cu alloys, Ni (>1.0%) including steel [(2)], etc.	Mostly rolled CS (dirty steel) –sometimes in rolled LAS [(4)]	Welded CS–sometimes in rolled LAS [(4)]
Usual source of hydrogen	• Gaseous H_2 diffusion/ cathodic reaction (H^++e → H) • During steel making (e.g., melting) • During fabrication (e.g., hot work, welding, plating, acid cleaning) • Hydrogen generating environment (e.g., water, wet H_2S, HF services, and cathodic protection)	• Gaseous H_2, diffusion/ dissolved hydrogen to form nondiffusible hydrocarbon gas ; C (in steel) + $4H^+ \rightarrow CH_4$; nonreversible reaction	[*Upstream*] • ppH_2S ≥ 0.3 kPa (0.05 psia) with free water mainly and acidic environment [*Downstream*] • Wet H_2S service (≥50 ppmw dissolved H_2S) in acidic and alkaline environments • If HF acid exists, the more severe the acidic corrosion	• After the hydrogen created during the dissolving process of H_2S sets down at the boundary of the segregation (especially flattened and elongated MnS) or voids, they make the H_2 gas and expand the volume. As a result, the crack initiates and propagates to the direction of perpendicular of thickness.	• After the hydrogen created during dissolving process of H_2S sets down at the high stressed zone, they make the H_2 gas and expand the volume. As a result, the micro crack initiates at HAZ bond line and accumulated and failed through thickness.
Corrosion range and severity	• 0~150 °C (severe at 20 ~ 70 °C for CS and LAS) • Unclear mechanism	• ppH_2 ≥ 7 kg/cm^2 and temperature at 204 °C (400 °F) and above	[*Upstream*] • ppH_2S ≥ 0.05 psia with free water mainly and pH < 6.5. pH↓ ~ more SSC • At 0~177 °C • Base metal, welds, HAZ (e.g., >22 HRC on CS) [*Downstream*] • At 0~150 °C • Wet H_2S service (≥50 ppmw dissolved H_2S) in acidic (pH < 6.5) and alkaline environments (pH > 8.4–9.0), see API RP581 for severity levels per H_2S ppm, pH, CN- and PWHT • Overhead systems • Mostly HAZ (e.g., >200 HBW on CS)	• At 0~150 °C (most severe at 0~65 °C) • Fe + H_2S → FeS + 2Ho (atomic hydrogen) penetrate and make hydrogen gas, Ho + Ho→ H_2↑ • Also occurs at low strength or low tensile residual stress steels • See API RP581 for severity levels per H_2S ppm, pH, CN- in service and sulfur in steel	• At 0~150 °C (most severe at 0~65 °C) • Fe + H_2S → FeS+ 2Ho Ho (atomic hydrogen) penetrate and make hydrogen gas, Ho + Ho → H_2↑ • Mainly occurs at high strength or high residual stress steels
Failure initiation	• Rapid crack propagation due to cathodic reaction • More severe at higher gas pressure, higher tensile strength (>115ksi) or higher hardness steel (>22 HRC). • In H2S, PH3, As H3 and + 5 & +6 hydrides service • Sometimes delayed cracking	• Decarburization on the surface • Internal crack due to expansion of methane bubble. • Increase the porosities and decrease the strength and toughness	• Higher hardness zone than above • Forging (A105): At ≥187 HBW • Casting: Gray, austenitic, white C.I (ferritic D.I except A395) • Crack propagation of thickness direction in weld HAZ • Often occurs in hydrogen embrittlement environment	• Stepwise crack (cross tearing) in the metal and blistering on the steel surfaces • Crack propagation	• The crack may occur at large nozzles with highly restricted geometrically during welding. (vessels, H/EX, tanks, not common in pipelines)

Table 2.139 (2/2) Simplified characteristics of several H_2S & hydrogen-assisted corrosion types

Item	HE (hydrogen embrittlement)	HTHA & surface decarburization	SSC (sulfide stress cracking) upstream & downstream	HIC (blistering & stepwise wise cracking)	SOHIC (stress oriented HIC)
How to prevent others – For reference	• Dehydration (preheating, postheating, use of low hydrogen welding electrode, dry and baking of welding electrodes • Anodic protection • To control below the dew point of gas phase • Avoid high-strength steels	• Use killed steels • Use Cr-Mo steels for more severe condition • Good welding practice • Use SS cladding • PWHT for CS & Cr-Mo steels • See Table 4.147 for PWHT requirements.	[Upstream] • Use SS clad steel. [Downstream] • SMTS $\leq$ 70 ksi for CS & LAS • Use SS clad steel. • PWHT required or use SS in the service with amine	• Use clean steels $S \leq 0.001$~0.008%, ($\leq$0.01% for seamless) ($\leq$0.025% for forging) $P \leq 0.010$~0.015% • Add Ca in the steel (to make the sulfide to the spheroidal shape), Ca/S = 1.5–2.0 • Degas • Killed & fine grain • HIC test • WFMT • Prevention: Q-T. N-T (N) > as rolled • Use coating or corrosion inhibitor (but the effectiveness is low)	• T.S < 70 ksi PWHT or normalizing • Use clean steels (S & P ↓), $S \leq 0.001$~0.003%, ($\leq$0.01% for seamless) ($\leq$0.025% for forging) $P \leq 0.010$~0.015%
Related codes (see applicable codes, standards, reports, and references below for more details)(5)	There are no regulations except the diffusible hydrogen control of welding in clients' specification.	• API RP/TR941 (Nelson • Curves) – keep the temperature allowance 14–28C (25–50 °F).	• NACE MR0175/ ISO15156^ • NACE MR0103/ ISO17945* • NACE SP0472 (welding & hardness)* • NACE TM 0177 (SSC Test) • NACE SP0296 existing • NACE Publ.8X194 & 8X294	• NACE TM0284 (stepwise crack test) • NACE MR0175/ • ISO15156^ • NACE SP0472* • NACE SP0296* • NACE Publ.8X194* & 8X294*	• NACE MR0175/ • ISO15156^ • NACE TM0103 (SOHIC test) • NACE SP0472* • NACE SP0296* • NACE Publ. 8X194* & 8X294*
Others phenomena or supplementary requirements [for reference]	• May be caused by supersaturated hydrogen on the steels including hydrogen in metal structure during cooling from high temperature • May be occurred the delayed crack due to nondischarged hydrogen in the steels when rapid cooling is done after welding • See Sect. 2.4.2.12 for more detail.	• Recently often occurs in downstream pipeline of heavy oil desulphurization unit separator • Coating or CRA cladding on the metal surface may mitigate the hydrogen diffusivity, but not immune from the HTHA	• Stainless steels(3): max. 22~36 HRC as per materials groups • Ni alloy; max. 22~40 HRC as per materials groups • CS & LAS: PWHT in all SSC environment • CS normalized steels in all SSC environment • LAS: Normalized or Q-T steels in all SSC environment	• Scarcely occur in seamless pipes, casting, forging • Most of the dry sour service may be transformed to the wet H_2S (sour) during shutdown unless the sufficient neutralizing treatment and drying do not applied • HE, HIC, SOHIC may occur in HF acid • pH of HIC test solution: 2.7–4.0 or 4.8–5.4 • The acceptable criteria of HIC test, CLR% $\leq$ 5/10/15, CTR% $\leq$ 1.5/3/5, CSR% $\leq$ 0.5/1/2 for class 1, 2, and 3 (15,5,2) respectively • Weight of materials cost (app'x) • Conventional: 100 (base) • HIC resistant (chemical controlled): 110–120 • HIC tested steel: 125–140	

Notes: *HTHA* high-temperature hydrogen attack, *pp* partial pressure, * for downstream (refinery), ^ for upstream (oil & gas production)
(1) SSC and HE are developed by cathodic reaction (rapid reaction-more catastrophic) at the crack tip while SCC by anodic reaction (slow reaction) at the crack tip. (See Fig. 2.153)
(2) Most failures of Ni (>1.0%) containing steels have occurred in OCTG of well production. NACE MR0103/ISO17945 does not adopt this restriction
(3) ASS containing lead (Pb) or selenium (Se) for the purpose of improving machinability
(4) HIC or SOHIC of LAS typically occurs in upstream (NACE MR0175), but rarely happens in downstream industries (may not be occurred)
(5) NACE STG 34 Technology Group is on preparing a new standard for Requirements for CS Equipment and Piping in wet H_2S environments

References: For More Detail and/or Use as Check List (See CO_2 Corrosion for CO_2-H_2S)

– *NACE Paper* **19**-12765/12814/12854/12866/12875/12894/12916/12943/12946/12967/13022/13041/13076/13332/13368/13370/13400/13401/13483, **18**-10495/10548/10583/10632/10669/10688/10798/10810/10821/10836/10842/10849/10851/10873/10895/10899/10918/10919/10920/10931/10938/10956/10963/10964/10970/10984/10990/11015/11027/11060/11070/11081/11084/11090/11123/11136/11173/11183/11193/11212/11229/11256/11266/11322/11358/11450/11472/11477/11478/11538/11553, **17**-8881/8929/8930/8933/8943/8965/8998/9019/9051/9073/9084/9112/9115/9129/9135/9200/9203/9242/9244/9251/9318/9319/9337/9342/9416/9425/9446/9449/9463/9479/9551/9592/9622/9634/9646/9667/9718/9745/9760, **16**-7119/7126/7183/7209/7223/7250/7313/7319/7325/7340/7362/7397/7478/7502/7537/7545/7568/7618/7623/7629/7643/7657/7658/7659/7695/7783/7792/7795/7887, **15**-5484/5485/5502/5578/5583/5607/5635/5640/5656/5672/5687/5701/5717/5718/5720/5742/5781/5794/5843/5851/5855/5894/5909/5917/5925/5927/5988/6004/6034/6050/6090/6119/

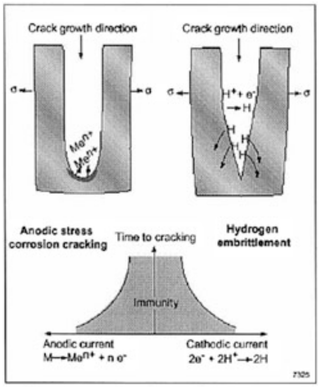


Figure 2.153 Reactions of SSC vs. HE/SSC (source: M.Fontana, Corrosion Engineering, 1986)

6137/6146, **14**-3727/3783/3793/3807/3816/3828/3835/3861/3863/3870/3893/3907/3912/3938/3947/4017/4042/4051/4061/4191/4207/4243/4274/4287/4288/4298/4320/4326/4361, **13**-2079/2235/2248/2275/ 2282/2293/2339/2406/2436/2462/2476/2486/2493/2524/2526/2531/2550/2561/2562/2580/2630/2639/2676/2698, **12**-1090/1113/1129/1136/1161/1213/1238/1295/1306/1350/1353/1443/1466/1474/1477/1520/1522/1537/1552/1575/1577/1651/ 1684/1702/1726, 11117, 11115, 11110, 10349, 10308, 10307, 10280, 09565, 09362, 09360, 09352, 09337, 09285, 09091, 09084, 08405, 07663, 07657, 07500, 07102, 07100, 06158, 06125, 06124, 05627, 05110, 05017, 05101, 04760, 04759, 04751, 04743, 04172, 04143, 04133, 04130, 04121, 04120, 04114, 04111, 04018, 03132, 03112, 02046, 02040, 02037, 01322, 01105, 01104, 01102, 01098, 01083, 01077, 01073, 01069, 01004, 00688, 00471, 00335, 00163, 00157, 00149, 00139, 99608, 99597, 99431, 99429, 99428, 99416, 99384, 99297, 99297, 98583, 98395, 98274, 98121, 98117, 98114, 98107, 98106, 98104, 98102, 97525, 97514, 97207, 97062, 97059, 97026, 97024, 95063, 96606, 96074, 96067, 96026, 95329, 95066, 95063, 95054, 94519, 94376, 94083, 94076, 94064, 92449, 92441, 92002, etc.

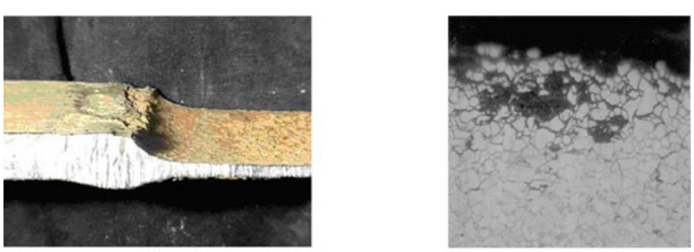
- *NACE MP 2015-09 (p16-18), 2015-08 (p20-23, 60), 2015-05 (p2-5), 2015-04 (p50-54), 2015-02 (p42-44), 2011-10 (p10-11), 2011-08 (p72-78),2011-06 (p10-12), 2009-12 (p48), 2008-10 (p44), 2008-06 (P14), 2007-04 (p58), 2006-08 (p52-56), 2004-11 (p55), 2004-09 (p46), 2001-11 (p50),*
- *NACE Corrosion Journal*: xxxx-yy: year-month 2017-02 (p155-168), 2016-12 (p1519-1525, 1556-1564, 1565-1579), 2016-10 (p1220-1222), 2016-09 (p1107-1115), 2016-08 (p999-1009), 2016-06 (p791-804), 2016-05 (p636-654, 679-691), 2015-08 (p945-950), 2015-05 (p641-645), 2015-03 (p305-315, 316-325), 2014-04 (p351-365, 375-389), 2013-12 (p1195-1204), 2013-06 (p624-638), 2013-02 (p145-156), 2012-11 (p1015-1028), 2012-08 (p730-738), 2012-07 (p620-624, 662-671), 2012-03 (p35004.1-12), 2012-01 (p15006.1.11), 2011-08 (p85003.1-16, p85005.1-6), 2011-06 (p65001.1-12), 2011-05 (p56001.1-11), 2011-01 (p15001.1-12, p15004.1-16), 2010-11 (p115003.1-12), 2010-05 (p56002.1-6), 2010-04 (p45003.1-8), 2009-09 (p595-600), 2009-05 (p291-307), 2008-10 (p788-799), 2008-07 (p586-699), 2008-07 (p586-699), 2008-06 (p483-495), 2008-05 (p372-400), 2006-12 (p1092-1099), 2006-05 (p425-443), 2005-02 (p167-173), 2004-12 (p1115-1121), 2003-07 (p640-653), 2003-01 (p68-81), 2002-10 (p881-890), 2002-09 (p783-792), 2001-03 (p236-252), 2000-05 (p534-543), 2000-02 (p167-182)

2.4.2.2 HF Corrosion Cracking

HF is highly reactive with many substances. It is highly corrosive, and contact between HF and metals, glass, concrete, strong bases, sodium hydroxide (NaOH), potassium hydroxide (KOH), ceramics, leather, natural rubber, and other materials may result in violent reactions (Fig. 2.154). It should be noted that the corrosive action of HF on metals can result in the formation of hydrogen gas. Corrosion by HF acid can result in high rates of general or localized corrosion and may be accompanied by hydrogen cracking, blistering, and/or HIC/SOHIC. HF acid concentration (water content), temperature, alloy composition, and the presence of contaminants, including oxygen and sulfur compounds, are the controlling factors. See Table 4.147 for PWHT requirements of CS in HF environments.

Applicable Codes, Standards, or Reports

API RP751, API RP581, API Publ. 939-B, NACE Publ.5A171, NACE SP0296/0472, ASTM A106-S9, ASTM A516-S54, ASTM A961-S62, NiDI Publ. 10074/443, etc.



(a) (b)

Figure 2.154 HF corrosion phenomena (**a**) Cross-section of a CS pipe showing preferential corrosion of the pipe with a high residual element content on the right (%Cr + %Ni + %Cr) as compared to the low residual pipe section at the left of the weld. (Source: API RP571). (**b**) Intergranular corrosion of CS pipe exposed to AHF with AsF_5, hardness HRB 60 (400×). (Source: NACE Paper 01345)

References: For More Detail and/or Use as Check List

- *NACE Paper* 19-13428, 18-10863, 17-8978, 15-5560, 14-3794, 11358, 10234, 10074, 07750, 07570, 07481, 06588, 06532, 04645, 04643, 04635, 04229, 03651, 01345, 01155, 00518, 99381, 99382, 97115, 97503, 97513, 95092, 95339, 95341, 95342, 95344, 94511, 93623, 92107,92452, 90019, 89260,
- *NACE MP* Feb.2007, p54, etc.
- *NACE Corrosion Journal* 1994-12 (p963-971), 1997-04 (p327-332)

2.4.2.3 Amine Corrosion and Cracking

Amines currently used in H_2S removal plants have caused intergranular SCC (IGSCC) of CS piping and vessels. Some of the more common amine solutions are MEA (monoethanolamine), DEA (diethanolamine), DIPA (di-isopropanolamine) and MDEA (methyl diethanolamine). Cracks have occurred in both lean and rich amine service. 300 series ASS are usually employed extensively in amine units to remove from hydrocarbon streams that contain very little or no H_2S. Amine cracking is most often associated with Lean Amine Services. Cracking has been reported down to ambient temperatures. Increasing temperature and stress levels increases the likelihood and severity of cracking. Amine concentration does not appear to have a significant effect on the propensity of cracking. Most cracks show not only SCC in alkaline service but also SSC, HIC, SOHIC, and hydrogen blistering which are based on the corrosion in wet H_2S (sour) service (Fig. 2.155). See Table 4.147 for PWHT requirements of CS in amine environments.

(a) (b)

Figure 2.155 Alkaline SCC in a pipe weld in MEA service. (Source: API RP945). (**a**) Alkaline SCC in a pipe weld in an MEA unit; nital etched specimen at 6× magnification. (**b**) The bottom panel illustrates the intergranular nature of the cracks; nital etched at 200× magnification

Applicable Codes, Standards, or Reports
API RP945, API RP581, API RP571, etc.

References: For More Detail and/or Use as Check List

- NACE Paper **19**-13225, **18**-11185, **16**-7913/7476/7187, **15**-5954/5888, **14**-4222, **13**-2368/2207/2038/2037, **12**-1288, 10192, 10187, 10183, 09334, 07398, 00492, 06446, 06441, 05388, 05386, 04481, 00698, 00497, 00495, 00494, 00492, 98405, 96396, 96394, 96392, 936391, 96389, 95572, 95571, 92453, 92447, 92044, 85159,
- NACE Corrosion Journal: 2016-10, p1300-1310/2012-07, p600-609/2008-02, p124-130/1997-02, p163-168/1997-03, p186-194/ 1995-04, p321-328, etc.

2.4.2.4 Caustic Corrosion and Cracking

Caustic (sodium hydroxide) solution (≥2 NaOH wt%, but ≥5 NaOH wt% for some users) corrodes carbon steel at temperatures over 45–93 °C (113–200 °F) per NaOH concentration and stress relieved. The corrosion pattern shows cracking mode as well as general corrosion. At temperatures above about 80 °C (176 °F), both carbon and stainless steels (300 and 400 Series) can fail by SCC ("caustic embrittlement"). Nickel and nickel alloys are the preferred alloy for hot caustic service. Where stress corrosion cracking rather than corrosion is the problem, consider PWHT before resorting to materials upgrade (Fig. 2.156). See Table 4.147 for PWHT requirements of CS in caustic environments. See Sect. 2.1.6.7(a) for caustic corrosion of stainless steels.

The following conditions require an additional stress relieving (or PWHT) or material upgrading for Area "A" in Fig. 2.156c.

(a) If welded (or directly contacted on the service metal) and steam traced
(b) If welded and electric heat traced and metal temperature exceed 46 °C (115 °F)
(c) If subject to periodic steamout
(d) When the caustic solutions with different concentration are mixing, the mixed temperature may be higher than individual temperature of each service concentration due to exothermic reaction. Therefore, the PWHT requirement should be based on the mixed temperature.

Applicable Codes, Standards, or Reports
NACE SP0403 (for CS, SS, Ni alloys, Local PWHT), API RP581, NiDI Publ. 10019 & 281, MTI MS-6, MTI TAB No.13, EPRI NP-5129, EPRI NP-4051, EPRI Tech Report-A Model of Caustic SCC Initiation and Growth in Alloy 600, Safe Handling of Caustic Soda, JSIA (Japan soda Industry Association-2006), etc.

References: For More Detail and/or Use as Check List

- NACE Paper **18-**10842, 11154, 09175, 09169, 09062, 08551, 08194, 07453, 07451, 06501, 06497, 06219, 05196, 04572, 04555, 03518, 01407, 00596, 99284, 98590, 93033, 90563, 90191, 89249, etc.
- NACE MP Sep. 2011, p51/ Apr. 2011, p12-13 & 68-70/ Feb. 2009, p15/ Sep. 2007, p79/ Dec. 2004, p39, etc.
- NACE Corrosion Journal May 2005, p404-410/ Oct. 2003, p843-850/ Dec. 1999, p1144-1154/ Apr. 1989, p273-282/ Jun. 1986, p368-372/ Feb. 1986, p63-70/ Dec. 1985, p720-727/ Oct. 1985, p575-581/ Jul. 1985, p381-385/ May. 1985, p274-280/ Sep. 1983, p363/ Feb. 1983, p66-70, etc.

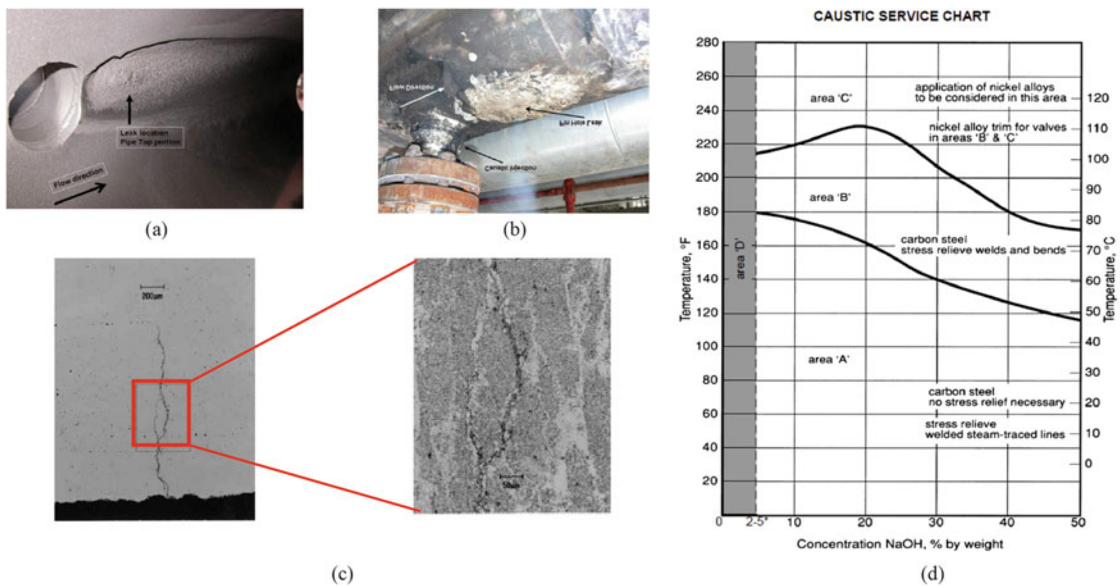


Figure 2.156 Caustic corrosion and SCC of several metals. (**a**) Caustic Corrosion (internal) of CS Piping. (Source: NACE Paper 08511). (**b**) Caustic Corrosion (external) of CS Piping. (Source: NACE Paper 08511). (**c**) Failure in CS Storage Tank in Caustic Service (NACE SP0403). (**d**) Caustic Service Chart (NACE SP0403)

In addition, there are several failure reports for Ni Alloys (e.g., Alloy 600, 690) in high temperature and pressurized water reactor steam service in power plants below.

Failure Reports of Ni Alloys (e.g., Alloy 600, 690) in Caustic Solution

- NACE Paper 09062/07453/07451/90191/89249
- NiDI Publ. 10019/281
- MTI MS-6 materials selector ammonia and caustic soda
- E.D. Eason, E.E. Nelson, EPRI TR-104073s, a model of caustic SCC initiation and growth in alloy 600 (1994)
- K.R. Chasse, EPRI NP-5129 Mechanisms of IGC and SCC of alloy 600 by high temperature caustic solutions containing impurities, Jul (1987)
- J.P.N. Paine, D. Cubicciotti, EPRI NP-5129 mechanisms of IGC and SCC of alloy 600 by high temperature caustic solutions contaminants, Jun (1985)
- N.S. McIntyre et al., Microscopic cracking on flat alloy 600 surfaces following accelerated caustic corrosion: mapping of strains and microstructure during the corrosion process. NACE Corros. **71**(1), 65–70 (2015)
- D.H. Hur, A correlation between anodic film properties and SCC behavior of alloy 600 and alloy 690 in high-temperature caustic solutions. NACE Corros. **59**(3), 203–206 (2003)
- Y. Yi et al., Effect of an inhibitor on the SCC behavior of alloy 600 in a high-temperature caustic solution. NACE Corros. **59**(3), 403–410 (2005)
- K.H. Lee et al., Effect of heat treatment applied potential on the caustic SCC of inconel 600. NACE Corros. **41**(9), 540–553 (1985)
- J.K. Sung, Effect of heat treatment on caustic SCC behavior of alloy 600. NACE Corros. **55**(12), 1144–1154 (1999)
- M. Navas et al., Effect of silicon compounds on SCC of alloy 600 in caustic solutions. NACE Corros. **55**:(7), 674–685 (1999)
- U.C. Kim, Electrochemical Behaviors of Alloy 690 in Caustic Solutions Containing Pb at 300 °C. NACE Corros. **66**(1), 105002-1–6 (2010)
- H. Kawamura, H. Hirano, IGC and SCC propagation behavior of alloy 600 in high-temperature caustic solution. NACE Corros. **55**(6), 566–575 (1999)
- R. Bandy et al., Intergranular failures of alloy 600 in high temperature caustic environments. NACE Corros. **41**(3), 142–150 (1985)
- B.W. Brisson et al., IGSCC initiation and growth in mill-annealed alloy 600 tubing in high-temperature caustic. NACE Corros. **54**(7), 504–514 (1998)
- A. Bhattacharya, SCC of DSS in Caustic Solutions, GIT doctorate paper, Dec. (2008)

2.4.2.5 Alkaline Carbonate SCC

ACSCC (carbonate cracking) manifests itself as surface-breaking cracks that typically develop at or near carbon steel welds under a combination of tensile stress and corrosion in an alkaline carbonate-containing environment. The location of these cracks is usually in the base metal within 50 mm (2 inches) of the weld (see Fig. 2.157). The cracking is predominantly intergranular in nature, and typically occurs

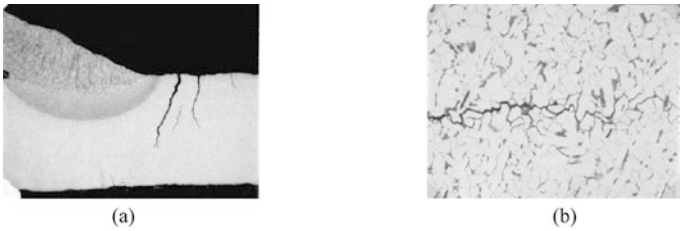


Figure 2.157 Carbonate SCC of CS. (Source: NACE Publ. 34108). (**a**) Photomicrograph of ACSCC in Coupon. (**b**) Photomicrograph of crack tip of Fig (**a**) left

in as-welded CS fabrications as a network of very fine, oxide-filled cracks. The pattern of cracking observed on the steel surface is sometimes described as a spider web of small cracks.

In most refineries where ACSCC has occurred, it has typically been found in the main fractionator overhead condensing and reflux system, the downstream wet gas compression system in the FCCU, and the sour water systems emanating from these areas.

See Sect. 2.1.7(b) for hot alkaline SCC of stainless steels. See Table 4.147 for PWHT requirements of CS in carbonate environments.

Industrial standards state the following survey data for Alkaline Carbonate SCC (ACSCC) of carbon steels:

(a) API RP581 defines the following environmental factors for increased susceptibility to ACSCC:
   – ; > 50 ppm H2S in the liquid water phase and pH of 7.6 or greater
   – ; Occurs in non-stress-relieved carbon steel
   – ; *Medium risk*
      ; Occurs at $8.4 \leq pH < 9.0$ and $500\ ppm \leq CO_3^{-2} \leq 1000\ ppm$
      ; Occurs at $pH \geq 9.0$ and $100\ ppm \leq CO_3$–$2 \leq 500$ ppm
   – ; *High risk*
      ; Occurs at $7.6 \leq pH < 8.4$ and $CO_3^{-2} > 1000$ ppm
      ; Occurs at $8.4 \leq pH < 9.0$ and $CO_3^{-2} > 1000$ ppm
      ; Occurs at $pH \geq 9.0$ and $CO_3^{-2} \geq 400$ ppm.

(b) API RP571 defines the following environmental factors for increased susceptibility to ACSCC:
   – ; > 50 ppm H2S in the liquid water phase and pH of 7.6 or greater
   – ; Occurs with non-stress-relieved carbon steel [PWHT required at 650–665 °C (1200–1225 °F)]
   – ; Occurs at $pH > 9.0$ and $CO_3^{-2} > 100$ ppm
   – ; Occurs at $8.0 < pH < 9.0$ and $CO_3^{-2} > 400$ ppm.

(c) NACE Publ. 34108 reported ACSCC occurred at pH 8.5–10 (peak at 9.0–9.5) in refinery FCCU overhead system. See NACE Publ. 34,108 [PWHT at min. 621 °C (1150 °F)] and NACE SP0427 [PWHT at min. 649 °C (1200 °F)] for more details on carbonate SCC in refinery sour water.

Applicable Codes, Standards, or Reports
NACE Publ. 34,108, API RP581, API RP571, etc.

References: For More Detail and/or Use as Check List

– NACE Paper 19-12930/12935/12817/13390/13433, 18-10842/11141/11179, 17-9596, 14-3975, 13-2713, 08599, 08265, 07564, 04639, 04392, 04201, 01040, 99038, 98247, 98026, 95610, 95164, 92454, 91312, 90206, 89177, etc.
– NACE MP Jul. 1991, p41–45, Apr. 2005, p56, etc.
– NACE Corrosion Journal, Cl- on Corrosion and SCC of DSS in Hot Alkaline-Sulfide Solutions, v68-n10, 2012.pdf
– K.R. Chasse, A study on the mechanism of SCC of DSS in hot alkaline-sulfide solution-Doctorate Paper in GIT, Dec. 2011

2.4.2.6 Polythionic Acid SCC (PTASCC)

PTASCC can occur during shutdown and start-up from/for high-temperature operation when sulfur, air, and moisture are present in the service. PTASCC normally has an intergranular corrosion cracking (IGC) pattern due to sensitization (e.g., Cr-carbides at 400–815 °C (750–1500 °F)) of the material, so it occurs in the equipment and piping made by unstabilized 300 series SS, Alloy 600(H), and Alloy 800 (H). By the reactions of sulfur impurities with water, air, or oxygen, H_2S and SO_2 are formed as intermediate products that further form complex compound products like tetrathionate ($S_4O_6^{2-}$), polythionate ($S_xO_6^{2-}$), and polythionic acid ($H_2S_xO_6$– PTA). See Sect. 2.1.6.8 for PTASCC in stainless steels.

2.4.2.7 Chlorides SCC (CLSCC)

CLSCC typically occurs in 300 series SS, DSS, and some nickel alloys under the combined tensile stress and chloride-containing solution. The severity depends on the chloride concentration, temperature, pH, dissolved oxygen, PRE of the metal, stress condition, hardness, etc.

See Sect. 2.1.6.2 for CLSCC for stainless steels.

2.4.2.8 Nitrate SCC – Source: http://jes.ecsdl.org/content/87/1/209.short

SCC of mild steel in nitrate (NO_3^-) aqueous solutions is shown to depend upon the stress-accelerated age hardening of the steel (Fig. 2.158). A correlation between the cracking times and the extent of aging was made. Both the extent of aging after a standard treatment and the rate of cracking after several heat treatments were correlated with the free nitrogen factor. Oxygen and nitrogen in the air react during the

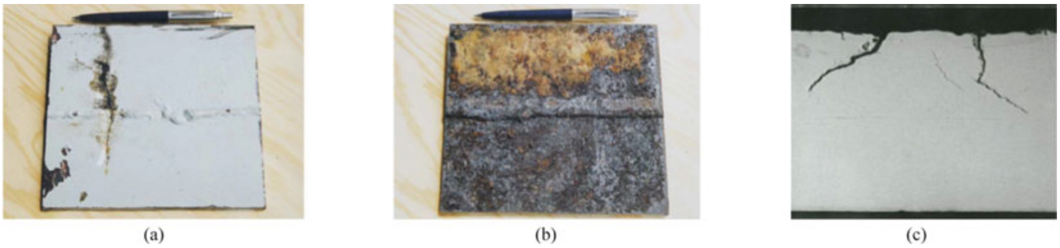


Figure 2.158 Nitrate SCC of CS casing of Heat Recovery Steam Generator (HRSG) in a Co-Generation Plant. (**a**) The outer surface of a steel plate cut from an HRSG casing. Note the crack running perpendicularly to butt-weld. (**b**) The inner surface of a steel plate cut from HRSG casing. Note the rusty corrosion products and adhering insulation (top). (**c**) Cross-section through casing plate. Small cracks originating from inner surface of the plate. Corrosion products: Nitrate (as N) 760 ppm, sulfate 2 ppm, chloride 6 ppm, pH 5.3, outer surface of an HRSG casing at different locations yielded values that ranged from 24 °C (75 °F) – 29 °C (85 °F) at startup to 46 °C (115 °F) – 64 °C (148 °F) during operation. (Source: NACE Paper 07485)

combustion process to produce NO_x. Hydrogen in the natural gas fuel (principally methane, CH_4) combines with oxygen to produce water vapor. The source of the nitrate ions (NO_3^-) has been concluded to be nitric acid (HNO_3), produced by the interaction of NO_x and water vapor in the combustion gases. Cracking proceeds rapidly when steels are loaded to stresses slightly less than the yield point but greater than a certain threshold stress. The acceleration of quench aging of mild steel by elastic stresses was shown. The age-hardening mechanism of SCC was partially confirmed. The conditions under which cracking occurs do not differ in principle from those necessary to produce caustic embrittlement.

Meanwhile, a steel that is in contact with a more concentrated ammonium nitrate solution is attacked along the grain boundaries by intergranular corrosion (IGC). The ammonium nitrate solution is most probably formed by the combination of NO_x from the exhaust of the gas turbine with aerosols in the combustion air. Crystals of nitrate tend to deposit in the cooler regions of a Waste Heat Recovery Boiler (WHRB).

During startup and shutdown, the metal temperatures in the boilers tend to fall below the dew point.

Condensing water (with some sulfuric acid) will dissolve the precipitated ammonium nitrate, resulting in the formation of a concentrated nitrate solution on the steel surface. In locations where high mechanical stresses occur and/or a critical deformation rate is exceeded, IGC will lead to the development of cracks (stress assisted IGC crack). This, in turn, in general is often called SCC, which was observed in the WHRB of combined cycle power plants (Fig. 2.159).

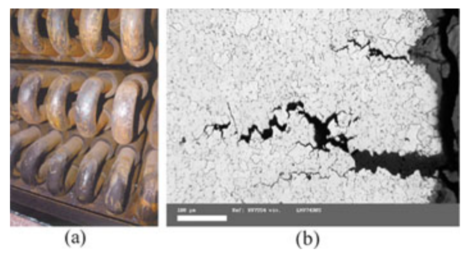


Figure 2.159 Nitrate SCC. (Source: 53 publication HRSG 19112, www.hbscc.nl). (**a**) Overview of an area where SCC occurred. Finned pipes are used to increase the surface area of H/EXs. (**b**) Cross section of tube material reveals Nitrate SCC

Applicable Codes, Standards, or Reports

NFPA 490 Code for the Storage of Ammonium Nitrate, HRSG publication 191102-53,

References: For More Detail and/or Use as Check List

- NACE Paper **19**-12743/13198, **17**-9425, **16**-7162, **14**-3754, 11201, 10230/10233, 09434, 08599, 07485, 06524, 02025, 99471
- NACE MP Sep.2008-p64,
- R.G.I. Leferink, et al., Nitrate SCC in Waste Heat Recovery Boilers, 53 publication HRSG 191102,
- J.A. Donovan, Temperature dependence of nitrate SCC, AIME Symposium DP-MS-77-25 (1977),
- Safe Production, Handling and Storage of Ammonium Nitrate, Nitrogen paper 223, Sep-Oct., 1996

2.4.2.9 Sulfate SCC

Sulfate SCC can occur when copper alloys (commonly admiralty brass) are subjected to external or internal stress, and are exposed to solutions containing sulfates at ambient temperatures. Unlike NH3 SCC that can occur in an extremely short period of time, sulfate SCC is slow to occur, taking as long as 10–15 years to be detectable with low sulfate concentrations.

Meanwhile, Alloys 600 and 800 used in nuclear plants have been found susceptible to SCC in acid sulfate environments, but the mechanism is unclear (Fig. 2.160). See Sect. 2.4.1.6 for SRB (sulfate-reducing bacteria) corrosion

Applicable Codes, Standards, or Reports

NACE TM0197/0374, ASTM D516

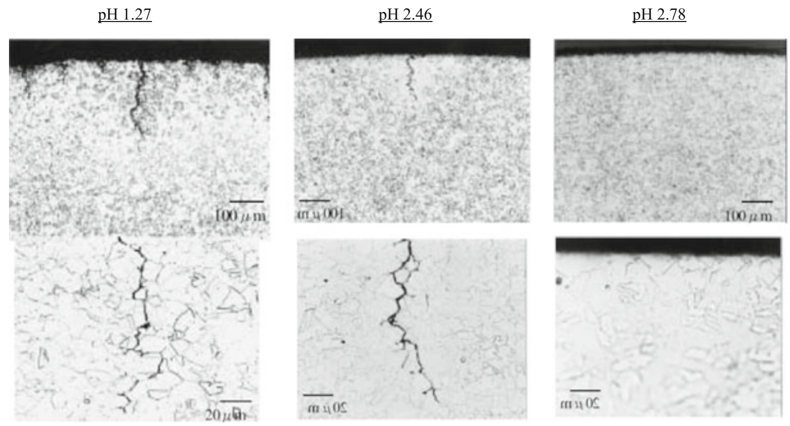


Figure 2.160 Sulfate SCC in Alloy 600 exposed to a 0.50 M SO_4 environment at 325 °C for 500 hours; Crack depth gets progressively larger as room temperature pH decreases from 2.78 to 1.27. (Source: S. Fukuchi, et al.'s EPRI paper, Jun. 1994)

References

– NACE Corrosion Vol.52, No.3, p282 (1996), Vol.53, No.2, p171 (1997), Vol.67, No.11, p115 (2011), Vol.50, No.6, p468(1994),
– S. Fukuchi, et al., Effect of water chemistry on corrosion resistance of alloy 600 SG tubes under acidic conditions, EPRI NP-7346-M (June 1991)
– Proc. 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems–Water Reactors, The Minerals, Metals, & Materials Society, p1267 (2005)

2.4.2.10 Anhydrous Ammonia Cracking (AAC as a SCC)

Anhydrous ammonia (water <2000 ppm), a major commercial chemical (Table 2.140) which is a main source of anhydrous ammonia cracking (AAC-Fig. 2.161a, b), is used in the manufacture of fertilizers, HNO3, acrylonitrile, and other products. Metallurgical-grade NH3 may contain only 10~20 ppm (by volume) water, because this compound contributes an oxidizing species in the solution annealing of stainless steels.

Table 2.140 Commercial grades of anhydrous ammonia (MTI-MS-6)

Property	Commercial grade	Refrigeration grade	Metallurgical grade
Water content	<5000 ppm	≤75 ppm	≤33 ppm
Oxygen content	<5 ppm	≤4 ppm	≤2 ppm

Use of CS is normally acceptable in NH_3 service if PWHT is performed to avoid the sensitivity to AAC environment.

Most cases of AAC have occurred in ambient-temperature pressurized storage vessels, for the most part in spheres. When the reduction of area on tensile test of CS is less than 50%, the susceptibility of AAC is increased per the water content in liquid ammonia. See Fig. 2.161c.

There have been no documented cases of AAC in cryogenic storage vessels. But a few problems have been observed in semi-storage. When AAC on CS does occur, cracks are primary transgranular and progress at a relatively slow rate compared to other AAC phenomena. AAC is accelerated by cold work, by welding (hard HAZ), by applied stresses, and by the use of higher-strength steels (e.g., above HRC 20 or 225 BHN are harmful).

AAC occurs both in high-strength Q-T (A517 Gr. F) alloy steel as well as in the lower strength CS (A516 Gr.60), but susceptibility appears less in the lower-strength materials, probably because they are less hardenable, e.g., upon welding. The highest susceptibility to AAC for CS has been found to be in liquid ammonia with 3-10 ppm oxygen and a water content < 100 ppm. However, AAC can occur in ammonia with an oxygen content ≥ 0.5 ppm when the water content is very low (< 100 ppm).

Nitrogen also appeared to be an AAC accelerator when present in combination with oxygen.

AAC can be alleviated by thermal stress relief at minimum 600 °C (1112 °F) of storage vessel in combination with inhibition by addition of about 2000 ppm water as a minimum.

Stress relief is a primary requirement, because water inhibition (>2000 ppm water) may not be effective above the liquid level as a result of the lower vapor pressure (as little as 1 ppm of oxygen may be dangerous), and oxygen scavengers (e.g., hydrazine, ammonium carbonate, and ammonium bicarbonate) or getters (e.g., internal nickel waste plates) may be helpful. See Fig. 2.161d.

Figure 2.161e shows guidelines for changes in required inspection frequency when oxygen or water content is outside the preferred range (for low-alloy steel in liquid NH_3).

Flame-spraying with Al or Zn may prevent AAC on CS when PWHT is impractical. Figure 2.161f shows the effect of grain size on the time to cracking of Yellow Brass (C26800) in liquid ammonia. See Table 4.147 for PWHT requirements of CS in anhydrous ammonia environments.

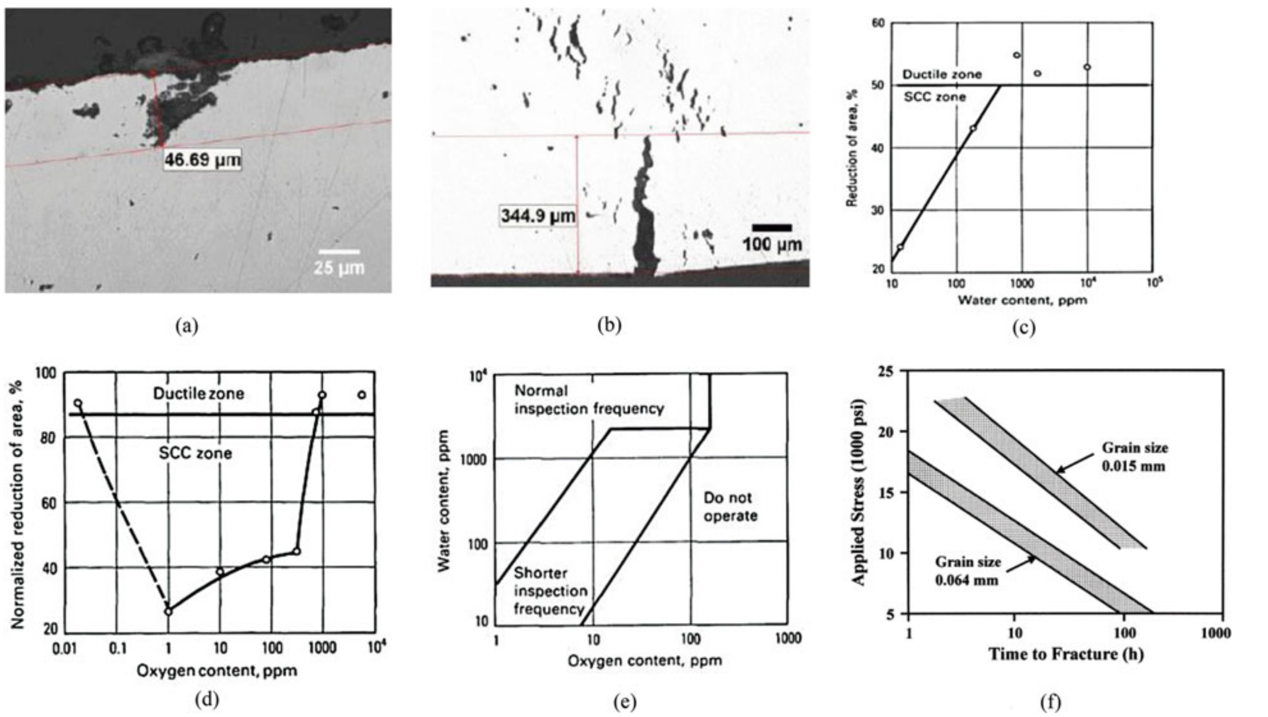


Figure 2.161 Anhydrous ammonia cracking on CS-typical and O_2 and water effects. (Source: ASM Handbook) and grain size effect on yellow brass. (Source: MTI-MS-6). (**a**) Crack 1 on CS. (**b**) Crack 2 on CS. (**c**) Effect of water content on apparent ductility observed in slow strain rate tests of low-alloy steel in liquid NH_3. Oxygen content was 200 ppm, added as air. (**d**) Effect of oxygen content on apparent ductility observed in slow strain rate tests of low-alloy steel in liquid NH_3. (**e**) Guidelines for changes in inspection frequency when oxygen or water content is outside the preferred range (for low-alloy steel in liquid NH_3). (**f**) The Effect of Grain Size on the Time to Cracking of Yellow Brass (C26800) in Ammonia (MTI-MS-6)

Applicable Codes, Standards, or Reports
ASTM B858 (TM for Ammonia Vapor Test for Determining Susceptibility to SCC in copper Alloys), API RP571, MTI MS-6, NiDI Publ. 9013, ASM Handbook Vol.13, etc.

References

NACE Paper 89098/89568, 91298, 95331, etc.

2.4.2.11 Fatigue Corrosion Cracking

Fatigue corrosion cracking occurs under the combined effects of cyclic loading (e.g., loading (tensile-compressive/ tensile-tensile/ compressive-compressive with moderate/high cycle frequency) and corrosion environment (internal as well as external). The mechanical threshold stress in the fatigue cycle will be more rapidly reduced in the corrosion environment as shown in Fig. 2.162. This fatigue can occur at dissimilar weld joints or at thermally fatigued zones (i.e., coke drum) in high-temperature service even though it has low cycle frequency. The most common facilities for fatigue corrosion cracking environment are below:

- Rotating equipment (i.e., pumps, compressors, etc.).
- Fixed equipment (i.e., coke drum, deaerators, cyclones, etc.).
- Small branch connections in which process-induced vibrations are possible, such as common vents and drains, small-diameter connections in pump areas, components in cyclic pressure or temperature service.
- Aboveground pipelines, such as in arctic installations, may be prone to wind-induced fatigue.
- Subsea pipelines/flowlines/risers with moderate and high cycles.
- Structures and bridges in seashore.
- Inadequate flexibility design (i.e., surge, pulse, etc.), especially for large-diameter piping.

As a typical case, cracks of deaerators (CS deaerating and storage sections) are found on the internal surfaces and associated with welds, especially circumferential welds, but have also been associated with internal and external welded attachments. Cracks occur both perpendicular and parallel to the hoop stress direction and are normally transverse to the weld. They are normal to the plate surface and propagate in a transgranular fashion; the crack tips are commonly blunt and may exhibit branching as well as being filled with an adherent oxide product. The mechanisms of deaerator failure are not fully understood but appear to be mainly corrosion fatigue sometimes in

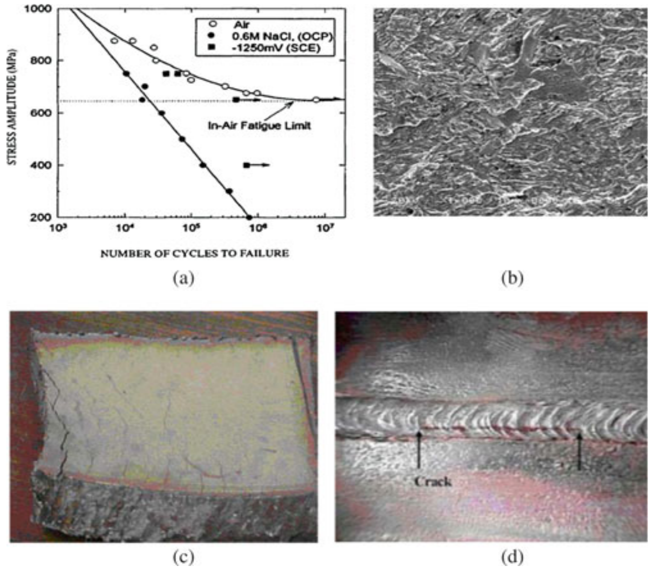


Figure 2.162 Fatigue corrosion cracking. (**a**) S-N Curves for a high-strength steel under different environmental conditions. Stress ratio $R = — 1$. Loading frequency 1 Hz for tests in 0.6MNaCl solution. Horizontal arrows indicate failure condition not attained. OCP = open circuit potential. (Source: Note 1). (**b**) SEM Fractographs for Corrosion Fatigue Fracture Surfaces of Sensitized 304 SS in 3.5%NaCl solution. (Source: NACE Paper C2012–1626). Note 1. Y-Z. Wang, R. Akid, and K. J. Miller, "The Effect of Cathodic Polarization on Corrosion Fatigue of a High Strength Steel in Salt Water," *Fatigue Fract. Engineering. Mater. Struct.* 18(3), 295 (1995). Publ. Blackwell Science Ltd., Oxford, U.K. (**c**) Thermal fatigue cracks on the inside of a heavy wall SS piping downstream of a cooler H_2 injection into a hot HC line (API RP571). (**d**) Fatigue Crack in 16" Pipe to Elbow Weld in the Fill Line of Crude Oil Storage Tank after 50 years in Service (API RP571)

association with stress corrosion cracking. Fluctuations in flow and water level, vibration, and startup and shutdown (rapid startup after cold layup) are thought to provide cyclic stresses sufficient to fracture the magnetite scale adhering on the crack sides and thus expose fresh metal to corrosion and further cracking. The startup stresses can be reduced by avoiding procedures resulting in pressure fluctuations, sudden pressure loss, and excessive water/steam hammer. Even with these precautions, water/steam hammer may occur in the return line whenever the condensate temperature exceeds 100 °C (212 °F) because the hot condensate is often a two-phase steam and water mixture.

NACE SP0590 (Prevention Detection and Correction of Deaerator Cracking) states the following startup procedure to minimize the stress (fatigue stress corrosion); rapid startup after cold layup can produce stresses very conductive to corrosion fatigue.

Regardless of the startup procedures used, emphasis should be placed on making sure an appropriately gradual, steady, and monitored start-up is followed. If deaerator manufacturer's recommendations for temperature ramp-up rate are not available, a maximum temperature ramp-up rate of 8 °C (15 °F) per 5 minutes is suggested. An adequate steam supply for startup, as well as operation, should be available. Startup stresses can be reduced by avoiding procedures resulting in pressure fluctuations, sudden pressure loss, and excessive water/steam hammer. Also, a vessel warm-up period can be included as part of the startup when high operating temperature or hot, superheated steam is used.

The typical preventions are to apply full penetration welding, flushing weld deposits, PWHT, expansion joints, appropriate material selection, minimizing stress concentration parts (e.g., smooth contour grinding any edges and corners, etc.), periodical test and inspection, and corrosion inhibition (Fig. 2.162).

In addition, in severe corrosion environments (e.g., sour service) the degradation of fatigue performance should also be considered by appropriate Knockdown Factors (KDF), which are factors degraded from the standard S-N curves in air that have been studied and developed for a certain oil and gas production site with high cycle environment, especially for subsea riser design.

Applicable Codes, Standards, or Reports

API RP571, NACE SP0590 (Deaerator Cracking), API TR934-G (Coke Drums), ASTM STP465 (Low Cycle Fatigue Testing), ASTM E1681 (Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials), ASTM E2368 (Practice for Strain Controlled Thermomechanical Fatigue Testing), ASTM F1801 (Practice for Corrosion Fatigue Testing of Metallic Implant Materials), API TR 17TR8, Appendix D (HPHT Design Guideline, Fatigue), etc.

References: For More Detail and/or Use as Check List

NACE Paper **19**-13071/13271/13350, **18**-11001/11124/11228/11517, **17**-8853/8918/9001/9181/9200/9203/9402/9669/9745, **16**-7599/7901, **15**-5605/ 5717/5843/6122/7599/7901, **14**-4070, **13**-2119/2493/2613, **12**-1134/1477/1577/1626, 11108/11119/11297, 10302/10311/ 10312/10313, 09090/09303, 08458/08488/08489, 07103/07503/07054, 04144/04552, 03522/03527, 02431, 01115/01238, 00012/00214/00227/00303/00375, 99461/99610/99611, 98738/98744, 96125/96245/96261/96262/96536, 95414, 94212/94216/94218/94396, 92150/92151/92156, 89040/89462/89570/89617, etc.

RPSEA 07121-1403 (2012), OMAE2011-50204, J.W. Hutchinson, International Journal of Solids and Structures, 47 (2010) p1443-1448, ASM Elements of Metallurgy and Engineering Alloys, Chap. 14 (2008)

2.4.2.12 Hydrogen Embrittlement (HE) Other Than HTHA

(a) Hydrogen is reactive so it pairs up into molecules of two atoms of hydrogen H + −H+. The methods for hydrogen to enter metals are pickling, chemical metal removal (polishing), welding, plating operations, crevice corrosion conditions, service conditions, and cathodic protection.

Typically plating on CS or LAS causes a reaction that releases hydrogen atoms (atomic hydrogen). Some of the hydrogen atoms pair up and form hydrogen molecules ($H^+ - H^+$) and bubble to the surface as hydrogen gas. Other hydrogen atoms bond to the iron atoms on the part being plated.

It is these hydrogen atoms that cause the problem. Allowed to remain weakly bonded to iron, they will diffuse deeper into the metal. Absorbed hydrogen atoms concentrate at minute faults in the iron and create tension, which can lead to an explosion-like breaking of the part. As a result of the penetration of atomic hydrogen, a loss in ductility of high-strength steels can lead to brittle cracking (Fig. 2.163). HE can occur for carbon and low-alloy steels, SS (mainly 400 series and PHSS, rarely ASS and DSS), some high-strength nickel-based alloys, and aluminum alloys (rarely). HE has cathodic reaction (rapid reaction-catastrophic crack) at the crack tip while SCC has anodic reaction (slow reaction), as seen in Fig. 2.153.

(a) (b)

Figure 2.163 Hydrogen embrittlement. (Source: Fastener Engineering & Research Association report, 2007). (**a**) A Typical HE Failure of a Plated Bolt. (**b**) A Typical Columnar Structure on HE

HE effect is normally pronounced at temperatures from ambient to about 149 °C (300 °F). Effects decrease with increasing temperature and HE is not likely to occur above 71–82 °C (160–180 °F), and HE typically shows the following two forms.

First Form:

- The presence of hydrogen will not decrease the YS or TS. However, the elongation to failure or the ductility will decrease.
- Failure mode will be transgranular and brittle in form.

Second Form:

- YS, TS, and ductility will all be decreased.
- Failure mode in this case can be either transgranular or intergranular.
- HE is another case of delayed failure.
- The fact is both stress and hydrogen dependent. Failure will not initiate until both conditions are met.
- As no anodic process is associated with this failure mode no corrosion products should be found on the fracture surface, provided the material is removed immediately from the environment after failure.

See Sect. 4.3 for hydrogen-induced cracking during welding.

(b) Normally the following three conditions for HE must be satisfied:
  1. Hydrogen must be present at a critical concentration within the steel/alloy.
  2. The strength level and microstructure of the steel/alloy must be susceptible to embrittlement.
  3. A stress above the threshold for HE must be present from residual stresses and/or applied stresses.

(c) The HE may be prevented from the following controls:
  1. To lower strength and residual stress of steel i.e., high-strength steels are heat-treated to lower strength and still be used in some refinery plants
  2. To control or consider the amount of hydrogen pickup in processing (operation)
  3. To neutralize just after chemical cleaning, or to avoid overpotential on cathodic protection (CP)
  4. To develop alloys with improved resistance to HE, i.e., change CS to LAS or alloys
  5. To develop low or no embrittlement plating (and residual stress reduced) or coating processes
  6. To restrict the amount of in situ hydrogen introduced during the service life of a part (See Sect. 2.6.2.6, General Notes)
  7. To bake out after welding, i.e., temperature holding around 163 °C (325 °F) for 24 hours is usually sufficient to remove hydrogen (See Sects. 4.3.4 and 4.4.3 for more details)

Applicable Codes, Standards, or Reports

NACE TM0177/0284, API RP571, API RP581, API RP941, WRC Publ. 240 (HE in ASS), ASTM A143/B577/F326/F519/G129/G142/G146, etc.

References

Surface Treatment Data file 1 (HE)-FERA, NACE Paper **19**-13473, **18**-10509, **17**-8889/9255, **16**-7440, **15**-5853/6053, **14**-3892/3948/4124/4292, **13**-2078, **12**-1467, 10084/10290/10295, 08111, 07200/07493, 06290/06575, 5098/05146/05462, 04104/04545/04546/04563, 03133/03534/03659, 02430, 01011/01018/01091/01229, 98253/98265/98269/98432, 96246/96307/96554, 95161, 94223.94224/94227/94250/94396, 93288, 90202, 89189, NACE MP p60-63 Sep.2011, NACE Corrosion Journal-various papers, etc.

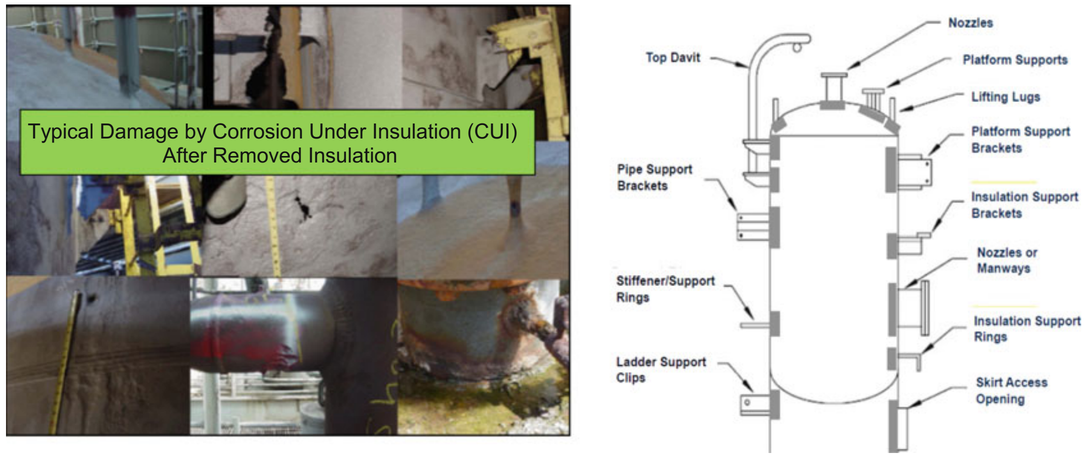


Figure 2.164 Corrosion under insulation (CUI). (Source: NACE SP0198/ API RP583 modified)

2.4.2.13 Corrosion Under Insulation and Fireproofing (CUI and CUF) – Commonly Called CUI

Corrosion under insulation and fireproofing is a major integrity threat, particularly for ASS and DSS as well as CS and LAS (Fig. 2.164). It results from water ingress into the insulation and migration to lower spots. Susceptibility to CUI is dependent on the temperature range of operation, the age of the coating, and the condition of the insulation. CUI has been observed on systems operating between −12 °C and 177 °C (10 °F and 350 °F), with the maximum corrosion rate observed in the range of 90–95 °C (194–203 °F). Above 120–177 °C (248–350 °F), when water get vaporizes, corrosion issues may become nil.

(a) The most susceptible areas and conditions to CUI are as follows:
1. For Pressure Vessels
   - Area etched for vertical pressure vessel in Fig. 2.164
   - Areas exposed to steam vents
   - Areas exposed to deluge systems
   - Areas subject to process spills, ingress of moisture, or acid vapors
   - Nozzles, platform support protrusions, etc.
   - Areas downwind of cooling towers exposed to cooling tower mist
   - Areas of protrusions (i.e., transition points) through the jacketing at manways, nozzles, and other components
   - Areas where insulation jacketing is damaged or missing
   - Areas where caulking is missing or hardened on insulation jacketing
   - Areas where the jacketing system is bulged or stained
   - Areas where banding on jacketing is missing
   - Areas where thickness monitoring plugs are missing
   - Areas where vibration has caused damage to the insulation jacketing
   - Areas exposed to process spills, the ingress of moisture, or acid vapors
   - Areas insulated solely for personnel protection
   - Areas under insulation with deteriorated coatings or wraps
   - Areas with leaking steam tracing
   - Pipe and flanges on pressure safety valves
   - Systems that operate intermittently above 120 °C (250 °F)
   - Systems operating below the atmospheric dew point
   - Systems that cycle through the atmospheric dew point
   - Ice-to-air interfaces on insulated systems that continually freeze and thaw
   - Insulation support rings below damaged or inadequately caulked insulation on vertical heads and bottom zones
   - Stiffening rings on insulated vessels/columns in vacuum service
   - Insulated zone at skirt weld or leg supports
   - Ladder and platform attachments
   - Termination of insulation at nozzles, saddles, davit arm supports, lifting lugs, body flanges
2. Piping General
   - Dead-legs, vents, drains, bolted on pipe shoes, valves and fittings
   - Steam-tracing/electric-tracing tubing penetrations
   - Termination of insulation at flanges and other piping components
   - CS/LAS flanges, bolting, and other components in high-alloy piping

- Jacketing seams on the top of horizontal piping
- Termination of insulation on vertical piping
- Areas where smaller branch connections intersect larger-diameter lines
- Low points in piping with breaches in the insulation
- Close proximity to water (wharf) and/or ground (increased absorption)
- Wet due to flooding or submerging into water
- Damage due to foot traffic
- Flanges with stud bolts where insulation bonnets are installed, not sealed

3. Cold Piping
   - Flanges with stud bolts where insulation bonnets are installed but not sealed
   - Piping below flood grade where rising water penetrates the insulation jacketing causing ice lens with swelling that causes jacketing failure
   - Holes or cuts in the insulation vapor retarder or jacket
   - Ice-to-air interfaces

(b) The most susceptible temperature zones to CUI

Figure 2.165 indicates the most susceptible temperature ranges to CUI in terms of the used metal. The temperatures are based on the normal operation including the temperatures exposed by the cyclic service.

Applying the suitable external paintings (as per project specification for external painting and coating of new equipment and piping)

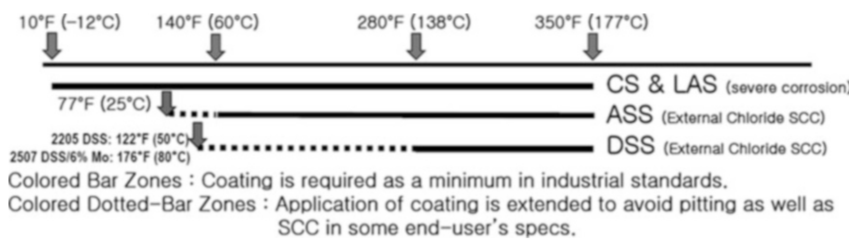


Figure 2.165 Most susceptible temperature ranges to CUI. (Source: NACE SP0198/ API RP583)

are the best mitigation methods against CUI risks. The risk is reduced to >175 °C (347 °F) and < −5 °C (25 °F). As a most common practice, a protective coating (including thermal spray aluminum-TSA) or aluminum foil wrapping should be applied to avoid CUI. See Sect. 3.4.6 for thermal spray coating.

(c) Prevention of CUI (Corrosion Under Insulation or Fireproofing)

1. Coatings

To apply the NACE SP0198, Table 1 for stainless steels (SS) & Table 2 for CS and LAS. Galvanized materials or zinc-containing paints, etc., shall not be used on the surfaces of austenitic stainless steel or high-nickel alloy pressure components. Alternative coatings and/or materials shall be used.

Inorganic zinc coatings without a topcoating are prone to rapid failure of CS or LAS in the presence of moisture. For example, calcium silicate-insulated piping, when exposed to condensed water, can generate an alkaline environment with a pH of 9–10 on the wetted pipe surfaces. This environment may be detrimental to alkyd and inorganic zinc coatings and can lead to pitting near the joints between the blocks of insulation. Inorganic zinc coatings used without a topcoat on CS structural steel being fireproofed are generally not effective since zinc is amphoteric. This is because the alkaline conditions beneath concrete and cementitious fireproofing can accelerate corrosion of the inorganic zinc coating material. Also, inorganic zinc coatings used on their own are not effective coatings under fireproofing. Zinc is amphoteric and can be attacked in the alkaline conditions that exist beneath concrete and cementitious fireproofing. If inorganic zinc-rich coating is applied on CS or LAS in a shop and topcoat is applied in the field, proper cleaning of the primer inorganic zinc-rich coating is required. The use of inorganic zinc-rich coating under insulation is not a preferred system for service temperatures in the CUI range up to approximately 175 °C (350 °F). However, bulk piping is often coated with inorganic zinc-rich coating in the shop and some owners purchase this piping for use under insulation. In these cases, the inorganic zinc-rich coating should be top coated per the NACE SP0198, Table 2 to extend its life. The combination of primer and finish coatings shall be confirmed by a coating specialist. For CS and LAS, an alternative coating, such as TSA, may offer superior protection against CUI in the wide service temperature range, −45 to 595 °C (−50 to 1100 °F). Meanwhile, even though NACE SP0198, Table 1 indicates the top coating system on ASS and DSS surfaces under insulation, these top coatings may or may not be applicable in accordance with design life, maintenance/inspection plan, field condition and experience, or project specification.

2. Aluminum wrapping on stainless steel surfaces

Even though TSA (Thermal Spray Aluminum) on the external surfaces of ASS (300 series stainless steel) or DSS (2205 or 2507 duplex stainless steel) has a good CUI resistance, a bonded aluminum foil instead of TSA may be used for small bore piping of NPS 24 and smaller.

Aluminum Foil Wrapping on ASS or DSS surfaces to prevent CISCC operating continuously in the temperature range in Fig. 2.165 may be applied in accordance with the following guidelines:

[General]

– For a small bore piping (up to 24 NPS piping),
– 20–30 deg. spiral wrapping band like API RP583, Fig. 22 for piping type,
– Aluminum foil thickness: 0.1 mm (4 mil) nominal, 0.064 mm (2.5 mil) minimum,
– Minimum 50 mm (2 in.) overlapping,
– Hold with Aluminum or SS wire,
– The foil should be molded around flanges and fittings,
– To apply other instructions in the API RP583, 11.5.3,

[Pressure Vessels]

– Held by insulation sprags and insulation support clips/rings

[Piping and Pipelines]

– Formed to shed water on the vertical line.
– Foil is molded around flanges and fittings
– Steam traced lines are double wrapped with the first layer applied directly onto the pipe, followed by the steam tracing, and then more foil over the top.

3. Others to avoid CUI
   (a) Appropriate Insulation Materials Selection: To apply the NACE SP0198 and ASTM C795
   (b) Keep insulation dry at all times and keep surfaces to be insulated clean and dry.
   (c) Ensure that a full bedding coat of asphalt cutback is applied when required.
   (d) Use the insulation thickness designated in the project insulation specifications.
   (e) Determine whether the insulation should be single-layer or double-layer.
   (f) Ensure that all insulation joints are staggered, especially on double-layer systems.
   (g) Ensure that a bedding coat has been applied between the first and second insulation layers for systems operating below −40 °C (−40 °F). Do not apply the coat to the metal substrate.
   (h) Ensure that the insulation has no gaps greater than 3.2 mm (0.125 in).
   (i) Replace the affected section of insulation if the gap exceeds 3.2 mm (0.125 in). Do not use finishing cement to fill the gap.
   (j) Use valve stem extension handles, where applicable, for insulated valves.
   (k) For systems requiring a vapor barrier, ensure that the vapor barrier has been applied to the exterior of the insulation.
   (l) Do not use screws to secure jacketing on systems with vapor barriers.
   (m) Ensure that insulation has been secured with the specified wire, bands, or tape.
   (n) Ensure that all insulation terminations have end caps.
   (o) Ensure that watershed angles are provided.
   (p) Ensure that installed insulation is protected from rain and washdown until jacketing is installed.
   (q) Ensure that the proper jacketing type and metal thickness is installed.
   (r) Ensure that the jacketing is installed in watershed fashion on horizontal runs.
   (s) Ensure that the bands and breather springs are the correct size and material. These are installed on the outside of the jacketing around the equipment.
   (t) Ensure that the bands are turned under or caulked at the clips.
   (u) Ensure that the nozzle openings and all other protrusions are flashed and caulked.
   (v) Ensure that the system has been caulked. Caulking should be left beaded, not feathered.
   (w) Order duplicate equipment nameplates for systems operating below 0 °C (32 °F). These should be banded, not screwed, to the outside of the jacketing.
   (x) TML (thickness measurement location) windows should be considered for CUI.
   (y) Keep a sound periodic inspection plan of insulation and fireproofing.
   (z) Inspection on stream: See Sect. 5.4.4.2.

Applicable Codes, Standards, or Reports (Included Retired Documents)

NACE SP0198, API RP583/RP571/ RP581/RP574/570/653, MTI Technical Report No.4/7/22, MTI R-9, MTI Project 118, Norsok M-501, DIN 32521, AWS C2.18, NACE No.12, NACE Publ. 14C296, CINI Manual Section 7, ASTM STP 880, ASTM G189, ASTM C795 Thermal Insulation for Use in Contact with ASS, ASTM C692 for Evaluating the Influence of Thermal Insulations on External SCC Tendency of ASS, NBIC NB-23 (inspection), etc.

References: For More Detail and/or Use as Check List

NACE Papers **19**-12952/12965/13042, **18**-11415, **17**-8876/8877/9287/9296/ 9331/9369*, **16**-7368/7486*/7565/7804/7831, **15**-5448/5747/5757/5949*, **14**-4079/4196*, **13**-2500*/2570, **12**-1100*/1160/1661, 11281, 10022/10373, 09135/09348, 08036*/08380*/08558, 07566, 04022*/04023*, 03022/03026/03029, 96088, NACE MP May 2016 P17-19, Oct. 2013 P46-48, NACE MP May 2013 P74-77, NACE MP Jan. 2013 P52-58, NACE MP Nov. 2004 P38-40 (dry air injection), NACE MP Apr. 2007 P58, EFC Publication #55 "Corrosion under Insulation (CUI) Guidelines, MTI TAB-CUI No.7, JPCL p34-37 Jul. 2009, etc. * included TSA.

2.4.3 Local and Cracking Corrosion and Prevention in High Temperatures, ≥204 °C/(400 °F)

This section discusses high-temperature corrosion while Sect. 2.3 discussed metallic degradation at high/elevated temperatures. Normally electrolyte (water) is not necessary in these corrosion mechanisms, and hence it is also known as dry corrosion or scaling. Typically, Ni, Cr, Mo, Cb, W, and Si are good elements for high-temperature corrosion resistance.

Codes and Standards have many requirements exposed or operated in the elevated temperature service, such as temperature limitations, chemical composition control, grain size limitations, etc., in accordance with several different metal degradation mechanisms which are introduced below. See Sect. 2.3 for metal loss and degradation (non-high temperature corrosion issues) in high temperature.

References (General Guidelines) for High-Temperature Corrosion: For More Details and/or Use as Check List

– API RP571/581/941
– NiDI Publication 10056, 10001, 9004, 1285
– ASM metal handbook, Vol.13 series
– M.G. Fontana, Corrosion engineering, McGraw-Hill
– Roberge P.R, Handbook of corrosion engineering, McGraw-Hill
– G.Y. Lai, High-temperature corrosion of engineering alloys, ASM
– NACE Paper **18**-11027/11028, **17**-9269/9280/9497, **16**-7302, **15**-5668/7302, **14**-4075, **13**-2184/2196/2287/2307, **12**-1429, 11191/11409, 10353, 09250/09231, 08464, 07339/07462, 06229/06436, 05421/05445, 03353/03718, 02123/02374/02382, 01159, 00530, 99071/99272/99382, 98189/98742, 97147, 96143/96168/96441, 95099/95458/95466, 94174/94189/94535, 92135/92451, 90294, 89143/89206, 84072, 83089, 77049

2.4.3.1 High-Temperature Oxidation

Oxidation is a deposition of oxides on the metal surface. Oxidation can often serve as a protective scale, but can also result in poor thermal conductivity at the oxide-metal interface, leading to other accelerated corrosion problems (Figs. 2.166 and 2.167). CS and LAS are the most widely utilized materials for plant construction. The applications include furnaces, fired heaters, steam generators, boilers, reactor vessels, incinerators and flue gas systems in power generation, waste incineration, oil refining, and petrochemical and chemical processing plants. In most cases, the materials used in this equipment are most commonly limited by the loss of strength due to exposure to high temperature. This is why Ni additions are commonly utilized. At sufficient levels, it imposes an austenitic microstructure and minimizes the phenomenon of 475 °C (885 °F) embrittlement. However, in applications involving oxidative conditions, additions of Cr tend to promote the formation of protective films, which reduce corrosion rates to acceptable levels. Exhaust gases which contain H_2O, NO_x and O_2 can accelerate corrosion and require >17%Cr and > 8%Ni to reduce corrosion to acceptable levels. At very high temperatures (>1000 °C), alternative materials must be utilized, which contain high levels of Ni and Co which impart both enhanced high temperature strength and resistance to corrosive attack in many environments. In some cases, where particularly corrosive environments are encountered, ceramic materials either as coatings or monolithic materials may be required. See ASM Metal Handbook, Vol.13 series for structures and thermal properties (melting temperatures) of various metal oxides.

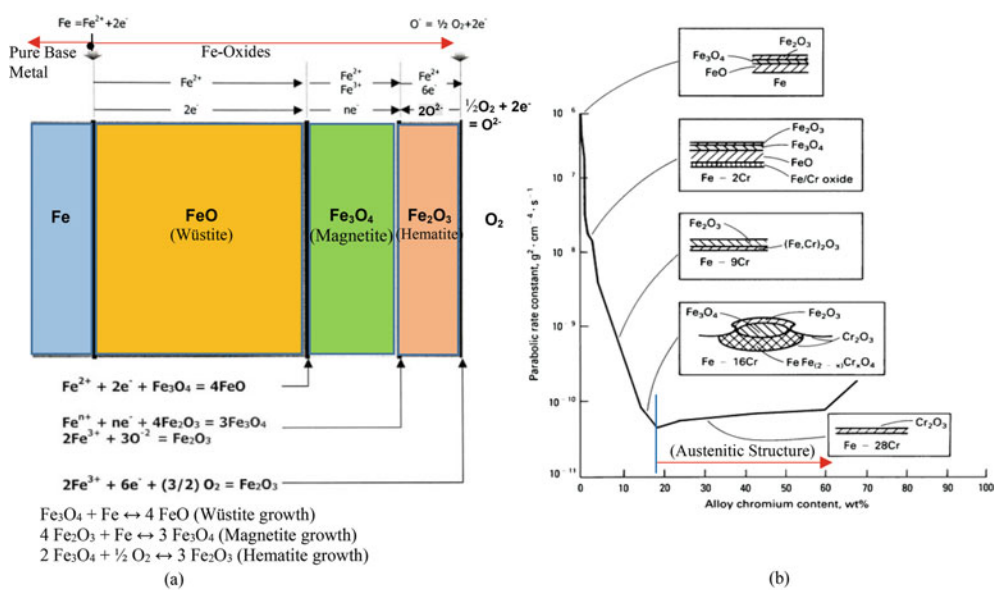


Figure 2.166 Oxidation on carbon steel. (Source: ASM Metal H/B Vol.13). (**a**) Schematic diagram of oxidation mechanism for the diffusion-controlled growth of multilayered scale during isothermal heating 570 °C (1060 °F) in dry oxygen. (**b**) Schematic of the variation with alloy Cr content of the oxidation rate and oxide scale structure (based on isothermal studies at 1000 °C (1832 °F), in 0.13 atm oxygen). (Source: ASM Metal H/B Vol.13 – modified)

The oxidation of copper alloys is usually not a problem, because these are rarely used where operating temperatures exceed 260 °C (500 °F). Thermal cycling, applied stresses, moisture, and sulfur-bearing gases will decrease scaling resistance. In refineries and petrochemical plants, high-temperature oxidation is primarily limited to the outside surfaces of furnace tubes, tube hangers, and other internal furnace components that are exposed to combustion gases containing excess air. At elevated temperatures, steam decomposes at metal surfaces to hydrogen and oxygen and may cause steam oxidation of steel, which is somewhat more severe than air oxidation at the same temperature. Fluctuating steam temperatures tend to increase the rate of oxidation by causing scale to spall and thus expose fresh metal to further attack.

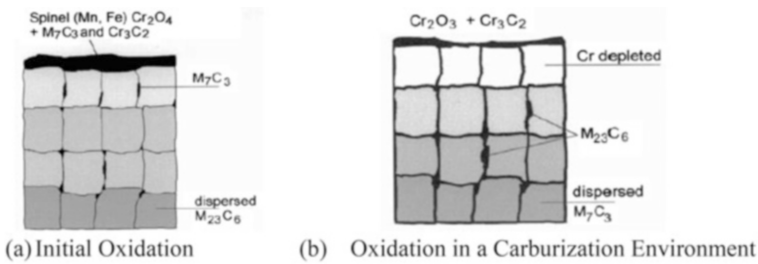


Figure 2.167 Oxidation and carburization on alloy 600. (Source: NACE Paper 01374). (**a**) Initial Oxidation. (**b**) Oxidation in a Carburization Environment

Figures 2.168 and 2.169 show the estimated corrosion rates (metal loss) of several commercial metals in high-temperature oxidation environments without other contaminations which are indicated in API RP581 & 571. See Table 2.15 for high-temperature scaling and API RP581, Para. 2.B.9 for high-temperature oxidation corrosion rates for each metal.

Meanwhile, hot oxidation can be accelerated by fused (molten) or solid deposit, such as Na_2SO_4 in sulfur (S), sodium (Na), potassium (K), and/or vanadium (V) in coal or fuel oil of power generation equipment, gas turbines, combustion engines, oil refinery FCCU regenerators, waste incinerators, and papers/pulp industries. It also calls out as fuel-ash corrosion or oil-ash corrosion. Two general forms of sulfate hot corrosion additionally exist on high-temperature oxidation environment (see Fig. 2.170).

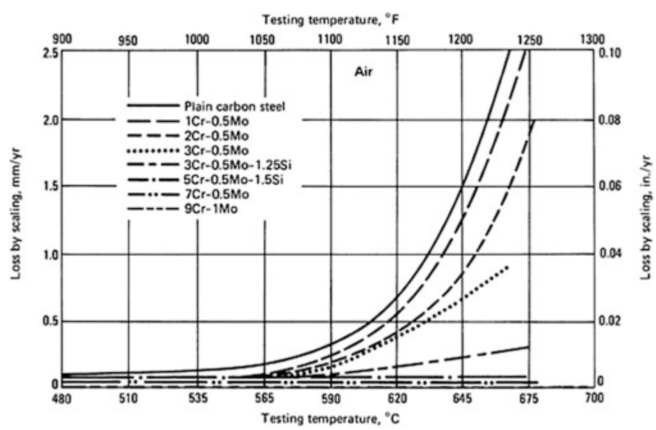


Figure 2.168 Estimated metal loss from oxidation scale of several CS and las in air. (Source: ASM Metal H/B Vol.1)

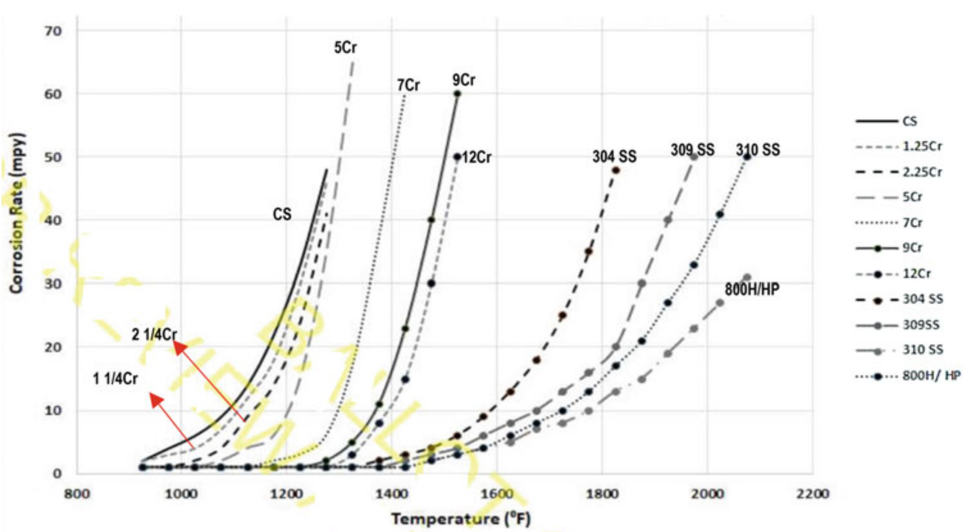


Figure 2.169 Estimated oxidation corrosion rates of several commercial metals in air. (Source: API RP581/571)

Type I, High-Temperature Hot Corrosion (HTHC)

HTHC occurs through multiple mechanisms. It is generally thought to transpire by basic fluxing and subsequent dissolution of the normally protective oxide scales by molten sulfate deposits that accumulate on the surfaces of high temperature components such as bot section turbine blades and vanes. High-temperature hot corrosion usually occurs at metal temperatures ranging from 850 °C to 950 °C (1560–1740 °F).

Type I hot corrosion involves general broad attack caused by internal sulfidation above 800 °C (1470 °F); alloy depletion is generally associated with the corrosion front. This basic fluxing attack may involve raising the Na_2O activity in the molten sulfate by formation of metal sulfides. Basic fluxing may also occur above 800 °C (1470 °F) when P_{SO3} is low since the basicity of the molten sulfate deposits is controlled primarily by the partial pressure of sulfur trioxide, p_{SO3}. As the reaction proceeds, the $SO_2 + O_2$ concentration determines if the sulfate-induced hot corrosion is sustained. Very small amounts of sulfur and sodium or potassium can produce sufficient Na_2SO_4 or K_2SO_4. In gas turbine environments, a sodium threshold level below 0.008 ppm by weight precluded type I hot corrosion.

Type II, Low-Temperature Hot Corrosion (LTHC)

LTHC occurs in the temperature range of 650–750 °C (1200–1380 °F) where p_{SO3} is relatively high or melts are deficient in the oxide ion concentration leading to acidic fluxing of metal oxides that result in pitting attack. Sulfides are found in the pitted area when nickel based alloy are utilized. The LTHC may involve a gaseous reaction of SO_3 or SO_2 with CoO and NiO that results in pitting from the formation of low-melting mixtures of Na_2SO_4 and $NiSO_4$ or Na_2SO_4 and $CoSO_4$ in Ni-Cr, CoCr, Co-Cr-Al, and Ni-Cr-Al alloy systems. The interaction of these oxidation products with salt deposits forms a complex mixture of salts with a lower melting temperature. When the salt mixture melts, the corrosion rate increases rapidly. If other reactants are added, melting temperatures of the resultant salts can be further lowered. High chromium content (>25 to 30 wt% Cr) is required, generally, for good corrosion resistance to hot corrosion.

See NACE Paper 11,365 for mitigation strategies for HTHC and LTHC.

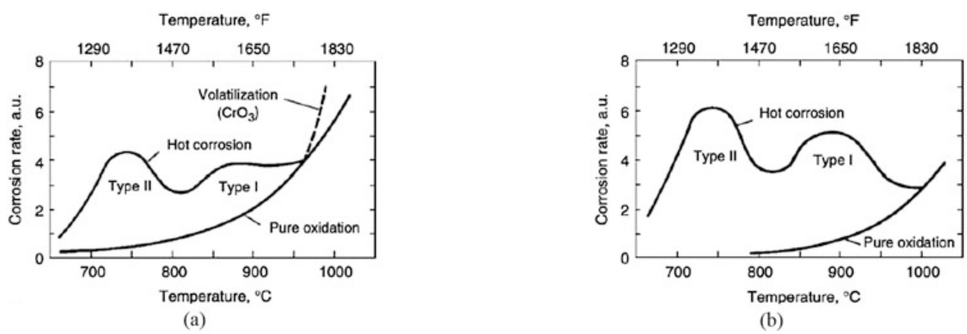


Figure 2.170 Various types of high-temperature corrosion per temperature of alloys (ASM Metal H/B Vol.13B). (**a**) Chromia-forming alloys. (**b**) Alumina-forming alloys

Applicable Codes, Standards, or Reports (Included Retired Documents)

API RP571/ RP581 Parts of High-Temperature Oxidation

References; for More Details and/or Use as Check List

– NACE Paper No. **19**-12750/12751/13243/13520, **18**-11199, 17-9426/9006, **16**-7854, 15-5919/5903/5734, **13**-2646/2172/1725, 11365, 11193, 11186. 11151, 10203, 10198, 09266, 09231, 08446, 07611, 07470, 06453, 05448, 05398, 03509, 03505, 03476, 03465, 03509, 03476, 03465, 03456, 02526, 02393, 02368, 01374, 01356, 01352, 01163, 01151, 01149, 00259, 00244, 98416, 98413, 98194, 97132, 96442, 96171, 96138, 96137, 95558, 95181, 93258, 92302, 90294, 90291, 90267, 89611, etc.
– NACE MP Dec. 2011, p23/May 2010, p63/Aug. 2008, p64-65/Jun. 2008, p68-73/May 2006, p/Dec. 2004, p46
– NACE Corrosion Mar. 2016, p422-438/Nov. 2015, p1342-1359/Aug. 2015, p992-1002/Oct. 2008, p722-727/Aug. 2008, p64/Jun. 2008, p68-73/Aug. 2007, p794-799/Oct. 2005, p961-967/Aug. 2005, p751-756/Mar. 2005, p201-218/Apr. 2003, p350-355/Aug. 1999, p805-813/May 1999, p456-460/Mar. 1998, p53/Feb. 1998, p102-105/Mar. 1995, p191-200/Jan. 1994, p4-11/Nov. 1992, p891-197/Apr. 1990, p296-301/Dec. 1989, p1020-1027/Aug. 1989, p662-675/May 1989, p408-415/Sep. 1988, p611-614/Dec. 1986, p708-717/Apr. 1984, p152-157/Jun. 1983, p241-247
– G.Y. Lai, High-temperature corrosion of engineering alloys, ASM, (1996)
– M.G. Fontana, Corrosion Engineering, 11-10 Oxidation Resistance, 3rd Ed
– X. Li et al., Development and oxidation resistance of B-doped silicide coatings on Nb-based alloy. Corros. Sci. Technol. 233–236 (2008)

2.4.3.2 Carburization

Figure 2.171 shows the primary and secondary carbides precipitation of two alloys modified of HK 40. In a high-temperature environment [typically >593 °C (1100 °F)] in the presence of carbon compounds (carbides in hydrocarbon, coke, rich CO & in gases, methane, ethane, etc.), the carbon content of the metal may increase, resulting in embrittlement and subsequent cracking and/or failure of components (Fig. 2.172). Carburization may also lead to a breakdown and catalysis of carbon to produce metal dusting and to "green rot" in Cr-Ni alloys. The affected materials are carbon and low-alloy steels, 300 series SS, 400 series SS, cast stainless steels, nickel-based alloys with significant iron content (e.g., Alloys 600 and 800), and HK/HP alloys.

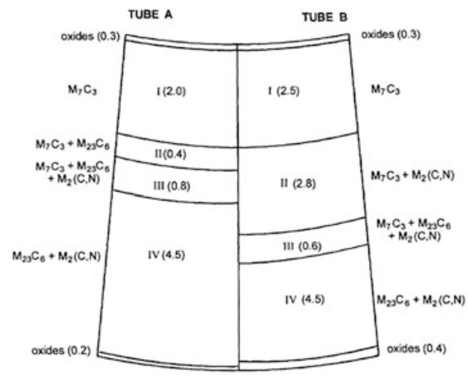


Figure 2.171 Primary and Secondary Carbides precipitation of Two Alloy Modified of HK 40. (Source: D.J. Hall, High Temperature-High Pressure 14, p527, 1987)

Applicable Codes, Standards, or Reports

API RP571 Part of Carburization, NACE TM0498 Evaluation of the Carburization of Alloy Tubes Used for Ethylene Manufacture, MTI Publication No. 52 Carburization, API TR942-B, etc.

References: For More Detail and/or Use as Check List

- G.Y. Lai, High-temperature corrosion of engineering alloys, ASM, (1996)
- NACE Paper No. **18**-11182/10875, **17**-9006, **15**-5754, **12**-1638, 11145, 07418, 05426, 03508, 03474, 03473, 02386, 02378, 02373, 01392, 01391, 01389, 01388, 01374, 99269, 99080, 98441, 98431, 97139, 96138, 95469, 95464, 95460, 94184, 94183, 93241, 92307, etc.
- D.J. Hall et al., Carburization behavior of HK-40 steel in furnace used for ethylene production. High Temp. High Press. **14**, 527 (1987)

2.4.3.3 Metal Dusting

Under certain hot gas environments in the range 482–816 °C (900–1500 °F), carbides may form in the metal and subsequently decompose into graphite and metal species, which in turn can act as catalysts for decomposition of carbon monoxide (CO) into carbon (C) and oxygen (O_2). This condition can result in extremely rapid and localized attacks and loss of material. Figure 2.173a shows corrosion by metal dusting of 304H SS pipe, and Fig. 2.173b shows scaling by metal dusting of Alloy 800 tubes for Hydrogen Reformer in Refinery Plant.

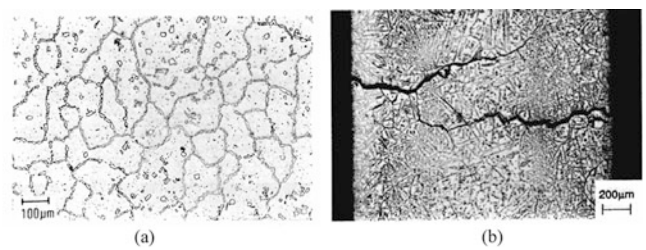


Figure 2.172 Carbide precipitation and transgranular cracks of alloy 800 by carburization. (Source: D.J. Hall, High Temperature-High Pressure 14, p527, 1987). (**a**) Phase boundary reaction-controlled $M_{23}C_6$ precipitation in Alloy 800. (**b**) Transgranular Cracks of Alloy 800 by Carburization

Damage increases with increasing temperature. Meanwhile a somewhat aggravating problem in carburizing atmospheres is "metal dusting," "catastrophic carburization," or "carbon rot." This occurs at lower temperatures, typically 430–650 °C (800–1200 °F) in heat treating furnaces. Such temperatures exist in a carburizing furnace [nominal 950 °C (1750 °F)] where alloy tube hangers, atmosphere sampling tubes, or electrical leads pass through furnace walls, and in some areas of furnace chains. Eventually metal dusting results from carburization or graphitization of steels and alloys occurring in carbonaceous atmosphere.

Metal dusting is often reported in CO-containing syngas production plants of ammonia, methanol or GTL industries.

In the petrochemical industry, a small amount of sulfur compounds (e.g., 40–50 ppm H2S) is sometimes added to the process gas stream to "poison" the high-temperature chemical reaction that is metal dusting.

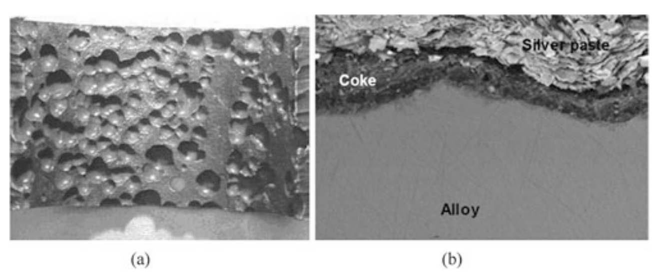


Figure 2.173 Metal dusting. (Source: API RP571). (**a**) Metal Dusting of 304H SS pipe. (**b**) Metal Dusting of Alloy 800 Tubes for Hydrogen Reformer in Refinery Plant

The effected materials are low-alloy steels, 300 series SS, Ni-based alloys and heat-resisting alloys in fired heater tubes, thermowell components, reformer outlet piping, etc.

Normally metal dusting is recognized as a catastrophic carburization.

Applicable Codes, Standards, or Reports

API RP571, Part of Metal Dusting, MTI Project 133-99 An Overview of Metal Dusting

References: For More Detail and/or Use as Check List

- NACE Paper No. **19**-13258, **18**-11200, **17**-9439, **15**-5614, **13**-2769, **12**-1149/1473, 11158, 11148, 11146, 11144, 09161, 09157, 09153, 09150, 09149, 07430, 07417, 07416, 05413, 05409, 03471, 02394, 01387, 01386, 01385, 01384, 01383, 01382, 01379, 10378, 01375, 01374, 01373, 01372, 00532, 00257, 99075, 98445, 97139, etc.

- NACE Corrosion Journal, 2012-09 (p810-821), 2004-07 (p632-642), 2006-01 (p54-63)
- G.Y. Lai, High-temperature corrosion of engineering alloys, ASM, (1996)
- Alloy Suppliers' Reports

2.4.3.4 Nitriding

This form of attack is similar in many regards to carburization as nitrogen (N), like carbon (C), is an interstitial atom and can defuse into material at intermediate temperature. As a result, the surfaces may be hardened, and readily cracked as seen in Figs. 2.174 and 2.175. Several applications in the chemical industry involve exposure to reactive N-containing environments (e.g., NH_3 > 13–20%), such as production of ammonia, nitric acid and nylon. Ni additions are most effective in minimizing nitridization, which allow the use of stabilized stainless steels up to about 600 °C (1112 °F). For higher temperatures, nickel- or cobalt-based alloys are usually required. For severe conditions, high levels of aluminum (>4.5%) or ceramic materials may be required.

For thin walls with maximum operating temperature (or design temperature) of 371 °C to 482 °C (700 to 900 °F), 321(H), 347(H) SS, or Alloy 800 may be used even though thickness failure may occur and with the need to avoid excessive stress or impact. Over 482 °C (900 °F), Alloy 600 or 800 may be used.

For heavy walls, minimum 3 mm corrosion allowance instead of weld overlay may be applicable up to 400 °C (750 °F), but weld overlay is recommended over 400 °C (750 °F).

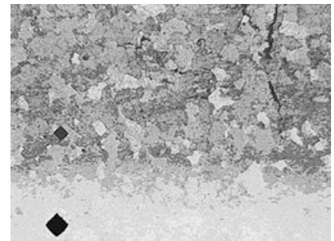


Figure 2.174 A higher magnification photomicrograph showing the diamond-shaped hardness. Indentations in the hard nitrided layer (540 BHN) versus the softer base metal (210 BHN). Mag. 150×. (Source: API RP571)

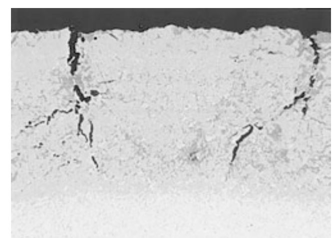


Figure 2.175 Tube showing the interface between the shallow nitrided layer on the surface (gray) and the unaffected base metal (white). Cracks initiate from the O.D. surface at the top. Mag. 50×. (Source: API RP571)

References

- API RP571, Part of Nitriding
- G.Y. Lai, High-temperature corrosion of engineering alloys, ASM, (1996)
- Alloy Suppliers' Reports

2.4.3.5 High-Temperature Sulfidation

Corrosion of carbon and low-alloy steel and other alloys result from their reaction with sulfur compounds in high-temperature environments [>260 °C (500 °F) except >230 °C (446 °F) in hydrocarbons, including naphthenic acid and/or mercaptans]. The presence of hydrogen accelerates corrosion.

Crude oils, coal, and other hydrocarbon streams contain sulfur at various concentrations. Total sulfur content is made up of many different sulfur-containing compounds.

Sulfidation is primarily caused by H_2S and other reactive sulfur species as a result of the thermal decomposition of sulfur compounds at high temperatures. Some sulfur compounds react more readily to form H_2S. Therefore, it can be misleading to predict corrosion rates based on weight percent sulfur alone. A sulfide scale on the surface of the component offers varying degrees of protection depending on the alloy and the severity of the process stream.

Figure 2.176 shows the percent of each root cause of high-temperature sulfidation corrosion failures which are from the 48 failures in 1963–2003, NACE/API/Owner-Operators Citation. The most critical cause was wrong materials selection (chemical composition). Figure 2.177 shows a failure of low-silicon-containing CS in sulfidation environment. API RP939C indicates CS has to contain Si of 0.1% as a minimum (0.13% preferable). 5Cr-1Mo steel may not have benefits for cost and integrity compared to 9Cr-1Mo in high-temperature sulfidation environments.

There are two types of corrosion mechanisms as below:

(i) High-Temp H_2 ($ppH_2 \geq 50$ psia)/H_2S
   To use Couper-Gorman curves in NACE Publ. 34103 and API RP939-C unless the end-user has other experience or guideline.
(ii) High-Temp free H_2 ($ppH_2 < 50$ psia)/sulfur and naphthenic acid (TAN)
   To use Modified McConomy curves and/or API RP581 unless the end-user has other experience or guideline.

Hydrocarbons, including naphthenic acid, can accelerate the sulfidation corrosion, as shown in Fig. 2.178.

Codes and Standards

- API RP939-C Guidelines for Avoiding Sulfidation (Sulfidic) Corrosion Failures in Oil Refineries
- API RP571 Part of (High Temperature) Sulfidation
- API RP581 RBI Technology- Part of (High Temperature) Sulfidation

References: For More Detail and/or Use as Check List

- NACE Publication 34103 Overview of Sulfidic Corrosion in Petroleum Refining
- Chevron 2012 Report for High Temperature Sulfidation
- NACE Paper 19-13038, 18-11142, 17-8909, 16-7598, 15-6169, 14-4125, 13-2517, 12-1326, 10358

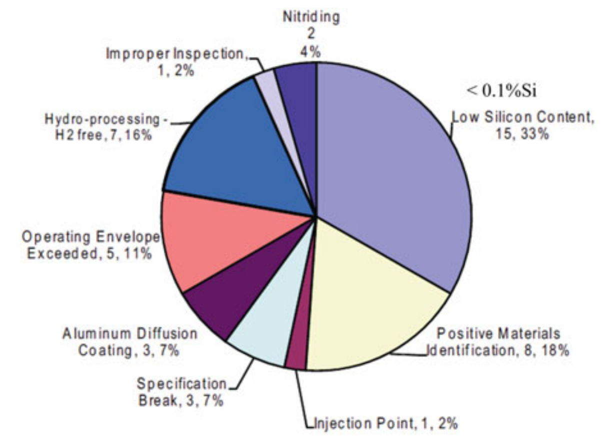


Figure 2.176 Root causes of high-temperature sulfidation corrosion failures history (from total 48 failures in 1963–2003, NACE/API/Owner-Operators Citation from API RP939-C)

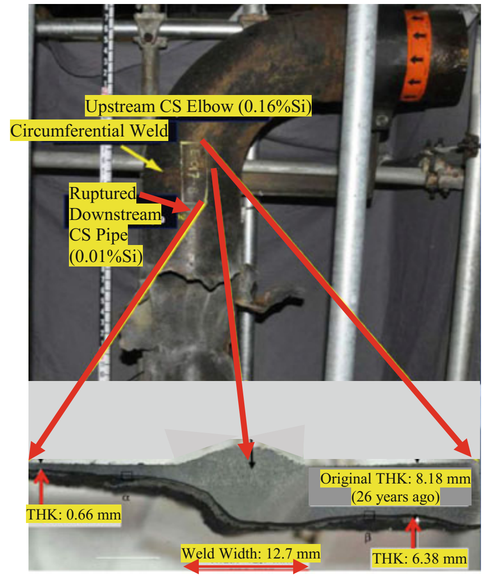


Figure 2.177 Failure of low-silicon-containing CS in sulfidation environment. (Source: US CSHIB Technical Report, 2014)

Figure 2.178 Naphthenic acid corrosion accelerated on high-temperature sulfidation corrosion. (Source NiDI Publ.9021)

2.4.3.6 High-Temperature Hydrogen Attack (HTHA)

HTHA is one of the most critical cracking mechanisms of CS and LAS at high temperature in refinery (e.g., hydrotreating, hydrogen units), ammonia plants, petrochemical plants, and other chemical facilities at 204 °C (400 °F) and above. In 1949, the first Nelson curve (by G.A. Nelson) was reported to indicate the susceptibility of CS, C-0.5%Cr, and 1 to 3Cr-0.5 to 1Mo steels in API. Some more considerations, such as safety margin of temperature (minimum 14–28 °C (25–50 °F)), definition of the applied temperature, PWHT, effective control of existing C-0.5Mo steel, incubation time for new construction, and maintenance are required. Typically, CRA cladding or weld overlay on CS and LAS dramatically reduces the HTHA; however, the material cannot be completely immune from the HTHA during long-term operations. API RP941 including API TR941 shows the mechanism and application guideline. See Table 2.139 for a comparison of several hydrogen-assisted cracking, Tables 2.141 and 2.143 for test and inspection, and Table 4.147 for PWHT.

API 941 (now API RP941) has been developed as follows:

; 1st Edition: July 1970 – Based on Nelson's 1965 curves +2.25Cr-1Mo
; 2nd Edition: June 1977 – Lowered curve for C-0.5Mo/failures in conditions around the curve
; 3rd Edition: May 1983 – More C-0.5Mo failures (catalytic reforming units)
; 4th Edition: April 1990 – C-0.5Mo curve removed and presented separately/caution on use of C-0.5Mo
; 5th Edition: April 1998 – Updated Appendices and Figures
; 6th Edition: March 2004 – Added Appendices (Clad and Inspection Plan)
; 7th Edition: August 2008 – Updated use of existing C-0.5Mo steel
; 8th Edition: February 2016 – Added CS + PWHT curve

2.4.4 Test and Inspection for Metal Loss/Damage/Prevention due to Corrosion

2.4.4.1 Summary of Typical Metallurgical Damage Mechanisms and Defects

Table 2.141 shows the summary of the typical metallurgical damage mechanisms and defects as well as corrosion mechanisms. The recognition of the metal damage mechanisms before the test/inspection and monitoring may be very important to find adequate FFS and remaining lifetime.

Table 2.141 (1/3) Damage mechanisms and defects screening table (ASME PCC-3, Table B-1 modified)

Damage Mechanism	Damage Type [1]	MOC												Susceptible Temperature					Related Service Contains:															Service Flow		Type of Loading			
		Mainly by inappropriate MOC [66]	*CI (Cast Iron)*	CS (Carbon Steel)	LAS (Low Alloy Steel)	ASS (300 series SS)	MSS & FSS (400 series SS)	DSS (Duplex SS)	Ni-Fe Alloys (Fe/Ni=0.6-1.3) [61]	Ni Alloys (Ni> 50%)	Cu Alloys	Ti or Ti Alloys	Al Alloys	T ≥ 538°C	427°C ≤ T < 538°C	121°C ≤ T < 427°C	0°C ≤ T < 121°C	T < 0°C	Water, Steam, or Wet Air [65]	Hydrogen	Carbon	Sodium	Carbonate	Sulfur or Its Compounds	Amines	Ammonia	Chloride	HF	*Cyanides (HCN)*	Phosphoric Acid	Particulates and the size & hardness	pH	Others	Motionless-Static/Stagnant [3]	Hydrodynamic/Velocity Dominant	Static or High Residual Stress [2]	Impact Load	Thermal Gradients or Shock	Cyclic Stress(e.g., Frequent.Vibratory)
475°C Embrittlement [4]	M.D	o					●	★							●	●																							
Acid-Dew Point Corrosion [5]	G Corr		o	●	●	●	●	●	●							●	●		●								●	●		●		o	●						
Acid-HCl solution [6]	G Corr		o	●	●	●	●	●	●	●	●	●	●				●		◙								●					o	●						
Acid-H_2SO_4 solution [7]	G Corr		o	●	●	●	●	●	●	●	●	●	●			●	●		◙													o			●				
Acid-HF solution [8]	G Corr/Crack		o	●	●	●	●				●	●					●		◙									●	◙			o	●			◙			
Acid-Phenol (Carbolic) [58]	G Corr		o	●	●	(58)										●			◙													o	◙		●				
Acid-PTASCC [10]	Crack					●			●					◙			●		●					●												●			
Acid-Phosphoric [62]	G Corr		o	●	●							●	●			●	●		●											●		o							●
Acid-SW (H_2S, HCl, NH_4Cl) [11]	G Corr		o	●	●								●			●	●		●	●				●		◙	◙		◙			o	◙						
Acid-Wet Corrosion [12]	G Corr		o	●	●											●	●		◙		●						◙					o	◙						
Amine Corrosion (alkaline) [13]	G Corr		o	●	●						●					●	●								●				◙			o			◙				
Amine Crack (alkaline) [13]	Crack		o	●							●					●	●								●							o				◙			
Brittle Fracture [14]	Crack	o	★	●	●		●	◙					●			●	●	●																		●	●	●	●
Carbonate SCC (alkaline) [15]	Crack		o	●	●											●	●		◙				●	◙		◙			◙			o				●			
Carburization [16]	M.D		o	●	●	●	●	●	●	●				★	●						●																		
Caustic SCC (alkaline) [17]	Crack		o	●	●	●	●	●								●	●		●													o	●			●			
Caustic Gouging (alkaline) [17]	G Corr		o	●	●											●	●		●													o	●		●				
Cavitation [18]	G Corr	o	o	●	●	●	●	●	●	●	●	●	●			●	●		●														●		●				
Chelant Corrosion	G Corr		o	●	●											●			●													o			●				
CLSCC [19]	Crack					●		●	●							●	●		●								●						●			●			●
CO_2 (Carbonic Acid) Corrosion [67]	G Corr	o	o	o	o												o		o					o			o					o							
CUI [20]	G Corr		o	●	●	●	●	●			●	●	●				●	●	●								◙							●					
Creep-Rupture [21]	Crack	o	o	●	●	●	●	●	●	●	●	●	●	●	●																					●			
Crevice Corrosion [9]	G Corr		o	●	●	●	●	●	●	●	●	●	●			●	●		●								◙						◙	●					
Dealloying (Selective Leaching)[22]	G Corr		o								●					●	●		●				●										●						
Decarburization [23],[33]	M.D		o	●	●									●						●													●						
Dissolved O_2 Attack	G Corr		o	●	●												●		●														●						
Electrical Discharge	G Corr		o	●	●	●	●	●	●	●	●	●	●			●	●																						
Erosion-FAC [24]	G Corr		o	●	●						◙					●	●																		●				
Erosion-droplets	G Corr	o	o	●	●	●	●	●	●	●	●	●	●			●	●		●														●		●				
Erosion-solids	G Corr	o	o	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●												●				●				
Erosion-Corrosion [24]	G Corr		o	●	●	●	●	●	●	●	●	●	●			●	●		●	●	●	●	●	●	●	●	●	●	◙	●			●		●				

See Section 4 in this book for Weld Damage

Table 2.141 (2/3) Damage mechanisms and defects screening table (ASME PCC-3, Table B-1 modified)

Damage Mechanism	Damage Type [1]	MOC: Mainly by inappropriate MOC [66]	MOC: CI (Cast Iron)	MOC: CS (Carbon Steel)	MOC: LAS (Low Alloy Steel)	MOC: ASS (300 series SS)	MOC: MSS & FSS (400 series SS)	MOC: DSS (Duplex SS)	MOC: Ni-Fe Alloys (Fe/Ni=0.6-1.3) [61]	MOC: Ni Alloys (Ni> 50%)	MOC: Cu Alloys	MOC: Ti or Ti Alloys	MOC: Al Alloys	Susceptible Temperature: T ≥ 538°C	Susceptible Temperature: 427°C ≤ T < 538°C	Susceptible Temperature: 121°C ≤ T < 427°C	Susceptible Temperature: 0°C ≤ T < 121°C	Susceptible Temperature: T < 0°C	Related Service Contains: Water, Steam, or Wet Air [65]	Related Service Contains: Hydrogen	Related Service Contains: Carbon	Related Service Contains: Sodium	Related Service Contains: Carbonate	Related Service Contains: Sulfur or Its Compounds	Related Service Contains: Amines	Related Service Contains: Ammonia	Related Service Contains: Chloride	Related Service Contains: HF	Related Service Contains: *Cyanides (HCN)*	Related Service Contains: Phosphoric Acid	Related Service Contains: Particulates and the size & hardness	Related Service Contains: pH	Related Service Contains: Others	Service Flow: Motionless-Static/Stagnant [3]	Service Flow: Hydrodynamic/Velocity Dominant	Type of Loading: Static or High Residual Stress [2]	Type of Loading: Impact Load	Type of Loading: Thermal Gradients or Shock	Type of Loading: Cyclic Stress(e.g., Frequent.Vibratory)
Ethanol SCC [25]	Crack		○	○													○		○								○						○			○			○
Fatigue Corrosion-cyclic [26]	Crack		○	●	●	●	●	●	●	●	●	●	●			●	●	●	●				●	●	●	●	●	●	◙	●			●						●
Fatigue Corrosion-contact [63]	Crack		○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●																					●
Fatigue Corrosion-thermal/creep [26]	Crack		○	●	●	●	●	●	●	●	●	●	●	●	●	●																						●	
Fatigue Corrosion-vibration [64]	Crack		○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●																					●
Filiform Corrosion [59]	G Corr		○	◙	◙								◙				●		●														●	●					
Flue Gas Dew Point Corrosion [27]	G Corr	○	○	●	●	●	●	●	●	●							●		●					◙			●	●				○	◙						
Fretting Corrosion [45]	G Corr		○	●	●	●	●	●	●	●	●	◙	●	●	●	●	●	●																					●
Fuel Ash Corrosion [28]	G Corr		○	●	●	●	●	●	●	●	●		●	●	●							●		●									◙						
Galvanic Corrosion [29]	G Corr		○	●	●	●	●	●	●	●	●	●	●			●	●		●														●						
Graphitization [30]	M.D		○	●	●									●	●																								
High Temp H_2S/H_2 (sulfidation) [31]	G Corr		○	●	●	●	●	◙			●		●	◙	●					●				●									◙						
High Temp H_2S (sulfidation) [31]	G Corr		○	●	●	●	●	◙			●		●	◙	●									●									◙						
Hot Tensile [32]	M.D		○	●	●	●	●	●	●	●	●	●	●	●	●																								
HTHA [33]	Crack		○	●	●									●	●					●													●						
Hydrogen Embrittlement [34]	M.D	○	○	●	●		●					●					●			◙				●									●						
HIC/SOHIC [35]	Crack			●	●							●					●							●					◙			○	●						
IGC [36]	Crack					●		●	●	●						●	●		●					●			♦						●						
Knife Line Attack [37]	Crack/W.D	○				●											●		●														●						
Liquid (Molten) Slag Attack	G Corr		○	●	●	●				●				●																			●	●					
LME [38]	Crack		○	●	●	●	●	●	●	●	●	●	●	●	●	●																							
Metal Dusting [39]	G Corr		○	●	●	●				●				●							●																		
MIC [40]	G Corr		○	●	●	●	●	◙	◙		●		◙				●	●	●								◙						●	●					
Naphthenic Acid [41]	G Corr		○	●	●	●	●	◙	◙		●		●		◙	●								●								○	◙		◙				
NH_3 Grooving (alkaline)	G Corr										●					●	●								●	●						○			●				
NH_3 SCC-Anhydrous (H_2O<0.2%) [42]	Crack		○	●							●					●	●									●						○				●			
NH_4HS (Alkaline SW) [46]	G Corr		○	●	●						●		●				●		●					●		●						○			●				
Nitrate SCC [57]	Crack		○	○	○											○	○		○							○							○			○			
Nitriding [43]	G Corr		○	○	○	○	○							○	○	○										○							○						
Oxidation-High Temperature [44]	G Corr		○	●	●	●	●	●	●	●				●					●														●						
Phosphate Attack	G Corr		○	●	●											●	●		●													○			●				
Pitting [19]	G Corr					●	●	●	●	●	●	●	●			●	●		●								◙					○	●						♦

See Section 4 in this book for Weld Damage

Table 2.141 (3/3) Damage mechanisms and defects screening table (ASME PCC-3, Table B-1 modified)

Damage Mechanism	Damage Type [(1)]	MOC												Susceptible Temperature					Related Service Contains:															Service Flow		Type of Loading			
		Mainly by inappropriate MOC [(66)]	CI (Cast Iron)	CS (Carbon Steel)	LAS (Low Alloy Steel)	ASS (300 series SS)	MSS & FSS (400 series SS)	DSS (Duplex SS)	Ni-Fe Alloys (Fe/Ni=0.6-1.3) [(61)]	Ni Alloys (Ni> 50%)	Cu Alloys	Ti or Ti Alloys	Al Alloys	T ≥ 538°C	427°C ≤ T < 538°C	121°C ≤ T < 427°C	0°C ≤ T < 121°C	T < 0°C	Water, Steam, or Wet Air [(65)]	Hydrogen	Carbon	Sodium	Carbonate	Sulfur or Its Compounds	Amines	Ammonia	Chloride	HF	*Cyanides (HCN)*	Phosphoric Acid	Particulates and the size & hardness	pH	Others	Motionless-Static/Stagnant [(3)]	Hydrodynamic/Velocity Dominant	Static or High Residual Stress [(2)]	Impact Load	Thermal Gradients or Shock	Cyclic Stress(e.g., Frequent.Vibratory)
Seawater/Brine [(60)]	G Corr/Crack		o	o	o	o	o	o	o		o	o					o		o								o						o	o	o	o			o
Sensitization (Cr-carbides) [(36)]	M.D	o				●		◙	●					●	●																								
σ/γ Phase Embrittlement [(47)]	Crack	o				●	●	★						●																									
Softening (overaging) [(48)]	M.D	o	o	●	●	●	●	●	●	●	●	●	●	●	●																								
Spheroidization [(30)]	M.D	o	o	●	●									●	●																								
SSC [(35)]	Crack		o	●	●		●									●	●		◙					◙								o	◙			●			●
Strain Aging [(50)]	M.D	o	o	●	◙												●																						
Stray Current Corrosion [(51)]	G Corr		o	●	●	●	●	●	●	●	●	●	●			●	●																						
Stress Relaxation (Reheat) Crack[(52)]	Crack	o			o	o			o					o	o	o																							
Sulfate SCC [(49)]	Crack										o						o		o							o						o							
Temper Embrittlement [(54)]	M.D	o			●									●	●	●																							
Titanium Hydriding [(55)]	M.D											★				o	o		o	o				o			o						o						
Under Deposit Corrosion [(53)]	G Corr		o	●	●	●	●	●	●	●	●	●	●			●	●		●	●	●	●	●	●	●	●	●	●	◙	●	●		●						
Weld Decay [(56)]	G Corr/W.D	o				●										●	●		●														●						
Wear-Abrasive [(68)]	G Corr	o	o	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●													●				●				
Wear-Adhesive/Sliding (physical)[(68)]	G Corr	o	o	●	●	●	●	●	●	●	●	●	●			●	●																						●
Others[(69)]																																							

See Section 4 in this book for Weld Damage

Abbreviation (commentary; added some marks): ★ = very susceptible (commented or added), ●, o, ◙ = can be affected (a careful consideration with appropriate material selection, fabrication, and normal/upset process condition is required), o = added as comments, ◙ = commented, *Blank* not affected or No data/Not used, *CLSCC* chloride induced stress corrosion cracking, *Corr* corrosion, *Emb* embrittlement, *FAC* flow accelerated corrosion, *G Corr* general corrosion (metal loss including uniform corrosion, local corrosion and/or pitting), *(SO)HIC* (stress oriented) hydrogen induced cracking/blistering, *H.E* hydrogen embrittlement, *HTHA* high temperature hydrogen attack, *IGC* intergranular corrosion cracking, *KLA* knife line attack, *LME* liquid metal embrittlement, *M.D.* metallurgical damage/degradation due to second phase precipitations (as a result, susceptible to brittle fracture), *MIC* microbiological induced corrosion, *MOC* materials of construction (material selection and fabrication), *SCC* stress corrosion cracking, *SSC* sulfide stress cracking, *SW* sour water, *T* maximum operating temperature, *Temp* temperature, *W.D* weld damage/cracking combined with corrosive service, 475 °C = 885 °F

Notes:

(1) Manufacturing, weld, and casting defects can become a factor and also can lead to other damage mechanisms

(2) Static stress may include residual tensile stress

Commentary Notes:

(3) Including dead legs

(4) 475 °C (885 °F) embrittlement. See Sects. 2.1.6.4 and 2.3.4 in this book for more details

(5) Dew Point Corrosion: See API RP571, API 560, ASME STS-1, ISO 13705, and Table 2.138(11) in this book for more details

(6) HCl Acid: See API RP571 for more details

(7) H_2SO_4 Acid: See API RP571, and Table 2.8 for more details

(8) HF Acid: See API RP571, Sects. 2.4.2.2, 4.7.2.4(a), Tables 2.94, 3.10, and 4.134 in this book for more details

(9) Crevice Corrosion: See Sect. 2.1.6.2(b) and Tables 2.124(11), 2.138(5) and 2.144 in this book for more details

(10) PTASCC (polythionic acid): See Sects. 2.1.6.8 and 2.4.2.6, Table 2.191b in this book for more details

(11) Acidic Sour Water: See Table 2.124(3) and Sect. 2.4.2.1 in this book for more details

(12) Acid Wet Corrosion: See API RP581 and API RP571 for more details

(13) Amine Crack: See Sect. 2.4.2.3 in this book and API RP945 for more details

(14) Brittle Fracture: See Sects. 1.3.5, 2.1.4.9, 2.2.1.2, 2.3.2, 2.3.6.1, 2.4.2.1, Tables 2.35, 2.65, Fig. 2.111, and Table 5.2 in this book and API RP920

(15) Carbonate SCC: See Sect. 2.4.2.5, Table 2.142 in this book and NACE Publ. 34108 for more details
(16) Carburization: See Sect. 2.4.3.2 in this book and API RP581, NACE TM0498, NiDI Publ. 11022 for more details
(17) Caustic Gouging: See Sect. 2.4.2.4 in this book for more detail
(18) Cavitation: See Tables 2.124(9) and 2.138(9), Fig. 2.179, and Sect. 2.4.5.2(e) in this book for more details
(19) CLSCC and Pitting: See Sects. 2.1.6.2 and 2.4.2.7 in this book for more details
(20) CUI: See NACE SP0198, ASTM STP 880, API RP583/510/570/574, Sect. 2.4.2.13 CUI-general, and Sect. 5.4.4.2 inspection for CUI on stream for more details
(21) Creep-Rupture: See Sects. 1.3.3, 2.3.9 in this book and API 579/ASME FFS-1, ASTM E139 for more details
(22) Dealloying: See API RP571, Tables 2.124(13), 2.138(15), and 5.40 in this book for more details
(23) Decarburization: See API RP571 for more details
(24) FAC (flow accelerated corrosion): See Sect. 2.4.5.2(a) in this book and API RP571 and API RP14E for more details
(25) Ethanol: See Table 4.134 in this book and API RP571 and API RP939-D/API Bulletin 939-E for more details
(26) Fatigue Corrosion: See Sects. 2.3.10 and 2.4.2.11 in this book for more details
(27) Flue Gas: The service temperature should be maintained at least 10–15 °C higher than the dew point when dew point control is considered. See API RP571, API 560, ASME STS-1, ISO 13705, NiDI Report 10,072 for more details
(28) Fuel Ash: See Sect. 2.4.3.1 and API RP571 for more details
(29) Galvanic Corrosion: See Sects. 2.1.6.10, 2.4.1.3, Tables 2.79, 2.124(8), and 2.138(4) in this book for more details
(30) Graphitization: See Sects. 1.1.10.2(j), 2.1.3.2(a), 2.3.1, Table 2.15 notes in this book and WRC bulletin 32 for more details
(31) High Temperature H_2S/H_2 Corrosion: See Sect. 2.4.3.5 in this book for more details
(32) Hot Tensile: See Sects. 2.1.4.2(b)4), 5.2.2.2 and ASTM E21 for more details
(33) HTHA: See Sect. 2.4.3.6 and Table 2.139 in this book and API RP941, API TR941, and API RP571 for more details
(34) H.E: See Sects. 1.3.6.2, 2.4.2.6, 2.4.2.12, 2.4.4.6, Table 2.139 in this book and ASME Sec. II, Part D, A-702, NACE SP047, API TR934-F Part 1 for more details
(35) SOHIC occurs at the hardened HAZ. See Sect. 2.4.2.1 in this book for more details
(36) IGC: See Sects. 2.1.6.3, 2.4.4.6, Table 2.42, Fig. 2.88 in this book for more details
(37) KLA: Only for stabilized ASS (e.g., 321 SS, 347 SS, etc.) See Sect. 4.11.6.7 in this book for more details
(38) LME: See Sects. 2.1.6.6 and 2.3.6 Figs. 4.70, 4.71 in this book and API RP571 for more details
(39) Metal Dusting: See Sect. 2.4.3.3 in this book, API RP571, and MTI 133-99 for more details
(40) MIC: See Sects. 2.4.1.4, 3.5.3.7, 5.5.5.1, 5.5.5.5, Tables 2.134(7), and 2.138(15) API RP571, NiDI 10,085, NACE Publ. 46,107, NACE TM0106/0194, and Sect. 2.4.1.6 in this book for more details
(41) Naphthenic Acid: See Sect. 2.4.3.5, Table 2.124(5) in this book, API RP581, API RP571, API RP939-C and NACE Publ. 34103 for more details
(42) Anhydrous NH3: See Sect. 2.4.2.10, Table 2.137 in this book, API RP571, MTI MS-6, and NiDI Publ. for more details
(43) Nitriding: See Sect. 2.4.3.4 in this book and API RP571 for more details
(44) High-Temperature Oxidation: See Sect. 2.4.3.1, Table 2.124(4) in this book, API RP581, and API RP571 for more details
(45) Erosion/Fretting corrosion: See Sect. 2.4.5 in this book and API RP14E for more details
(46) See API RP581 for more details
(47) σ/γ Phase = sigma/chi phase: See Sects. 2.3.3 and 2.1.6.5 in this book for more details
(48) Softening: See API RP571 for more details
(49) Sulfate SCC: See Sect. 2.4.2.9 in this book for more details
(50) Strain Aging: See API RP571, NACE Paper 04117/09086/03108/02066 and ASM Handbook Vol. 1 for more details
(51) Stray Current Corrosion: See NACE Publ. 01110/10B189, NACE Paper 18–11,270/18–11,045/16–7230/15–5588/12–1694/98559/ 91,516/90390/90173 and ASM Handbook Vol. 3C for more details
(52) Reheat Crack (Stress Relaxation Crack): mostly in heavy wall and LAS-V enhanced steel. See Sects. 2.1.6.9 and 2.3.8 in this book for more details
(53) Underdeposit Corrosion: See Table 2.138(13) in this book and API RP571 for more details
(54) Temper Embrittlement: See Sects. 2.1.4.2(c) and 2.3.2 in this book for more details
(55) Ti Dehydriding: Occurs in the absence of a galvanic coupling. See Sect. 2.1.7.4 in this book for more details
(56) Weld Decay: See Sect. 4.11.6.6 in this book for more details
(57) Nitrate SCC: See Sect. 2.4.2.8 in this book for more details
(58) Phenol (Carbolic Acid): CS & LAS are very corrosive at 5–15% phenol and $T > 175$ °C or $v > 10$ m/sec. CS, LAS, 304(L) SS are extremely corrosive at $T > 260$ °C. See API RP571 for more details
(59) Filiform Corrosion: On the coated metal surfaces. See NACE paper 08488/03600 for more details
(60) Seawater & Brine: Dissolved oxygen and chlorinated condition are also key factors. See API 17 series (subsea) and Seawater Handbook for more details
(61) Alloy 825, Alloy 800 series, Alloy 20 series, etc.
(62) See API RP571 for more details
(63) e.g., valve stem & seats
(64) e.g., tubes to baffles in H/EX
(65) Depending on the pH in most cases
(66) Metallurgical, Welding, Heat Treatment, and/or Physical Damage, not directly related to corrosion
(67) Wet CO_2: See Sect. 2.4.1.7 in this book for more details
(68) Wear-Adhesive/Sliding: See Sect. 2.4.5 in this book for more details
(69) Elemental Sulfur Corrosion in Sour Gas Production: See NACE Paper 18-11266, 16-7783, 15-5930, 12-1575, 12-1604, 12-1090, 11121, 11123, 11124, 11125, 11398, 09363, 08637, 07397, 05646, 97033, 95047, 94070, 92002, 92059, 90039, 89012, 89181, NACE Corrosion Journal p558-566, Jul. 1995, p286-308, Apr. 1991, p269-271, Apr. 1991

2.4.4.2 Summary of Environmentally Assisted Cracking (EAC)- Most Critical Issues in Oil and Gas Industries

Typical Requirements for Carbon Steel per the step to Prevent Corrosion in Critical Corrosion Environments (Table 2.142)

Table 2.142 Typical requirements for CS per the step to prevent corrosion in critical corrosion environments

Corrosive service	Wet H_2S (sour) and HF	Amine	Caustic, carbonate, deaerator, anhydrous Ammonia	Hydrogen/HTHA
Materials selection	– Solid or clad (weld overlay) – Corrosion allowance	– Solid or clad (weld overlay) – Corrosion allowance	– Solid – Corrosion allowance	– Solid
Requirements for base metal (when purchasing)	– Chemical Control(1) – UT – Vacuum degassing – Normalizing – HIC test (per severity) – PMI	– Vacuum degassing – Normalizing		– Vacuum degassing
Service process control	Fluid velocity for sour water	Fluid velocity		
Products (for fabrication or construction)	– WPS/PQR – UT, RT, WFMT – Hardness Control or PWHT(2)	– Hardness control or PWHT(2)	– Hardness Control or PWHT(2)	– Hardness Control or PWHT(2) – UT, RT, WFMT
On-stream & maintenance	– Thickness & Crack monitoring – PWHT after repair welding	– Thickness & Crack monitoring – PWHT after repair welding	– Thickness & Crack monitoring – PWHT after repair welding	– Thickness & Crack monitoring – PWHT after repair welding
Applicable Standards(3),(4)	– ANSI/NACE MR0175/ISO15156 petroleum and natural gas industries – Materials for use in H_2S-containing environments in oil and gas production – ANSI/NACE MR0103/ISO17945 petroleum, petrochemical and natural gas industries-metallic materials resistant to SSC in corrosive petroleum refining environments – NACE TM0284 evaluation of pipeline and pressure vessel steels for resistance to HIC. – NACE TM0177 laboratory testing of metals for resistance to SSC and SCC in H_2S environments – NACE SP0296 detection, repair, mitigation of cracking of refinery pressure vessels in wet H_2S environments – ISO 21457 – EEMUA 179 – EUR 12959 EN – EFC Publ. 15 & 17 – NACE Publ. 8X194 – NACE Publ. 2X194 – NACE Publ. 5A171 – NACE Publ. 1F192	– API RP945, – API RP581, – API RP571,	– NACE SP0403 avoiding caustic SCC of CS refinery equipment and piping – NACE SP0590 prevention, detection and correction of deaerator cracking – NACE report 34,108 review and survey of alkaline carbonate SCC in refinery sour waters – NACE Publ.5A192 – API RP571 – MTI MS-6 – NiDI Publ. 9013	– API RP/TR941 – NACE Publ.1C184 – API RP571 – API-RP581 – API TR934F – API RP934A/C/E – API RP934H/I (later) – ASME B31.12

∗Basic requirement: fully killed carbon steel (base metal)
Notes
(1) Including welding electrodes/ PMI may be required.
(2) PWHT is preferable except carbon steel piping in wet H_2S (sour) service.
(3) See Sect. 4.12.3.15 for the PWHT requirements in EAC environments.
(4) Other Standards for Common Application.
– NACE SP0472–2015 Methods and Controls to Prevent Cracking of CS Weldments in Corrosive Petroleum Refining Environments

2.4.4.3 Summary of Typical Test/Inspection and Monitoring for Metal Damage and Corrosion

Table 2.143 shows the summary of a typical test and inspection plan for each damage mechanism and defect in ASME PCC-3.

Table 2.143 (1/2) Typical plan for inspection and monitoring methods (ASME PCC-3, Table C-1 modified)

Damage Mechanism	Damage Type [b]	Typical Examination Methods [a]															
		Surface					Subsurface					Other/Additional Methods					
		VT [c]	PT [c]	F-PT [c]	MT [d]	WF MT[d]	UT -T	UT -S	UT -SW	UT -SWa	RT	ECT	AE	DM	HT	Rep	BP
475°C Embrittlement [4]	M.D																●
Acid-Dew Point Corrosion [5]	G Corr	●					●	●									●
Acid-Wet Corrosion [12]	G Corr	o					o										
Acid-HCl [6], H_2SO_4 [7], Phenol (Carbolic) [58]	G Corr	●					●										
Acid-HF solution [8]	G Corr/Crack	●	o	o	o	o	●	o	o	o	●						
Acid-Polythionic - SCC [10]	Crack	o	●	●				●	●	●	o						
Acid-Phosphoric [62]	G Corr	o					o										
Acid-SW (H_2S, HCl, NH_4Cl) [11]	G Corr	●					●				?						
Amine Corrosion (alkaline) [13]	G Corr	●					●										
Amine Crack (alkaline) [13]	Crack	●			●	●			●	●			●				
Brittle Fracture [14]	Crack	o	o		o			o	o	o	o				o		
Carbonate SCC (alkaline) [15]	Crack	●			o	●			●	●							
Carburization [16], Metal Dusting [39]	M.D	●					●	●	●	●						o	●
Caustic SCC (alkaline) [17]	Crack	●		●	o	●			●	●	●	●					
Caustic Gouging (alkaline) [17]	G Corr	●						●			●	●					●
Cavitation [18]	G Corr	●					o										
Chelant Corrosion [70]	G Corr	●					●					●					●
CLSCC [19]	Crack	o	o	o					o	o	o	o					
CO_2 (wet, Carbonic Acid) Corrosion [67]	G Corr	o					o	o									o
CUI [20]	G Corr	●					●	●									
Creep-Rupture [21]	Crack	o	o	o	o	o		o	o	o			o	o		o	o
Crevice Corrosion [9]	G Corr	●															●
Dealloying (Selective Leaching) [22]	G Corr															●	●
Decarburization [23],[33]	M.D														●		●
Dissolved O_2 Attack [69]	G Corr	●										●					●
Electrical Discharge	G Corr	●															
Erosion-FAC/corrosion [24], droplets, solids	G Corr	●					●	●	●	●				●			
Ethanol SCC [25]	Crack	●			●	●			●	●							
Fatigue Corrosion-cyclic/vibration[26] [64]	Crack	●	●	●	●	●		●	●	●		●	●				●
Fatigue Corrosion-contact [63]	Crack	●	●	●		●							●				
Fatigue Corrosion- creep [26]	Crack	●						●	●	●			●	●		●	●
Fatigue Corrosion-thermal [26]	Crack	●	●	●	●	●		●	●	●			●	●			●
Filiform Corrosion [59]	G Corr	●					o										●
Flue Gas Dew Point Corrosion [27]	G Corr	●					●										
Fretting Corrosion [45]	G Corr	●	●	●													●
Fuel Ash Corrosion [28]	G Corr	o					o										
Galvanic Corrosion [29]	G Corr	●															?
Graphitization [30]	M.D	o													●	●	●
High Temp H_2S/H_2 (sulfidation) [31]	G Corr	●					●				?						
High Temp H_2S (sulfidation) [31]	G Corr	●					●										
Hot Tensile [32]	M.D	●												●		●	●
HTHA [33]	Crack	o						●	●	●			●				●
Hydrogen Embrittlement [34]	M.D	o	o	o	o	o	o	o	o	o							●
HIC/SOHIC/SSC [35]	Crack	o		●		●		●	●	●	o	●	●			●	●
IGC [36]	Crack															●	●
Knife Line Attack [37]	Crack/W.D	●	o	o				●	●	●			●				
Liquid (Molten) Slag Attack	G Corr/Crack	●					●	●									●
LME [38]	Crack		●	●	●	●		●	●	●	o		●			●	●
MIC [40]	G Corr	●					●	●									●
Naphthenic Acid [41]	G Corr	●					●				?						
NH_3 Grooving (alkaline)	G Corr	●					●										
NH_3 SCC-Anhydrous (H_2O<0.2%) [42]	Crack	●			●	●			●	●		●					
NH_4HS (Alkaline SW) [46]	G Corr	●					●										
Nitrate SCC [57]	Crack	o				o			o	o							
Nitriding [43]	G Corr															o	o
Oxidation-High Temperature[44]	G Corr	●					●	●									●

F fluorescent, -*S* straight beam, -*SW* shear wave, *DM* dimension/thickness measurement, *HT* hardness test, *Rep* in-place metallurgy test with replica, *BP* boat/plug sample test

Table 2.143 (2/2) Typical plan for inspection and monitoring methods (ASME PCC-3, Table C-1 modified)

Damage Mechanism	Damage Type [(b)]	Typical Examination Methods [(a)]															
		Surface					Subsurface					Other/Additional Methods					
		VT [(c)]	PT [(c)]	F-PT [(c)]	MT [(d)]	WF MT[(d)]	UT -T	UT -S	UT -SW	UT -SWa	RT	ECT	AE	DM	HT	Rep	BP
Phosphate Attack [(71)]	G Corr	o					●										●
Pitting [(19)]	G Corr	●	●					●				●					●
Sensitization (Cr-carbides) [(36)]	M.D															●	●
σ/γ Phase Embrittlement [(47)]	Crack															●	●
Softening (overaging) [(48)]	M.D														●		●
Spheroidization [(30)]	M.D														●	●	●
Strain Aging [(50)]	M.D														●		●
Stray Current Corrosion [(51)]	G Corr	●					●	●	●	●							
Stress Relaxation (Reheat) Crack [(52)]	Crack	o	o	o	o	o	o	o	o	o	o					o	o
Sulfate SCC [(49)]	Crack	o	o	o	o	o	o	o	o	o	o					o	o
Temper Embrittlement [(54)]	M.D																●
Titanium Hydriding [(55)]	M.D	o	o	o			o	o	o	o							
Under Deposit Corrosion [(53)]	G Corr	o					●	●									●
Weld Decay [(56)]	G Corr/W.D	●	o	o				●	●	●							●
Wear-Adhesive/Sliding [(68)]	G Corr	●					●							●			

Abbreviation (commentary): ● , o = applicable ● = applicable (by ASME PCC-3), o = added as comments, ? = rarely applicable (commented), *Blank* not affected or No data, *CLSCC* chloride induced stress corrosion cracking, *Corr* corrosion, *Emb* embrittlement, *DM* dimensional measurement, *FAC* flow-accelerated corrosion, *G Corr* general corrosion (metal loss including uniform corrosion, local corrosion and/or pitting), *(SO)HIC* (stress-oriented) hydrogen induced cracking/blistering, *H.E* hydrogen embrittlement, *HTHA* high-temperature hydrogen attack, *IGC* intergranular corrosion cracking, *LME* liquid metal embrittlement, *M.D.* metallurgical damage/degradation due to second phase precipitations, *MIC* microbiological induced corrosion, *MOC* materials of construction (material selection and fabrication), NH_3 ammonia, *SCC* stress corrosion cracking, *SSC* sulfide stress cracking, *SW* sour water, *T* maximum operating temperature, *Temp* temperature, *W.D* weld damage/cracking combined with corrosive service, 475 °C = 885 °F, *F* fluorescent, *-S* straight beam, *-SW* shear wave, *DM* dimension/thickness measurement, *HT* hardness test, *Rep* in-place metallurgy test with replica, *BP* boat/plug sample test

[*For Test and Inspection-NDE*]
AE acoustic emission test, *BP* boat & plug sample, *ECT* eddy current test, *F-PT* fluorescent liquid penetration test [Note (c) below], *PT* liquid penetration test [Note (c) below: see Table 5.5 in this book.], *MT* magnetic particle test [Note (c) below: see Table 5.5 in this book.], *Rep* in-place metallography (by replica), *RT* radiography test [see Table 5.7 in this book.], *UT-S* ultrasonic test with straight beam [for metal loss: see Table 5.8 in this book.], *UT-SW* ultrasonic test with shear wave [for crack detection: see Table 5.8 in this book.], *UT-SWa* ultrasonic test with shear wave-advanced technologies [for crack detection – e.g., phased array ultrasonic testing-PAUT, time of flight diffraction-TOFD: see Table 5.8 Note (2) in this book.], *UT-T* ultrasonic test for thickness measurement [see ASTM E797.], *VT* visual test including Borescope [Note (c) below], *WFMT* wet florescent magnetic particle test [Note (d) below: see Table 5.6 in this book.]

Notes:
[(a)] Many of these examination methods depend upon proper access and surface preparation and thus will not be appropriate for all situations. Many factors influence the detectability of imperfections, including using qualified personnel to perform the inspection
[(b)] Manufacturing, weld, and casting defects can become a factor and can also lead to other damage mechanisms
[(c)] These methods are capable of detecting imperfections that are open to the surface only
[(d)] These methods are capable of detecting imperfections that are open to the surface or slightly subsurface (≤ 3 mm depth typically). Not applicable for ASS

Commentary General Notes:
[(aa)] All NDE techniques, procedures, and acceptance categories should meet Sects. 5.3 and 5.4 in this book unless otherwise noted in the project specifications
[(bb)] Tube Internal Surfaces: by IRIS, LOTIS®, etc.; Pipe/Pipeline Internal Surfaces: by Smart Pigging, InVista®,
[(cc)] Piping/Pipeline External Surfaces: by PECT, Guided Wave Test, EMAT, etc. ; Heater Tube External Surfaces: by MANTIS®, FTIS®, etc.

Commentary Notes:
[(4) to (68)] See Notes in Table 2.141
[(69)] Dissolved oxygen in the various solution can be a synergy effect for more corrosion
[(70)] Chelant corrosion: The chelants usually used in boiler water treatment are EDTA (ethylenediaminetetraacetic acid) or and NTA (nitrilotriacetic acid) to prevent the formation of these deposits by reacting with the cations (positively charged particles of Ca, Mg and Fe) in the feed water, to form a soluble salt. If chelant does not effectively react with alkaline deposit, weak acid corrosion may occur
[(71)] Phosphate attack: Localized attack under deposits, scale, producing gouges, grooves, or depressions similar to those resulting from caustic. Phosphate concentrates in the deposit as the temperature increases, and the pH drops perhaps to the range of 5–5.5 depending on the level of concentration. X-ray diffraction may be used for detecting and analysis

2.4.4.4 Standards for Atmosphere, Salt Spray, MIC, and Galvanic Corrosion Tests: TM = Test Method(s), Spec = Specification

- API RP571, 4.3.1 and Table 4–6 (Galvanic Corrosion), 4.3.8 (MIC)
- ASTM B117 Practice for Operating Salt Spray (Fog) Apparatus
- ASTM B368 TM for Copper-Accelerated Acetic Acid-Salt Spray (Fog) Testing (CASS Test)
- ASTM B808 TM for Monitoring of Atmospheric Corrosion Chambers by Quartz Crystal Microbalances
- ASTM B810 TM for Calibration of Atmospheric Corrosion Test Chambers by Change in Mass of Copper Coupons

- ASTM B826 TM for Monitoring Atmospheric Corrosion Tests by Electrical Resistance Probes
- ASTM D2010 TM for Evaluation of Total Sulfidation Activity in the Atmosphere by the Lead Dioxide Technique
- ASTM D2059 TM for Resistance of Zippers to Salt Spray (Fog)
- ASTM D5894 Practice for Cyclic Salt Fog/UV Exposure of Painted Metal (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet)
- ASTM G33 Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens
- ASTM G60 Conducting Cyclic Humidity Exposures
- ASTM G50 Practice for Conducting Atmospheric Corrosion Tests on Metals
- ASTM G71 Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes
- ASTM G82 Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance
- ASTM G84 Practice for Measurement of Time-of-Wetness on Surfaces Exposed to Wetting Conditions as in Atmospheric Corrosion Testing
- ASTM G85 Practice for Modified Salt Spray (Fog) Testing
- ASTM G87 Practice for Conducting Moist SO_2 Tests
- ASTM G91 Practice for Monitoring Atmospheric SO_2 Deposition Rate for Atmospheric Corrosivity Evaluation
- ASTM G92 Practice for Characterization of Atmospheric Test Sites
- ASTM G101 Guide for Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels
- ASTM G116 Practice for Conducting Wire-on-Bolt Test for Atmospheric Galvanic Corrosion
- ASTM G140 TM for Determining Atmospheric Chloride Deposition Rate by Wet Candle Method
- ASTM G202 TM for Using Atmospheric Pressure Rotating Cage
- NACE TM0106, Detection, Testing, and Evaluation of MIC on External Surfaces of Buried Pipelines
- BS EN ISO 9223 Corrosion of metals and alloys – Corrosivity of atmospheres – Classification
- DIN 50018 Testing in a Saturated Atmosphere in the Presence of Sulfur Dioxide (SO_2)
- BS EN ISO 12944 (Part 1–8) Paints and varnishes corrosion protection of steel structures by protective paint systems
- BS EN ISO 14713 Protection against corrosion of iron and steel in structures – Zinc and aluminum coatings – Guidelines.
- SAE J-2334 Laboratory Cyclic Corrosion Test
- MIL-STD-889B Dissimilar Metals, 1993
- NiDI Publication 14027 Managing Galvanic Corrosion
- NACE Paper 89183/89186/90103/92165/93293/94275/96274/98280/99171/01246/02006/02201/02235/02446/ 02451/ 03550/03558/ 03569/04602/06515/07526/08505/10210/11227/12-1267/ 12-1711/13-2250/14-3795/14-4254/16-7034/16-7357/ 16-7769/ 17-9343/ 17-9650
- Others: Several Automotive Companies' Standards for Salt Spray Testing

2.4.4.5 Standards for Immersion Tests-General Corrosion Rate by Weight Loss of Metal

[NACE/ASTM]

- NACE TM0169–2012/ASTM G31-2012a, Laboratory Immersion Corrosion Testing of Metals
- ASTM B895 TM for Evaluating the Corrosion Resistance of Power Metallurgy (P/M) Stainless Steel Parts/Specimens by Immersion in a Sodium Chloride Solution
- ASTM D1280 Guide for Total Immersion Corrosion Test for Soak Tank Metal Cleaners
- ASTM E1597 TM for Saltwater Pressure Immersion and Temperature Testing of Photovoltaic Modules for Marine Environments
- ASTM F482 TM for Corrosion of Aircraft Metals by Total Immersion in Maintenance Chemicals
- ASTM F483 TM for Total Immersion Corrosion Test for Aircraft Maintenance Chemicals
- ASTM G44 Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution

2.4.4.6 Standards for IGC, Pitting, SCC, Crevice, Hydrogen Embrittlement (HE), and Fatigue Corrosion Tests

Table 2.144 shows the comparison tables of major corrosion tests (IGC, Pitting, Crevice, and General) of Ni-based SS and alloys.

[Other Standards-ASTM/ANSI/NACE/ISO] See Sect. 2.4.4.2 above for EAC environments

- ASTM B858 TM for Ammonia Vapor Test for Determining Susceptibility to SCC in Copper Alloys
- ASTM B912 Standard Spec for Passivation of Stainless Steels Using Electropolishing
- ASTM C227 TM for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
- ASTM C692 TM for Evaluating the Influence of Thermal Insulations on External SCC Tendency of ASS
- ASTM E1681 TM for Determining a Threshold Stress Intensity Factor for Environment Assisted Cracking of Metallic Materials
- ASTM E2368 Practice for Strain Controlled Thermomechanical Fatigue Testing
- ASTM F326 TM for Electronic Measurement for Hydrogen Embrittlement from Cadmium-Electroplating Processes
- ASTM F519 TM for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments
- ASTM F746 TM for Pitting or Crevice Corrosion of Metallic Surgical Implant Materials
- ASTM F1113 TM for Electrochemical Measurement of Diffusible Hydrogen in Steels (Barnacle Electrode)

Table 2.144 (1/5) Summary of typical corrosion tests for SS and nonferrous alloys[(8)]

ASTM/ISO/DIN tests	Purpose	Reagent	Temp.	Time[(4)]	Limitations/specimens	Test results[(9)]
ASTM A249-supplementary S7 for ASS tubes (Ni < 19% and/or Mo < 4%) ASTM A312-supplementary S9 for ASS pipes	Weld decay	50%HCl acid	Boiling	1–2 hrs	The weld decay test is sensitive for the presence of δ ferrite in the weld material. increasing amounts of δ ferrite will result in a higher ratio, *R*. alloys with the high Ni or Mo content may not form δ ferrite and therefore may not be sensitive to this test.	Corrosion ratio, $R = (W0–W)/(B0–B)$[(7)] $R \leq 1.25$ unless required $R \leq 1.0$ in P.O. or other agreement between purchaser and supplier
ASTM A262-practice A for ASS	Etch structure test: rapid method of screening	Oxalic acid ($H_2C_2O_4 \cdot 2H_2O$). Alternative solution: ammonium persulfate ($(NH_4)_2S_2O_8$) Practice B, C, E, and F test solution may be also used to screen specimens	Ambient	15–240 hrs	For qualitative identification of free IGC attack. May be in connection with other tests (B, C, E, and F). It may be difficult to reveal the presence of step structures on some specimens containing Mo (316, 316L, 317, 317L SS), which are free of Cr-carbide sensitization, by electrolytic etching with oxalic acid. Not for rejection of material.	Acceptable etch-step, dual, end grain I and II Suspected Etch-ditch
ASTM A262-practice B for ASS G28- method A for wrought Ni-Cr alloys (Streicher test)	IGC[(5)] (Cr-carbides & σ phase) and general corrosion rate	75%$Fe_2(SO_4)_3$ or 95–98%H_2SO_4	Boiling	24–120 hrs	A262: Typically for stabilized SS, but for unstabilized SS as well. Typically, not detect the IGC associated with σ phase for wrought 316/316L/317/317L SS. G28: General corrosion rate may easily be obtained from the IGC of UNS N10276, N06022, N06059, and N06455.	Corrosion rate in mpy or mm/yr (associated with Cr-carbides precipitation & σ phase)
ASTM A262-practice C for ASS ISO 3651-1 for ASS & DSS (Huey test)	Detecting susceptibility to IGC[(5)] attack (Cr-carbides) and general corrosion rate	65% HNO_3 acid	Boiling	240 hrs 5 boiling periods × 48 hrs each	Mainly be used as a check on whether the material has been correctly heat treated. – Cr-carbides; 304, 304L, 316, 316L, 317, 317L, 321, 347, CF-3, CF-8, CF-3 M, CF-8 M – Cr-carbides & σ phase; 316, 316L, 317, 317L, 321, 347, CF-3M, CF-8M – End-grain pitting; 304, 304L, 316, 316L, 317, 317L, 321, 347 – This test is also used for 309, 310, 348, 410, 430, 446, CN-7 M (alloy 20). Use specimens sensitized by heat-treatment at 650–675 °C for 30–120 minutes (or by welding) for extra low carbon ($C < 0.03\%$) or stabilized ASS-for Cr-carbides & σ phase detection.	Corrosion rate in mpy or mm/yr (associated with Cr-carbides, σ phase precipitation)
ASTM A262-practice E for ASS (Strauss test)	Detecting susceptibility to IGC[(5)] attack (Cr-carbides)-	Copper–copper sulfate–16%H_2SO_4 acid		15 hrs	– Cr-carbides; 201, 202, 301, 304, 304L, 316, 316L, 317, 317L, 321, 347	Visual examination for 180° bent specimen
ASTM A262-practice F for ASS with Mo	Detecting susceptibility to IGC[(5)] attack and general corrosion rate	Copper–copper sulfate–50% H_2SO_4 acid	Boiling	120 hrs	To measure the IGC susceptibility of "as received" stainless steels. – Cr-carbides; CF-3M (316L cast), CF-8M (316 cast) and 316Ti. – This test is not for detection of Cr-carbides associated with σ phase.	Corrosion rate in mpy or mm/yr (associated with Cr-carbides)

Table 2.144 (2/5) Summary of typical corrosion tests for SS and nonferrous alloys[8]

ASTM/ISO/DIN tests	Purpose	Reagent	Temp.	Time[4]	Limitations/specimens	Test results[9]
ASTM A380 Iron contamination on SS surfaces gross indications– when iron contamination is clearly visible after completion of the test, items should be cleaned per this practice	*Water-wetting and drying*	Water with wet-dry cyclic conditions	Atm	Remains dry for a total of 8 h in a 24-hrs wet-dry cycles	Formation of rust stains may be accelerated by periodically wetting the surface with preferably distilled or deionized water or clean, fresh, potable tap water.	No evidence of rust stains or other corrosion products
	High-humidity test	Humid air	95–100% humidity at 40–45 °C (100–115 °F]	24–26 hrs	In a suitable humidity cabinet.	No evidence of rust stains or other corrosion products
	Copper sulfate test for 200 and 300 series ASS, the precipitation hardening alloys, and the ferritic 400 series SS with 16% Cr or more. *Cautions:* Not recommended for MSS, lower Cr FSS, and food industry/medical SS.	Distilled water: 250 ml 96–100% H_2SO_4: 1 ml Copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$): 4 g Always add acid to cold water.)	Boiling temperature	24 hrs	This highly sensitive method is to apply the test solution to the surface to be inspected, additional solution if needed to keep the surface wet for a period of 6 min. The specimen shall be rinsed and dried in a manner not to remove any deposited copper. Copper deposit will indicate the presence of free iron.	If free iron is present, a blue color will appear.
	Ferroxyl test					If free iron is present, a blue color will appear.
ASTM A923- test method A for DSS	To detect detrimental intermetallic phase after exposure to 320–955 °C (600–1750 °F)	29%NaOH etch test	Controlled by voltage (1–3)	5–60 sec.	Used as a screening test for test method (TM) B or C. Etch structure types: – Unaffected structure – Possibly affected structure – Affected structure – Centerline structure	Unaffected structure: acceptable in TM A. When TM A is used as a screening test for TM B or TM C, specimens having acceptable etch structures need not be subjected to TM B or TM C.
ASTM A923: test method B for DSS		Charpy impact; the detrimental intermetallic phase can reduce the toughness	−40 °C (−40 °F) or − 46 °C (−50 °F)		Charpy V-notch impact test for base metal, weld metal, and HAZ @ −40 °C (−40 °F) or − 46 °C (−50 °F) per material	Min. impact energy shall be 25–40 ft-lb (34–54 J) per material
ASTM A923: test method C for DSS		$FeCl_3$, pH = 1, 25 °C	25–40 °C per material	24 hrs	Rapid screening test	Corrosion rate: shall be ≤10 mdd. mdd = mg/(dm^2. day)
ASTM G28-method B for wrought Ni-Cr alloys	Detecting susceptibility to IGC[5]	23%H_2SO_4 + 1.2% HCl + 1% $FeCl_3$ + 1%CuCl for UNS N10276, N06022, N06059, N06200, and N06686	Boiling	24–120 hrs per alloy; 24 hrs for left materials	Typically used to evaluate as-received material and to evaluate the effects of subsequent heat treatments. In Ni-rich, Cr-bearing alloys, this test may be applied to wrought and weldments of products, but not applicable to cast products.	Corrosion rate in mpy or mm/yr insensitive to Mo variation
ASTM G35-for SS and Ni-Cr-Fe alloys	Polythionic acid SCC	Polythionic acid solution-sulfurous acid and technical grade H_2S; or, distilled water, commercial grade SO_2, and technical grade H_2S	22–25 °C	1 hr	Typically used to evaluate SS (302, 304) or other materials in the "as received" condition or after being subjected to high-temperature service, 482–815 °C (900–1500 °F), for prolonged periods of time.	The time required to initiate cracks, the rate of crack growth, and time to failure of the stressed and sensitized U-bend specimen.

Table 2.144 (3/5) Summary of typical corrosion tests for SS and nonferrous alloys[8]

ASTM/ISO/DIN tests	Purpose	Reagent	Temp.	Time[4]	Limitations/specimens	Test results[9]
ASTM G36-for SS and alloys	Cl-SCC resistance	45%$MgCl_2$	154–156 °C (constant boiling temperature)	<168 hrs or 168–336 hrs	Ruptured specimens should also be examined for evidence of mechanical failure resulting from the action of applied stress on specimens whose cross sections have been reduced by general or pitting corrosion, or both. Such failures usually show evidence of ductility. Duplicate tests with thicker specimens should be made in case of doubt.	The time required to initiate cracks, the rate of crack growth, and time to failure of the stressed and sensitized U-bend specimen.
ASTM G37- for cu-Zn alloys (Brass)	Accelerate SCC test	Mattsson's solution, pH 7.2 ($CuSO_4$ + $(NH_4)_2SO_4$ + NH_4OH)	18–24 °C	48–96 hrs	To determine the relative SCC susceptibility of different brasses under the same or different stress conditions, or To determine the *absolute* degree of SCC susceptibility, if any, of a particular brass or brass component under one or more specific stress conditions.	Criterion used for definition of failure This leads to the possibility of confusing SCC failures with mechanical failures induced by corrosion-reduced net cross sections.
ASTM G41-for metals	SCC in hot salt	3.5%NaCl or other slats or synthetic seawater	230–540 °C		The hot salt test consists of exposing a stressed, salt-coated test specimen to elevated temperatures for various predetermined lengths of time, depending on the alloy, stress level, temperature, and selected damage criterion (i.e., embrittlement, cracking, or rupture, or a combination thereof).	Cracking initiates at salt-metal-air interfaces on the surface of a test specimen. Cracking is sensitive for the particle size of salt.
ASTM G44-for aluminum & ferrous alloys ISO 9591 for aluminum slloys G47-ferrous alloys	SCC	3.5%NaCl, pH = 6.4–7.2, relative humidity = 35–55%	26–28 °C	20–90 days	The alternate immersion test utilizes a 1-h cycle that includes a 10-min period in an aqueous solution of 3.5% NaCl followed by a 50-min period out of the solution, during which the specimens are allowed to dry. This 1-h cycle is continued 24 h/day for the total number of days.	Used for both stressed and unstressed corrosion specimens for SCC. Historically, it has been used for SCC testing, but is often used for other forms of corrosion, such as uniform, pitting, IGC, and galvanic.
ASTM G48-method A for SS & Ni alloys	Pit/general corrosion	$FeCl_3$	22–50 °C	72 hrs	Weight loss measurement and pit density	Pitting – yes or no[1]
ASTM G48-method B for SS & Ni alloys	Crevice/ general corrosion	$FeCl_3$	22–50 °C	72 hrs	Weight loss measurement and pit density	Crevice corrosion – yes or no[1]
ASTM G48-method C for Ni alloys	CPT[2]	Acidified $FeCl_3$	0–85 °C	72 hrs	Weight loss measurement and pit density Test shall begin at 5 °C below CPT.	Pitting – yes or no[1]
ASTM G48-method E for SS	CPT					
ASTM G48-method D for Ni alloys	CCT[3]	Acidified $FeCl_3$	0–85 °C	2 hrs	Weight loss measurement and pit density Requires crevice assembly Test shall begin at 5 °C below CPT.	Crevice corrosion — yes or no[1]
ASTM G48 method F for SS	CCT					
ASTM G103- for low Cu 7xxxx series Al-Zn-Mg alloys	SCC	6%NaCl	Boiling, pH = 6.4–7.2	≥10 min.	Specimen-Bent beam, U-bends for thin products/ C-rings or tension specimens for thicker products and for short transverse testing. Not applicable to 7xxx series alloys with >1.2%Cu.	Specimen surfaces should be examined for visual evidence of cracking or the initiation of gas evolution from the surface in areas of highest stress.

Table 2.144 (4/5) Summary of typical corrosion tests for SS and nonferrous alloys[8]

ASTM/ISO/ DIN tests	Purpose	Reagent	Temperature	Time[4]	Limitations/specimens	Test results[9]
ASTM G123-for wrought SS & Ni (<33%) alloys	SCC in acidified NaCl solution	25%NaCl, pH 1.5 with phosphoric acid	Boiling, >200 °C (390 °F)	1008 hrs (42 days)	To simulate cracking of U-bend specimen in water, especially cooling waters that contain chloride. It is not intended to simulate cracking that occurs at high temperatures, with chloride or hydroxide.	Crack and the time
NACE TM0177	SSC	Saturated with H_2S (1 atm) *Solution A*: for method A, C, and D 5%NaCl+0.5% glacial acetic acid starting pH = 2.6–2.8 *Solution B*: for method C or D if specified in P.O. method A, C, and D 5%NaCl+0.5% glacial acetic acid +0.41% sodium acetate Starting pH = 3.4–3.6 *Solution C*: for MSS & method A, C, and D In Brine solution[8] *Solution D*: for high strength steel (i.e., API 5CT-C110) & method A, C, and D starting pH = 3.8–4.0	21–27 °C	See right	Four test methods: *Method A* – To prove brittle failure resistance in the corrosive environment under applied or residual stress. Uniaxial tensile specimen is loaded at a given stress level, usually between 80% and 90% of its yield strength (YS) in 30 days (720 hrs). *Method B* – To evaluate resistance to cracking failure in low-pH aqueous environments containing H_2S by Bent-Beam Test. 50% probability of failure based on critical stress factor in 30 days (720 hrs). *Method C* – To evaluate EC resistance to cracking failure under circumferential loading by C-ring test which is usually determined by time-to-cracking in 30 days (720 hrs). *Method D* – Double Cantilever Beam Test is to determine the mode 1 critical stress intensity factor for SSC, K1SSC, in the corrosive environment. Short test for 14 days (336 hrs).	Acceptance: A: no failure B: ≤50% failure C: no failure D: Average K1SCC (threshold stress intensity factor for SSC) no failure
ISO 7539 for metals and alloys	SCC	[8]	[8]	[8]	Part 1: General guidance on testing procedures Part 2: Preparation and use of bent-beam specimens Part 3: Preparation and use of U-bend specimens Part 4: Preparation and use of uniaxially loaded tension specimens Part 5: Preparation and use of C-ring specimens Part 6: Preparation and use of pre-cracked specimens for tests under constant load or constant displacement Part 7: Slow strain rate testing	[8]
ISO 9591 for aluminum alloys-alternate	SCC	3.5%NaCl, pH = 6.4 to 7.2 for alternate immersion	From 0 °C to 100 °C	[8]	Specimen: Bent beam, U-bends for thin products/ C-rings or tension specimens for thicker products	Crack, including any metallographic examinations. Threshold stress, time of failure
ISO 9591 for aluminum alloys-continuous	SCC	pH = 3.0, 2%NaCl, 0.5% Na2CrO4 for continuous immersion	25 °C	[8]		
ISO 15324 for SS and Ni alloys	Relative resistance of SCC	0.1 M NaCl dripped on 300 °C specimen	20–26 °C	500 hrs	[8]	Threshold stress without SCC in 500 hrs
ISO 3651-Part 2 for FSS & DSS	IGC[5]	16–40% H_2SO_4 + $Fe_2(SO_4)_3$ or $CuSO_4$[6]	50–60 °C	20 ± 5 hrs	Use specimens sensitized by heat-treatment at 650 (for 10 minutes) or 700 °C for 30 minutes followed by water quenching for stabilized SS with extra low carbon ($C \leq 0.03\%$).	Cracking – yes or no
DIN SEP 1877 -method II	IGC by bend test	40%H_2SO_4 + 25 g/l $Fe_2(SO_4)_3$	Boiling	24 hrs	Not suitable for Cr > 20% alloys. Cracks from IGC should open. Similar with Streicher test	Cracking – yes or no

Table 2.144 (5/5) Summary of typical corrosion tests for SS and nonferrous alloys[8]

ASTM/ISO/ DIN tests	Purpose	Reagent	Temperature	Time[4]	Limitations/specimens	Test results[9]
Green death for high Ni alloys	CPT & CCT	11.9%H_2SO_4 + 1.3% HCl + 1%$FeCl_3$ + 1% $CuCl_2$	Boiling up to 103 °C (217 °F)∗	24–72 hrs	[8].∗ The CPTs of some alloys (i.e., alloy C-22, alloy 686, alloy 59) are shown at 120 °C and above.	Pitting & crevice corrosion – yes or no

Notes: *IGC* intergranular corrosion, *CPT* critical pitting temperature, *CCT* critical crevice temperature

(1) At the test temperature specified

(2) The pitting starting temperature (CPT) may be estimated by the equation: CPT (°C) = (2.5 × %Cr) + (7.6 × %Mo) + (31.9 × %N) – 41.0

(3) The crevice corrosion starting temperature (CCST) may be estimated by the equation: CCST (°C) = (1.5 × %Cr) + (1.9 × %Mo) + (4.9 × %Nb) + (8.6 × % W) – 36.2

(4) Testing time depends on the tested material

(5) See Table 2.63 for more details on test methods of IGC.

(6) The test solution should be used one of the three methods (A, B, and C) which are grouped by material (chemical composition)

Method A	
Austenitic alloys where Cr > 16% and Mo ≤ 3%	(e.g., 304L; 316L).
Duplex alloys where Cr > 16% and Mo ≤ 3%	(e.g., 2101; 2304; 2003).
Method B	
Austenitic alloys where Cr > 20% and 2% 4%	(e.g., 317L).
Duplex alloys where Cr > 20% and Mo > 2%	(e.g., 2205; Z100; 2507).
Method C	
Austenitic alloys where Cr > 17% and Mo > 3%	(e.g., 6% Mo; 904L).
Austenitic alloys where Cr > 25% and Mo > 2%	(e.g., Alloy 28).
Duplex alloys where Cr > 20% and Mo > 3%	(e.g., 2205; Z100; 2507).

(7) Corrosion ratio (*R*) calculation:
Where,
*W*o = average weld-metal thickness before the test,
W = average weld-metal thickness after the test,
*B*o = average base-metal thickness before the test, and
B = average base-metal thickness after the test

(8) See each standard for more details on the scope of application, specimen sampling/size/numbers/identification/surface preparation/rinsing, safety, precautions, test report, terms and definitions, acceptance criteria, lab conditions, and any other options/alternatives

(9) Corrosion rate calculation: to use Table 2.125.

- ASTM F1459 TM for the Determination of the Susceptibility of Metallic Materials to Hydrogen Gas Embrittlement (HE)
- ASTM F1624 TM for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique
- ASTM F1801 Practice for Corrosion Fatigue Testing of Metallic Implant Materials
- ASTM F1940 TM for Process Control Verification to Prevent Hydrogen Embrittlement in Plated or Coated Fasteners
- ASTM F2078 Terminology Relating to Hydrogen Embrittlement Testing
- ASTM F2111 Practice for Measuring Intergranular Attack or End Grain Pitting on Metals Caused by Aircraft Chemical Processes
- ASTM G30 Practice for Making and Using U-Bend SCC Test Specimens
- ASTM G35 Practice for Determining the Susceptibility of SS and Related Ni-Cr-Fe Alloys to SCC in Polythionic Acids
- ASTM G36 Practice for Evaluating SCC Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution
- ASTM G37 Practice for Use of Mattssons Solution of pH 7.2 to Evaluate the SCC Susceptibility of Cu-Zn Alloys
- ASTM G38 Practice for Making and Using C-Ring SCC Test Specimens
- ASTM G39 Practice for Preparation and Use of Bent-Beam SCC Test Specimens
- ASTM G41 Practice for Determining Cracking Susceptibility of Metals Exposed Under Stress to a Hot Salt Environment
- ASTM G44 Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% NaCl Solution
- ASTM G46 Guide for Examination and Evaluation of Pitting Corrosion
- ASTM G47 TM for Determining Susceptibility to SCC of 2XXX and 7XXX Aluminum Alloy Products
- ASTM G49 Practice for Preparation and Use of Direct Tension SCC Test Specimens
- ASTM G58 Practice for Preparation of SCC Test Specimens for Weldments
- ASTM G64 Classification of Resistance to SCC of Heat-Treatable Aluminum Alloys
- ASTM G78 Guide for Crevice Corrosion Testing of lron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments
- ASTM G103 Practice for Evaluating SCC Resistance of Low Copper 7XXX Series Al-Zn-Mg-Cu Alloys in Boiling 6% Sodium Chloride Solution
- ASTM G110 Practice for Evaluating IGC Resistance of Heat Treatable Aluminum Alloys by Immersion in Sodium Chloride + Hydrogen Peroxide Solution

- ASTM G123 TM for Evaluating SCC of Stainless Alloys with Different Nickel Content in Boiling Acidified Sodium Chloride Solution
- ASTM G129 Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking (EAC)
- ASTM G139 TM for Determining SCC Resistance of Heat-Treatable Aluminum Alloy Products Using Breaking Load Method
- ASTM G142 TM for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both
- ASTM G146 Practice for Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service
- ASTM G148 Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique
- ASTM G150 TM for Electrochemical Critical Pitting Temperature Testing of SS
- ASTM G168 Practice for Making and Using Precracked Double Beam SCC Specimens
- ASTM G186 TM for Determining Whether Gas-Leak-Detector Fluid Solutions Can Cause SCC of Brass Alloys
- ASTM G188 Specification for Leak Detector Solutions Intended for Use on Brasses and Other Copper Alloys
- ASTM G192 TM for Determining the Crevice Repassivation Potential of Corrosion-Resistant Alloys Using a Potentiodynamic-Galvanostatic-Potentiostatic Technique
- NACE Report 35103 External SCC of Underground Pipelines

See Sect. 2.1.6 frailties of SS, Sect. 2.3 metal loss and degradation of metals in high temperature, and Sects. 2.4.2 and 2.4.3 several environmentally assisted cracking for more details.

2.4.4.7 Standards for Tests and Data Collection in Soil and Concrete Rebar Corrosion and Cathodic Protection (CP)

See Sect. 2.4.5 for Erosion, Abrasion, Adhesive Wear, and Friction.

[ASTM] TM = Test Method(s), Spec = Specification

- C876 TM for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete
- C1152 TM for Acid-Soluble Chloride in Mortar and Concrete
- C1218 TM for Water-Soluble Chloride in Mortar and Concrete
- Cl582 Spec for Admixtures to Inhibit Chloride-Induced Corrosion of Reinforcing Steel in Concrete
- G162 Practice for Conducting and Evaluating Laboratory Corrosion Tests in Soils
- G4 Conducting Corrosion Tests in Field Applications
- G51 TM for Measuring pH of Soil for Use in Corrosion Testing
- G52 Practice for Exposing and Evaluating Metals and Alloys in Surface Seawater
- G57 TM for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method
- G97 Laboratory Evaluation of Mg Sacrificial Anode Test Specimens for Underground Applications
- G109 TM for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments
- G158 Standard Guide for Three Methods of Assessing Buried Steel Tanks
- G162 Practice for Conducting and Evaluating Laboratory Corrosion Tests in Soils
- G180 TM for Corrosion Inhibiting Admixtures for Steel in Concrete by Polarization Resistance in Cementitious Slurries
- G187 TM for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method
- G198 TM for Determining the Relative Corrosion Performance of Driven Fasteners in Contact with Treated Wood
- G200 TM for Measurement of Oxidation-Reduction Potential (ORP) of Soil

[NACE]

- SP0100 CP to Control External Corrosion of Concrete Pressure Pipelines and Mortar-Coated Steel Pipelines for Water or Waste Water Service
- SP0107 Electrochemical Realkalization and Chloride Extraction for Reinforced Concrete
- SP0186 Application of CP for External Surfaces of Steel Well Casings
- SP0193 Application of CP to Control External Corrosion of CS On-Grade Storage Tank Bottoms
- SP0196 Galvanic Anode CP of Internal Submerged Surfaces of Steel Water Storage Tanks
- SP0290 Impressed Current CP of Reinforcing Steel in Atmospherically Exposed Concrete Structures
- SP0308 Inspection Methods for Corrosion Evaluation of Conventionally Reinforced Concrete Structures
- SP0388 ICCP of Internal Submerged Surfaces of CS Water Storage Tanks
- SP0390 Maintenance and Rehabilitation Considerations for Corrosion Control of Atmospherically Exposed Existing Steel-Reinforced Concrete Structures
- SP0408 CP of Reinforcing Steel in Buried or Submerged Concrete Structures
- SP0575 Internal CP Systems in Oil-Treating Vessels
- SP0892 Coatings and Linings over Concrete for Chemical Immersion and Containment Service
- TM0101 Measurement Techniques Related to Criteria for CP on Underground or Submerged Metallic Tank Systems

– TM0105 Test Procedures for Organic-Based Conductive Coating Anodes for Use on Concrete Structures
– TM0108 Testing of Catalyzed Titanium Anodes for Use in Soils or Natural Waters
– TM0294 Testing of Embeddable Impressed Current Anodes for Use in CP of Atmospherically Exposed Steel-Reinforced Concrete
– TM0497 Measurement Techniques Related to Criteria for CP on Underground or Submerged-Metallic Piping Systems

[ACI]

– ACI 222R Protection of Metals in Concrete Against Corrosion
– ACI 222.2R Report on Corrosion of Prestressing Steels
– ACI 222.3R Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures

2.4.4.8 Standards for Tests and Guidelines in Coating, Rust Prevention, Cleaning, and Passivation

[ASTM] TM = Test Method(s), Spec = Specification

– A239 Practice for Locating the Thinnest Spot in a Zinc (Galvanized) Coating on Iron or Steel Articles
– A380 Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems
– A780 Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings
– A967 Chemical Passivation Treatments for Stainless Steel Parts
– B201 Practice for Testing Chromate Coatings on Zinc and Cadmium Surfaces
– B322 Cleaning Metals Prior to Electroplating
– B449 Spec for Chromates on Aluminum
– B456 Spec for Electrodeposited Coatings of Copper Plus Nickel Plus Chromium and Nickel Plus Chromium
– B555 Guide for Measurement of Electrodeposited Metallic Coating Thicknesses by Dropping Test
– B600 Descaling and Cleaning Titanium and Titanium Alloy Surfaces
– B614 Descaling and Cleaning Zirconium and Zirconium Alloy Surfaces
– B734 Spec for Electrodeposited Copper for Engineering Uses
– B765 Guide for Selection of Porosity and Gross Defect Tests for Electrodeposits and Related Metallic Coatings
– B798 TM for Porosity in Gold or Palladium Coatings on Metal Substrates by Gel-Bulk Electrography
– B799 TM for Porosity in Gold and Palladium Coatings by Sulfurous Acid/Sulfur-Dioxide Vapor
– B809 TM for Porosity in Metallic Coatings by Humid Sulfur Vapor (“Flowers-of-Sulfur”)
– B866 TM for Gross Defects and Mechanical Damage in Metallic Coatings by Polysulfide Immersion
– B877 TM for Gross Defects and Mechanical Damage in Metallic Coatings by the Phosphomolybdic Acid (PMA) Method
– B920 Practice for Porosity in Gold and Palladium Alloy Coatings on Metal Substrates by Vapors of Sodium Hypochlorite Solution
– B961 Spec for Silver-Coated Copper and Copper-Alloy-Stranded Conductors for Electronic Space Application
– D665 TM for Rust Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water
– D870 Practice for Testing Water Resistance of Coatings Using Water Immersion
– D1014 Practice for Conducting Exterior Exposure Tests of Paints and Coatings on Metal Substrates
– D1735 Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus
– D1748 TM for Rust Protection by Metal Preservatives in the Humidity Cabinet
– D2247 Practice for Testing Water Resistance of Coatings in 100% Relative Humidity
– D2803 Guide for Testing Filiform Corrosion Resistance of Organic Coatings on Metal
– D3451 Guide for Testing Coating Powders and Powder Coatings
– D3603 TM for Rust-Preventing Characteristics of Steam Turbine Oil in the Presence of Water (Horizontal Disk Method)
– D4585 Practice for Testing Water Resistance of Coatings Using Controlled Condensation
– D5065 Guide for Assessing the Condition of Aged Coatings on Steel Surfaces
– D5367 Practice for Evaluating Coatings Applied Over Surfaces Treated with Inhibitors Used to Prevent Flash Rusting of Steel When Water or Water/Abrasive Blasted
– D5534 TM for Vapor-Phase Rust-Preventing Characteristics of Hydraulic Fluids
– D6557 TM for Evaluation of Rust Preventive Characteristics of Automotive Engine Oils
– D6675 Practice for Salt-Accelerated Outdoor Cosmetic Corrosion Testing of Organic Coatings on Automotive Sheet Steel
– D7087 TM for an Imaging Technique to Measure Rust Creepage at Scribe on Coated Test Panels Subjected to Corrosive Environments
– D7376 Practice for Outdoor Evaluation of Wet Stack Storage Conditions on Coil-Coated Metals
– F485 TM for Effects of Cleaners on Unpainted Aircraft Surfaces
– F519 TM for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments
– G33 Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens
– ASTM STP 538 Cleaning Stainless Steels

[NACE/SSPC/AWS]

– NACE No. 1/SSPC-SP 5 White Metal Blast Cleaning
– NACE No. 2/SSPC-SP 10 Near-White Metal Blast Cleaning
– NACE No. 3/SSPC-SP 6 Commercial Blast Cleaning
– NACE No. 4/SSPC-SP 7 Brush-Off Blast Cleaning
– NACE No. 6/SSPC-SP 13 Surface Preparation of Concrete

- NACE No. 8/SSPC-SP 14 Industrial Blast Cleaning
- NACE No. 8/SSPC-SP 16 Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, SS, and Nonferrous Metals
- NACE No. 10/SSPC-PA 6 Fiberglass-Reinforced Plastic (FRP) Linings Applied to Bottoms of CS Aboveground Storage Tanks
- NACE No. 11/SSPC-PA 8 Thin-Film Organic Linings Applied in New CS Process Vessels
- NACE No. 12/AWS C2.23M/SSPC-CS Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel
- NACE No. 13/SSPC-ACS-1 Industrial Coating and Lining Application Specialist Qualification and Certification
- NACE VIS 7/SSPC-VIS 4, Guide and Visual Reference Photographs for Steel Cleaned by Waterjetting
- NACE VIS 9/SSPC-VIS 5, Guide and Reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning
- SSPC-VIS 2, Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces
- NACE RP0105 Liquid-Epoxy Coatings for External Repair, Rehabilitation, and Weld Joints on Buried Steel Pipelines
- NACE RP0281 Method for Conducting Coating (Paint) Panel Evaluation Testing in Atmospheric Exposures
- NACE SP0375 Field-Applied Underground Wax Coating Systems for Underground Pipelines: Application, Performance, and QC
- NACE RP0399 Plant-Applied, External Coal Tar Enamel Pipe Coating Systems: Application, Performance, and QC
- NACE RP0402 Field-Applied FBE Pipe Coating Systems for Girth Weld Joints: Application, Performance, and QC
- NACE RP0495 Guidelines for Qualifying Personnel as Abrasive Blasters and Coating and Lining Applicators in the Rail Industries
- NACE RP0602 Field-Applied Coal Tar Enamel Pipe Coating Systems: Application, Performance, and QC
- NACE RP0692 Application of a Coating System to Exterior Surfaces of Steel Rail Cars
- NACE SP0108 Corrosion Control of Offshore Structures by Protective Coatings
- NACE SP0109 Field Application of Bonded Tape Coatings for External Repair, Rehabilitation, and Weld Joints on Buried Metal Pipelines
- NACE SP0181 Liquid-Applied Internal Protective Coatings for Oilfield Production Equipment
- NACE SP0185 Extruded Polyolefin Resin Coating Systems with Soft Adhesives for Underground or Submerged Pipe
- NACE SP0188 Discontinuity (Holiday) Testing of New Protective Coatings on Conductive Substrates
- NACE SP0191 Application of Internal Plastic Coatings for Oilfield Tubular Goods and Accessories
- NACE SP0274 High-Voltage Electrical Inspection of Pipeline Coatings
- NACE SP0288 Inspection of Linings on Steel and Concrete
- NACE SP0295 Application of a Coating System to Interior Surfaces of New and Used Rail Tank Cars
- NACE SP0297 Maintenance Painting of Electrical Substation Apparatus Including Flow Coating of Transformer Radiators
- NACE SP0298 Sheet Rubber Linings for Abrasion and Corrosion Service
- NACE SP0302 Selection and Application of a Coating System to Interior Surfaces of New and Used Rail Tank Cars in Molten Sulfur Service
- NACE SP0386 Application of a Coating System to Interior Surfaces of Covered Steel Hopper Railcars in Plastic, Food, and Chemical Service
- NACE SP0394 Application, Performance, and QC of Plant-Applied Single Layer FBE External Pipe Coating
- NACE SP0395 Fusion-Bonded Epoxy Coating of Steel Reinforcing Bars
- NACE SP0398 Recommendations for Training and Qualifying Personnel as Railcar Coating and Lining Inspectors
- NACE SP0490 Holiday Detection of FBE External Pipeline Coating of 250–760 μm (10–30 mil)
- NACE SP0592 Application of a Coating System to Interior Surfaces of New and Used Rail Tank Cars in Concentrated (90–98%) Sulfuric Acid Service
- NACE SP0892 Coatings and Linings over Concrete for Chemical Immersion and Containment Service
- NACE TM0102 Measurement of Protective Coating Electrical Conductance on Underground Pipelines
- NACE TM0104 Offshore Platform Ballast Water Tank Coating System Evaluation
- NACE TM0105 Test Procedures for Organic-Based Conductive Coating Anodes for Use on Concrete Structures
- NACE TM0109 Aboveground Survey Techniques for the Evaluation of Underground Pipeline Coating Condition
- NACE TM0174 Laboratory Methods for the Evaluation of Protective Coatings and Lining Materials on Metallic Substrates in Immersion Service
- NACE TM0183 Evaluation of Internal Plastic Coatings for Corrosion Control of Tubular Goods in an Aqueous Flowing Environment
- NACE TM0185 Evaluation of Internal Plastic Coatings for Corrosion Control of Tubular Goods by Autoclave Testing
- NACE TM0186 Holiday Detection of Internal Tubular Coatings of 250–760 μm (10–30 mils) Dry-Film Thickness
- NACE TM0204 Exterior Protective Coatings for Seawater Immersion Service
- NACE TM0304 Offshore Platform Atmospheric and Splash Zone Maintenance Coating System Evaluation (discontinued)
- NACE TM0384 Holiday Detection of Internal Tubular Coatings of Less Than 250 μm (10 mils) Dry-Film Thickness
- NACE TM0404 Offshore Platform Atmospheric and Splash Zone New Construction Coating System Evaluation

[BS EN ISO/AWS]

- BS EN ISO 1461 Hot dip galvanized coatings on fabricated iron and steel articles – Specifications and test methods
- BS EN ISO 4628-3 Paints and varnishes – Evaluation of degradation of paint coatings – Designation of intensity, quantity, and size of common types of defects – Part 3: Designation of degree of rusting

- BS 7079-Part A1/ISO 8501-1 Preparation of Steel Substrates Before Application of Paints and Related Products – Visual Assessment of Surface Cleanliness – Part 1: Rust Grades and Preparation Grades of Uncoated Steel Substrates and of Steel Substrates After Overall Removal of Previous Coatings
- BS EN ISO 8501 Corrosion Protection of Steel Structures by Painting
- BS EN ISO 9227 Corrosion Test in Artificial Atmospheres-Salt Spray Tests
- BS EN 10240 Coatings for steel tubes: Specification for hot dip galvanized coatings
- BS EN ISO 12944 (part 1–8) Paints and Varnishes: Corrosion Protection of Steel Structures by Protective Paint Systems
- BS EN 2516 Passivation of Corrosion-Resisting Steels and Decontamination of Nickel-Based Alloys
- AWS C2.23 Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel
- SAE AMS QQ-P-35A Passivation Treatments for Corrosion-Resistant Steel
- AMS 2700 Passivation of Corrosion-Resistant Steels
- NASA Lewis Specification No. RM-1 Chemical Cleaning of Columbium and Tantalum Alloys
- MIL STD 1330D Precision Cleaning and Testing of Shipboard Oxygen, Helium, Helium-Oxygen, Nitrogen, and Hydrogen Systems
- MIL-STD-1622B Standard Practice for Cleaning of Shipboard Compressed Air Systems

2.4.4.9 Other Standards for Corrosion Tests

[ASTM] TM = Test Method(s), Spec = Specification

- A923 TM for Detecting Detrimental Intermetallic Phase in DSS
- A1004 Practice for Establishing Conformance to the Minimum Expected Corrosion Characteristics of Metallic, Painted-Metallic, and Nonmetallic-Coated Steel Sheet Intended for Use as Cold-Formed Framing Members
- A1071 TM for Evaluating Hygrothermal Corrosion Resistance of Permanent Magnet Alloys
- B812 TM for Resistance to Environmental Degradation of Electrical Pressure Connections Involving Aluminum and Intended for Residential Applications
- B825 TM for Coulometric Reduction of Surface Films on Metallic Test Samples
- B827 Practice for Conducting Mixed Flowing Gas (MFG) Environmental Tests
- B845 Guide for Mixed Flowing Gas (MFG) Tests for Electrical Contacts
- B912 Standard Spec for Passivation of Stainless Steels Using Electropolishing
- C227 TM for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
- C1431 Guide for Corrosion Testing of Aluminum-Based Spent Nuclear Fuel in Support of Repository Disposal
- Cl524 TM for Water-Extractable Chloride in Aggregate (Soxhlet Method)
- CI617 Practice for Quantitative Accelerated Laboratory Evaluation of Extraction Solutions Containing Ions Leached from Thermal Insulation on Aqueous Corrosion of Metals
- D130 TM for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
- D610 Practice for Evaluating Degree of Rusting on Painted Steel Surfaces
- D7I4 TM for Evaluating Degree of Blistering of Paints
- D849 TM for Copper Strip Corrosion by Industrial Aromatic Hydrocarbons
- D876 TM for Nonrigid Vinyl Chloride Polymer Tubing Used for Electrical Insulation
- D1141 Practice for the Preparation of Substitute Ocean Water
- D1193 Spec for Reagent Water
- D1275 TM for Corrosive Sulfur in Electrical Insulating Liquids
- D1384 TM for Corrosion Test for Engine Coolants in Glassware
- D1414 TM for Rubber O-Rings
- D1611 TM for Corrosion Produced by Leather in Contact with Metal
- D1654 Standard TM for Evaluation of Painted or Coated Specimens
- D1743 TM for Determining Corrosion Preventive Properties of Lubricating Greases
- D1838 TM for Copper Strip Corrosion by Liquefied Petroleum (LP) Gases
- D2251 TM for Metal Corrosion by Halogenated Organic Solvents and Their Admixtures
- D2570 TM for Simulated Service Corrosion Testing of Engine Coolants
- D2649 TM for Corrosion Characteristics of Solid Film Lubricants
- D2688 TM for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Method)
- D3310 TM for Determining Corrosivity of Adhesive Materials
- D3316 TM for Stability of Perchloroethylene with Copper
- D3482 Practice for Determining Electrolytic Corrosion of Copper by Adhesives
- D4048 TM for Detection of Copper Corrosion from Lubricating Grease
- D4310 TM for Determination of Sludging and Corrosion Tendencies of Inhibited Mineral Oils
- D4340 TM for Corrosion of Cast Aluminum Alloys in Engine Coolants Under Heat-Rejecting Conditions

- D4350 TM for Corrosivity Index of Plastics and Fillers
- D4412 TM for Sulfate-Reducing Bacteria in Water and Water-Formed Deposits
- D4627 TM for Iron Chip Corrosion for Water-Miscible Metalworking Fluids
- D4658 TM for Sulfide Ion in Water
- D4778 TM for Determination of Corrosion and Fouling Tendency of Cooling Water Under Heat Transfer Conditions
- D5485 TM for Determining the Corrosive Effect of Combustion Products Using the Cone Corrosimeter
- D5968 TM for Evaluation of Corrosiveness of Diesel Engine Oil at 121 °C
- D5969 TM for Corrosion-Preventive Properties of Lubricating Greases in the Presence of Dilute Synthetic Seawater Environments
- D6138 TM for Determination of Corrosion-Preventive Properties of Lubricating Greases Under Dynamic Wet Conditions (Emcor Test).
- D6208 TM for Repassivation Potential of Aluminum and Its Alloys by Galvanostatic Measurement
- D6294 TM for Corrosion Resistance of Ferrous Metal Fastener Assemblies Used in Roofing and Waterproofing
- D6594 TM for Evaluation of Corrosiveness of Diesel Engine Oil at 134 °C
- D7038 TM for Evaluation of Moisture Corrosion Resistance of Automotive Gear Lubricants
- D7095 TM for Rapid Determination of Corrosiveness to Copper from Petroleum Products Using a Disposable Copper Foil Strip
- D7583 TM for John Deere Coolant Cavitation Test
- D7667 TM for Determination of Corrosiveness to Silver by Automotive Spark-Ignition Engine Fuel-Thin Silver Strip Method
- E745 Practices for Simulated Service Testing for Corrosion of Metallic Containment Materials for Use With Heat-Transfer Fluids in Solar Heating and Cooling Systems
- E937 TM for Corrosion of Steel by Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members
- F897 TM for Measuring Fretting Corrosion of Osteosynthesis Plates and Screws
- F1089 TM for Corrosion of Surgical Instruments
- F1110 TM for Sandwich Corrosion Test
- F1111 TM for Corrosion of Low-Embrittling Cadmium Plate by Aircraft Maintenance Chemicals
- F1182 Spec for Anodes, Sacrificial Zinc Alloy
- F1875 Practice for Fretting Corrosion Testing of Modular Implant Interfaces: Hip Femoral Head-Bore and Cone Taper Interface
- F2129 TM for Conducting Cyclic Potentiodynamic Polarization Measurements to Determine the Corrosion Susceptibility of Small Implant Devices
- F2832 Guide for Accelerated Corrosion Testing for Mechanical Fasteners
- G1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
- G2 TM for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680 °F (360 °C) or in Steam at 750 °F (400 °C)
- G3 Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing
- G4 Guide for Conducting Corrosion Tests in Field Applications
- G5 Reference TM for Making Potentiodynamic Anodic Polarization Measurements
- G16 Guide for Applying Statistics to Analysis of Corrosion Data
- G28 Detecting Susceptibility to IGC in Wrought, Ni-Rich, Cr-bearing Alloys
- G34 TM for Exfoliation Corrosion Susceptibility in 2XXX and 7XXX Series Aluminum Alloys (EXCO Test)
- G52 Practice for Exposing and Evaluating Metals and Alloys in Surface Seawater
- G59 TM for Conducting Potentiodynamic Polarization Resistance Measurements
- G61 TM for Conducting Cyclic Potentiodynamic Polarization Measurements for Localized Corrosion Susceptibility of Fe-, Ni-, or Co-Based Alloys
- G66 TM for Visual Assessment of Exfoliation Corrosion Susceptibility of 5XXX Series Aluminum Alloys (ASSET Test)
- G67 TM for Determining the Susceptibility to IGC of 5XXX Series Aluminum Alloys by Mass Loss After Exposure to Nitric Acid (NAMLT Test)
- G69 TM for Measurement of Corrosion Potentials of Aluminum Alloys
- G96 Guide for Online Monitoring of Corrosion in Plant Equipment (Electrical and Electrochemical Methods)
- G97 TM for Laboratory Evaluation of Magnesium Sacrificial Anode Test Specimens for Underground Applications
- G100 TM for Conducting Cyclic Galvanostaircase Polarization
- G102 Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements
- G106 Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements
- G107 Guide for Formats for Collection and Compilation of Corrosion Data for Metals for Computerized Database Input
- G108 TM for Electrochemical Reactivation (EPR) for Detecting Sensitization of AISI Type 304 and 304L SS
- G111 Guide for Corrosion Tests in High-Temperature or High-Pressure Environment, or Both
- G112 Guide for Conducting Exfoliation Corrosion Tests in Aluminum Alloys
- G135 Guide for Computerized Exchange of Corrosion Data for Metals
- G157 Guide for Evaluating Corrosion Properties of Wrought Fe- and Ni-Based Corrosion-Resistant Alloys for Chemical Process Industries
- G158 Guide for Three Methods of Assessing Buried Steel Tanks

- G161 Guide for Corrosion-Related Failure Analysis
- G165 Practice for Determining Rail-to-Earth Resistance
- G170 Guide for Evaluating and Qualifying Oilfield and Refinery Corrosion Inhibitors in the Laboratory
- G184 Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using Rotating Cage
- G185 Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using the Rotating Cylinder Electrode
- G188 Spec for Leak Detector Solutions Intended for Use on Brasses and Other Copper Alloys
- G189 Guide for Laboratory Simulation of Corrosion Under Insulation
- G193 Terminology and Acronyms Relating to Corrosion
- G198 TM for Determining the Relative Corrosion Performance of Driven Fasteners in Contact with Treated Wood
- G199 Guide for Electrochemical Noise Measurement
- G205 Guide for Determining Corrosivity of Crude Oils
- G208 Standard Practice for Evaluating and Qualifying Oilfield and Refinery Corrosion Inhibitors Using Jet Impingement Apparatus
- G209 Standard Practice for Detecting mu-phase in Wrought Nickel-Rich, Chromium, Molybdenum-Bearing Alloys
- G210 Standard Practice for Operating the Severe Wastewater Analysis Testing Apparatus
- G215 Standard Guide for Electrode Potential Measurement
- G217 Standard Guide for Corrosion Monitoring in Laboratories and Plants with Coupled Multielectrode Array Sensor Method
- R0006 Condensed Metric Practice Guide for Corrosion (This is not an ASTM standard)

[ANSI/NACE/ISO]

- NACE RP0300/ISO 16784-1, Corrosion of metals and alloys – Corrosion and fouling in industrial cooling water systems – Part 1

[NACE/ASTM]

- NACE/ASTM G 193–2009, Standard Terminology and Acronyms Relating to Corrosion

[NACE]

- SP0291 Care, Handling, and Installation of Internally Plastic-Coated Oilfield Tubular Goods and Accessories
- RP0303 Field-Applied Heat-Shrinkable Sleeves for Pipelines: Application, Performance, and QC
- RP0392 Recovery and Repassivation After Low pH Excursions in Open Recirculating Cooling Water Systems
- RP0497 Field Corrosion Evaluation Using Metallic Test Specimens
- SP0106 Control of Internal Corrosion in Steel Pipelines and Piping Systems
- SP0169 Control of External Corrosion on Underground or Submerged Metallic Piping Systems
- SP0170 Protection of ASS and Other Austenitic Alloys from Polythionic Acid SCC During Shutdown of Refinery Equipment
- SP0176 Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production
- SP0177 Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems
- SP0189 On-Line Monitoring of Cooling Water Systems
- SP0192 Monitoring Corrosion in Oil and Gas Production with Iron Counts
- SP0195 Corrosion Control of Sucker Rods by Chemical Treatment
- SP0198 Control of Corrosion Under Thermal Insulation and Fireproofing Materials
- SP0199 Installation of Stainless Cr-Ni Steel and Ni-Alloy Roll-Bonded and Explosion-Bonded Clad Plate in Air Pollution Control Equipment
- SP0200 Steel-Cased Pipeline Practices
- SP0205 Design, Fabrication, and Inspection of Tanks for the Storage of Petroleum Refining Alkylation Unit Spent Concentrated Sulfuric Acid at Ambient Temperatures
- SP0206 Internal Corrosion Direct Assessment Methodology for Pipelines Carrying Normally Dry Natural Gas (DG-ICDA)
- SP0207 Performing Close-Interval Potential Surveys and DC Surface Potential Gradient Surveys on Buried or Submerged Metallic Pipelines
- SP0273 Handling and Proper Usage of Inhibited Oilfield Acids
- SP0285 Corrosion Control of Underground Storage Tank Systems by Cathodic Protection
- SP0286 Electrical Isolation of Cathodically Protected Pipelines
- SP0287 Field Measurement of Surface Profile of Abrasive Blast-Cleaned Steel Surfaces Using a Replica Tape
- SP0292 Installation of Thin Metallic Wallpaper Lining in Air Pollution Control and Other Process Equipment
- SP0294 Design, Fabrication, and Inspection of Tanks for the Storage of Concentrated Sulfuric Acid and Oleum at Ambient Temperatures
- SP0296 Detection, Repair, Mitigation of Cracking of Refinery Pressure Vessels in Wet H_2S Environments
- SP0304 Design, Installation, and Operation of Thermoplastic Liners for Oilfield Pipelines
- SP0387 Metallurgical and Inspection Requirements for Cast Galvanic Anodes for Offshore Applications
- SP0391 Materials for the Handling and Storage of Commercial Concentrated (90–100%) Sulfuric Acid at Temperatures
- SP0407 Format, Content, and Guidelines for Developing a Materials Selection Diagram (MSD)
- SP0487 Considerations in the Selection and Evaluation of Rust Preventives and VCI for Interim (Temporary) Corrosion Protection

- SP0491 Worksheet for the Selection of Oilfield Nonmetallic Seal Systems
- SP0492 Metallurgical and Inspection Requirements for Offshore Pipeline Bracelet Anodes
- SP0499 Corrosion Control and Monitoring in Seawater Injection Systems
- SP0502 Pipeline External Corrosion Direct Assessment Methodology
- SP0507 External Corrosion Direct Assessment (ECDA) Integrity Data Exchange (IDX) Format
- SP0508 Methods of Validating Equivalence to ISO 8502-9 on Measurement of the Levels of Soluble Salts
- SP0572 Design, Installation, Operation, and Maintenance of Impressed Current Deep Anode Beds
- SP0590 Prevention, Detection, and Correction of Deaerator Cracking
- SP0775 Preparation, Installation, Analysis, and Interpretation of Corrosion Coupons in Oilfield Operations
- TM0172 Determining Corrosive Properties of Cargoes in Petroleum Product Pipelines
- TM0177 Laboratory Testing of Metals for Resistance to SSC and SCC in H_2S Environments
- TM0187 Evaluating Elastomeric Materials in Sour Gas Environments
- TM0190 Impressed Current Laboratory Testing of Aluminum Alloy Anodes
- TM0192 Evaluating Elastomeric Materials in CO_2 Decompression Environments
- TM0194 Field Monitoring of Bacterial Growth in Oil and Gas Systems
- TM0197 Laboratory Screening Test to Determine the Ability of Scale Inhibitors to Prevent the Precipitation of Barium Sulfate and/or Strontium Sulfate from Solution (for Oil and Gas Production Systems)
- TM0198 Slow Strain Rate Test Method for Screening CRAs for SCC in Sour Oilfield Service
- TM0199 Standard Test Method for Measuring Deposit Mass Loading (Deposit Weight Density) Values for Boiler Tubes by the Glass-Blasting Technique
- TM0208 Laboratory Test to Evaluate the Vapor-Inhibiting Ability of VCI Materials for Temporary Protection of Ferrous Metal Surfaces
- TM0296 Evaluating Elastomeric Materials in Sour Liquid Environments
- TM0297 Effects of High-Temperature, High-Pressure CO_2 Decompression on Elastomeric Materials
- TM0298 Evaluating the Compatibility of FRP Pipe and Tubulars with Oilfield Environments
- TM0374 Laboratory Screening Tests to Determine the Ability of Scale Inhibitors to Prevent the Precipitation of Calcium Sulfate and Carbonate from Solution (for Oil and Gas Production Systems)
- TM0397 Screening Tests for Evaluating the Effectiveness of Gypsum Scale Removers
- TM0498 Evaluation of the Carburization of Alloy Tubes Used for Ethylene Manufacture

[Others]

- AWS PRGC The Practical Reference Guide for Corrosion of Welds – Causes and Cures

[Most Common Standards for Corrosion Test]

- Copper Sulfate Test for free iron/iron-oxides contamination detecting, passivation condition of SS with Cr > 16%: Copper film is immediately visible per ASTM A380, A967, F1089 (for surgical instruments), and MIL-STD-753, Rev. C, Method 102
- Detecting Detrimental Intermetallic Phase in DSS – ASTM A923
- Ferroxyl Test (hypersensitive test) for iron/iron-oxide contamination detection on SS: Blur color appears per ASTM A380, A967
- Galvanic Corrosion Test – ASTM G71 and G82
- Hydrogen-Induced Cracking (HIC) Test – NACE TM0284
- Intergranular Corrosion (IGC) Test – ASTM A262 (for ASS), A763 (for FSS)
- Mo (molybdenum) Detecting Test on SS: ASTM STP 550, PMI machine, or Use MolyTester accepted by TÜV, Lloyds, Veritas, etc.
- Nondestructive Rapid Identification of Metals and Alloys by Spot Test: ASTM STP 550
- Pitting and Crevice Corrosion Test – ASTM G48
- Salt Spray Test – ASTM A967, B117
- Stress Corrosion Cracking (SCC) Test – ASTM G30/G35/G36/G38/G 39/G44/G49/G58, NACE TM0198
- Sulfide Stress Corrosion Test (SSC) – NACE TM0177
- Zinc Contamination Check on Stainless Steels – NACE Paper 14–3993 with NACE TM0198/0177 and ASTM G39

2.4.5 Erosion, Abrasion, Adhesive Wear, and Friction

2.4.5.1 Definition

Erosion, abrasion, adhesive wear, fretting, and friction create physical metal loss not only by particles flow patterns velocity and impinging angle, surface roughness, galling, time and temperature, etc., but also by a combination of corrosion and physical friction forces (Fig. 2.179).

Table 2.145 shows the comparison of erosion, abrasion, and adhesive wear (galling), and the countermeasures.

See Sect. 2.6.2.5 ASTM A532 and A932 for abrasion-resistant cast irons.

See Sect. 2.1.7.7 for hardfacing alloys to avoid the erosion, abrasion, and adhesive wearing.

2.4.5.2 Major Factors Affecting Erosion-Corrosion in Piping, Pipelines, and Tubes

(a) Effect of Service Velocity/Flow Pattern-Service Phase.

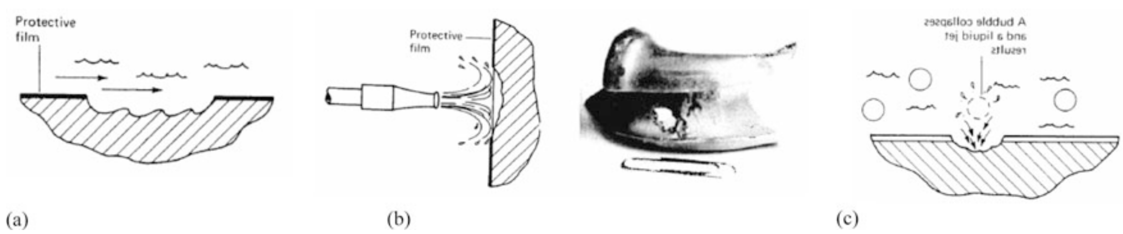


Figure 2.179 Types of typical erosion corrosion. (**a**) Typical Erosion pattern by service flow. (**b**) Erosion corrosion by impinging angle. (**c**) Erosion corrosion by cavitation

Table 2.145 Comparison of erosion vs. abrasion vs. adhesive wear (galling)

Erosion	Abrasion	Adhesive wear (fretting or galling)
[Definition and description] Defined as the removal of material from a solid surface by the abrasive action of moving fluids. Solid particles, liquid droplets, or cavitation can induce these forces. Erosion occurs when solid particles, liquid droplets, or a liquid jet (high velocity & turbulent flow, high Reynolds number) creates impingement on the solid surface. In a ductile metal, the maximum erosion by solid particle impingement occurs at an impingement angle of approximately 20°. The erosion of brittle material is maximum at 90°. Cavitation is a form of erosion and arises when a solid and a fluid are in relative motion and bubbles formed in the fluid become unstable and implode against the surface of the solid. In the oil and gas industry, erosion-corrosion in which joint action involving corrosion and erosion occurs with corrosive gas/liquid flow that contains solids (sands) is typically experienced. The erosive wear depends on the number of impinging particles, average particle mass, impingement velocity, angle of impingement, and characteristics of the surface. **[Countermeasures]** Generally controlled or minimized by reducing fluid velocity, material selection, or material coatings and altering the angle of contact (avoiding angles or obtrusions into the flow stream that could result in turbulent flow). API RP14E requires meeting the maximum erosional velocity for offshore production platform piping systems which are also used in onshore piping systems.	**[Definition and description]** A process by which hard particles or protuberances are forced against and moved along a solid surface. Abrasive wear results from a cutting action by a rough, hard surface sliding against a softer surface or by contaminant hard particles trapped between the sliding surfaces. Erosive wear by abrasive erosion is caused by the relative motion of solid particles, which are entrained in a fluid, moving nearly parallel to a solid surface. This kind of wear can be experienced with sandy fluids. **[Countermeasures]** Similar to erosive wear, abrasive wear is typically controlled or minimized through the use of coatings, altering the angle of contact, base material, and fluid velocity. Unlike erosive wear, abrasive wear is most severe at angles close to 90° and least severe at angles approaching 0°. Also, for homogeneous materials, abrasive wear resistance is likely to be proportional to the hardness of the surface at hardness levels lower than that of the abrasive constituent; the wear rate decreases dramatically as the surface hardness surpasses the hardness of the abrasive constituent. This indicates that the abrasive wear is decreased through the use of harder materials and hard surfacings.	**[Definition and description]** Often called galling or fretting. It is caused by localized bonding between contacting solid surfaces, leading to material transfer between the two surfaces or loss from either surface. Some particles during galling or fretting may become embedded in the surfaces. When two surfaces are bonded together, the contacting asperities may form a strong bond due to the extremely high localized pressure and heat generated by subsequent motion. If these bonds sever at the interface, little damage occurs and the parts run smoothly. However, if fracture takes place in either material, gross damage—galling—results. **[Countermeasures]** Adhesive wear is the loss of material occurring when two surfaces in intimate contact locally bond together and a volume of metal is transferred from one surface to the other when the surfaces are subsequently torn apart by relative movement. Particles that are removed can be temporarily or permanently bonded to the new surface. Because adhesive wear occurs through intimate contact of surfaces, it is often dramatically reduced by the presence of a separating layer or by minimizing contact stresses. Lubricants, such as oils, grease, or specially designed polymeric solid films, act as separating layers while reducing friction and contact stresses. Generally, smooth surfaces are more susceptible to adhesive wear than rough surfaces, and adhesive wear is more severe when the two materials involved are of similar chemistry and hardness. Therefore, abrasive blasting and/or the application of soft metallic coatings such as silver or copper have been effective at reducing adhesive wear.

Source: NACE Publ. 1F192 modified

When stream flows, it creates a shear on the inside wall of pipes. This shear removes small chips from pipe wall, causes metal loss, and decreases the lifetime of the pipe. This shear will be higher if the fluid denser (lower density) and/or fluid carries some eroding material like sand. Softened metal surfaces may be more susceptible to erosion.

Maximum erosion velocity (*Ve, ft/sec*) for metal (continuous flow) in solid free fluids (gas-liquid phases) which is related with flow accelerated corrosion (FAC) can be simplified as below where no specific information as to the erosive/corrosive properties of the fluid is available:

$Ve = \mathrm{C}/(\sqrt{\text{mixture density}})$ in ft/sec as a function of metals and bulk density.

where mixture density (ρ_m) is in lb/ft^3.

Conditions (per API RP14-E) in solids-free	*C*	Remark (ρ_m)
Continuous service for CS & LAS	100	$\rho_m = \frac{M_L + M_G}{[(M_L + \rho_L)] + [(M_G + \rho_G)]}$ M_L: Liquid mass flow rate, lb/hr M_G: Gas mass flow rate, lb/hr ρ_L: Liquid density, lb/ft^3 ρ_G: Gas density, lb/ft^3
Intermittent service for CS & LAS	125	
Corrosion is not anticipated, or use of corrosion-resistant alloys (SS or Ni alloys), or corrosion inhibitor, continuous service	150–200	
Corrosion is not anticipated, or use of corrosion-resistant alloys (SS or Ni alloys), or corrosion inhibitor, intermittent service	250	

Notes: source: API RP14E-modified
(1) "C" in Some Company Standards;
150–200 for noncorrosive fluid,
125–250 for corrosive and noncorrosive fluid with Intermittent flow,
300 for noncorrosive fluid, 13Cr steel & ASS,
350–450 for noncorrosive fluid, 2205 DSS
(2) Where solids and/or corrosive contaminants are present or where "C" values higher than 100 for continuous service are used, periodic surveys to assess pipe wall thickness should be considered.
(3) Typical erosion-corrosion rate in seawater with various velocities (Fig. 2.180)
(4) See API RP14E for Erosion velocity chart per gas/liquid ration (ft^3/barrel), operating pressure (psia), and pipe inside cross section area (inch^2/1000) under some specific condition

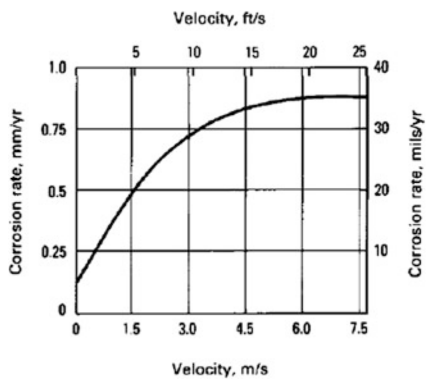


Figure 2.180 Typical erosion-corrosion rate of CS in seawater with various velocities. (Source: API RP14E)

Vapor Velocity Criteria: The recommended linear velocity for hydrocarbon vapor lines is max. 18 m/s (60 ft/s) (some companies permit up to 23 m/s (75 ft/s)). The recommended maximum allowable velocity in pressurized overhead lines, compressor and transfer lines of gas phase is typically 30 m/s (100 ft/s).

Meanwhile, typical service velocity ranges for CS pipe sizing to avoid erosion corrosion and dead-leg corrosion are shown in Table 2.146.

(b) Effect of particle size/hardness/density/velocity

As increase the particle size, hardness, density, and velocity, erosion rate in hydrocarbon process fluids remarkably increases as seen in Figs. 2.181 and 2.182. See Table 2.124 as well.

Figure 2.182 indicates the wear energy (metal loss) had the following relations.

Wear Energy (Metal Loss) = Velocity $\times$ 2^{Density}

Figures 2.183 and 2.184 show the impingement and nonimpingement velocity limit curves for oxygen piping/pipelines. These curves can be used for line sizing for the utility gas fluids. The impingement and nonimpingement areas may be defined as below.

Table 2.146 Typical erosion-corrosion rate of CS in seawater with various velocity[(1),(2)]

Nominal pipe size (NPS, inches)	Recommended velocity range, m/sec (ft/sec) in liquid flow
1	0.9–1.5 (3–5)
1.5	1.1–1.7 (3.5–5.5)
2	1.2–2.1 (4–7)
3	1.5–2.4 (5–8)
4	1.8–3.0 (6–10)
6	2.4–3.7 (8–12)
8	2.4–3.7 (8–12)
≥10	3.0–3.7 (10–12)

source: API RP14E
Notes:
(1) Velocity limitation for severe corrosion environments: See Table 2.173m
Velocity limitation for copper alloys: See Table 2.80 and Fig. 2.97
(2) Recommended pressure drop (psi/1000 ft): max. 30–45 except 25–38 for NPS 8 and 20–30 for NPS 10 and larger

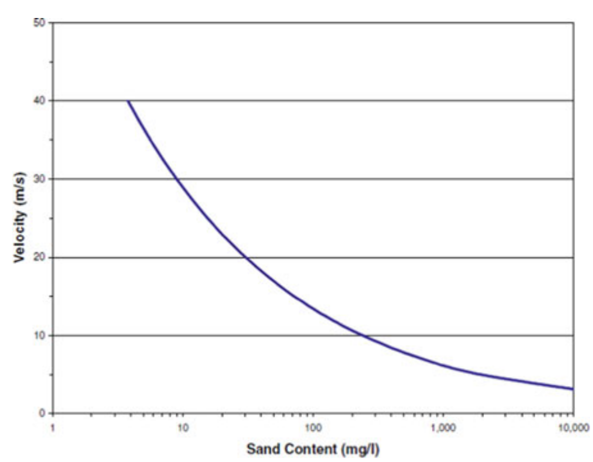


Figure 2.181 A sample of Conservative velocities for Zeron 100 (25Cr-7Ni-3.5Mo-0.7W) in process fluids with Sands Bitumen. (Source: Rolled Alloys Technical Report for Erosion Corrosion Reisstance of Zeron 100, 2006)

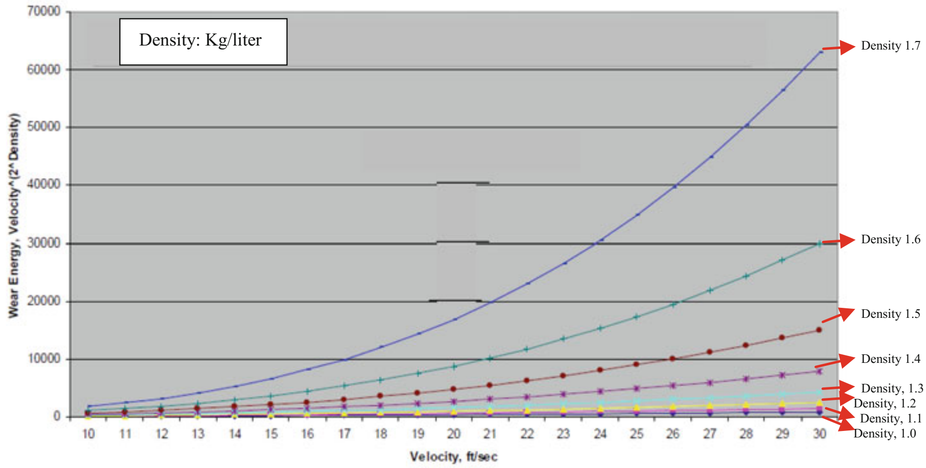


Figure 2.182 Wear energy (metal loss) per density & velocity of Canadian oil sands bitumen

Impingement areas (typical)	Nonimpingement areas (typical)
– Tees, both butt weld and socket-weld and socket-weld elbows – Branch connections such as fabricated branches, weldolets, sockolets, and threadolets – Multiple-hole diffusers and surrounding body – Short-radius elbows (radius of curvature <1.5 × diameter) – Socket-weld and threaded reducers – Reducers (eccentric and concentric) with greater than 3:1 inlet to outlet reduction section ratio (for flow from large to small) – Mitered elbows (mitered cut angle more than 20°) – Piping downstream of a pressure letdown valve up to a length of NPS 8 pipe diameters (pipe diameters can be based on valve outlet size) – Valves – Conical strainers and Y strainers – Filters – Orifices plates – Noise reduction, silencers – Max. particle size: 150 microns – Other accessories, thermowells, etc.	– Straight piping runs – Butt-weld tees, with long (or smooth) crotch radius (for flow from main to branch) – Long radius diameter elbows (equal or greater than 1.5 × diameter) – 90-degree mitered elbows made of 6 pieces (5 welds) as well as 45-degree mitered elbows made of 3 pieces (2 welds), providing that all internal surfaces are ground smooth – Particle size: >150 microns – Eccentric and concentric reducers with a maximum 3–1 reduction ratio.

References for Effect of Particle's Size/ Hardness/ Density/Velocity in Two Phase Fluids with/without Particles.
; API RP14E, DNV RP O501, EIGA IGC Doc 13/12/E, NACE Paper 02498, NACE Corrosion Vol.45, No.10, p793-804 (1989), NACE Corrosion Vol.16, No.2, p86t-92t (1960), NASA Technical Paper 1755 (1981), ASM Metal Handbook, Vol.13

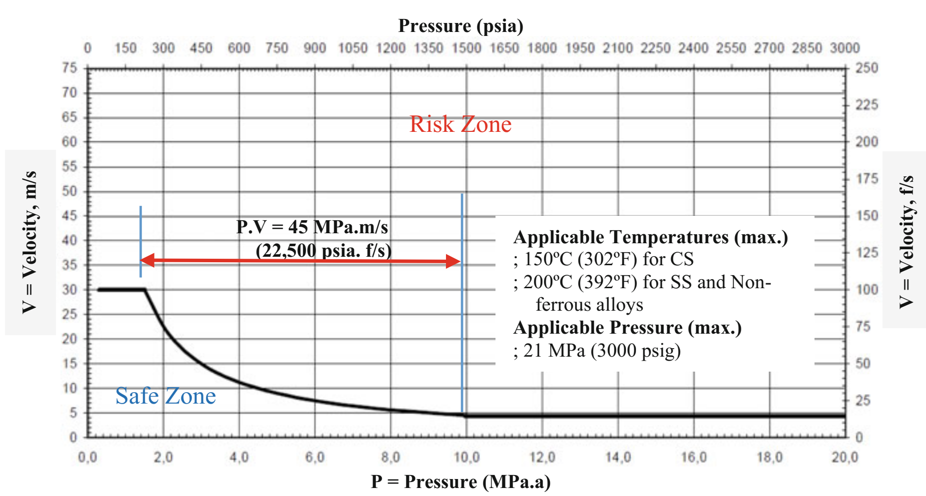


Figure 2.183 Impingement velocity limit curve for oxygen piping/pipelines. (Source EIGA IGC Doc 13/12/E-2012)

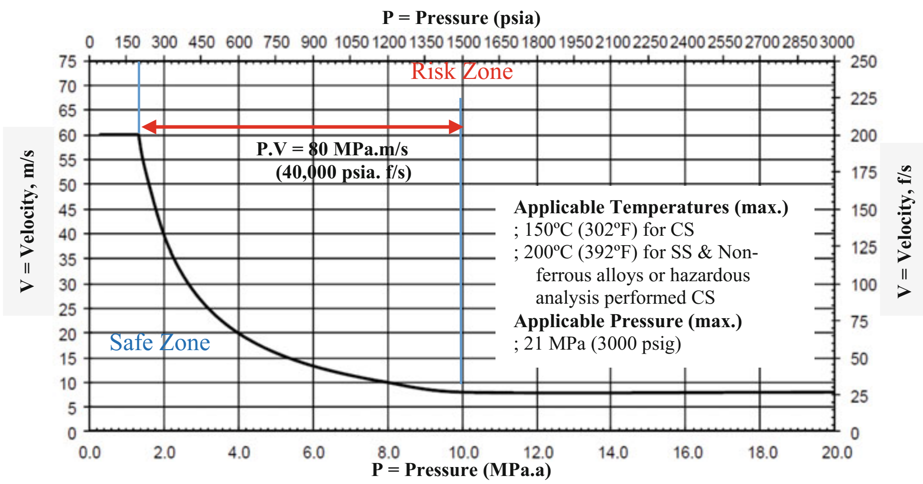


Figure 2.184 Nonimpingement velocity limit curve for oxygen piping/pipelines. (Source EIGA IGC Doc 13/12/E-2012)

(c) Geometry Effect – Impinging Angle (e.g., 45°, 80°, 180° bend)
Figure 2.185 shows the typical trend of metal loss for typical ductile and brittle materials per the impinging angle in piping. Ductile materials have a peak angle at 40 deg, while brittle materials show the continuously raised metal loss per the impinging angle.

(d) Effect of Surface Roughness and Tubular Pipe Size – Wall Shear Stress, Moody Diagram
Figure 2.186 shows the relative roughness of several piping materials [(a) conventional relative roughness of Several pipes, (b) Farshad's new relative surface roughness per piping ID], and (c) Moody Diagram for friction factor (f), Reynolds numbers ($Re = \rho VD/\mu = VL/\nu$), relative roughness (e/D). The friction factor may be also calculated by the following formulas.

; $f = 64/Re$ for $Re \leq 2100$ (laminar flow)

; $f = 1.325/[\ln(e/3.7D + 5.74/Re^{0.9})]^2$ for $5000 < Re \leq 10^8$ (turbulent flow) and $10^{-6} \leq e/D \leq 10^{-2}$.

; $f = 0.001375 \times [1 + \{20{,}000 \times e/D + 1{,}000{,}000 \times \mu/(\rho \times V \times D)\}^{0.33}]$ in wet CO_2 (carbonic acid) circuit

Pipe wall shear stress (τ) by fluid may be calculated from friction factor, fluid velocity, fluid density, dynamic viscosity, etc., as below:

$$; \tau = \frac{f \rho V^2}{2}$$

e = roughness (mm), D = Pipe ID (mm), V = fluid velocity (m/s), ρ = fluid density (kg/m^3),

μ = dynamic viscosity (Pa.s or kg/m.s), L = pipe length (m), ν = kinetic viscosity (m^2/s)

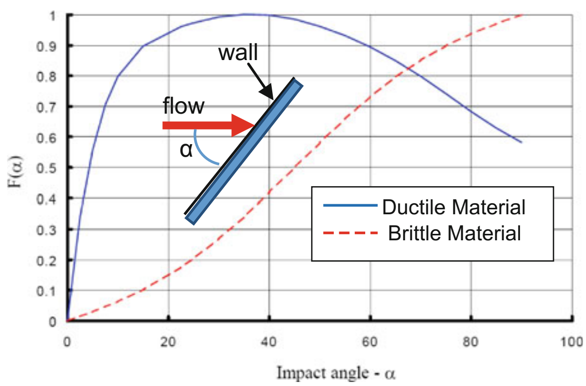


Figure 2.185 Metal loss [F(α) ≈ erosion wear] for typical ductile and brittle materials. (Source: DNV RP O501)

The calculated shear stress on the internal surface of a pipe may be used in the evaluation of fluid-velocity-related corrosion-erosion rate. A higher roughness on the pipe increases the shear stress. As a result, erosion-corrosion will be greatly increased. See 3.4.5 (1) for the details on metal surface finish. This shear stress is also a key factor for wet CO_2 corrosion severity (higher shear stress, higher wet CO_2 corrosion).

(e) Effect of Cavitation
Cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. Cavitation damage is a form of a localized attack found on many types of materials exposed to turbulent flow rates of liquids. Although mainly mechanical in nature, this type of damage is more severe in mediums where the cavitation mechanism acts synergistically with corrosion. The mechanical action of cavitation usually attacks protective surfaces, exposing unprotected surfaces to corrosion. Cavitation is often defined as the growth and collapse of vapor bubbles because of local pressure fluctuations in a liquid. If the pressure suddenly falls below the vapor pressure, these bubbles then collapse violently when they are submitted to a higher pressure (Figs. 2.179c and 2.187). This collapse is accompanied by the sudden flow of liquid, which imposes stress pulses capable of causing plastic deformation on solid surfaces.

Cavitation can be confirmed with the aid of hydrodynamic analysis, which is used to minimize and locate the formation of bubbles or shift the bubble collapse to a certain area where there will be a minimal effect.

There are only a few standard tests (e.g., ASTM G32 Cavitation Erosion Using Vibratory Apparatus & ASTM D2809 Cavitation Corrosion and Erosion-Corrosion Characteristics of Aluminum Pumps with Engine Coolants) for this type of corrosion, and hence this can be avoided through experience, process control, and actual scale tests. A cavitation index which is the ratio of the pressure differential between the equipment inlet pressure and the fluid vapor pressure to the pressure differential pressure across the equipment may be used for evaluation (See NACE Paper 98683 for cavitation index).

Metal loss rates (as mg) after 24 hours due to cavitation erosion of typical hydraulic equipment materials in "Avoid Cavitation Damage" reported by W.J. Rheingans are shown below.

: Rolled Stellite (0.6) < Welded aluminum bronze (3.2) < Cast aluminum bronze (5.8) < Welded 17Cr-7Ni SS-2 layers (6) < Hot rolled 26Cr-12Ni SS (8) < Tempered rolled 12Cr SS (9) < Cast 18Cr-8Ni SS (13) < Cast 12Cr SS (20) < Cast manganese bronze (80) < welded mild CS (97) < Plate CS (98.0) < Cast steel (105) < Aluminum (124) < Brass (156) < Cast iron (224)

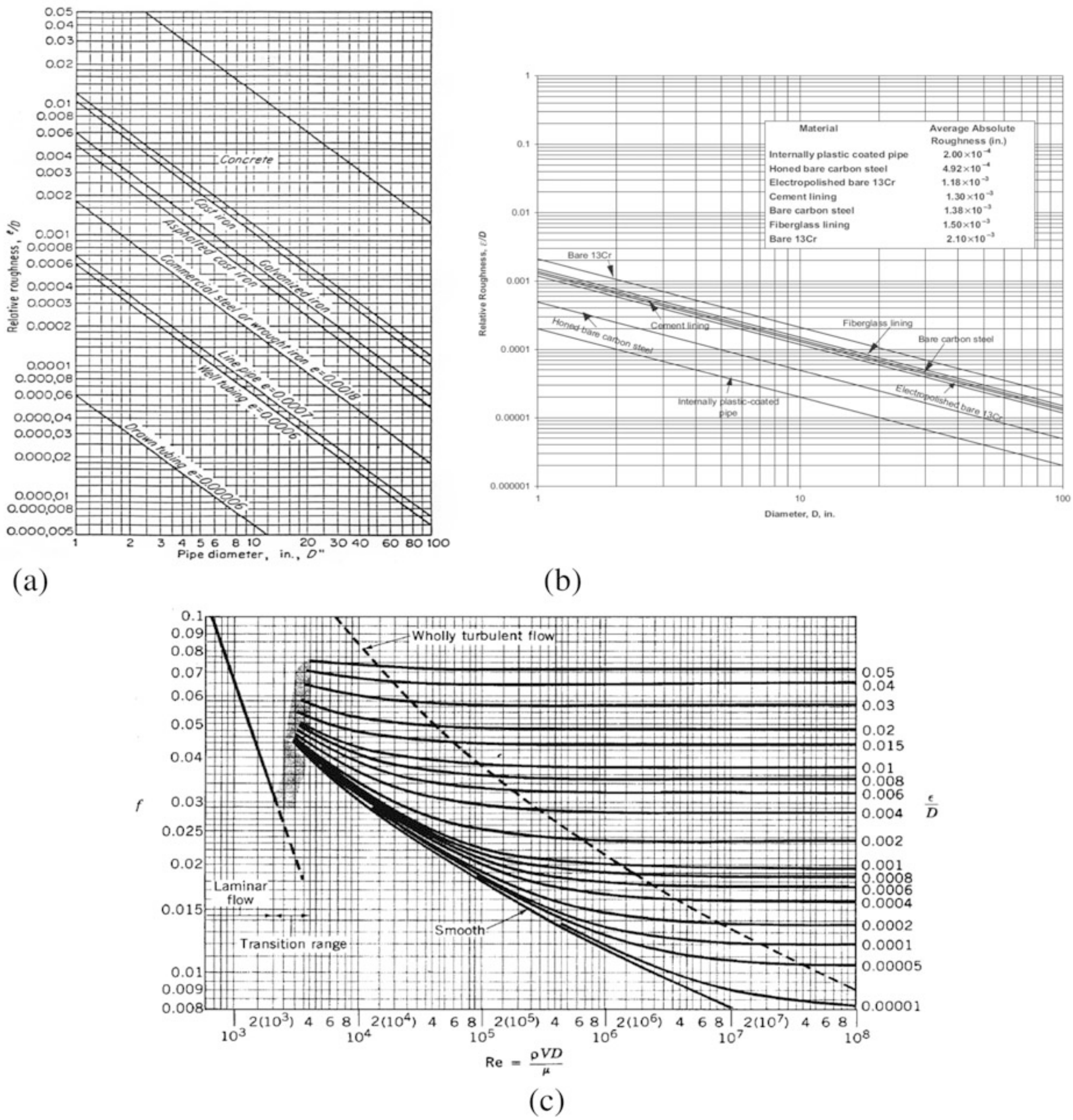


Figure 2.186 Moody diagram for friction factor, Reynolds numbers, and relative roughness. (**a**) Conventional relative roughness of several pipes. (**b**) Farshad's new relative surface roughness per piping ID (nonlinear mathematical models). (**c**) Moody diagram

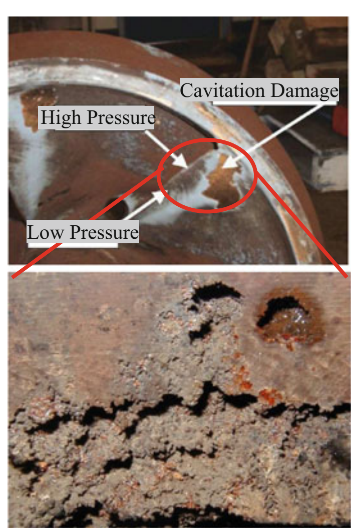


Figure 2.187 A sample of cavitation corrosion of pump impeller

2.4.5.3 Erosion Prevention-Hardfacing of Valve Trims

(a) Hardfacing Materials
13Cr, Hard 13Cr, Ni-Cr, Cr-Ni, Stellite, Triballoy, Deloro, Nistelle, Delchrome, Stelcar, Jet Kote, Talonite, etc. may be used for hardfacing materials on the base metal. See Sect. 2.1.7.7 for hardfacing alloys and Table 2.109 for valve trim of hardfacing (API 600 gate valves) for more details.
(b) Application types of Hardfacing (Typical)
1. Fusion Welding
2. Metallizing
   – Wire Spray
   – Power Spray
   – Electric Arc Spray
3. Thermal Spray
   – Plasma Coating
   – Plasma Transfer Arc (PTA) Coating
   – HVOF (High Velocity Oxygen Fuel)

(c) Materials and Hardfacing of Valve Trims: See Table 2.108, 2.109, 2.110, and 2.111.

References, Standards, and Guidelines for Erosion-Corrosion

- API RP14E Design and Installation of Offshore Production Platform Piping Systems
- API RP571, 4.2.14 (erosion) and 4.2.15 (cavitation)
- ASTM A532 Abrasion-Resistant Cast Irons
- ASTM A942 Centrifugally Cast White Iron and Gray Iron Dual Metal Abrasion-Resistant Roll Shells
- ASTM B611 Abrasive Wear Resistance of Cemented Carbides
- ASTM C131 TM for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the LA Machine
- ASTM D2809 TM for Cavitation Corrosion and Erosion-Corrosion Characteristics of Aluminum Pumps with Engine Coolants
- ASTM F897 TM for Measuring Fretting Corrosion of Osteosynthesis Plates and Screws
- ASTM G32 TM for Cavitation Erosion Using Vibratory Apparatus
- ASTM G40 Terminology Relating to Wear and Erosion
- ASTM G56 TM for Abrasiveness of Ink-Impregnated Fabric Printer Ribbons and Other Web Materials
- ASTM G65 TM for Measuring Abrasion Using the Dry Sand and Rubber Wheel Apparatus
- ASTM G73 TM for Liquid Impingement Erosion Using Rotating Apparatus
- ASTM G75 TM for Determination of Slurry Abrasivity (Miller No) and Slurry Abrasion Response of Materials (SAR No)
- ASTM G76TM for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets
- ASTM G77 TM for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test
- ASTM G81 TM for Jaw Crusher Gouging Abrasion Test
- ASTM G98 TM for Galling Resistance of Materials
- ASTM G99 Wear Testing with a Pin-on-Disk Apparatus
- ASTM G105 TM for Conducting Wet Sand/Rubber Wheel Abrasion Tests
- ASTM G119 Guide for Determining Synergism between Wear and Corrosion
- ASTM G115 Guide for Measuring and Reporting Friction Coefficients
- ASTM G119 Guide for Determining Synergism Between Wear and Corrosion
- ASTM G132 TM for Pin Abrasion Testing
- ASTM G133 TM for Linearly Reciprocating Ball-on-Flat Sliding Wear
- ASTM G134 TM for Erosion of Solid Materials by Cavitating Liquid Jet
- ASTM G143 TM for Measurement of Web/Roller Friction Characteristics
- ASTM G164 TM for Determination of Surface Lubrication on Flexible Webs
- ASTM G171 TM for Scratch Hardness of Materials Using a Diamond Stylus
- ASTM G174 TM for Measuring Abrasion Resistance of Materials by Abrasive Loop Contact
- ASTM G176 TM for Ranking Resistance of Plastics to Sliding Wear Using Block-on-Ring Wear Test – Cumulative Wear Method
- ASTM G181 TM for Conducting Friction Tests of Piston Ring and Cylinder Liner Materials Under Lubricated Conditions
- ASTM G182 TM for Determination of the Breakaway Friction Characteristics of Rolling Element Bearings
- ASTM G194 TM for Measuring Rolling Friction Characteristics of a Spherical Shape on a Flat Horizontal Plane
- ASTM G195 Guide for Conducting Wear Tests Using a Rotary Platform Abraser
- ASTM G196 TM for Galling Resistance of Material Couples
- ASTM G203 Guide for Determining Friction Energy Dissipation in Reciprocating Tribosystems
- ASTM G204 TM for Damage to Contacting Solid Surfaces under Fretting Conditions
- ASTM G206 Guide for Measuring the Wear Volumes of Piston Ring Segments Run against Flat Coupons in Reciprocating Wear Tests
- ASTM G211 TM for Conducting Elevated Temperature Erosion Tests by Solid Particle Impingement Using Gas Jets
- NACE SP0298, Sheet Rubber Linings for Abrasion and Corrosion Service
- NACE Paper **18**-10883/ **17**-8931/ **16**-7377/ **15**-5582/ 14-4092/ **14**-3803/ **13**-2322/2201, 12751, 11415/11005, 10392, 09184, 07253, 04125/04522/04659/04660, 03247, 02209, 01513/01458/01162, 00637, 98059/98193, 96514/ 96497, 95283, 94404, 92300, 89508
- NACE MP p50-53 Dec. 2007, NACE MP p46-50 Feb. 2012, NACE MP p56-59 Jan. 2010, NACE MP p42-45 Nov. 2001
- Graeme Addie et al., Slurry Pump Wear Factors, ASME Fluids Engineering Division summer meeting, 1996

– Uhlig's Corrosion Handbook-Erosion Corrosion in Single and Multiphase Flow
– JFE EverhardTM Catalog for Abrasion-Resistant Steel Plate
– DNV RP O501 Erosion Wear in Piping Systems
– EIGA IGC Doc 13/12/E Oxygen Pipeline and Piping Systems

2.5 Test Reports (MTR) and Positive Materials Identification (PMI)

2.5.1 Material Identification and PMI Requirements

2.5.1.1 Material Identification for Traceability

Material identification provides "proof positive" verification to keep correct design and fabrication with safety.

Material identification is also particularly important in failure investigations, to rule out product malfunction, and identify components of the same material stock. MTR or CMTR (certified mill test report) is required not only for all pressure-retaining components in boilers, pressure equipment, and piping/instruments, but also for structures of loaded parts. The inspection and review for the MTR (or CMTR) and the raw materials shall be done before marking and cutting of the raw materials. The CMTR is a test report where there is specific reference to the tests being conducted on the actual material supplied while the MTR is a report documenting the results of tests performed to fulfill the basic requirements in the material specification. The CMTR may contain results of some or all of the tests required for classification, or other tests as agreed upon by the purchaser and supplier.

The following information are in the MTR and the critical data are also stamped on the material surface.

- Heat No. and Lot No.
- Materials Class (code number with grade, class, or type)
- Size (thickness, length, schedule, etc.)
- Chemical Composition, Carbon Equivalent, and Other Specific Elements (if required)
- Mechanical Properties (T.S, Y.S, elongation, bend test, hardness, etc.)
- Heat Treatment Records (Normalizing, Quenching, and Tempering, etc., if required)
- Impact Test Results (if required)
- Physical Data (if required)
- Corrosion Test Records (if required)
- NDE Test Results (if required)

ASME Sec. VIII, Div.1, UG-77 (Material Identification) for Pressure vessel states that:

(a) Material for pressure parts preferably should be laid out so that when the vessel is completed, one complete set of the original identification markings required by ASME Sec. VIII, Div.1, UG-94 will be plainly visible. The pressure vessel manufacturer shall maintain traceability of the material to the original identification markings by one or more of the following methods: accurate transfer of the original identification markings to a location where the markings will be visible on the completed vessel; identification by a coded marking traceable to the original required marking; or recording the required markings using methods such as material tabulations or as built sketches which assure identification of each piece of material during fabrication and subsequent identification in the completed vessel. Such transfers of markings shall be made prior to cutting except that the manufacturer may transfer markings immediately after cutting provided the control of these transfers is described in his written QC System (see ASME Sec. VIII, Div.1, 10-6). Except as indicated in (b) below, material may be marked by any method acceptable to the Inspector. The Inspector need not witness the transfer of the marks but shall satisfy himself that it has been correctly done (see Div.1, UHT-86).
(b) Where the service conditions prohibit die-stamping for material identification, and when so specified by the user, the materials manufacturer shall mark the required data on the plates in a manner which will allow positive identification upon delivery. The markings must be recorded so that each plate will be positively identified in its position in the completed vessel to the satisfaction of the Inspector. Transfer of markings for material that is to be divided shall be done as in (a) above.
(c) When material is formed into shapes by anyone other than the Manufacturer of the completed pressure vessel, and the original markings as required by the applicable material specification are unavoidably cut out, or the material is divided into two or more parts, the manufacturer of the shape shall either:
    1. Transfer the original identification markings to another location on the shape; or
    2. Provide for identification by the use of a coded marking traceable to the original required marking, using a marking method agreed upon and described in the quality control system of the Manufacturer of the completed pressure vessel. Identification in accordance with ASME Sec. VIII, Div.1, UG-93, in conjunction with the above modified marking requirements, shall be considered sufficient to identify these shapes. Manufacturer's Partial Data Reports and parts stamping are not a requirement unless there has been fabrication to the shapes that include welding, except as exempted by ASME Sec. VIII, Div.1, UG-11.

ASME Sec. VIII, Div.2, Annex 6-A states the Positive Material Identification Practice.

2.5.1.2 Material Traceability

Traceability means the ability to identify a specific piece of steel in a structure, throughout the life of the structure, and its certified Mill Test Report (MTR). As such, traceability requirements are significantly more expensive than the identification requirements above.

Traceability must be clearly specified in the contract documents prior to the ordering of material. The following elements of traceability should be selected only as needed:

(a) Lot traceability vs. piece-mark traceability vs. piece traceability: Lot traceability means that the materials used in a given project can be traced to the set of MTRs for that project. Piece-mark traceability means that the heat number can be correlated for each piece mark, of which there can be many individual pieces. Piece traceability means that the heat number can be correlated for each piece, which effectively demand separate piece marks for each piece. Each of these three successive levels of traceability adds significant costs. Piece traceability, the most expensive option, is necessary only in critical applications, such as the construction of a nuclear power facility. Piece-mark traceability is often specified for main members in bridges. Lot identification is most common in other applications where traceability is required.
(b) Main-material traceability vs. all-material traceability: Main-material traceability means that beams, columns, braces, and other main structural members are traced as specified above. All-material traceability means that connection and detail materials are also traced as specified above. All-material traceability, the more expensive option, is necessary only in critical applications, such as the construction of a nuclear power facility. In other cases, main-material traceability is sufficient, when traceability is a requirement.
(c) Consumables traceability means that lot numbers for consumables such as bolts, welding electrodes, and paint can be traced. This is necessary only in critical applications, such as construction of a nuclear power facility.
(d) Required record retention defines the level of detail required in documenting traceability (who, what, when, where, how, etc.).
(e) Fool-proof record retention vs. fraud-proof record retention: Fool-proof record retention means internal verification of records. Fraud-proof record retention means external certification of records. Fraud-proof record retention is necessary only in critical applications, such as the construction of a nuclear power facility. In other cases, foolproof record retention is sufficient, when traceability is a requirement.

2.5.1.3 PMI (Positive Materials Identifications) Specification

(a) Intent

PMI (Fig. 2.188) involves NDE or physical testing to ensure the materials, products, weld overlay surfaces, and welding filler metals for fixed equipment (normally) and pipings. Some customers specify the reporting methods as well as the location, number, and time (e.g., before/after welding, before/after PWHT) of sampling in the specifications. This is in addition to regular materials verification in MTR (Mill Test Report) review, marking verification, and traceability. Table 2.147 through Table 2.149 show the permissible ranges of elements in ASTM A571.

API RP578 (Material Verification Program for New and Existing Alloy Piping Systems) addresses Quality Assurance (QA), Material Verification Program as an Element of Maintenance Systems, Test Methods & Objectives, Equipment Calibration & Precision, Personnel Qualifications, Material Acceptance Methods, Dissimilar Welding & Weld Overlay, Traceability, and Marking and Recording (Table 2.149).

Figure 2.188 PMI Measurement

Table 2.147 Normal elements and ranges for stainless steels using X-ray fluorescence spectroscopy-XRF[a] (ASTM A751 – modified)

Element	ranges %	Element	ranges %	Element	ranges %
Mn	0.005–15.0	Al	0.002–5.5	Ti	0.005–2.5
P	0.001–15.0	Mo	0.005–8.0	Co	0.005–4.0
Si	0.005–5.0	Cu	0.005–4.0	Sn	0.002–0.20
Cr	0.01–26.0	Cb	0.005–3.0	W	0.005–3.0
Ni	0.01–36.0	V	0.005–2.0		

Commentary Note: XRF = X-ray fluorescence
[a] The accuracy tolerance of the PMI machine may be accepted if the purchaser approves

Table 2.148 Normal elements and ranges for stainless steels using spark emission spectroscopy[a] (ASTM A751 modified)

Element	ranges %	Element	ranges %	Element	ranges %
C	0.004–5.0	Al	0.001–5.5	W	0.005–3.0
S	0.0005–0.1	Mo	0.0005–8.0	Pb	0.002–0.05
N_2	0.0020–0.3	Cu	0.005–4.0	B	0.0005–0.05
Mn	0.005–15.0	Cb	0.005–3.0	Ca	0.0002–0.01
P	0.001–1.5	V	0.005–2.0	Mg	0.001–0.01
Si	0.005–5.0	Ti	0.005–2.5	Ce	0.001–0.2
Cr	0.01–26.0	Co	0.005–4.0	Zr	0.001–0.1
Ni	0.01–36.0	Sn	0.001–0.20	Ta	0.005–0.5

Commentary Notes:
[a] Spark Emission Spectroscopy is not recommended for SS used in EAC environment
[b] The accuracy tolerance of the PMI machine may be accepted if the purchaser approves

(b) Applicable Materials (slightly different per company's specification)
   a. Low-Alloy Steels
   b. ASS – all (or except 304, 410, 410S)
   c. DSS (e.g., 2205, 2507, 2304)

Table 2.149 Normal elements and ranges for stainless steels by analysis of solutions using inductively coupled plasma (ICP) emission spectroscopy or direct plasma (DCP) emission spectroscopy (ASTM A751 modified)

Element ranges %		Element ranges %		Element ranges %		Element ranges %	
B	0.0002–0.01	Ce	0.001–0.2	La	0.001–0.01	Zr	0.001–0.1
Ca	0.0002–0.01	Mg	0.0002–0.01	Ta	0.005–0.5		

Commentary Notes:
[a]Spark Emission Spectroscopy is not recommended for SS used in EAC environment
[b]The accuracy tolerance of the PMI machine may be accepted if the purchaser approves

d. Super Stainless Steels (e.g., 254SMO®, AL-6XN®, 25-6Mo)
e. Nickel Alloys (e.g., Inconel, Incoloy, Hastelloy)
f. Copper Alloys (e.g., Monel, Cupro Nickel)
g. Titanium Alloys
h. Bolting – all (or except SA-193-B7/ SA194-2H)

(c) Chemical Composition Verified per Materials
PMI requirements greatly depends on the need of end-users. The required chemical element analysis is based on the range permitted in the used material standard as a minimum. Some end users require the elements which are to be analyzed without the additionally permitted chemical ranges as seen in Table 2.150 and 2.151. Also, some end-users require the narrower chemical range as seen in Tables 2.152, 2.153, and 2.154.

(d) Chemical Composition Requirements in ANSI/*NACE MR0175*/ISO 15156-3 (in Wet H_2S (sour) Service)
a. Solid-Solution Nickel-Based Alloys (Table A.12 in MR0175)
b. Some Austenitic Stainless Steels (Table D.1 in MR0175)
c. Some Highly Alloyed Austenitic Stainless Steels (Table D.2 in MR0175)
d. Some Solid-Solution Nickel-Based Alloys (Table D.3 in MR0175)
e. Some Copper Nickel Alloys (Table D.4 in MR0175)
f. Some Ferritic Stainless Steels (Table D.5 in MR0175)
g. Some Martensitic Stainless Steels (Table D.6 in MR0175)
h. Some Duplex Stainless Steels (Table D.7 in MR0175)
i. Some Precipitation-Hardened Stainless Steels (Table D.8 in MR0175)
j. Some Precipitation-Hardened Nickel-Based Alloys (Table D.9 in MR0175)
k. Some Cobalt-Based Alloys (Table D.10 in MR0175)
l. Some Titanium Alloys (Table D.11 in MR0175)

Table 2.150 (1/2) Elements per the PMI analyzed[a] (MSS SP-137 valves and fittings – modified)

ASME B16.34 Mat'l groups	Major elements	Grade or brand	UNS no.	Cr	Ni	Mo	Cb (Nb)	Ti	Cu	W	V	Fe[b]
1.9	1 ¼Cr-½ Mo	F11	K11597	X		X						
1.10	2 ¼Cr-1 Mo	F22	K21590	X		X						
1.14	5Cr-1/2Mo	F5	K41545	X		X						
1.15	9 Cr-1 Mo	F9	K90941	X		X						
1.17	9 Cr-1 Mo-V-Cb	F91	K90901	X		X					X	
N/A	13Cr (410)	F6a	S41000	X	X							
N/A	13Cr-4Ni (415)	F6NM	S41500	X	X							
2.1/2.3	18Cr-8Ni	304(N/H)	S30400/03/09	X	X							
2.2/2.3	18Cr-8Ni-2Mo	316(L/H)	S31600/03/09	X	X	X						
2.2	19Cr-13Ni-3 Mo	317(H)	S31700/03	X	X	X						
2.4	18Cr-10Ni-Ti	321(H)	S32100/09	X	X			X				
2.5	18Cr-10Ni-Cb	347(H)	S34700/09	X	X		X					
2.6	23Cr-12Ni	309H	S30909	X	X							
2.7	25Cr-20Ni	310H	S31009	X	X							
2.8	22Cr-5Ni-3Mo	F51,F60, 2205	S31803	X	X	X						
2.8	25Cr-7Ni-4Mo	F53, 2507	S32750	X	X	X						
2.8	20Cr-18Ni-6Mo	F44, 254SMO	S31254	X	X	X						
3.1	35Ni-35Fe-20Cr-Cb-3Cu-2Mo	Alloy 20	N08020	X	X	X	X		X			X
3.2	99Ni	Alloy 200	N02200		X							
3.4	67Ni-30Cu	Alloy 400	N04400		X				X			
3.5	72Ni-15Cr-8Fe	Alloy 600	N06600	X	X							X
3.6	33Ni-42Fe-21Cr	Alloy 800	N08800	X	X							X

Table 2.150 (2/2) Elements per the PMI analyzed[(a)] (MSS SP-137 valves and fittings – modified)

ASME B16.34 Mat'l groups	Major elements	Grade or brand	UNS no.	Cr	Ni	Mo	Cb (Nb)	Ti	Cu	W	V	Fe[(b)]
3.7	65Ni-28Mo-2Fe	B335	N10665		X	X						X
3.7	64Ni-29.5Mo-2Cr-2Fe-3 W	B335	N10675	X	X	X				X		X
3.8	60Ni-22Cr-9Mo- 3.5Cb	Alloy 625	N06625	X	X	X	X					
3.8	42Ni-21.5Cr-3Mo-2.3Cu	Alloy 825	N08825	X	X	X			X			
3.8	54Ni-16Mo-15Cr-4 W	Alloy C276	N10276	X	X	X				X		
3.8	55Ni-21-Cr-13.5Mo-3 W	Alloy C-22	N06022	X	X	X				X		
3.11	44Fe-25Ni-21Cr-4Mo-1Cu	Alloy 904	N08904	X	X	X			X			X
3.12	46Fe-24Ni-21Cr-6Mo	Alloy AL6XN	N08367	X	X	X						X

Commentary Notes:
[(a)] MSS-SP-137 is a minimum requirement without the limits of individual element. Purchaser's PMI specification should be complied
[(b)] The element's limits for Fe may be waived if purchaser accepts

Table 2.151 Elements per the PMI Analyzed[(a)] (MSS SP-137 bolting materials for valves and fittings – modified)

ASME B16.34 bolting material	Major elements	UNS no.	Cr	Ni	Mo	Cb (Nb)	Ti	Cu	W	V	Fe[(b)]
A194 Gr. 4 nuts	1/2C-1/5Mo	K14510			X						
A193-B7/7M, A320 L7, L7M A194 Gr. 7, 7 M nuts	1Cr-1/5Mo	G41400	X		X						
A193-B16	1Cr-1/5Mo-V	K14072	X		X					X	
A540 A194 Gr. 16 nuts	1Cr-1/2Mo-1/4 V	K14072 K14073	X		X					X	
A193-B5	5Cr-1/2Mo	S50100	X		X						
A193 B6, B6X, A194 Gr. 6 nuts	13Cr (410 SS)	S41000	X								
A193 B8, B8A A194, A320 Gr. 8 nuts	18Cr-8Ni (304 SS)	S30400	X	X							
A193 B8M, B8MA A194, A320 Gr. 8M nuts	18Cr-8Ni-2Mo (316 SS)	S31600	X	X	X						
A193 B8C, B8CA A194, A320 Gr. 8C nuts	18Cr-10Ni-Cb (347 SS)	S34700	X	X		X					
A453 Gr. 651	19Cr-9Ni-1½Mo-1 W	S63198	X	X	X				X		
A453 Gr. 660	14Cr-24Ni-1Mo (alloy A-286)	S66286	X	X	X						
A193 B8R, B8RA	22Cr-12Ni-5Mn-2Mo-N (XM-19)	S20910	X	X	X	X				X	
A193 B8P, B8PA	18Cr-11Ni (305 SS)	S30500	X	X							
A193 B8T, B8TA A194, A320 Gr.8T nuts	18Cr-10Ni-Ti (321 SS)	S32100	X	X			X				
A564 Gr. 630	17Cr-4Ni-5Cu (17–4 PHSS)	S17400	X	X				X			
A193 B8MLCuN, 8MLCuNA	20Cr-18Ni-6Mo (alloy 254SMO)	S32154	X	X	X			X			
B164	67Ni-30Cu (alloy 400)	N04400		X				X			
B166	72Ni-15Cr-8Fe (alloy 600)	N06600	X	X							X
B335	65Ni-28Mo-2Fe-1Cr (alloy B-2)	N10655	X	X	X						X
B335	64Ni-29.5Mo-2Cr-2Fe-3 W (alloy B-3)	N10675	X	X	X				X		X
B408	33Ni-42Fe-21Cr (alloy 800)	N08800	X	X							X
B473	35Ni-35Fe-20Cr-Cb (alloy 20)	B08020	X	X		X					X
B574	54Ni-16Mo-15Cr (alloy C-276)	N10276	X	X	X						
B574	55Ni-21Cr-13.5Mo (alloy C-22)	N06022	X	X	X						
B637	53Ni-19Cr-19Fe-Cb-Mo (alloy 718)	N07718	X	X	X	X					X

Commentary Notes:
[(a)] MSS-SP-137 is a minimum requirement without limits of individual element. Purchaser's PMI specification should be complied
[(b)] The element's limits for Fe may be waived if purchaser accepts

Table 2.152 Ferrous metals (base metal) – for reference

Materials	Cr	Ni	Mo	Nb (Cb)	Ti	Max. C	Mn	Notes
1Cr-1/2Mo	0.70–1.30		0.40–0.70					See the company's PMI spec.
1 ¼Cr-1/2Mo	0.85–1.70		0.40–0.70					
2 ¼Cr-1Mo	1.80–2.80		0.70–1.25					
5Cr-1/2Mo	3.60–6.20		0.40–0.70					
9Cr-1Mo	7.50–10.50		0.75–1.25					
SA-302-A			0.40–0.65				0.85–1.40	
SA-302-B			0.40–0.65				1.0–1.60	
SA-302-C		0.35–0.75	0.40–0.65				1.0–1.60	
SA-302-D		0.65–1.10	0.40–0.65				1.0–1.60	
2 ½ Ni		2.0–2.75						
3 ½ Ni		3.0–4.0						
9 Ni		6.0–10.0						
405 SS	11.0–15.0							
410S SS	11.0–14.0					0.08		
304/304L SS	17.0–21.0	7.5–11.0				0.08/0.03		
316/316L SS	15.5–18.5	9.5–14.5	1.75–3.25			0.08/0.03		
317/317L SS	17.5–20.5	10.0–16.0	2.75–4.25			0.08/0.03		
321 SS	16.0–21.0	8.0–13.0			(Note 1)			
347 SS	16.0–20.0	8.0–14.0		(Note 1)				
12Cr-4Ni	11.0–14.5	3.25–4.75	0.30–1.20					
25Cr-20Ni	22.0–28.0	18.0–23.0						
2205 DSS	21.0~23.0	4.5~6.5	2.5~3.5					N: 0.08~0.20

Table 2.153 Nonferrous metals – for reference

Materials	Cr	Ni	Mo	Cu	Max. C	Notes
20Cr-28Ni-2Mo-3Cu (N08020)	19–21	32–38	2–3	3–4		See the company's PMI spec.
70%Cu-30%Ni (C71500)		28–34		Min. 65		
Ni-Cu (N04400-Monel 400)		60–75		24–36		
Ni-Fe-Cr (N08800, N08810, N08811)	19–23	28–38				
Ni-Cr-Fe (N06600- Inconel 600)	14–17	Min. 72				
254SMO® (S31254)	19.5–20.5	17.5–18.5	6.0–6.5		0.02	
Alloy 59 (N06059)	22.0–24.0	Min. 59	15.0–16.5		0.01	

Table 2.154 Weld overlayed metal (diluted metal) – for reference

Materials	Cr	Ni	Mo	Cu	Nb (Cb)	Max. C	Mn	Notes
1 ¼Cr-1/2Mo	0.80–1.70		0.35–0.75					See the company's PMI spec.
2 ¼Cr-1Mo	1.70–2.80		0.70–1.40					
5Cr-1/2Mo	3.50–7.00		0.35–0.75					
7Cr-1/2Mo	5.00–9.00		0.35–0.75					
9Cr-1Mo	7.0–12.0		0.70–1.40					
Mn-1/2Mo			0.35–0.75			0.20	1.07–1.62	
2 ½ Ni		2.0–2.75						
3 ½ Ni		3.0–3.75						
410 SS	9.5–15.0					0.15		
410S SS	9.5–15.0					0.08		
430 SS	13.0–20.0							
308 SS	16.0–25.0	8.0–12.0						
309 SS	19.0–28.0	10.0–16.0						
310 SS	22.0–32.0	18.0–25.0						
316 SS	15.0–22.5	9.5–16.0	1.5–3.5					
317 SS	17.5–21.5	12.0–16.0	2.75–4.25					
320 SS	16.5–21.0	32.0–36.0	1.5–3.5	2.0–5.0	0.30–1.10			
347 SS	16.5–25.0	8.0–12.0			0.30–1.10			
Thyssen 25/35R	21.0–31.0	29.0–41.0			0.50–1.50			
ERNiCr-3	16.0–25.0	58.0–75.0			1.50–3.50			
ERNiCrFe-2	11.0–19.0	54.0–75.0	0.35–2.80					
ERNiCrMo-3	17.5–26.0	48.0–73.0	5.5–11.5					
ENiCrMo-3	17.5–26.0	48.0–73.0	5.5–11.5					
INCO 617/ 117	20.0–24.0	39.0–61.0	5.5–11.5					
ERNiCu-7		54.0–78.0		18.0–36.0				
ENiCu-7		54.0–78.0		18.0–36.0				

m. R05200 Tantalum Alloy (Table D.12 in MR0175)

(e) Analyzers

1. Models: Most clients' specifications designate the approved model names/numbers which comply with ASTM methods (E62, E350, E352. E353. E354, E478, E322, E572, E1086, or E1476), ASME Sec. II, Part A/B/C, ASME Section VIII, Div.2, Annex 6-A, or API RP578.
2. Test Equipment

   The most common equipment are below.

   – Portable X-ray fluorescence (XRF), e.g., Niton®, X-Met®, Texas Nuclear®, etc.

   – Portable optical emission spectroscopy (OES), e.g., Arc-Met®

   The spark area can be appeared after examination of OES, as a result, the HAZ due to spark may show higher hardness value than that of unexamined metal surface. Therefore, the OES for materials for EAC environment must be carefully selected.

   – Table 2.155 shows the capabilities and the comparison of several identification methods.

   – Table 2.156 shows the applicable characteristics and the comparison of several identification methods.
3. Tolerance of measured data: max. 10–15% (5% preferable)

(f) Extent of Verification

It depends on the risk level of the components. Tables 2.157 and 2.158 show some reference application of PMI.

(g) Reporting

ASME Section VIII, Div.2 Annex 6–1 recommends using the PMI report template as Table 2.159.

(h) References

– API RP578 Material Verification Program for New and Existing Alloy Piping Systems.

– ASME Sec. VIII, Div.1, UG-77

– MSS SP-137 Quality Standard for Positive Material Identification of Metal Valves, Flanges, Fittings, and Other Piping Components

Table 2.155 Applicable characteristics and the comparison of several identification methods

Metal properties	X-ray spectrometry	Emission spectrometry	Electromagnetic (Eddy current)	Conductivity resistivity	Thermoelectric (Seebeck)	Chemical spot test	Tribo-electric	Spark testing	Notes
Chemical composition	E, A(1)	E, A	G, B	F, B	G, B	G, A(2)	F, B(3)	G, B	Spectrometry is the best method. Spectrometry and chemical spot test are widely used.
Identification/ response to specific alloy	E, A	E, A	G, B(4)	F	G, B(5)	E	F	G	
Response to surface chemistry	E, A	E, A	F-G, B	F, B	E, B	E	–	–	
Physical properties:	–	–	F-G, B(6)	–	G, B(7)	–	–	–	Electromagnetic, thermoelectric, and conductivity responses are all relative and based on known responses to measured variables.
Hardness (surface, through thickness)	–	–	F-B(6)	–	G, B(7)	–	–	–	
TS & YS	–	–	F-G, B(6)	–	G, B(7)	–	–	–	
Monitoring process variables	–	–	F-G, B(6)	F, B	F, B	–	–	–	Electromagnetic, thermoelectric, and conductivity responses are all relative and based on known responses to measured variables.
Cold work	–	–	F-G, B	F, B	F-G, B	–	–	–	
Warm work	–	–	F-G, B	F, B	F-G, B	–	–	–	
Anneal	–	–	F-G, B	F, B	F-G, B	–	–	–	
Case/through hardening	–	–	F-G, B	F, B	F-G, B	–	–	–	
Temper	–	–	F-G, B	F, B	F-G, B	–	–	–	

E excellent, *G* good, *F* fair, *P* poor, − not applicable, *A* direct-reading quantitative, and *B* indirect-reading qualitative

Source: ASTM E1476

Notes:

(1) Not suitable for low atomic number alloys such as carbon, silicon, and phosphorous

(2) Single element per spot test

(3) Not suitable for steels

(4) Responds well to manganese reversions in steel

(5) Responds well to electrically or thermally active elements, or both

(6) Requires controlled processing, composition, etc.

(7) Thermoelectric properties influenced by metallurgical exchange in ferrous materials

Table 2.156 Applicable characteristics and the comparison of several identification methods

Metal properties	X-ray spectrometry	Emission spectrometry	Electromagnetic (Eddy current)	Conductivity resistivity	Thermoelectric (Seebeck)	Chemical spot test	Tribo-electric	Spark testing
Direct-read/response:	E, A	E, A	G, B	G, B	G, B	B(1)	G, B(3)	N, B
Composition	E(2)	E	G(3)	G(3)	G(3)	E	F-G	N
Physical properties	N	N	G	G	G	N	N	N
Automatic operation:	E	E	E	G	E	N	N	N
Permanent record:	Yes	Yes	Yes	Yes	Yes	Possible	Yes	No
Portable:	Yes	Moderate	Yes	Yes	Yes	Yes	Yes	Yes
Environment:								
Heat/cold	−11 to −60 °C (13–140 °F)	−11 to −60 °C (13–140 °F)	G(4)	F	E(5)	N	N	G
Vibration	–	N	G	P	G	N	N	G
Moisture	–	N	G	P	G	P	N	G
Dirt, oil, mill scale		N	G(5)	N	G(6)	G(6)	F(6)	G
Illumination	–	N	G	G	G	G(7)	G	G(7)
Relative speed	Moderate	Moderate	High	Medium high	High	Slow	Medium high	Medium high

E excellent, *G* good, *F* fair, *P* poor, − not applicable, *A* direct-reading quantitative, and *B* indirect-reading qualitative
Source: ASTM E1476
Notes:
(1) Requires color determination by perception: single element per test
(2) Not responsive to elements with atomic numbers of 22 or less
(3) Responses to composition and processing. Variables must be determined and analyzed
(4) Variations ±20° not troublesome; can operate at any of a wide range of temperatures if variations are limited
(5) If known standards and piece are at same temperature, results are accurate up to 260 °C (500 °F)
(6) Heavy mill scale must be removed
(7) Moderate lighting necessary

Table 2.157 Extent of verification of major materials (% random base) – for reference

Equipment/materials	Shop	Field
Pressure vessels, tanks, H/EXs – pressure-containing external components and pressure-containing internal heads, flanges, and tubesheets for H/EXs, heaters, and boilers	100%	N/A
Tubes, H/EXs, condenser, boilers, including heat recovery steam generators	5% of each heat	1% if tubing performed in field
Piping and piping components (prior to fabrication), including piping specialty items	100%	5%
Fired heater, boiler, and furnace tubes	100%	1% if tubing performed in field
Pumps, compressors, steam turbines, combustion turbines, Turbo expanders and other process equipment – pressure-containing components	100%	N/A
Valves – bodies and bonnets for valves greater than NPS 2”	100%	N/A
Valves – bodies and bonnets for valves, NPS 2” and smaller	100% on 5 pieces or less 5% on 6–200 pieces	N/A
Flow meters –the pressure containing components of each insert type flow meter	100%	N/A
Level displacers and float switches –chamber and head of each displacer and switch shall be verified.	100%	N/A
Pressure relief valves; rupture discs and pressure-containing portions of any instrument through which the process fluid flows	100%	N/A
Furnaces – shop and field-fabricated pressure-containing components and weld, wholly or partially outside the casing plate or header box.	Pipe 5% of each heat/lot. Fittings 5% of each heat/lot min. of 4	1%
Furnaces – pressure-containing components which are inside the casing plates	5%	1%
Expansion joints – all pressure-retaining components	100%	N/A
Pressure-containing instrument housings in alloy systems with a design pressure greater than ASME class #900 (PN 150) [e.g., gauge glass housings, orifice meter tubes]	5%	5%

Table 2.158 Extent of verification of other materials (other than base metal) – for reference

Equipment/materials	Shop	Field
RTJ ring gaskets	100%	N/A
Spiral wound metallic gaskets	Min. 5% when the windings or ID ring are higher alloy than 304 SS. PMI shall be of the area at the ends where there is no filler or if provided, the ID ring.	Min. 5% when the windings or ID rings are higher alloy than 304 SS. PMI shall be of the area at the ends where there is no filler or if provided, the ID ring.
Welds – vessel, H/EX pressure containing circumferential and longitudinal seams – or cover pass only.	100% – 1 test per seam if less than 3048 mm (10 ft) otherwise 1 test per 3048 mm (10 ft)	N/A
Welds – ressure-containing welds other than pressure vessels and H/EXs.	10%	N/A
Welds – piping (other than socket)	10%	10%
Welds – socket	Random 1%	Random 1%
Welding consumables	1 electrode or wire sample per heat	1 electrode or wire sample per heat
Shop-fabricated spools: pipe fittings and flanges (after fabrication) (each pipe and fittings will have already been 100% tested by supplier)	Pipe 5% of each heat/lot Fittings 5% of each heat/lot, min. of 4	N/A
Studs/nuts		
Studs/nuts – ASTM A193-B16 and Cr $\geq$ 20%	10%	1% of each heat/lot, min. or 4
Studs/nuts	1% of each heat/lot	1% of each heat/lot, min. or 4
Pressure retaining fasteners for equipment	10% or where the heat/lot can be documented, 1% each heat/lot	1% of each heat/lot, min. or 4

Table 2.159 Technical datasheet for PMI report

Technical data sheet positive material identification (PMI)												
Analysis mode data sheet												
Fabricator:						Inspection date:						
Location:						PMI service vendor:						
Job title:						Operators:						
Job number:						Analysis model number/calibrated date: /						
Document/DWG no.:						Analysis serial number:						
Purchase order no.:						Cadmium-109 source age:						
Materials standard spec/grade:						Fe (Iron)-55 source age:						
Range in standard spec	Alloy element, wt%										Accept	Reject
		Cr	Mo	Ni	Nb	Ti	Cu	W	Al	V		
	Min.											
	Max.											
Measured, wt%												
Size and THK	ID for tubular product = ______mm, thickness for tubular product or plate= ______mm											
Component*							Heat #					
*Comments – refers to the specific elbow fitting, pipe segment, plate, etc. being inspected.												
REVISION LOG												
Rev	Date	Approved	Description			Rev	Date	Approved	Description			
1						4						
2						5						
3						DWG no.:						

Source: ASME Section VIII, Div.2, Table 6-A.9.2–1-modified

2.5.2 *Heat Analysis and Product Analysis – Table 2.160*

1. The chemical composition in mill certificates specifies the values by heat analysis (ladle analysis).
2. The chemical composition of clients' specification, including PMI (positive material identification), requires the value of product analysis (sample analysis).

Table 2.160 Classes of elements analysis

Classes	Role
Heat analysis (ladle analysis)	The result of chemical analysis for specimen from the liquid metal in ingot.
Product analysis (sample analysis)	The result of chemical analysis for specimen from the final products. It can be contaminated with other elements and the main elements may be slightly changed during rolling, casting, forging, and extrusion work.

The following acceptable tolerance tables for product analysis should be applied (See Tables 2.161, 2.162, 2.163, 2.164, 2.165, 2.166, 2.167, 2.168, 2.169, and 2.170).

Table 2.161 Chemical requirements (product analysis tolerances) of CS and LAS plates

Element	Upper limit, or maximum specified value, %	Permitted variations, %	
		Under minimum limit	Over maximum limit
Boron (B)	Any range	B	B
Carbon (C)	To 0.15 Over 0.15–0.40 Over 0.40–0.75 Over 0.75	0.75 0.03 0.04 0.04	0.03 0.04 0.05 0.06
Chromium (Cr)	To 0.90 Over 0.90–2.00 Over 2.00–4.00	0.04 0.06 0.10	0.04 0.06 0.10
Columbium (Cb)	To 0.10	0.01 C	0.01
Copper (Cu)	0.20 minimum only To 1.00 Over 1.00–2.00	0.02 0.03 0.05	. . . . 0.03 0.05
Manganese (Mn) A	To 0.60 Over 0.60–0.90 Over 0.90–1.20 Over 1.20–1.35 Over 1.35–1.65 Over 1.65–1.95 Over 1.95	0.05 0.06 0.08 0.09 0.09 0.11 0.12	0.06 0.08 0.10 0.11 0.12 0.14 0.16
Molybdenum (Mo)	To 0.20 Over 0.20–0.40 Over 0.40–1.15	0.01 0.03 0.04	0.01 0.03 0.04
Nickel (Ni)	To 1.00 Over 1.00–2.00 Over 2.00–3.75 Over 3.75–5.30 Over 5.30	0.03 0.05 0.07 0.08 0.10	0.03 0.05 0.07 0.08 0.10
Nitrogen (N)	To 0.030	0.005	0.005
Phosphorus (P)	To 0.04 Over 0.04–0.15	– –	0.010 B
Silicon (Si)	To 0.30 Over 0.30–0.40 Over 0.40–2.20	0.02 0.05 0.06	0.03 0.05 0.06
Sulfur (S)	To 0.06 Over 0.06	– B	0.010 B
Titanium (Ti)	To 0.15	0.01 C	0.01
Vanadium (V)	To 0.10 Over 0.10–0.25 Over 0.25 Minimum only specified	0.01 C 0.02 0.02 0.01	0.01 0.02 0.03 –
Zirconium (Zr)	To 0.15 incl.	0.03	0.03

Notes: "–": No requirements, [source: ASTM A6 table A permitted variations in product analysis]
A Permitted variations in manganese content for bars and bar size shapes shall be:
To 0.90 incl. ± 0.03;
Over 0.90 to 2.20 incl. ± 0.06
B Product analysis not applicable
C 0.005, the minimum of the range is 0.01%
Commentary General Notes:
(1) Each chemical composition in MTR should have the same decimal places with that in this table
(2) The chemical composition required for specific service and purpose (e.g., wet H_2S (sour), HF, J-factor, X-Bar, Ceq, Pcm, etc.) may not allow to apply the variations in this table

- Chemical Requirements (Product Analysis Tolerances) of CS and LAS Plates
- Limits of Chemical Elements for Carbon Steel Plates for Pressure Vessels
- Chemical Requirements (Product Analysis Tolerances) of Stainless Steel Plates
- Product Analysis Tolerances for Carbon and Low-Alloy Steels (piping fittings, forging, and valves)
- Product Analysis Tolerances for Higher-Alloy and Stainless Steels (piping fittings, forging, and valves)
- Product Analysis Tolerances for Stainless Steel Bars, Billets, and Forgings
- Product Analysis Tolerances for Steel Castings – CS & LAS
- Chemical Requirements (Product Analysis Tolerances) of Nickel, Nickel Alloys and Cobalt Alloys.
- Chemical Requirements (Product Analysis Tolerances) of Nickel-Copper Alloy (UNS N04400) Plate, Sheet, and Strip

Meanwhile the chemical tolerances for bolting materials are addressed in the followings.

- ASTM A193 (Alloy-Steel and Stainless Steel Bolting for High-Temperature or High-Pressure Service and Other Special Purpose Application), Table 1
- ASTM A320 (Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service), Table 3
- ASTM A437 (Alloy-Steel Turbine-Type Bolting Material Specially Heat-Treated for High-Temperature Service), Table 2
- ASTM A454 (High-Temperature Bolting, with Expansion Coefficients Comparable to ASS), Table 3

Table 2.162 Limits of chemical elements for carbon steel plates for pressure vessels

Elements	Heat analysis, max.%	Product analysis, max.%	Elements	Heat analysis, max.%	Product analysis, max.%
Chromium (Cr)^{A,B}	0.30	0.34	Nickel (Ni)^{A}	0.40	0.43
Columbium (Cb)^{D}	0.02	0.03	Titanium (Ti)^{E}	0.03	0.04
Copper (Cu)^{A}	0.40	0.43	Vanadium (V)^{C}	0.03	0.04
Molybdenum (Mo)^{A,B}	0.12	0.13			

Notes: [source: ASTM A20]

[A] In addition for each heat, based upon the heat analysis, the sum of Cu, Ni, Cr, and Mo shall not exceed 1.00%, unless one or more of those elements are specified or restricted by the applicable product specification for the applicable grade, class, and type

[B] In addition for each heat, based upon the heat analysis, the sum of Cr and Mo shall not exceed 0.32%, unless one or both of those elements are specified or restricted by the applicable product specification for the applicable grade, class, and type

[C] By agreement between the purchaser and the supplier, the heat analysis limit for V is permitted to be increased to a value not higher than 0.10%, and the product analysis limit for vanadium is permitted to be increased to a value not higher than 0.11%

[D] By agreement between the purchaser and the supplier, the heat analysis limit for Cb is permitted to be increased to a value not higher than 0.05%, and the product analysis limit for Cb is permitted to be increased to a value not higher than 0.06%

[E] By agreement between the purchaser and the supplier, the heat analysis limit for titanium is permitted to be increased to a value not higher than 0.04%, and the product analysis limit for Ti is permitted to be increased to a value not higher than 0.05%

Commentary General Notes:

(1) Each chemical composition in MTR should have the same decimal places with that in this table

(2) The chemical composition required for specific service and purpose (e.g., wet H_2S (sour), HF, J-factor, X-Bar, Ceq, Pcm, etc.) may not be applied the variations in this table

Table 2.163 Product analysis tolerances for steel sastings – CS & LAS

Element	Range ^{A}, %	Tolerance $^{B,\ C}$ over the maximum or minimum limit, %	Element	Range ^{A}, %	Tolerance $^{B,\ C}$ over the maximum or minimum limit, %
Aluminum (Al)	Up to 0.03 0.03–0.10 About 0.10	0.01 $0.08 \times \%Al + 0.02$ 0.03	Nickel (Ni)	Up to 2.0 About 2.0	$0.10 \times \%N_L + 0.03$ 0.25
Carbon (C)	Up to 0.65 About 0.65	$0.03 \times \%C_L + 0.02$ 0.04	Phosphorus (P)	All	$0.13 \times \%P_L + 0.005$
Chromium (Cr)	Up to 2.0 About 2.0	$0.07 \times \%Cr_L + 0.04$ 0.18%	Silicon (Si)	Up to 0.60 About 0.60	$0.22 \times \%Si_L - 0.01$ 0.15
Copper (Cu)	Up to 0.15 About 0.15	$0.18 \times \%Cu_L + 0.02$ 0.05	Sulfur (S)	All	$0.36 \times \%S_L + 0.001$
Manganese (Mn)	Up to 1.0 About 1.0	$0.08 \times \%Mn_L + 0.01$ 0.09	Tungsten (W)	Up to 0.10 About 0.10	$0.08 \times \%W_L + 0.02$ 0.02
Molybdenum (Mo)	Up to 0.6 About 0.6	$0.04 \times \%Mo_L + 0.03$ 0.06	Vanadium (V)	Up to 0.25 About 0.25	$0.23 \times \%V_L + 0.004$ 0.06

Notes: *xxL = lowest of XX*, [source: ASTM A703]

[A] The range denotes the composition limits up to which the tolerances are computed by the equation, and above which the tolerances are given by a constant

[B] The subscript L for the elements in each equation indicates that the limits of the element specified by the applicable specification are to be inserted into the equation to calculate the tolerance for the upper limit and the lower limit, if applicable, respectively. Examples of computing tolerances are presented in footnote *C*

[C] To compute the tolerances, consider the manganese limits 0.50–80% of Grade WC4 of Specification ASTM A217/A217M. In accordance with Table 1, the maximum permissible deviation of a product analysis below the lower limit 0.50 is 0.05% = (0.08 3 0.50 + 0.01). The lowest acceptable product analysis of Grade WC4, therefore, is 0.45%. Similarly, the maximum permissible deviation above the upper limit of 0.80% is 0.074% = (0.08 3 0.80 + 0.01). The highest acceptable product analysis of Grade WC4, therefore, is 0.874. For Grade WCC of Specification ASTM A 216/A 216 M, the maximum manganese content is 1.40% if the carbon content is 0.20%. In this case, the highest acceptable product analysis is 1.49 = (1.40 + 0.09)

Commentary General Notes:

(1) Each chemical composition in MTR should have the same decimal places with that in this table

(2) The chemical composition required for specific service and purpose (e.g., wet H_2S (sour), HF, J-factor, X-Bar, Ceq, Pcm, etc.) may not adopt the variations in this table

Table 2.164 Chemical requirements (product analysis tolerances) of stainless steel plates

Elements	Limit or maximum of specified range, %	Tolerance over the max. limit or under the min. limit	Elements	Limit or maximum of specified range, %	Tolerance over the max. limit or under the min. limit
Aluminum (Al)	To 0.15 Over 0.15–0.50 Over 0.50–2.00	−0.005, +0.01 0.05 0.10	Nitrogen (N)	To 0.02 Over 0.02–0.19 Over 0.19–0.25 Over 0.25–0.35 Over 0.35–0.45 Over 0.45–0.55	0.006 0.01 0.02 0.03 0.04 0.05
Carbon (C)	To 0.010 incl. Over 0.010–0.030 Over 0.030–0.20 Over 0.20–0.60 Over 0.60–1.20	0.002 0.005 0.01 0.02 0.03	Phosphorus (P)	To 0.040 Over 0.040–0.20	0.005 0.010
Chromium (Cr)	Over 4.00–10.00 Over 10.00–15.00 Over 15.00–20.00 Over 20.00–30.00	0.10 0.15 0.20 0.25	Selenium (Se)	All range	0.03
Cobalt (Co)	Over 0.05–0.50 Over 0.50–2.00 Over 2.00–5.00	0.01[A] 0.02 0.06	Silicon (Si)	To 1.00 Over 1.00–3.00 Over 3.00–6.00	0.05 0.10 0.15
Columbium (Cb) Plus tantalum (Ta)	To 1.50	0.05	Sulfur (S)	To 0.040 Over 0.040–0.20 Over 0.20–0.50	0.005 0.010 0.020
Copper (Cu)	To 0.50 Over 0.50–1.00 Over1.00–3.00 Over 3.00–5.00 Over 5.00–10.00	0.03 0.06 0.10 0.15 0.20	Tantalum (Ta)	To 0.10	0.02
Manganese (Mn)	To 1.00 Over 1.00–3.00 Over 3.00–6.00 Over 6.00–10.00 Over 10.00–15.00 Over 15.00–20.00	0.03 0.04 0.05 0.06 0.10 0.15	Titanium (Ti)	To 1.00 Over 1.00–3.00	0.05 0.07
Molybdenum (Mo)	Over 0.20–0.60 Over 0.60–2.00 Over 2.00–8.00	0.03 0.05 0.10	Tungsten (W)	To 1.00 Over 1.00–2.00	0.03 0.05
Nickel (Ni)	To 1.00 Over 1.00–5.00 Over 5.00–10.00 Over 10.00–20.00 Over 20.00–30.00	0.03 0.07 0.10 0.15 0.20	Vanadium (V)	To 0.50 Over 0.50–1.50	0.03 0.06

Notes: [source: ASTM A480, Table A1.1 Chemical Requirements (Product Analysis Tolerances)]

[A] Production analysis limits for cobalt under 0.05% have not been established, and the manufacturer should be controlled for those limits

Commentary General Notes:

(1) Each chemical composition in MTR should have the same decimal places with that in this Table

(2) The chemical composition required for specific service and purpose (e.g., wet H_2S (sour), HF, J-factor, X-Bar, Ceq, Pcm, etc.) may not adopt the variations in this table

Table 2.165 Product analysis tolerances for carbon and low-alloy steels (Cr < 4.0%)

Elements	Limit, or maximum of specified range, %	Permissible variations over maximum limit or under minimum limit,%	Elements	Limit, or maximum of specified range, %	Permissible variations over maximum limit or under minimum limit,%
Aluminum (Al)	To 0.15 Over 0.15–0.50 Over 0.50–0.80	−0.005/+0.01 0.05 0.07	Nickel (Ni)	To 1.00 Over 1.00–5.00 Over 5.00–10.00 Over 10.00–20.00	0.03 0.07 0.10 0.15
Boron (B)	To 0.01	0.0005	Nitrogen (N)	To 0.02 Over 0.02–0.19	0.005 0.01
Carbon (C)	To 0.010 Over 0.010–0.030 Over 0.030–0.20 Over 0.20–0.80	0.002 0.005 0.01 0.02	Phosphorus (P)	To 0.040 Over 0.040–0.20	0.005 0.010
Columbium (Niobium) (Cb/Nb)	To 1.50	0.05	Silicon (Si)	To 1.00 Over 1.00–3.00	0.02 0.10
Chromium (Cr)	To 0.90 Over 0.90–2.10 Over 2.10–4.00	0.03 0.05 0.07	Sulfur (S)	To 0.040 Over 0.040–0.20	0.005 0.010
Copper (Cu)	To 0.50 Over 0.50–1.00 Over 1.00–3.00	0.03 0.05 0.10	Titanium (Ti)	To 1.00	0.05
Lead[A] (Pb)	Over 0.15–0.35	0.03	Tungsten (W)	To 0.50 Over 0.50–1.00 Over 1.00–2.00 Over 2.00–4.00	0.02 0.03 0.05 0.06
Manganese (Mn)	To 1.00 Over 1.00–3.00	0.03 0.04	Vanadium (V)	To 0.10 Over 0.10–0.25 Over 0.25–0.50 Minimum value specified, under minimum limit only	0.01 0.02 0.03 0.01
Molybdenum (Mo)	to 0.20 over 0.20 to 0.60 over 0.60 to 2.00	0.01 0.03 0.05	Zirconium (Zr)	To 0.01	0.005

Notes: [sources: ASTM A960 common requirements for wrought steel piping fittings and ASTM A961 common requirements for steel flanges, forged fittings, valves, and parts for piping applications]

[A]Product analysis tolerance for lead applies both over and under to a specified range of 0.15–0.35%

Commentary General Notes:

(1) Each chemical composition in MTR should have the same decimal places with that in this table

(2) The chemical composition required for specific service and purpose (e.g., wet H_2S (sour), HF, J-factor, X-Bar, Ceq, Pcm, etc.) may not adopt the variations in this table

Table 2.166 (1/2) Product analysis tolerances for higher-alloy and stainless steels (Cr $\geq$ 4.0 wt%)[A]

Element	Limit or maximum of specified range, wt %	Tolerance over maximum limit or under minimum limit	Element	Limit or maximum of specified range, wt %	Tolerance over maximum limit or under minimum limit
Aluminum (Al)	To 0.15 Over 0.15–0.50	−0.005/ +0.01 0.05	Nickel (Ni)	To 1.00 Over 1.00–5.00 Over 5.00–10.00 Over 10.00–20.00 Over 20.00–30.00 Over 30.00–40.00	0.03 0.07 0.10 0.15 0.20 0.25
Carbon (C)	To 0.010 Over 0.010–0.030 Over 0.030–0.20 Over 0.20–0.80	0.002 0.005 0.01 0.02	Nitrogen (N)	To 0.02 Over 0.02–0.19 Over 0.19–0.25 Over 0.25–0.35 Over 0.35–0.45 Over 0.45	0.005 0.01 0.02 0.03 0.04 0.05
Cerium (Ce)	To 0.20	0.01	Phosphorus (P)	To 0.040 Over 0.040 to 0.20	0.005 0.010
Chromium (Cr)	Over 4.00–10.00 Over 10.00–15.00 Over 15.00–20.00 Over 20.00–30.00	0.10 0.15 0.20 0.25	Sulfur (S)	To 0.040 Over 0.040–0.20 Over 0.20–0.50	0.005 0.010 0.020

Table 2.166 (2/2) Product analysis tolerances for higher-alloy and stainless steels (Cr $\geq$ 4.0 wt%)[A]

Element	Limit or maximum of specified range, wt %	Tolerance over maximum limit or under minimum limit	Element	Limit or maximum of specified range, wt %	Tolerance over maximum limit or under minimum limit
Cobalt (Co)	0.05–0.20	0.01 [A]	Silicon (Si)	To 1.00 Over 1.00–3.00 Over 3.00–7.00	0.05 0.10 0.15
Columbium (Niobium) (Cb/Nb)	To 1.50	0.05	Tantalum (Ta)	To 0.10	0.02
Copper (Cu)	To 0.50 Over 0.50–1.00 Over 1.00–3.00	0.03 0.05 0.10	Titanium (Ti)	To 1.00	0.05
Manganese (Mn)	To 1.00 Over 1.00–3.00 Over 3.00–6.00 Over 6.00–10.00	0.03 0.04 0.05 0.06	Tungsten (W)	To 0.05 Over 0.05–1.00 Over 1.00–2.00 Over 2.00–4.00	0.02 0.03 0.04 0.06
Molybdenum (Mo)	To 0.20 Over 0.20–0.60 Over 0.60–2.00 Over 2.00–7.00	0.01 0.03 0.05 0.10	Vanadium (V)	To 0.10 Over 0.10–0.25	0.01 0.02

Notes: [source: ASTM A961 common requirements for steel flanges, forged fittings, valves, and parts for piping applications]
[A]Product analysis limits for cobalt under 0.05% have not been established and the producer should be consulted for those limits
Commentary General Notes:
(1) Each chemical composition in MTR should have the same decimal places with that in this table
(2) The chemical composition required for specific service and purpose (e.g., C, Nb, Ti, etc.) may not adopt the variations in this table

Table 2.167 (1/2) Product analysis tolerances for stainless steel bars, billets, and forgings

Element	Upper limit of maximum of specified range, %	Tolerances over the maximum (upper limit) or under the minimum (lower limit)	Element	Upper limit or maximum of specified range, %	Tolerances over the maximum (upper limit) or under the minimum (lower limit)
Aluminum (Al)	To 0.15 Over 0.15–0.50 Over 0.50–2.00 Over 2.00–5.00 Over 5.00–10.00	−0.005/+0.01 0.05 0.10 0.20 0.35	Nitrogen (N)	To 0.02 Over 0.02–0.19 Over 0.19–0.25 Over 0.25–0.35 Over 0.35–0.45 Over 0.45	0.005 0.01 0.02 0.03 0.04 0.05
Carbon (C)	To 0.010 Over 0.010–0.030 Over 0.030–0.20 Over 0.20–0.60 Over 0.60–1.20	0.002 0.005 0.01 0.02 0.03	Phosphorus (P)	To 0.040 Over 0.040–0.20	0.005 0.010
Chromium (Cr)	Over 4.00–10.00 Over 10.00–15.00 Over 15.00–20.00 Over 20.00–30.00	0.10 0.15 0.20 0.25	Selenium (Se)	All range	0.03
Cobalt (Co)	Over 0.05–0.50 Over 0.50–2.00 Over 2.00–5.00 Over 5.00–10.00 Over 10.00–15.00 Over 15.00–22.00 Over 22.00–30.00	0.01 0.02 0.05 0.10 0.15 0.20 0.25	Silicon (Si)	To 1.00 Over 1.00–3.00 Over 3.00–6.00	0.05 0.10 0.15
Columbium + Tantalum (Co + Ta)	To 1.50 Over 1.50–5.00 Over 5.00	0.05 0.10 0.15	Sulfur (S)	To 0.040 Over 0.040–0.20 Over 0.20–0.50	0.005 0.010 0.020
Copper (Cu)	To 0.50 Over 0.50–1.00 Over 1.00–3.00 Over 3.00–5.00 Over 5.00–10.00	0.03 0.05 0.10 0.15 0.20	Tantalum (Ta)	To 0.10	0.20

Table 2.167 (2/2) Product analysis tolerances for stainless steel bars, billets, and forgings

Element	Upper limit of maximum of specified range, %	Tolerances over the maximum (upper limit) or under the minimum (lower limit)	Element	Upper limit or maximum of specified range, %	Tolerances over the maximum (upper limit) or under the minimum (lower limit)
Manganese (Mn)	To 1.00	0.03	Titanium (Ti)	To 1.00	0.05
	Over 1.00–3.00	0.04		Over 1.00–3.00	0.07
	Over 3.00–6.00	0.05		Over 3.00	0.10
	Over 6.00–10.00	0.06			
	Over 10.00–15.00	0.10			
	Over 15.00–20.00	0.15			
Molybdenum (Mo)	Over 0.20–0.60	0.03	Tungsten (W)	To 1.00	0.03
	Over 0.60–2.00	0.05		Over 1.00–2.00	0.05
	Over 2.00–7.00	0.10		Over 2.00–5.00	0.07
	Over 7.00–15.00	0.15		Over 5.00–10.00	0.10
	Over 15.00–30.00	0.20		Over 10.00–20.00	0.15
Nickel (Ni)	To 1.00	0.03	Vanadium (V)	To 0.50	0.03
	Over 1.00–5.00	0.07		Over 0.50–1.50	0.05
	Over 5.00–10.00	0.10			
	Over 10.00–20.00	0.15			
	Over 20.00–30.00	0.20			
	Over 30.00–40.00	0.25			
	Over 40.00	0.30			

This table specifies tolerances over maximum limits or under minimum limits of the chemical requirements of the applicable material specification; it does not apply to heat analysis

Note: [source: ASTM A484]

Commentary General Notes:

(1) Each chemical composition in MTR should have the same decimal places with that in this table

(2) The chemical composition required for specific service and purpose (e.g., C, Nb, Ti, etc.) may not adopt the variations in this table

Table 2.168 (1/2) Chemical requirements (product analysis tolerances) of nickel, nickel alloys, and cobalt alloys

Element	Limit or maximum of specified element, %	Variation under min or over max, %	Element	Limit or maximum of specified element, %	Variation under min or over max, %
Aluminum (Al)	To 0.10	0.02	Nickel (Ni)	To 1.00	0.05
	Over 0.10–0.50	0.05		Over 1.00–5.00	0.10
	Over 0.50–2.00	0.10		Over 5.00–10.00	0.15
	Over 2.00–5.00	0.20		Over 10.00–20.00	0.20
	Over 5.00–10.00	0.25		Over 20.00–30.00	0.25
	Over 10.00–15.00	0.30		Over 30.00–40.00	0.30
				Over 40.00–60.00	0.35
				Over 60.00–80.00	0.45
				Over 80.00–99.00	0.60
Boron (B)	To 0.01	0.002	Nitrogen (N)	To 0.02	0.005
	Over 0.01–0.05	0.005		Over 0.02–0.19	0.01
	Over 0.05–0.15	0.010		Over 0.19–0.25	0.02
Carbon (C)	To 0.02	0.005		Over 0.25–0.35	0.03
	Over 0.02–0.20	0.01		Over 0.35–0.45	0.04
	Over 0.20–0.60	0.02		Over 0.45–0.60	0.05
	Over 0.60–1.00	0.03	Oxygen (O_2)	To 0.010	0.005
Cerium (Ce)	To 0.05	0.005	Platinum (Pt)	To 0.50	0.03
	Over 0.050–0.10	0.010			
	Over 0.10–0.20	0.015			
Chromium (Cr)	To 5.00	0.10	Rhenium (Re)	To 1.50	0.05
	Over 5.00–15.00	0.15		Over 1.50–3.00	0.10
	Over 15.00–25.00	0.25		Over 3.00–5.00	0.15
	Over 25.00–35.00	0.30		Over 5.00–7.00	0.20
	Over 35.00–45.00	0.40			
	Over 45.00–50.00	0.50			
Cobalt (Co)	To 0.10	0.01	Silicon (Si)	To 0.05	0.01
	Over 0.10–0.20	0.02		Over 0.05–0.25	0.02
	Over 0.20–1.00	0.03		Over 0.25–0.50	0.03
	Over 1.00–5.00	0.05		Over 0.50–1.00	0.05
	Over 5.00–10.00	0.10		Over 1.00–4.50	0.10
	Over 10.00–15.00	0.15			
	Over 15.00–20.00	0.20			
	Over 20.00–25.00	0.25			
	Over 25.00–30.00	0.30			
	Over 30.00–35.00	0.35			
	Over 35.00–50.00	0.50			

Table 2.168 (2/2) Chemical requirements (product analysis tolerances) of nickel, nickel alloys and cobalt alloys

Element	Limit or maximum of specified element, %	Variation under min or over max, %	Element	Limit or maximum of specified element, %	Variation under min or over max, %
Columbium (Nb) and/or Tantalum (Ta)	To 1.50 Over 1.50–3.00 Over 3.00–5.00 Over 5.00–7.00 Over 7.00–10.00 Over 10.00–13.00	0.05 0.10 0.15 0.20 0.25 0.30	Sulfur (S)	To 0.02 Over 0.02–0.06	0.003 0.005
Copper (Cu)	To 0.20 Over 0.20–0.50 Over 0.50–5.00 Over 5.00–10.00 Over 10.00–20.00 Over 20.00–30.00 Over 30.00–40.00 Over 40.00–50.00	0.02 0.03 0.04 0.05 0.10 0.15 0.20 0.25	Tin (Sn)	To 0.10 Over 0.01–0.05	0.002 0.005
Hafnium (Hf)	To 1.50 Over 1.50–3.00	0.05 0.10	Titanium (Ti)	To 0.10 Over 0.10–0.50 Over 0.50–1.00 Over 1.00–2.00 Over 2.00–3.50 Over 3.50–5.00 Over 5.00–10.00	0.02 0.03 0.04 0.05 0.07 0.10 0.20
Iron (Fe)	To 0.20 Over 0.20–0.75 Over 0.75–2.50 Over 2.50–5.00 Over 5.00–10.00 Over 10.00–15.00 Over 15.00–30.00 Over 30.00–50.00	0.02 0.03 0.05 0.07 0.10 0.15 0.30 0.45	Tungsten (W)	To 1.00 Over 1.00–3.00 Over 3.00–5.00 Over 5.00–10.00 Over 10.00–20.00	0.04 0.10 0.15 0.20 0.25
Lanthanum (La)	To 0.20	0.01	Vanadium (V)	To 0.50 Over 0.50–1.50	0.04 0.05
Lead (Pb)	To 0.10	0.01	Yttrium (Yt)	To 0.050 Over 0.050–0.10 Over 0.10–0.20	0.005 0.010 0.015
Magnesium (Mg)	To 0.10	0.01	Zinc (Zn)	To 0.10 Over 0.01–0.05	0.002 0.005
Manganese (Mn)	To 0.00 Over 1.00–3.00 Over 3.00–6.00 Over 6.00–10.00	0.03 0.04 0.07 0.10	Zirconium (Zr)	To 0.10 Over 0.10–0.20	0.01 0.02
Molybdenum (Mo)	To 1.00 Over 1.00–3.00 Over 3.00–5.00 Over 5.00–20.00 Over 20.00–30.00 Over 30.00–40.00	0.03 0.05 0.10 0.15 0.25 0.35			

Note: [source: ASTM B880, Table 1 Check Analysis Variation]
Commentary General Notes:
(1) Each chemical composition in MTR should have the same decimal places with that in this table

Table 2.169 Chemical requirements (product analysis tolerances) of nickel-copper alloy (UNS N04400) plates, sheets, and strips

Element	Composition limits, %	Element	Composition limits, %
Aluminum (Al)	0.5 max.	Sulfur (S)	0.015 max.
Carbon (C)	0.2 max.	Tin (Sn)	0.006 max.
Lead (Pb)	0.006 max.	Zinc (Zn)	0.02 max.
Phosphorous (P)	0.02 max.		

Note: [source: ASTM B127, Table S2.1]
Commentary General Notes:
(1) Each chemical composition in MTR should have the same decimal places with that in this table

2.5.3 Comparison of (C)MTR and PMI (Table 2.170)

CMTR, which stands for "Certified Mill Test Report" or "Certified Material Test Reports," is provided by the raw material producer (mill) with their quality assurance. So, CMTR is not different from MTR. Regardless of how this document is titled, it has the same purpose, which is to document the testing results for a particular heat of steel and to provide traceability to the material's origins.

PMI should be used as an additional tool on the (C)MTR which is a basic document for the identification of the materials. So, PMI shall not be in lieu of (C)MTR. Table 2.170 lists the differences between (C)MTR and PMI.

Table 2.170 Comparison of (C)MTR and PMI

Item	(C)MTR-certified materials test report	PMI-positive material identification
When tested What applicable	A QA document generated by the mill suppliers that contains details on material grade, type, heat number, country of origin, chemical composition (normally by ladle analysis), mechanical properties (basic – from atmosphere tensile test/optional – toughness test, NDE, grain size, specific chemical composition before or after PWHT) Normally, ladle analysis at mill per the heat number for new materials (base metal) Random test for bulk materials	Normally, production analysis for base metal and weldment Applicable new materials, existing materials, and welding electrodes, and weldments Significant higher amount test for bulk material as well
Contents in report	Chemical composition, mechanical test data (TS, YS, elongation, reduction of area, etc.), hardness, heat treatment (Q-T, normalized, etc. – heat curves per the purchaser's request), PWHT, impact test, specific simulation test per purchaser's request, base metal/weldments, etc.	Chemical composition[(3)]
Test equipment	Lab chemical analysis. Most mechanical test equipment in lab.	– Portable X-ray fluorescence (XRF), e.g., Niton®, X-Met®, Texas nuclear®, etc.) – Portable optical emission spectroscopy[(1)] (OES), e.g., Arc-Met® – Laboratory chemical analysis (seldom)
Limits of detected elements	Possible for all elements per request	May be limited some nonmetallic elements per the PMI test equipment
Extent of test material	Very low (per heat no. and lot no.) per industrial material standards	High for final product (5–100%)[(2)] per the material, service severity, shape in accordance with the end-user's specification
Accuracy	High (lab test) – periodical calibration for measuring equipment is strongly required.	Low (field test) – periodical calibration for measuring equipment is strongly required
Acceptable tolerance	See Tables 2.161, 2.162, 2.163, 2.164, 2.165, 2.166, 2.167, 2.168, and 2.169.	Max. 5–15% (5% preferable)
Examiner personnel qualification	Required	Required
Reference standards	ASTM A6/A20/A370/A751, BS EN 10204	API RP578, ASTM E 1476

Notes:
(1) The spark area (hardened surface) after OES exam can be appeared. Therefore, the OES for materials for EAC environment may be carefully selected
(2) See Tables 2.152 and 2.153 for reference
(3) Results from testing dissimilar metal welds should take into account the effects of dilution, which occurs during weld deposition. The owner/user should establish the minimum compositional requirements of the as-deposited weld metal necessary for the intended service

2.6 Characteristics of ASTM/ASME Materials (Ferrous and Nonferrous Metals)

2.6.1 Sections, Volumes, and Application Guidelines of ASTM

A; Ferrous Metals
B; Nonferrous Metals
C; Cementation, Ceramic, Concrete, and Masonry Materials
D; Miscellaneous Materials
E; Miscellaneous Subjects
F; Materials for Specific Applications
G; Corrosion, Deterioration, and Degradation of Materials
ES; Emergency Standards
P; Proposals (Table 2.171)

Table 2.171 (1/2) ASTM section and volume

Section	Volume	Titles
1 Iron and steel products	01.01	Steel-piping, tubing, fittings
	01.02	Ferrous castings; ferroalloys
	01.03	Steel-plate, sheet, strip, wire; stainless steel bar
	01.04	Steel-structural, reinforcing, pressure vessel, railway
	01.05	Steel-bars, forgings, bearing, chain, tool
	01.06	Coated steel products
	01.07	Ships and marine technology (I): F670 – F1511
	01.08	Ships and marine technology (II): F1546 – latest
	01.09	Fasteners; rolling element bearings
2 Nonferrous metal products	02.01	Copper and copper alloys
	02.02	Aluminum and magnesium alloys
	02.03	Electrical conductors
	02.04	Nonferrous metals – nickel, cobalt, lead, tin, zinc, cadmium, precious, reactive, refractory metals and alloys;
	02.05	materials for thermostats, electrical heating and resistance contacts, and connectors
		Metallic and inorganic coatings; metal powders and metal powder products
3 Metals test methods and analytical procedures	03.01	Metals – mechanical testing; elevated and low-temperature tests; metallurgy
	03.02	Corrosion of metals: wear and erosion
	03.03	Nondestructive testing (I): C1331 – E2373
	03.04	Nondestructive testing (II): E2374 – latest
	03.05	Analytical chemistry for metals, ores, and related materials
	03.06	Molecular spectroscopy and separation science; surface analysis
	03.07	Magnetic properties
4 Construction	04.01	Cement; lime; gypsum
	04.02	Concrete and aggregates
	04.03	Road and paving materials; pavement management technologies
	04.04	Roofing and waterproofing
	04.05	Chemical-resistant nonmetallic materials; vitrified clay, concrete, fiber-cement products; mortars and grouts; masonry; precast concrete
	04.06	Thermal insulation; building and environmental acoustics
	04.07	Building seals and sealant; fire standards; dimension stone
	04.08	Soil and rock (I): D 420-D 5876
	04.09	Soil and rock (II): D 5877 – latest
	04.10	Wood
	04.11	Building construction (I): E72 – E2110
	04.12	Building constructions (II): E2112 – latest; sustainability; property management systems; technology and underground utilities
	04.13	Geosynthetics
5 Petroleum products, lubricants, and fossil fuels	05.01	Petroleum products and lubricants (I): C1234 – D3710
	05.02	Petroleum products and lubricants (II): D3711 – D6122
	05.03	Petroleum products and lubricants (III): D6138 – D6971
	05.04	Petroleum products and lubricants (IV): D6973 – latest
	05.05	Petroleum products, liquid fuels, and lubricants (V): D7756 – latest; combustion characteristics; manufactured carbon and graphite products
	05.06	Gaseous fuels; coal and coke
6 Paints, related coatings, and aromatics	06.01	Paint – tests for chemical, physical, and optical properties; appearance
	06.02	Paint – products and applications; protective coatings; pipeline coatings
	06.03	Paint – pigments, drying oils, polymers, resins, naval stores, cellulosic esters, and ink vehicles
	06.04	Paint – solvents; aromatic; industrial, specialty and related chemicals
7 Textiles	07.01	Textiles (I): D 76 – D 4319
	07.02	Textiles (II): D 4393 – latest
8 Plastics	08.01	Plastics (I): D 256 – D 3159
	08.02	Plastics (II): D 3222 – D5083
	08.03	Plastics (III): D5117 – latest; reinforced plastic piping systems and chemical equipment; plastic building products
	08.04	Plastic piping systems
9 Rubber	09.01	Rubber, natural and synthetic – general test methods; carbon black
	09.02	Rubber products, industrial specifications and related test methods; gaskets; tires
10 Electrical insulation and electronics	10.01	Electrical insulation (I): D 69-D 2484
	10.02	Electrical insulation (II): D 2518 – latest
	10.03	Electrical insulating liquids and gases; electrical protective equipment
	10.04	Electronics; declarable substances in materials; 3D imaging systems; additive manufacturing technologies

Table 2.171 (2/2) ASTM section and volume

Section	Volume	Titles
11 Water and environmental technology	11.01	Water (I)
	11.02	Water (II)
	11.03	Occupational health and safety; protective clothing
	11.04	Waste management
	11.05	Environmental assessment, risk management and corrective action
	11.06	Environmental; biological effects and environmental fate; industrial biotechnology
	11.07	Air quality
	11.08	Pesticides, antimicrobials, and alternative control agents; hazardous substances and oil spill response
12 Nuclear, solar, and geothermal energy	12.01	Nuclear energy (I)
	12.02	Nuclear (II), solar, and geothermal energy, radiation processing
13 Medical devices and services	13.01	Medical and surgical materials and devices (I): E667 – F2477
	13.02	Medical and surgical materials and devices (II): F2502-latest; emergency medical services; search and rescue; anesthetic and respiratory equipment
14 General methods and instrumentation	14.01	Healthcare informatics
	14.02	Particle and spray characterization; forensic sciences; accreditation & certification; forensic psychophysiology; nanotechnology; forensic engineering
	14.03	Sensory evaluation; temperature measurement; language services and products
	14.04	Laboratory apparatus; degradation of materials; SI; oxygen fire safety
	14.05	Statistical methods; Hazard potential of chemicals; thermal measurements; manufacture of pharmaceutical and biopharmaceutical products
15 General products, chemical specialties, and end use products	15.01	Refractories, activated carbon; advanced ceramics
	15.02	Glass; ceramic whitewares
	15.03	Space simulation; aerospace and aircraft; composite materials
	15.04	Soaps and other detergents; polishes; leather; resilient floor coverings
	15.05	Engine coolants and related fluids; halogenated organic solvents and fire extinguishing agents
	15.06	Adhesives
	15.07	Sports equipment and facilities; pedestrian/walkway safety and footwear; amusement rides and devices; snow skiing
	15.08	Security systems and equipment; detention and correctional facilities; homeland security applications; driverless automatic guided industrial vehicles; exoskeletons and exosuits
	15.09	Light sport aircraft; unmanned aircraft systems; aircraft systems; aerospace personnel; general aviation aircraft
	15.10	Packaging; primary barrier packaging; cannabis
	15.11	Consumer products; business imaging products; vacuum cleaners
	15.12	Livestock, meat, and poultry evaluation systems; food service equipment
00 Index	00.01	Subject index and alphanumeric list

2.6.2 ASTM/ASME Materials Well Used in Energy and Chemical Industries

- Plates and Strips
- Pipes and Tubes
  - For Mass Transfer (Pipes and Tubes)
  - For Heat Transfer (Heat Exchangers)
- Tubes/Supports for Fired Heaters & Boilers
- Forgings & Wrought (Fittings)
- Castings
- Bolts and Nuts
- Insulation and Refractory Materials (Nonmetallic)

General Notes for All Types of Products in Sects. 2.6.2.1, 2.6.2.2, 2.6.2.3, 2.6.2.4, 2.6.2.5, 2.6.2.6, and 2.6.2.7

1. The temperature ranges are based on the AMSE Sec. VIII, Div.1 (with Sec. II, Part D) and/or B31.3 in noncorrosive service unless otherwise noted. This temperature range can be changed per the service conditions, such as applicable codes and standards, specific notes, material standards, service, mechanical design, piping materials classes, and end-users' specifications.
2. The designated temperatures, the lowest and highest are based on the minimum design metal temperature (MDMT) and Design temperature unless otherwise noted. The skin metal temperatures (i.e., tubes of fired heater/boilers) or steaming out temperature (i.e., under no service pressure) should be separately considered by the responsible engineers.

3. Other applicable standards (ASME, API, NACE, AWS, CSA, etc.) have some more specific material requirements. For example, limited chemical composition, mill treatment, service temperature & pressure, strength, material test & inspection, heat treatment, specific services, etc.
4. Dimension units unless otherwise specified.
   - Thickness (*t*): mm
   - Tensile strength (T.S.) or yield strength (Y.S.); ksi [1 ksi = 6.895 MPa]
   - Temperature: °C
5. The unit conversion is not standardized for rounding off in this book because most data are directly quoted from the individual codes/standards.
6. For corrosion and metallurgy of products other than Plates and Strips, see the Characteristics and Precautions of Plates and Strips for the same material group.
7. ASME code cases noted in the Tables (Sects. 2.6.2.1, 2.6.2.2, 2.6.2.3, 2.6.2.4, 2.6.2.5, and 2.6.2.6) should be only reference because they may or may not be expired.
8. The designated "Impact Test" is based on the Charpy V-notch (CVN) impact test unless otherwise specified.
9. Currently MTI technical committee for impact test requirement of LTCS (impact tested per ASTM) suggested to ASTM committees to change −46 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME BPVC requirements.
10. The specified temperature ranges are commonly used zones with or without impact test. The impact test requirements shall meet the applicable codes and standards.
11. See Table 2.100, Note 3 for General or Common Requirements for each material standard and group.
12. Some withdrawn standard materials are introduced in this section for reference because the evaluation for existing materials as well as new materials is frequently required for maintenance and RBI.
13. See ASME Sec. VIII, Div.1, Table UCS-23 for the materials listed in the ASME Sec. II, Part D, Subpart 1 (allowable stress values per temperature).
14. The impact test designated in this section is to perform CVN impact test per code unless otherwise specified.
15. "Blank" or "?" means no data or not applicable.
16. Use at colder than the minimum temperature designated for each standard material may be available if the applicable CVN impact test is successfully performed.
17. Use at warmer than the maximum temperature designated for each standard material may be available if the hot service is exposed in a short term or the applicable creep-rupture test is successfully performed, and the applicable code allows.
18. ASME metallic materials have been cooperated with ASTM materials since 1969. So, ASME material (SA/SB xxx) has the same contents with ASTM material (A/B xxx) unless it has ASME's sole symbol.
19. Many ASTM/ASME standards materials are designated with both dimensions of US customary and SI unit (i.e., SA-6/SA-6M and A6/A6M).
20. See ASME Sec.VIII, Div.1, UG-14 for rods and bars used pressure parts in pressure vessels.
21. See ASTM DS67B Handbook, CASTI Metals Data Book Series, EPRI-Carbon Steel Handbook, and Stahlschlüssel, Verlag Stahlschlüssel Wegst GmbH for Conversion of World Steel Standards.

Legend

BHN (= HBW)	Brinell hardness
Ceq [per IIW formula unless otherwise noted]	Carbon equivalent
Cl.	Class
DP	Design Pressure
HAZ	Heat affected zone
(A)HF	(anhydrous) hydrogen fluoric acid
Gr.	Grade
KSI	1000 psi = 6.895 MPa
min.	Minimum
max.	Maximum
NPS	Nominal Pipe Size, inch (e.g., NPS 2 = nominal 2 inch pipe)
N-T	Normalized and tempered
P. No	Parent number of the base metal (see Sect. 2.1.10.1 for more detail)
Q-T	Quenched and tempered
s.g.	Specific gravity or density (g/cm^3 or ton/m^3)
t, thick, or THK	Nominal wall thickness
(SM)TS	(specified minimum) tensile strength
(SM)YS	(specified minimum) yield strength
Sec.VIII-D1 or D2	ASME Section VIII, Division 1 or Division 2

Typical Clad Production Method and Dimensional Availability (Table 2.172)

Table 2.172 Typical clad production method and dimensional availability

Product	Wall thickness (mm)	Width/diameter (mm)	Max length (m)
Roll-bonded plate	Total thickness: 6–200 Cladding thickness: 1.5 mm to 40% of total thickness	1000–4000	14 or 20 depending on supplier
Explosive bonded plate	Cladding thickness: 1.5–25 mm. Minimum base metal thickness: 3× cladding thickness, maximum base metal thickness: no limit	50–3500	5
Explosive bonded plate with hot rolling		1000–4400	14
Overlay welded plate	Base metal >5 mm Clad layer >2.5 mm	Limited only by access of equipment	Limited only by access of equipment
Longitudinally welded clad pipe	6–32	219–1016	12.8 depending on supplier
Lined pipe	7–24 total wall Liner 2–20 mm	219–1016	9.6 or 12 depending on diameter
Seamless pipe extruded plug/mandrel mill	6–25	60–400 depending on supplier	Depending on diameter
Seamless pipe – explosive metallurgical joint	6–20	200–250	3 or 5 depending on supplier
Seamless pipe – after cold rolling	2–20	50–200	6–12
HIP (hot isostatic processing) clad pipe or fittings	>5 Clad layer: min. 2 mm thickness	25–1000 (or 762)	2 (or 4)
Weld overlay fittings	Base metal >5 mm Clad layer >2.5 mm	25 minimum	For small diameters limited by torch length, e.g., 1 m for diameter 50 mm No limit on large diameter

Source: NiDI Publ. 10,064, second Ed. modified

2.6.2.1 Plates and Strips – See General Notes

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C   Plates and Strips (1/23)

Material/brand	ASTM no. &Gr.	P no/Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Carbon steels (low and medium strength)	**A36**	1/1	41/25	−29 ~ 343	For <0 °C, Al-killed fine Grain practice and/or impact test (per S5 or S30) may be required. Si ≤ 0.04% except 0.15–0.40 for t > 38 mm Reference for impact test: CSA G40.20/21, Table 9 See ASTM A123 for hot dip galvanizing.	(a) For structures or nonpressure/low pressure parts ※ *Equivalent materials to A36* (1) **Products** – **ASTM no.** Hot rolled plate – A1011/1018-SS-36-1&2 Steel rivets – A502 Gr. 1 Bolts (general) – A307-A or F568M-Cl.4/6 High strength bolts – F3125(M), Gr.A325(M) Steel nuts – A563(M) Cast steel – A27(M) Gr. 65–35 CS forgings – A668(M)-Cl. D Hot formed tubing – A501 Cold formed tubing – A500 Gr. B Anchor bolts – F1554-Gr. 36 (1) TS & YS may not be the same as that of A36
	A283 Gr. A* Gr. B* Gr. C Gr. D	1/1	45–60/24 50–65/27 55–75/30 60–80/33	−29 ~ 343	* Withdrawn Note 21	(a) Low and intermediate tensile strength CS plates (b) For structural steel plates (e.g., storage tanks) or low-pressure parts [(D.P ≤ 2 kg/cm^{2}g (30 psig)] (c) Carbon limitation to be specified. (d) Rimmed or Semikilled before 2013. Killed since 2013
	A285 Gr. A Gr. B Gr. C	1/1	45–65/24 50–70/27 55–75/30	−29 ~ 482	Note 21	(a) Pressure vessel plates, CS, low and intermediate tensile strength (b) Semikilled or killed (if required by purchaser) (c) For low-pressure parts

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (2/23)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
	A737 Gr. B Gr. C	 1/2 1/3	 70–80/50 80–100/60	 −29 ~ 371	Gr. B: Co ≤ 0.05% Gr. C: *V*: 0.04–0.11% (heat) 0.03–0.12% (product) *N*: ≤0.03% Note 21	(a) Plates, high-strength, low-alloy steel for pressure vessel and piping (b) High yield strength-added alloy elements (c) Used for storage tanks (d) Product shape: coil or sheet (e) Normalized (N) or N-T (tempered)
	A299 Gr. A Gr. B	 1/2 1/3	 75–95/40&42 80–100/45&47	 −29 ~ 538	SMYS per thickness	(a) 0.84–1.50%Mn-0.13-0.45%Si CS (b) For welded boilers/pressure vessels (c) Max. THK: 200 mm (8 in.) (d) Normalized for 50 mm (2 in.) and above (e) Killed, fine grain (ASTM # > 5 or greater)
	A455	1/2	75–95/38* 73–93/37** 70–90/35***	−29 ~ 343	* *t* ≤ 9.5 mm ** *t* > 9.5 mm, <15 mm *** *t* > 15 mm, <20 mm Si: max. 0.10%, Note 21	(a) High-strength Mn steel for pressure vessels (b) Mn = 0.79–1.30% (c) Max. THK: 20 mm (0.75 in.) (d) Semikilled or capped (e) Can be killed by Al or Si if required by purchaser
	A662 Gr. A Gr. B Gr. C	 1/1 1/1 1/2	 58–78/40 65–85/40 70–90/43	 −60 ~ 371 (Note 14)	Supplementary requirements: See Note 14 &21	(a) C-Mn-Si steel for pressure vessel (b) Killed and fine grain practiced (c) Normalized for *t* > 40 mm (1.5 in.) (d) Gr. A, B, and C comply substantially with the requirements of ISO pressure vessel steels P9, P15, and P18, respectively
	A573 Gr. 58 Gr. 65 Gr. 70	 1/1	 58–71/32 65–77/35 70–90/42	 −29 ~ 482	*Max. thickness*: 40 mm (1.5 in.) Note 21	(a) Structural CS plates of improved toughness (b) Fine grain practiced (good toughness) (c) Used for storage tanks
	A992	1/1	65/50	−29 ~ 427		(a) For building framing or bridges, or for general structural purposes. (b) Killed steel. (0.10% ≤ Si ≤ 0.40% or Al ≥ 0.015%) (c) See ASTM A123 for hot dip galvanizing
	A562	1/1	55–75/30	−29 ~ 427	*Max. thickness*: 50 mm (2 in.) Note 21	(a) For pressure vessels with Mn-Ti for glass or diffused metallic coatings (b) A minimum specific ratio of Ti/C (>4) is to be specified to avoid free-iron carbides (c) Normalized
Carbon steels (low and medium strength)	**A131** A B D E AH32/36/40 DH32/36/40 EH32/36/40 FH32/36/40	 1/1	 58–75/34 58–75/34 58–75/34 58–75/34	 20 ~ 343 0 ~ 343 −20 ~ 343 −40 ~ 343 See right notes	 *Max. thickness:* 100 mm for plates 50 mm for shapes/bars *SMYS/SMTS* xH32: 64–75/32 xH36: 71–90/51 xH40: 74–94/57 33	(a) For structural shapes, plates, bars for ships (b) All grades except A & B: killed and find grain practice. A- & B-killed only. (c) A, B, D, E: Ordinary CS AHxx, DHxx, EHxx, FHxx: +Al, Cb, V, Ti, Cu, Cr, Ni, Mo, N – High strength –SMTS 46,51,57 ksi (d) CVN impact test temperature 20 °C (68 °F) for Gr. A 0 °C (32 °F) for Gr. B, AH32/36/40 −20 °C (−4 °F) for Gr. D, DH32/36/40 −40 °C (−40 °F) for Gr. E, EH32/36/40, FH32/36/40 (e) See ASTM A123 for hot dip galvanizing

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Plates and Strips (3/23)

Material/ brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Si-killed Coarse grain Carbon steel	**A515** Gr. 55 Gr. 60 Gr. 65 Gr. 70	 1/1 1/1 1/1 1/2	 55/30 60/32 65/35 70/38	−29 ~ 538	Killed *Max. thickness:* 300 mm 200 mm 200 mm 200 mm Mn: 0.60–1.20% For heat analysis Mn: 0.55–1.30% For product analysis Note 21	(a) As rolled: $t \le 50$ mm thick Normalized: $t > 50$ mm thick (b) For each reduction of 0.01% point below the specified maximum for carbon, an increase of 0.06% point above the specified maximum for Mn is permitted, up to a maximum of 1.50% by heat analysis and 1.60% by product analysis. (c) Recommended silicon killing when the service contains hydrogen or exposed to high-temperature sulfidation environment (>260 °C (500 °F)) (d) A515: For high temperature (good creep & rupture strength) – recommended at 343–427 °C (650–800 °F)/when impact test is not important. (e) A515: ASTM grain no. = 1–5 (coarse grain) (f) A516: Killed & ASTM grain no.: above #5 (g) A516: For low and medium temperature [−46 to 343 °C (−50 to 650 °F)] by high Mn-low C (h) A516: Impact test is required per thickness, heat treatment, and others
Si-(& Al) Killed Grain refined Carbon steel	**A516** Gr. 55 Gr. 60 Gr. 65 Gr. 70	 1/1 1/1 1/1 1/2	 55/30 60/32 65/35 70/38	−46 ~ 538	*Max. thickness:* 300 mm 200 mm 200 mm 200 mm Note 21	
Carbon steels	**A537** Cl. 1 Normalized	 1/2	70/50 65/45	−62($t \le 25$ mm) −60($t \le 75$ mm) −46($t \le 100$ mm)	$t \le 65$ mm 65 mm $< t \le$ 100 mm	(a) Killed (b) For low temperature of thick wall (c) *Q-T* (Cl.2&3); high strength ; $T \ge 595$ °C (1100 °F) -Cl.2 ; $T \ge 620$ °C (1150 °F) -Cl.3 (d) Used for LPG/ethylene storage tanks – hardness control required for sour service (e) Maximum temperatures ; 343 °C for Cl.1/371 °C for Cl.2 (f) Production test including full PWHT and impact test may be required for *Q-T* steel * Lower temperature may be acceptable if impact test is passed
	Cl. 2 Quenched- tempered (Q-T)	1/3	80/60 75/55 70/46	−68($t \le 65$ mm) −60($t \le 75$ mm) −40($t \le 100$ mm)	$t \le 65$ mm 65 mm $< t \le$ 100 mm 100 mm $< t \le$ 150 mm	
	Cl. 3 Quenched- tempered (Q-T)	1/3	80/55 75/50 70/40	−68($t \le 65$ mm) −60($t \le 75$ mm) −40($t \le 100$ mm) *	$t \le 65$ mm 65 mm $< t \le$ 100 mm 100 mm $< t \le$ 150 mm	
Carbon steels	**A414** Gr. A Gr. B Gr. C Gr. D Gr. E Gr. F Gr. G	 1/1 1/1 1/1 1/1 1/1 1/2 1/2	 45/25 50/30 55/33 60/35 65/38 70/42 75/45	−29 ~ 538		(a) Killed (by Al-Si: Si = 0.15–0.30%; or by Al) (b) Hot-rolled CS sheet for pressure vessels involving fusion welding or brazing (c) Welding and brazing technique is of fundamental importance and shall be in accordance with commercial practices
Structural steel Min. 0.2Cu	**A588** Gr. A Gr. B Gr. K	*M-no.* 1/2 1/2 1/2	 70/50* 67/46 63/42	~ 343 Impact test may be required for low temperature	*Plate thickness, t*: $\le$100 mm 100 $< t \le$ 125 mm 40 $< t \le$ 100 mm	(a) Weathering structural steels (b) See AWS D1.1 for welding and impact test * For all structural shapes Gr. A: ≤0.19C, 0.8–1.25Mn, 0.3–0.65Si, ≤0.4Ni, 0.4–0.65Cr, 0.25–0.4Cu, 0.02–0.10V Gr. B: ≤0.20C, 0.75–1.35Mn, 0.15–0.5Si, ≤0.5Ni, 0.4–0.7Cr, 0.2–0.4Cu, 0.01–0.10V Gr. K: ≤0.17C, 0.5–1.2Mn, 0.25–0.50Si, ≤0.4Ni, 0.4–0.7Cr, ≤0.1Mo, 0.3–0.5Cu, 0.005–0.05Cb
Structural steel Min. 0.2Cu	**A242**		 70/50* 67/46** 63/42***	⁂ ~ 343 ~ 343 ⁂ per impact test result	*Plate thickness, t*: ≤20 mm* 20 $< t \le$ 40 mm** 40 $< t \le$ 100 mm***	(a) Weathering structural steels (b) See AWS D1.1 for welding and impact test * Flange or leg thick. of structure: ≤40 mm(1.6 in.) ** Flange of structure: 40 $< t \le$ 50 mm (2 in.) *** Flange of structure: $t > 50$ mm (2 in.)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (4/23)

Material/brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Killed grain refined low-alloy steel	**A517** Gr. A Gr. B Gr. E Gr. F Gr. P	 11B/1 11B/4 11B/2 11B/3 11B/8	For all grades [≤65 mm] 115–135/ 100 [>65 mm] 105–135/90	For all grades −29 to 343	*Max. thickness:* Gr. A, B: 32 mm Gr. H, S: 50 mm Gr. P: 100 mm Gr. F: 65 mm Gr. E, Q: 150 mm Note 21	(a) For pressure vessel plates, alloy steel, high-strength, Q-T in fusion welded boilers and other pressure vessels (b) Killed, grain refined, and impact tested (c) Gr. A: 0.5Cr-0.25Mo-Si Gr. B: 0.5Cr-0.2Mo-V Gr. E: 1.75Cr-0.5Mo-Ti Gr. F: 0.75Ni-0.5Cr-0.5Mo-V Gr. P: 1.25Ni-1Cr-0.5Mo
Q-T steel	**API spec 2Y** Gr.50 Gr.60	 1/1 1/2	 65/50–75 65/50–70 75/60–90 75/60–85	−60 ~ 343 $t \leq 1''$ $t > 1''$ $t \leq 1''$ $t > 1''$		(a) Q-T for offshore structures (b) $C \leq 0.12\%$ (c) To apply both of Ceq & Pcm for carbon equivalent (d) See Note 13
Q-T steel	**A724** Gr. A Gr. B Gr. C	 1/4 1/4 1/4	 70/90–110 75/95–115 70/90–110	 −46* to 343 −46* to 343 −46* to 343	*Max. thickness, t*: 22 mm for Gr.A&B 50 mm for Gr.C * In case of $t \leq 25$ mm	(a) For welded pressure vessel, C-Mn-Si Q-T steel (b) Tempering temperatures/soaking time ≥595 °C (1100 °F) and ≥0.5 hr. for Gr.A&B ≥620 °C (1150 °F) and ≥0.5 hr. for Gr.C
High YS, Q-T alloy steel	**A514** Gr. A Gr. B Gr. E Gr. F Gr. H Gr. P Gr. Q Gr. S	 11B/1 11B/4 11B/2 11B/3 11B/3 11B/8 11B/9 11B/6	For all grades, 110–130/ 100* For $t \leq 65$ mm 100–130/90 For $t \leq 150$ mm	** ~ 343 ** per impact test result	*Max. thickness*: 150 mm *Hardness*: 235–293 HBW *Heat treatment* *Q*: ≥900 °C (1650 °F), *T*: ≥620 °C (1150 °F) See AWS D1.1 for welding details	(a) High YS, Q-T alloy steel plate, suitable for welded bridges and other structures. (b) Gr.A: 0.65Cr-0.23Mo-0.1Zr Gr.B: 0.52Cr-0.2Mo-0.05V-0.05Ti-0.002B Gr.E: 1.7Cr-0.5Mo-0.05Ti-0.003B Gr.F: 0.85Ni-0.52Cr-0.5Mo-0.05V-0.35Cu-0.003B Gr.H: 0.5Ni-0.52Cr-0.25Mo-0.05V-0.002B Gr.P: 1.35Ni-0.12Cr-0.52Mo-0.003B Gr.Q: 1.35Ni-1.3Cr-0.5Mo-0.05V Gr.S: 0.8Mo-0.06V-0.003B
Q-T steel structural	**A852** Withdrawn	1/3	90–110/70	−29 ~ 343	*Max. plate thickness*: 100 mm	(a) Chemical composition: C-Mn-Ni-Cu-V (b) See ASTM A123 for hot dip galvanizing.
Precipitation-strengthened low-alloy structural steel	**A710** Gr.A, Cl.1 Gr.A, Cl.2 Gr.A, Cl.3 Gr.B, Cl.1 Gr.B, Cl.2 Gr.B, Cl.3	*M-No* 12C/1 12A/1 12B/1	Gr.A; 60–90*/ 50–85* Gr.B; 80/70 *Thickness/ condition	** ~ 343	*Max. thickness*: Gr.A, Cl.1: 20 mm Gr.A, Cl.2&3: 200 mm Gr.B: 50 mm *Composition*: Gr.A: 0.85Ni-0.75Cr-0.2Mo-1.15Cu-0.02Cb-max.0.07C Gr.B: 0.9Ni-1.3Cu-0.04Cb-0.02Ti-0.06C	(a) Gr.A, Cl.1: As rolled-precipitation heat treated Gr.A, Cl.2: Normalized-precipitation heat treated Gr.A, Cl.3: Quenched-precipitation heat treated Gr.B, Cl.1: As rolled Gr.B, Cl.2: Normalized Gr.B, Cl.3: Normalized-precipitation heat treated (b) For navy aircraft carriers, cruisers, and submarines, as well as mining and dredging equipment, high-reliability lifting hardware, offshore drilling platforms, large valves, and heavy-duty truck frames ** Impact tested per A673 at: −45 °C for Gr.A, Cl.1; min.27 J for longitudinal./ min.20 J for transverse −23 °C for Gr.B, Cl.1&3; min.47 J for longitudinal −45 °C for Gr.B, Cl.2; min.27 J for longitudinal
High-strength Structural CS and LAS for bridges	**A709** 36 36 50 50S 50W HPS50W HPS70W HPS100W HPS100W [Gr. for SI unit]	*M-No* 1/1 1/1 1/2 1/2 11B/ 11 11B/2 11B/2	58–80/36 58/36 65/50 65/50–65 70/50 70/50 85–100/70 110–130/ 100 100–130/90	* ~ 343	*Max. thickness for TS*: 75 mm 76–100 mm 100 mm – 100 mm 100 mm 100 mm 65 mm 65–100 mm All grades: killed Suffix S = high ratio of YS/YS Suffix W = high tensile strength	(a) Structural shapes, plates, bars, and Q-T alloy steel for bridges (b) 36[250] – CS 50[345] – type 1 (+Cb), type 2 (+V), type 3 (+Cb + V+(Cb + V)), type 5 (+Ti, N, V) 50W[345W] + Ni, Cr, Cu, V per type A & B HPS50W [HPS 345W] – to be fine grain practice HPS70W [HPS 485W] – to be fine grain practice HPS100W [HPS 690W] (c) See ASTM A123 for hot dip galvanizing (d) Type A & B: The same as A588-Gr.A & B. (e) * Impact test zone; min. required energy per zone, material grade, thickness, and nonfracture or fracture-critical tension component Zone 1: −18 °C (0 °F) Zone 2: −18 to −34 °C (0 to −30 °F) Zone 3: −34 to −51 °C (−30 to −60 °F)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (5/23)

Material/ brand	ASTM no. &Gr.	P no/Gr no	SMTS/SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
High-strength Structural steel C-Mn-Si-Cb-V	**A572** Gr.42 Gr.50 Gr.55 Gr.60 Gr.65	 1/1 1/1 1/2 1/2 1/2	 60 65 70 75 80	 −29 ~ 343	*Max. plate thickness* 150 mm 100 mm 50 mm 32 mm 32 mm	(a) For high-strength low-alloy structural steel shapes, plates, sheet piling, and bars *Four types* 1: + Cb 2: + V 3: + Cb, V 5: + Ti, N, V (b) See ASTM A123 for hot dip galvanizing
Normalized low alloy structural steel C-Mn-Ni-Cu-V	**A633** Gr. A Gr. C Gr. D Gr. E	 1/1 1/1&2 1/1&2 1/2	 63–83/42 65–90/46–50 65–90/46–50 75–100/55–60	 −46* ~ 343 *To be impact tested for < −46 °C	*Max. plate thickness*: 100 mm (Gr.A,C,D) 150 mm (Gr.E) Different TS & YS Per thickness P no./*Gr no* Gr.1: SMTS<70ksi Gr.2: SMTS<80ksi Gr.3: SMTS≥80ksi	(a) High-strength low-alloy structural steel plater for use in welded, riveted, or bolted construction at −45 °C (−50 °F); impact tested (b) The normalizing temperature shall not exceed 925 °C (1700 °F). (c) Grade E material for *t* > 75 mm (3 in.) shall be double normalized (d) Fine grain practiced per ASTM A6 (e) Impact test required (f) Modified grade may be used, i.e., copper bearing steel to improve the atmospheric corrosion resistance/impact test at ≥ −60 °C (−75 °F) (g) See ASTM A123 for hot dip galvanizing
C-Mn-Si carbon steel	**A738** Gr. A Gr. B Gr. C Gr. D Gr. E	 1/2 1/3 1/3	 75/ 80/ 85/ 90/	 −29* ~ 343 Impact test required for −29 °C and colder	*Max. thickness:* Gr. A/C:150 mm (6 in.) Gr. B: 100 mm (4 in.) Gr. D: 40 mm (1.5 in.) Gr. E: 50 mm (2 in.) Note 21	(a) For pressure vessel heat treated, C-Mn-Si for moderate- and lower-temperature service (b) Heat treatment (c) Gr. A [*t* ≤ 65 mm (2.5 in.)]: N or Q-T Gr. A [*t* > 65 mm (2.5 in.)], Gr.B-E: Q-T Tempering temperature ≥ 595 °C (1100 °F)
TMCP steel Note 20	**A841** Gr.A/B/C-Cl.1 Gr.A/B/C-Cl.2 Gr. D Gr. E-Cl.4 Gr. E-Cl.5 Gr. F-Cl.6 Gr. F-Cl.7 Gr. F-Cl.8 Gr. G-Cl.9 Gr. G-Cl.10	 1/2 1/3 1/3 1/3 1/3 1/3	 65–90/45–50 75–100/55–60 145–170/100 84–104/70 88–108/75 82–102/70 86–106/75 90–110/80 100–120/85 109–129/90	 −40 ~ 343 −40 ~ 343 −40 ~ 343 −40 ~ 343 −40 ~ 343 −40 ~ 343 −40 ~ 343 −40 ~ 343 −195 ~ 343 −195 ~ 343	*Max. thickness:* 150 mm (Gr.50) 100 mm (Gr.60) TS/YS: per thick. Note 21	(a) TMCP for pressure vessel (b) Killed and grain refined (c) C content for Gr. C through E is very low (d) Gr. D: 1.25%Ni steel (e) Gr. G: 6.5%Ni steel (f) PWHT temperature – Note 22 ; ≤530 °C (985 °F) for Gr. G ; ≤650 °C (1200 °F) for other grades (g) Impact tested for all grades. Lateral expansion measurement is required for Gr. D & G
	A1066 Gr. 50 Gr. 60 Gr. 65 Gr. 70 Gr. 80	 3/1 3/2 3/3 3/3 3/3	 50/65 60/75 65/80 70/85 80/90	 −23 ~ 343 −23 ~ 343 −23 ~ 343 −23 ~ 343 −23 ~ 343	*Max. thickness:* 100 mm (Gr.50/60) 75 mm (Gr.65) 50 mm (Gr. 70) 25 mm (Gr. 80) Max. Ceq required per grade.	(a) TMCP for welded structural steel (b) *C* ≤ 0.14% for r.50, *C* ≤ 0.16% for all others (c) Si = 0.15–0.50% (d) Hot form and PWHT temperature ≤560 °C (1050 °F) for all grades unless proved for higher temperature (e) Impact tested for all grades at −23 °C (−10 °F)
	API spec 2W Gr.50 Gr.60	 1/1 1/2	 65/50–75 75/60–90	 −40 (to −60*) ~ 343	* Per impact test	(a) TMCP for offshore structures (b) For fabrication primarily by cold forming and welding
TMCP-QST Steel Note 20	**A913** Gr. 50 Gr. 60* Gr. 65* Gr. 70*	*M-No.* 1/2 1/3 1/3 1/4	 65/50 75/60 80/65 90/70	 * ~ 343 *Per impact test result	* Fine grain practiced per ASTM A6 Gr. 50: CeqIIW≤0.38% Gr. 60: CeqIIW≤0.40% Gr. 65: CeqIIW≤0.43% Gr. 70: CeqIIW≤0.45%	(a) High-strength LAS shapes of structural quality, produced by QST (quenched and self-tempered process) (b) Tempering: at 595–705 °C (1100–1300 °F) (c) PWHT ≤600 °C (1100 °F) – Note 22 (d) Impact tested per ASTM A673 (≥54 J at 21 °C)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (6/23)

Material/ brand	ASTM no.&Gr.	P no/Gr no	SMTS/SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Killed Grain refined Low-alloy steel	**A533** Gr. A Gr. B Gr. C Gr. D	*Cl.1&2* : 3/3 *Cl.3* : 11A/4	Cl.1: 80–100 Cl.2:90–115 Cl.3:100–125	−29 ~ 538* *343 preferable	*Max. t* Cl.1&2: 300 mm Cl.3: 65 mm *Min. t*: 6.5 mm Gr. A: 0.5Mo Gr. B: 0.5Mo-0.55Ni Gr. C: 0.5Mo-0.85Ni Gr. D: 0.5Mo-0.30Ni	(a) For pressure vessel plates, alloy steel, high-strength, and Q-T steels (b) Killed (c) These alloy steel plates in the as-rolled condition are sensitive to cracking during transit and handling, particularly in $t > 25$ or 50 mm [about 1 or 2 in.]. (d) Tempering temperature: ≥595 °C (1100 °F)
C-½Mo	**A204** Gr. A Gr. B Gr. C	3/1 3/2 3/2	65/37 70/40 75/43	−29 ~ 538 Max.465 °C (870 °F) to avoid graphitization.	Killed *Max. thickness*: 150 mm 150 mm 100 mm	(a) As rolled: $t \leq 38$ mm Normalized: $t > 38$ mm or when impact test required (b) Advanced high-temperature strength, graphitization resistance, hydrogen attack resistance than CS (c) It may not be used to resist HTHA in API RP941for new construction. Careful/periodic inspection in HTHA service is required for the existing facilities
C-½Mo-(Ni)	**A302** Gr. A Gr. B Gr. C Gr. D	3/2 3/3 3/3 3/3	75–95/45 80–100/50 80–100/50 80–100/50	−29 ~ 538	Killed & fine grain Gr. A/B: 0.5Mo Gr. C: 0.5Mo-0.55Ni Gr. D: 0.5Mo-0.85Ni See API RP/TR941	(a) For Mn-Mo and Mn-Mo-Ni alloy steel intended primarily for pressure vessels and boilers (b) Normalized for $t > 50$ mm (2 in.) (c) *Q-T* for $t > 100$ mm (4 in.) Tempering: 595–705 °C (1100–1300 °F)
½ Cr-½ Mo	**A387** Gr. 2 (K12143) Cl. 1 Cl. 2	3/1	55–80/33 70–90/45	−29 ~ 538	Killed & Coarse Grain Cl. 1:Annealed or N-T Cl. 2: N-T or *Q-T* Min. tempering temp: 620 °C (1150 °F)	(a) For high-temperature oxidation resistance & creep-rupture strength (see API RP/TR941) (b) PWHT is required at the thinner than that of CS (c) See Note 12 for N-T (d) Note 11
1 Cr-½ Mo	**A387** Gr. 12 (K11757) Cl. 1 Cl. 2	4/1	55–80/33 65–85/40	−29 ~ 649* *Max. 593 °C (1100 °F) preferable	Killed Cl. 1:Annealed or N-T Cl. 2: N-T or *Q-T* Min. tempering temp: 620 °C (1150 °F)	(a) For HTHA/high temperature oxidation resistance & creep-rupture strength (see API RP/TR941) (b) PWHT is required at the thinner than that of CS (c) Reference: API TR934-D (d) See Note 12 for N-T and Note 11 (e) Max. 100 mm (4″) preferable due to toughness
1¼Cr -½ Mo	**A387** Gr. 11 (K11789) Cl. 1 Cl. 2	4/1	60–85/35 75–100/45	−29 ~ 649* *Max. 593 °C (1100 °F) preferable	Killed Cl. 1:Annealed or N-T Cl. 2: N-T or Q-T Min. tempering temp: 620 °C (1150 °F)	(a) For HTHA/high temperature oxidation resistance & creep-rupture strength (see API RP941) (b) PWHT is required at the thinner than that of CS (c) Reference: WRC-411, API RP934-C ($t \geq 50$ mm), API RP934-C/E, API RP/TR941, API TR934-D (d) See Note 1, 10, 11, Table 2.31, Note (2), and Note 12 for N-T (e) Max. 100 mm (4″) preferable due to toughness
2¼ Cr-1Mo	**A387** Gr. 22 Cl. 1 Cl. 2	5A/1	60–85/30 75–100/45	−29 ~ 649	Killed Cl. 1:Annealed or N-T Cl. 2: N-T or Q-T Min. tempering temp: 675 °C (1250 °F)	(a) For HTHA/high temperature oxidation resistance & creep-rupture strength (see API RP941) (b) PWHT is required. (c) Gr.22, Cl.2: max. 593 °C(1100 °F) for B16.5 flange (d) Note 1, 10 & 11
2–3 ¼Cr-1Mo-V	**A542** Cl.1 Cl.2 Cl.3 Cl.4 Cl.4a	5C/1	105–125/85 115–135/100 95–115/75 85–110/55 85–110/60	−29 ~ 454 −29 ~ 454 −29 ~ 482 −29 ~ 482 −29 ~ 482	*Min. thickness:* 5 mm Killed and fine grain practiced Note 1	(a) Q-T steel for pressure vessel (b) For HTHA/high temperature oxidation resistance & creep-rupture strength (see API RP941) (c) Impact tested for Cl.4 & 4a (at −18 °C) (d) There are 5 types of material groups: Type A: 2.25Cr-1Mo-0.035V Type B: 2.25Cr-1Mo-0.025V Type C: 3Cr-1Mo-0.25V-Ti-B Type D: 2.25Cr-1Mo-0.3V-Ti-B Type E: 3Cr-1Mo-0.25V
2–3 ¼Cr-1Mo-V	**A832** Gr.21V Gr.22V Gr.23V	5C/1	85–110/60	−29 ~ 482 −29 ~ 482 −29 ~ 482	*Max. thickness:* 150 mm Note 1	(a) N-T steel for pressure vessel (b) Killed and fine grain practiced (d) Gr.21V: 3Cr-1Mo-0.25V-Ti-B Gr.22V: 2.25Cr-1Mo-0.30V-Ti-B-Cu-Ni-Cb-Ca Gr.23V: 3Cr-1Mo-0.25V-Cb-Ca

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Plates and Strips (7/23)

Material/ brand	ASTM no.&Gr.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
3 ½ Cr-1Mo	**A387** Gr. 21 Cl. 1 Cl. 2	5A/1	60–85/30 75–100/45	−29 ~ 649	Annealed or N-T (or Q-T by purchaser) Min. tempering temp: 675 °C (1250 °F)	(a) Killed (b) Reference: API RP934-A & H/API RP939-C/ RP941 & NACE Publ. 34,103 (c) See Note 1 & 11 (d) See Note 12 for N-T
5Cr- ½ Mo	**A387** Gr. 5 Cl.1 Cl.2	5B/1	60–85/30 75–100/45		Cl. 1:Annealed or N-T Cl. 2: N-T or Q-T Min. tempering temp: 675 °C (1250 °F) for Gr.9 and 705 °C (1300 °F) for Gr.5 Killed PWHT required Note 11 for classes Note 12 for N-T except 9Cr-1Mo-V	(a) For high-temperature sulfidation or HTHA environment. See API RP939-C/RP941 & NACE Publ. 34103 (e) General (mild) service (API RP577 & TR938-B): Max. 241 BHN for 5B/1 Max. 248 BHN (process)/275 BHN (utility) for 5B/2 (f) Environmental cracking service (max. hardness) 235 BHN for 5B/1 and 248 BHN for 5B/2 (g) Grade 91: to be normalized at 1040–1080 °C (1900–1975 °F)/to be tempered at 730–800 °C (1350–1470 °F) (h) Reference for Gr.91: API TR938-B (i) There are no allowable stress values in ASME Sec. II-Part D while there are the allowable stress values in ASME B31.3 for plate material of 9Cr-1Mo
9Cr- 1Mo	**A387** Gr. 9 annealed N-T or Q-T	5B/1	60–85/30 75–100/45	−29 ~ 649		
9Cr- 1Mo-V	**A387** Gr.91- Cl.2 N-T or Q-T	15E/1	85–110/60	−29 ~ 649		
2–4 Ni	**A543** Gr. B Gr. C	*Cl.1* 11A/5 *Cl.2* 11A/10 *Cl.3* 3/3	*Cl.1* 105–125/85 *Cl.2* 115–135/ 100 *Cl.3* 90–115/70	−68* ~ 538	t: normally 50 mm (2 in.) and above Mn. 5 mm (3/16 in.)	(a) For pressure vessel plates, Q-T Ni-Cr-Mo alloy steels (b) Gr.B: 2.25–4.0Ni, 1.0–1.9Cr, 0.2–0.65Mo Gr.C: 2.0–3.50Ni, 1.0–1.9Cr, 0.2–0.65Mo (c) Tempering temperature: ≥595 °C (1100 °F)
2 ¼ Ni	**A203** Gr. A Gr. B	9A/1 9A/1	65–85/37 70–90/40	−68* ~ 538 −68* ~ 538	*Max. t*: 150 mm 150 mm	(a) Killed and fine grain practiced (b) Impact tested and normalized (c) PWHT required for $t > 16$ mm (0.625″) * −68 °C (≤50 mm)/–59 °C (≤76 mm) ** −101 °C (≤50 mm)/–87 °C (≤76 mm)
3 ½ Ni	**A203** Gr. D Gr. E Gr. F	9B/1 9B/1 9B/1	65–85/37 70–90/40 75–100/ 50–55	−101** ~ 538 −101** ~ 538 −107 ~ 538	*Max. t*: 100 mm 100 mm 100 mm	(a) Killed and fine grain practiced (b) Impact tested and normalized for Gr.D&E (c) Impact tested and Q-T ($T > 595$ °C) for Gr.F (d) PWHT required for $t > 16$ mm (0.625″)
5 or 5 ½ Ni	**A645** Gr. A Gr. B	11A/2 11A/2	95–115/65 100–120/85	−140 ~ 121 −195 ~ 121		(a) Q-T steel for pressure vessel (b) Killed and fine grain practice (c) Impact tested
9 Ni	**A844** **A553**-I	11A/1	100–120 /85	−196 ~ 121* *Max. 93 °C (200 °F) For piping	*Max. t.* 50 mm A553-II for 8%Ni A553-III for 7%Ni	(a) Direct quenching process (b) Impact tested @-196 °C (−320 °F) (c) PWHT required for $t > 50$ mm (ASME Sec. VIII, Div.1, UHT-56). (d) Susceptible to hot crack for heavy wall welding (> 50 mm)
Low alloy steel 1.6Mn- 0.5Ni -V	**A225** Gr. C Gr. D	10A/1	105–135/70 80–105/60* 75–100/ 55**	*** ~ 343 ***per impact test result	* $t \leq 75$ mm (3 in.) **$t > 75$ mm (3 in.)	(a) For Mn-V-Ni alloy steel intended primarily for welded layered pressure vessels (b) Killed and fine grain practiced (c) Normalized for Gr. D (all) and Gr. C, $t > 50$ mm
20–28% Mn austenitic Steel			110/52	-196 ~ 121*	Q-T steel *For higher temperature application, consult with metallurgist	(a) See Sect. 2.1.4.4 for more details. (b) $C = 0.2$–0.6%, Si < 1.0%, $P < 0.03\%$, $S < 0.01\%$, $N < 0.1\%$ with trace Ni, Cr, Mo, Cu, Al, Ti, Nb, and B (if necessary)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C — Plates and Strips (8/23)

Material/ brand	ASTM no.&Gr.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
MSS 11.5~27Cr	**A240** 410 (S41000) (12Cr)	6/1	65/30	−29 ~ 649* *Recommended temperature: <400 °C (750 °F) for long-term operation	*Max. hardness:* 217 BHN for 410 s.g.: 7.70 Highly decreased the toughness after several hundred hours at 400~550 °C [called as 475 °C (885 °F) embrittlement)]	(a) Carbon content is 0.12~1.2% higher than that of FSS. Air hardening materials (b) Good corrosion resistance in high temperature sulfur, H_2, and wet H_2S services (c) Poor corrosion resistance in low-temperature oxidation environment than CS (d) Recommended only for nonpressure parts in weldable equipment and piping (e) Poor weldability (f) Careful chemical cleaning required
<Bar &Shape> MSS 12~16Cr-0~5Ni	**A479** S40300 S41000 S41040 S41400 S41425 S43100	6/3	70–110/ 40–85 70/110/ 40–85 70–125/ 40–100 115/90 120/95 115/90	−29 (−40*) ~ 649	s.g.: ≈ 7.81 * Impact test required TS & YS per type of heat treatment	(a) Better toughness in MSS (b) Good SSC resistance (c) For tool or machinery components (d) S40300: 12Cr S41040 (XM-30): 12Cr-0.1Cb S41400: 12Cr-1.5Ni S41425: 13Cr-5Ni-1.5Mo-0.3Cu-0.1N S43100: 16Cr-1.5Ni
<Bar> MSS 11~15Cr-0~7Ni	**A565** S64152 S41041 S41425 S41800 S42200 S42300 S42226	6/3	145/115 115/75 120/95 140/110 140/110 140/110 140/110	−29 ~ 649	s.g.: ≈ 7.81 TS & YS: only based on heat treatment, 'HT'. See A565 for other heat treatment conditions.	(a) MSS bars for high temperature service (b) For oxidation (scaling) resistance and at low stresses, up to 790 °C (1450 °F) (c) S64152: Gr. XM-32 S41800: Gr.615 S42200: Gr. 616 S42300: Gr. 619
FSS 11.5~27Cr	**A240** 405 (S40500) 410S (S41008) 430 (S43000) 409 (S40900) 446 (S44627) XM-33 (S44626)	7/1 7/1 7/2 7/1 10I/1 10I/1	60/25 60/30 65/30 55/25 65/40 68/45 Low YS because of decreasing the carbon to prevent of Cr-carbide.	−29 ~ 538* −29 ~ 649* −29 ~ 649* −29 ~ 538* −29 ~ 343 −29 ~ 343 *Recommended temperature: <400 °C (750 °F) for long-term operation; highly decreased the toughness after several hundred hours at 400~550 °C [475 °C(885 °F) embrittlement)]; more Cr, more early occurs	*s.g.* 405 : 7.72 410S : 7.70 430 : 7.72 409 : 7.75 446 : 7.80 XM-33 : 7.80 *Max. hardness:* 179 BHN except 183BHN for 410S SS/430 SS, 187 BHN for 446 SS. 405: 13Cr-Ni ≤ 0.6 410S: 12Cr-Ni ≤ 0.6-C ≤ 0.08 430: 17Cr-Ni ≤ 0.75 409: 11Cr-Ni ≤ 0.5 446: 25Cr-Ni ≤ 0.75-N ≤ 0.25 XM-33: 26Cr-Ni ≤ 0.5-1Mo-0.5Ti-N ≤ 0.04-Cu ≤ 0.2	(a) Good high temperature oxidation/sulfur/H_2/H_2S resistance (b) Good formability at low temperature. (c) Good pitting & SCC resistance for chloride (d) Less corrosion resistance in low-temperature oxidation environment than CS; ASS is a better choice except Cl-SCC and pitting (e) Sigma (σ) phase embrittlement 550~850 °C after several ten or hundred hours (f) 405 (13Cr): added aluminum to prevent 1st hardening (martensitic structure). Improved weldability. No forging product (g) 410S is a non-air hardening material. (h) 430 (18Cr): more corrosion resistance and improved high-temperature strength than 13Cr. However more susceptible to 475 °C (885 °F) embrittlement than 13Cr. (i) 405 and 410S: Recommended only for nonpressure parts in weldable equipment and piping (normally not used as solid materials for pressure parts unless otherwise approved) (j) 409 SS (S40900) has been replaced by three types, S40901, S40902, and S40903; it shall be satisfied by any one of S40910, S40920, or S40930 per the seller's option

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (9/23)

Material/brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
ASS (conventional) 18Cr-8Ni Or 23Cr – 12Ni Or 25Cr – 20Ni	**A240** 304 304L 309S 310S 316(Ti/Cb) 316L 316LN 317(L/LM) 321(H) 347(H/LN) 348(H) 304H 316H 347H	8/1	75/30 70/25 75/30 75/30 75/30 70/25 75/30 75/30 75/30 75/30 75/30 75/30 75/30 75/30	−254 ~ 816 −254 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 −198 ~ 816 *Recommended maximum Temperature* ; 538 °C (due to creep strength) *Min. Temperature* for 304, 304L, 316, 316L, 347 in B31.3: −254 °C (−425 °F)	*s.g.* 304L: 7.94 309S: 7.98 310S: 7.98 316: 7.98 316L: 7.98 321: 7.90 347: 8.02 304H: 7.94 316H: 7.98 *Suffix* L = low carbon (good IGC resistance) H = high carbon (good creep-rupture strength) 321: Ti added, 347: Nb added Max. temp. for low C (<0.03%): 427 °C (800 °F) [454 °C (850 °F) for ASS with Mo ≥ 2.5%] 321/347: stabilized annealing recommended for the service at 400 °C (750 °F) and warmer	(a) 304L, 316L, 321: Used at ≤427 °C (800 °F)] and mild acidic service (> pH 4.5) (b) All "H" grades: contain 0.04–0.1%C for high-temperature strength. Average grain size, ASTM no.7 or coarser per ASTM E112. See Note 8 in Pipes & Tubes for reference (c) 304, 316 for welded parts: use low carbon ($C \leq 0.03\%$) or dual grade (304/304L or 316/316L) (d) 309S (23Cr-13Ni), 310S (25Cr-20Ni): High-temperature oxidizing resistance. Grain size to be ASTM 6 or coarse for the service at 565 °C (1050 °F) and warmer (e) 316 (2%Mo), 317 (3%Mo): More corrosive than 304 in oxidizing acid (e.g., HNO_3, conc. H_2SO_4)/good pitting resistance in mild acidic environment (f) All 300 series: Susceptible to Cl-SCC and CUI (g) Large size and thick wall: economically preferable to use clad materials for corrosion resistance. Some companies want to use clad instead of solid SS because of mitigation effect of SCC propagation (h) 347 welding material should be used for 321 welding (i) Corrosion test (IGC, SCC, etc.) may be considerable for severe corrosion service (j) Passivation treatment and segregated work (from carbon and low alloy steels) are recommended for corrosive service
ASS 16-19Cr, 3.5–6.0Ni, 5.5-10Mn	**A240** 201–1 201–2 (S20100) 202 (S20200)	 8/3 8/3 8/3	 75/38 95/45 90/38	 −196 ~ 204 −196 ~ 204 −196 ~ 204	201: 17Cr-4Ni-6Mn-N 202: 18Cr-5Ni-7Mn-0.25N	(a) Type 201 is generally produced with a chemical composition balanced for rich side (type 201–1) or lean side (type 201–2) austenite stability depending on the properties required for specific applications
ASS **XM-19** 21Cr-12Ni-2Mo-5Mn-0.2N-0.1Nb-0.1V	**A240** S20910	8/3	100*/55*	−196~649	*105/60 for sheet and strip	(a) Slightly higher corrosion resistance than those of 316L or 317L SS (b) Higher strength than those of 316L or 317L SS (c) For boat and pump shafting in marine hardware or downhole (d) ASTM A276 for bar and shape in general (e) ASTM A479 for bar and shape in boilers and other pressure vessels (f) Brand name: Nitronic 50
ASS **Alloy 904L** 20Cr-25Ni-4.3Mo-1.5Cu Sandvik 2RK66	**A240** **B625** N08904	45/–	71/31	−196~370	*Hardness:* HV10 160–210 s.g.: 8.0 Annealed at At 1070–1100 °C PRE: 35	(a) Good resistance to Cl-SCC. Copper gives good corrosion resistance to reducing media (hot phosphoric acid, dilute H_2SO_4, etc.) (b) Offshore, seawater, chemical industry, good stability against reducing acids of medium strength like sulfuric acid, phosphoric acid, and various chloric media in refinery, paper, bleach, pulp, and fertilizer industry. See Note 2
PHSS **17-4PH** 17Cr–4Ni–4Cu+0.2Nb	**A693**–630 **A564**–630 S17400		115–190 /75–170	−29 ~ 343	*Hardness:* BHN 255~388 s.g.: 7.74	(a) 4wt% Cu (b) Martensitic structure-for erosion resistance, e.g., valve, pump, piston rod, ball bearing, shaft, etc. (c) See NACE Conference Paper 03102
17-7 PH 17Cr–7Ni–1Al	**A693**-631 **A564**--631 S17700		170–185 /140~150	−29~343	*Hardness:* BHN 352~388 s.g.: 7.81	(a) 1.1% Al (b) Quasi-austenitic structure – for spring, washer, valve materials

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (10/23)

Material/ brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
PHSS **XM-25** 15Cr-6Ni-0.7Mo-1.5Cu-1Mn	**A564** S45000 A693 S45000		125–165*/ 95 130/90 or 165/150	−29 ~ 427	*Hardness:* BHN 311 max. s.g.: 7.80	(a) Martensitic age-hardenable PHSS (alloy 450) (b) Good corrosion resistance (similar to 304 SS) (c) Brand name: Custom 450 (d) * Up to 13 mm (0.5 inch) (e) Specify SMTS/SMYS for A693 recommended
PHSS **660** 15Cr-25Ni-1.2Mo-2Ti	**NAS 660** S66286		140/95	−29 ~ 700	*Hardness:* BHN 160~350 s.g.: 7.98	(a) Good high-temperature strength, such as jet engines, gas turbines and turbo charger components (b) NAS: Nippon Yakin Kogyo brand (c) JIS G4312-SUH 660, AMS 5525-S66286
Lean DSS 20Cr-3.5Ni-1.7Mo-0.17N	**A240** S32003 (AL2003TM)	10H/1	65–70/ 95–100*	−29**~343 **For < −29 °C, impact test may be required per sec.VIII-D1.	*Hardness:* HRC 31 max. *Per thickness	(a) Exhibits corrosion performance superior to type 317L stainless steel in many environments (b) Lower cost alternative to austenitic type 316L and duplex 2205 alloys (c) ASME Code Case 2503–1 (d) See note 8
Lean DSS 21.5Cr-5Mn-1.5Ni-0.3Mo-0.22N	**A240** S32101 LDX2101®	10H/1	101/77 ($t \le 5$ mm) 94/65 ($t > 5$ mm)	−29*~316 *For < −29 °C, impact test may be required per Sec.VIII-D1.		(a) Used as a CRA material between 316L SS and 2205 DSS in chloride containing service (b) Less prone to precipitation of intermetallic phases than other DSS (c) The strength is similar to 2205 DSS (d) ASME Code Case 2418/NSF Approval Standard 61 (e) See Note 8 (f) Other type lean DSS: S32202, S32304, S32003 as an alternative (per service)
Lean DSS 24Cr-3Mn-3.6Ni-1.6Mo-0.27N	**A240** S82441 LDX 2404®	10H/1	107/78 ($t \le 10$ mm) 99/70 ($t > 10$ mm)	−29*~316 *For < −29 °C, impact test may be required per Sec.VIII-D1.		(a) See pipes, tubes, and fittings (b) See Note 8 (c) Other type lean DSS: S82011 as an alternative (per service)
DSS 3RE60 18.5Cr-4.9Ni-2.8Mo	**AISI 329** S31500	10H/1	105/80	−29*~316 *For < −29 °C, impact test is required.	s.g.: 7.80 Note 17	(a) Good resistance to SCC and pitting in chloride-bearing environments (b) High mechanical strength – roughly twice the proof strength of austenitic grades (c) Good resistance to erosion and corrosion fatigue (d) Reference: API TR938-C
DSS 22Cr-5Ni-3Mo	**A240** S31803(3Mo) S32205 (3.3Mo) (2205)	10H/1	90/65	−29*~316 *−51 °C in B31.3 *For < −29 °C, impact test may be required per Sec.VIII-D1. *Impact test required at −40 °C (−40 °F) in ASTM A923, test B	*Hardness:* ≤BHN 293 s.g.: 7.88 Nitrogen content, % S31803: 0.08–0.20 S32205: 0.14–0.20 Note 4 & 17	(a) Good Cl-SCC & pitting resistance (b) A276/A479 (bar/shape), JIS SUS 329 J3L (c) S32205 has slightly more pitting corrosion resistance and higher allowable strength than those of S31803; in many cases, used as dual certified of S31803/S32205 (d) Used in sour service at ≤36 HRC, YS ≤ 1000 MPa (160 ski), ppH2S ≤ 0.02 MPa.a (3 Pisa) up to 232 °C (450 °F); excellent resistance to corrosion in many nonoxidizing and mineral acids like hydrochloric and sulfuric acid (e) Reference: ASTM A923, API TR938-C
SDSS 25Cr-7Ni-3.25Mo-0.25N	**A240** S32750 (2507)	10H/1	116/80	−29*~316 *For < −29 °C, impact test may be required per Sec.VIII-D1.	*Hardness:* ≤BHN 310 s.g.: 7.80 N = 0.24–0.32 wt% PRE ≥40 Note 8 *Impact test required at −40 °C (−40 °F) in ASTM A923, test B	(a) Good Cl-SCC & pitting resistance (b) High strength (c) A276/A479 (bar/shape) (d) Used in sour service at ≤32 HRC, ppH2S ≤ 0.01 MPa.a (1.5 psia) up to 232 °C (450 °F) (e) Reference: ASTM A923, API TR938-C. (f) See Note 4, 9 & 17

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (11/23)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
SDSS 25Cr-7Ni-3Mo-0.5Cu-2W	**A240** S39274	10H/1	116/80	−29*~316 *For < −29 °C, impact test required per Sec. VIII-D1.	*Hardness:* ≤BHN 310 s.g.: 7.80 N = 0.24–0.32 wt%	(a) Good Cl-SCC & pitting resistance (b) High strength (c) Brand name: DP3W (d) Reference: ASTM A923, API TR938-C. (e) See Note 4 & 17
SDSS 25Cr-6.5Ni-3Mo-0.2N--0.5Cu-0.3W	**A240** S31260	10H/1	110/70	−29*~316 *For < −29 °C, impact test required per Sec. VIII-D1.	*Hardness:* ≤BHN 290 s.g.: 7.80 N = 0.1–0.3 wt%	(a) Good Cl-SCC & pitting resistance (b) High strength (c) Brand name: DP3 (d) Reference: ASTM A923, API TR938-C. (e) See Note 4 & 17
SDSS 25Cr-7Ni-3.5Mo-0.7Cu-0.5W-0.25N	**A240 A479** S32760	10H/1	109/80	−29*~316 *For < −29 °C, impact test required per Sec. VIII-D1. *Impact test required at −40 °C (−40 °F) in ASTM A923, test B	*Hardness:* ≤BHN 310 s.g.: 7.80 N = 0.24–0.32 wt% PRE ≈ 42 Note 4, 8, 9 & 17	(a) Added Cu & W (b) Good Cl-SCC & pitting resistance (c) Better crevice corrosion resistance than 2507DSS (d) Excellent corrosion resistance in nonoxidizing and mineral acids like HF & H_2SO_4 acid (e) Used in sour service at ≤34 HRC, Cl- ≤ 120,000 ppm, ppH2S ≤ 0.02 MPa.a (3 psia), or at Cl- ≤ 15,000 ppm, pH in aqueous phase >5.6, and ppH2S ≤ 0.10 MPa.a (15 psia). Excellent resistance to corrosion in many nonoxidizing and mineral acids like HCl & H_2SO_4 acid (f) A276 (bars & shapes), A473 (forgings) (g) Reference: ASTM A923, API TR938-C. (h) Brand name: Zeron 100
SDSS Safurex 29Cr-6.5Ni-2Mo	**A240 A479** S32906	10H/1	t ≤ 10 mm ; 116/94 t > 10 mm ; 109/80	−29*~316 *For < −29 °C, impact test required per Sec. VIII-D1.	s.g.: 8.00 A479: Bar Note 17	(a) Good chlorides SCC resistance to carbamate solution in urea process (e.g., for HP stripper) (b) DIN X2CrNiMoN 25 22 2 (A4-18005 BC.05) (c) See ASME Code Case 2295-2. (d) Seamless pipe/tube: A790/A789
Hyper DSS 27Cr-6.5Ni-5Mo	S32707	10H/1	133/101		SAF 2707 HD® "HD" stands for hyper-duplex. Note 9, See Figs. 2.196 and 2.197 isocororsion curves	(a) Excellent chlorides SCC resistance (b) PRE ≈ 49 (c) UNS S33207 (SAF 3207 HD, PRE > 50) is more advanced Hyper DSS than S32707 (d) Max. interpass temperature ≤ 100 °C (212 °F) for hyper DSS
Alloy (Incoloy) **330** 19Cr-35Ni-1.2Si-≤2Mn	**B536** N08330	46/–	70/30	−196~1148	*Hardness:* HRB: 70–90	(a) Good resistance to carburization, nitriding, and/or thermal cycling/shock (b) ASS. Not subject to embrittlement from σ formation (c) Brand name: RA330
Alloy **28** (Sanicro 28) 27Cr-32Ni-3.5Mo-1Cu	**B709** N08028	45/–	73/31	−196~538	*Hardness:* HRB: 70–90	(a) Excellent resistance to sulfide cracking in conditions characterized by high levels of H_2S, CO_2 and chlorides. Examples of applications are production tubing (OCTG) and heat exchangers used in the processing of sour crude. See Note 2 (b) High abrasion resistance
Alloy **654 SMO** 24Cr-22Ni-7Mo-3Mn	**A240** S32654	45/–	109/62	−196~400 Scaling temperature: 1000 °C (1830 °F)	*Hardness:* ≤BHN 250 s.g.: 8.00	(a) High strength (b) High PRE (≈54) – high resistance to SCC and pitting in chloride-bearing environments (c) CCT = 65 °C (149 °F) per ASTM G48A (d) CPT = 75 °C (167 °F) per ASTM G48A (e) Brand name: AvestaPolarit 654SMO®

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in³ (density) = 27.68 g/cm³ (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (12/23)

Material/ brand	ASTM no.	P no/Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
AL-6XN 20Cr-25Ni-6Mo-0.25Cu-0.2N	**A240** **B688** N08367	45/–	95*/45 *100 for <4.8 mm THK	−196~427	s.g.: 8.04	(a) Excellent Cl-SCC and pitting resistance [≤90 °C (194 °F) in seawater] (b) PRE ≥ 40; super austenitic stainless steel *ASME code cases (see the latest)* | **Wrought** | **Castings** Sec. VIII | 1997 | 2106 Sec. III | N-438 | 497 B31.1 | 155 | 155
Alloy **254SMO** 20Cr-18Ni-6.3Mo	**A240** S31254	8/4	94/44	−196~400	s.g.: 8.00	(a) Excellent cl-SCC and pitting resistance [≤90 °C (194 °F) in seawater] (b) PRE ≥ 40; super austenitic stainless steel (c) Welding electrode: same as alloy C22 or C276 (d) Brand name: AvestaPolarit 254SMO®
SR 50A® (CLI-R50A) 23Cr-21Ni-6.4Mo	Euronorm X 1NiCrMoN 21.22.7 S32050		99/49	−196~538		
Alloy (Incoloy) **25-6Mo** 25Ni-20Cr-6Mo-1Cu-N	**A240 &** **B625** N08926	45/–	94/43	−196~427	s.g.: 8.03 PRE ≈ 47 ASME code cases : 2120, N-453/454/455	(a) Good resistance to environments containing chlorides or other halides, especially suitable to handle high-chloride environments such as brackish water, seawater, caustic chlorides and pulp mill bleach systems (b) For chemical and food processing, pulp and paper bleaching plants, marine and offshore platform equipment, salt plant evaporators, air pollution control systems, and condenser tubing, service water piping, and feedwater heaters for the power industry
Alloy **20/20Cb3** (carpenter) 35Ni-20Cr-3Cu-2Mo-Cb **20Mo6** (carpenter) 35Ni-24Cr-6Mo-3Cu	**B463** (N08020) (N08026)	45/–	80/35 (annealed)	−196 ~ 427	IGC test may be required for max. corrosion resistance *s.g.* N08020: 8.08 N08026: 8.13	(a) Superior corrosion & stress fracture resistance in non-aerated superior corrosion and to 10–40% H_2SO_4 acid, below 60–80 °C (140–176 °F) (b) Good corrosion resistance in HF acid at atm and less than 10% HCl acid (c) 20Mo6 (super stainless steel) is developed from 20Cb3 to resist pitting and Cl-SCC (d) Welding: Use E-320 or ER-320 electrodes (e) PWHT: min. 538 °C (1000 °F) when severe chloride SCC environment. (f) Normally supplied as annealed condition (g) For synthetic rubber, high-octane gasoline, solvents, explosives, plastics, synthetic fibers, heavy chemicals, organic chemicals, pharmaceuticals and foodstuffs
93–99%Ni	**B160** N02200 N02201 N02211	41/–	55–80/ 15–60 50/10 50/10	−198 ~ 316 −198 ~ 649 −198 ~ 649	99.0%Ni, ≤0.15%C 99.0%Ni, ≤0.02%C 93.7%Ni, 4.5%Mn s.g.: 8.75	(a) Rod/Bar (b) SMTS & SMYS per cold/hot work or annealed (c) N02201: Intended essentially for fused caustic and other fused salts and for temperatures above 316 °C (600 °F)
NAS 144M 16.0~18.0Cr 14.0~16.0Ni 4.0~5.5Mo C≤0.10	–	8/4	70/30	−196~600	**Temp °C** | **KSI** | **(min.)** | **TS** | **YS** 200 | 70 | 30 300 | 70 | 28 400 | 70 | 26 500 | 66 | 23 600 | 57 | 21	(a) NAS: Nippon Yakin Kogyo ASS (b) Solution heat treated at 1100 to1150 °C (2010–2100 °F)] (c) Machinability: similar to ASS (d) Chemical cleaning: Use acetic-HF acid solution for equipment/piping in acetic-HCl acid service (e) Better pitting resistance than ASS (f) Good corrosion resistance in low concentration HCl, H_2SO_4 acid and acetic acid (g) NAS 144 MLK is developed from NAS 144 M to improve the intergranular corrosion cracking (IGC) resistance
NAS 144MLK 16.0~18.0Cr 15.0~17.0Ni 4.5~5.5Mo	(SUS 317 J1)		70/25		$C \leq 0.040$	

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Plates and Strips (13/23)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Alloy (Monel) **400** 67Ni-30Cu	**B127** (N04400)	42/–	75/40 (hot rolled) 70/28 (annealed)	−198 ~ 482	Specify heat treatment requirement e.g., 593–704 °C (1100–1300 °F) for SR in SCC environment Valve components: to be annealed. s.g.: 8.80 See Table A in Sect. 2.6.2.2.1 Pipes & Tubes, Alloy 400	(a) Equipment in dilute H_2SO_4, dilute HCl including salt deposit (NH_4HS), HF, organic acid, caustic service, and severe acidic solution (b) Not recommended in high-temperature [≥260 °C (500 °F)] sulfidation environment, in ammonia and its compound environment (due to SCC) and in HF vapor phase if moisture and oxygen are present, and limited to max. 125 °C (257 °F) in liquid AHF and max. 300 °C (572 °F) in vapor AHF (c) For fractionator top section or the overhead section equipment (d) Susceptible to mercury embrittlement (e) BS3072NA13 (sheet and plate), BS3073NA13 (Strip), SAE AMS 4544 (Sheet, Strip, and Plate), DIN 17750 (Plate, Strip and Sheet)
Alloy (Monel) **K-500** 66Ni-30Cu-3Al	**B127** (N05500)	42/–	140/110 (hot finish + age) 130/110 (annealed + age)	−252 ~ 649	s.g.: 8.44	(a) Good resistance to seawater corrosion (b)At ≥ −134 °C (−210 °F): very low permeability and nonmagnetic property (c) High strength by age hardening (d) Not recommended as bolting material in HF (e) Not recommended H_2S containing service (ppH_2S > 0.05psia) (f) Other properties: similar to Monel 400
Ni-Fe-Cr Alloy Alloy (Incoloy) **800, 800H, 800HT)** 32Ni-20Cr	**A240** **B409** 800 (N08800) Annealed	45/–	75/30	−198 ~ 816 (normally not used for applications that require creep-rupture strength)	※ Specify heat treatment requirement See Table B in Sect. 2.6.2.2.1 Pipes & Tubes, Alloy 800/H 800HT: Ti + Al = 0.4–0.7% for higher fatigue, creep-rupture (recommend.) s.g.: 7.94	(a) Very good chloride SCC resistance and good sulfide/ oxidation resistance (b) General corrosion resistance: similar to 300 series ASS (c) 800H modification was to control carbon (0.05–0.10%) and also may have average grain size, ASTM no.7 or coarser per ASTM E112 (d) 800HT has further modifications to higher Ti + Al levels, larger grain and more advanced fatigue strength (than 800H) to ensure optimum high temperature properties (e) Annealed at 928–1038 °C (1800–1900 °F) for alloy 800 and 11,121–1177 °C (2050–2150 °F) for alloy 800H/HT. the purpose is to soften the material after forming operations of alloy 800 while maintaining a relatively fine grain size. Because of the anneal cycle used on alloys 800H and 800HT, the large grain size produces a visibly undulated surface called “orange peel” after forming (f) Cr-depletion, which may be subject to IGC, can appear at 538–760 °C (1000–1400 °F). Therefore, for polythionic acid corrosion service, a prevention is required like 300 series ASS (g) γ’ phase precipitation (rich Ni, Al & Ti) at 540–705 °C (1000–1300 °F), more than 100 hours. Elongation is decreased (be brittle) (h) PWHT: min. 885 °C (1625 °F), min. 1.5 hr. (i) BS 3072NA15 (Plate & Sheet), BS 3073NA15 (Strip) (k) DIN 17460 (Plate, Sheet, & Strip), EN 10028–7 & EN 10095 (Plate, Sheet, & Strip) (l) Note 19
	800H (N08810) Annealed	45/–	65/25	−198 ~ 899	s.g.: 7.94	
	800HT (N08811) Annealed		65/25	−198 ~ 899 (recommended for applications that require creep-rupture strength)	800HT: Ti + Al = 0.85–1.2% See ASME Code Case 2339.	
Alloy (Incoloy) **825** 42Ni–21Cr-3Mo	**B424** N08825	45/–	85/35	−198 ~ 816 (normally recommended <540 °C (1000 °F)	s.g.: 8.14	(a) Good corrosion resistance to sulfuric, phosphoric acids, and neutral chloride media (except $MgCl_2$). See Note 2 (b) Phosphoric acid evaporators; pickling-tank heater & hooks and equipment; chemical process equipment; tank trucks; propeller shafts, pollution-control equipment, and spent nuclear fuel element recovery

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (14/23)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Alloy (Inconel) **718** 52Ni-19Cr-5Nb-3Mo-1Ti-Al-Ta	**B670** N07718	43/–	180/150	−254 ~ 700* *650 is preferable.		(a) Age hardened-very high strength (b) Good environmental cracking resistance (high H_2S & CO_2) at high temperatures in deep, extremely hostile, oil and gas production environments (c) For oil & gas drilling and production facilities (d) See ASME Code Case 1993, 2206, 2222 for bolting, bar, etc., and API 6A718 for oil and gas drilling and production equipment (e) SAE AMS 5596, 5597, 5950 (f) ISO 6208 (g) DIN 17750 (h) Susceptible to hydrogen stress cracking at high δ phase environment. See Note 18
Alloy (Inconel) **600** 76Ni-15.5Cr-8Fe	**B168** (N06600)	43/–	85/35 (hot rolled) 80/35 (annealed)	−198~649	s.g.: 8.47 See Note 6.	(a) Good corrosion resistance in oxidizing, reducing, and Cl-SCC environment (b) Oxidation resistance up to 1100 °C (2010 °F) in atmospheric and carburization resistance [≤1177 °C (2150 °F)], but normally limited max. 649 °C (1200 °F) due to strength (c) Not recommended in high-temperature salt water/caustic alkalis/mercury due to pitting/SCC/IGSCC above 540 °C (Cr_7C_3 below 760 °C/$Cr_{23}C_6$ below 760 °C). Solution heat treatment is required to minimize them. (d) Good corrosion resistance in sulfur-free gas service (e) ASME Code Case 1827, N-20, N-253, and N-576 (f) SAE/AMS 5540 (g) BS 3072NA14 and 3073NA14 (h) DIN 17750, ISO 6208, EN 10095, (i) MIL-DTL-23228
Alloy (Inconel) **601** 60.5Ni-23Cr-14Fe-1.3Al	**B168** (N06601)	43/–	80/35 (annealed)	−198~1200* * 1095 °C for long term or cyclic oxidation environment	s.g.: 8.11 See Note 6.	(a) Good high-temperature oxidation resistance [≤1200 °C (2200 °F) for short exposure]; better resistance than alloy 600; good for fired heater refractory anchor material (b) Unique resistance to oxide spalling under cyclic thermal conditions (c) Modified grade (GC): grain size control to inhibit the grain growth by Zr and Nitrogen (d) ASME Code Case 1500
Alloy 617 [Inconel 617] 46Ni-9Mo-22Cr-12.5Co-1.2Al	**B168** (N06617)	43/–	95/35 (annealed)	−198~1200* * TS&YS greatly decreased at ≤704 °C (1300 °F)	s.g.: 8.36	(a) High strength and excellent oxidation resistance at the temperatures over 1800 °F (980 °C) (b) Good fatigue stress resistance (c) Useful for components as ducting, combustion cans, and transition liners in both aircraft and land-based gas turbines
Alloy (Inconel) **625** 61Ni-21.5Cr-9Mo-3.6 (Nb + Ta)	**B443** (N06625) Gr. 1 (annealed)	43/–	120/60 (cold rolled) 110/55 (hot rolled, *t* ≤ 70 mm) 110/55 (cold rolled, *t* ≤ 9.5 mm)	−198~875* *649 preferable	s.g.: 8.44 Note 5, 15 & 16	(a) Developed high-temperature strength from Inconel 600 by Mo (b) Good corrosion resistance to Cl⁻ SCC (c) Good high-temperature oxidation resistance (d) PWHT not required for SCC resistance (e) Good weldability (f) Alloy 625 in the annealed condition is subject to severe loss of impact strength at room temperature after exposure in the range of 538–760 °C (1000–1400 °F) (g) Work-hardening rate is higher than ASS cold reduction (≥15%) requires a soft annealing
	Gr. 2 (sol. anneal.)		100/40			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Plates and Strips (15/23)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Alloy (Hastelloy) **B-2** 69Ni-28Mo-1Cr-1Co-1Mo-2Fe	**B333** N10665	44/–	110/51	−198~427 [annealing] (a) Solution heat treated & quenched at 1066 °C (1950 °F) (b) Bright annealing: 1150 °C (2100 °F) cooled in hydrogen	In order to prevent Cr-depletion (IGC- knife line attack) on weld HAZ: Fe ≤ 2.0%, *C* ≤ 0.025%, Si ≤ 0.1% Hardness: ≤HRB100 s.g.: 9.22	(a) Acid, HCl acid (at all concentrations and temperatures) – good reducing acid corrosion resistance (b) Good pitting and SCC resistance in nonoxidizing salt or halogen compound (c) Poor corrosion resistance in oxidizing environment (a few ppm) due to a little Cr (d) Nonmagnetic, high strength, low thermal expansion coefficient (e) Cr-depletion (IGC- knife line attack) can appear at weld HAZ (f) Rapidly corrode in Ferric & Cupric Salts (normally dissolved Fe, Cu in HCl acid) (g) Physical & metallurgical properties: similar to 300 series ASS. (h) Many crack on explosion/rolled bonding
Alloy (Hastelloy) **B-3** 65Ni-28.5Mo-1.5Cr-3W-3Co	**B333** N10675	44/–	110/51		Hardness: ≤HRB100 s.g.: 9.22	(a) Excellent resistance to pitting corrosion, to SCC and to knife-line and HAZ attack (b) Excellent resistance to hydrochloric acid at all concentrations and temperatures (c) Withstands sulfuric, acetic, formic and phosphoric acids, and other nonoxidizing media. It has a special chemistry designed to achieve a level of thermal stability greatly superior to that of alloy B-2 (d) Physical & metallurgical properties: similar to 300 series ASS
Alloy (Hastelloy) **C-276** 57Ni-15Cr-16Mo-2.5Co-4W	**B575** C-276 (N10276)	44/–	100/41	−198~688 (sol. Annealed) −198~427 (annealed)	Solution heat treated & quenched at 1121 °C (2050 °F) *Hardness*: ≤100 HRB s.g.: 8.89 PRE = %Cr + 1.5(% Mo + %W + %Nb) + 30(% N) – 0.5%C > 45 Note 3 & 5	(a) Good corrosion resistance in ferric & cupric chlorides, HCl acid, hot contaminated media (organic and inorganic), chlorine, formic and acetic acids, acetic anhydride, and seawater and brine solution (b) Corrosion resistance is better than B-2 if oxidizing salt such as ferric chloride is present in the acid (c) Corrosion resistance and mechanical properties can be decreased after long time aging at 650–1090 °C (1200–1995 °F) due to metallic compound precipitation (d) Solution heat treatment is done at 1121 °C (2050 °F) followed by rapid quenching (e) for chemical process equipment and desulfurization of flue gas equipment (f) Physical & metallurgical properties: Similar to 300 series ASS (g) See note 16 & 17
Alloy (Hastelloy) **C-4** 61Ni-16Cr-16Mo-2Co	**B575** C-4 (N06455)	44/–	100/45	−198~427	Solution heat treated & quenched at 1066 °C (1950 °F) *Hardness*: ≤100 HRB s.g.: 8.64 Note 3 & 5	(a) This alloy resists the formation of grain-boundary precipitates in the weld HAZ, thus making it suitable for most chemical process applications in as-welded condition (b) C-4 alloy also has excellent resistance to stress-corrosion cracking and to oxidizing atmospheres up to 1038 °C (1900 °F) (c) It has good corrosion resistance in hot contaminated mineral acids, solvents, chlorine and chlorine contaminated media (organic and inorganic), dry chlorine, formic and acetic acids, acetic anhydride, and seawater and brine solutions (d) Fine intergranular M_6C carbides can form in the 649 to 1093 °C (1200 to 2000 °F) but their damaging effect is minimal

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (16/23)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Alloy (hastelloy) **C-22** 55Ni-21Cr -13.5Mo- 2.5Co- 3W-3Fe	**B575** C-22 (N06022)	44/–	100/45	−198~427	(a) Solution heat treated & quenched at 1121 °C (2050 °F) (b) Bright annealing: 1149 °C (2100 °F) cooled in hydrogen *Hardness:* ≤100 HRB s.g.: 8.69 PRE = %Cr + 1.5 (%Mo + %W + % Nb) + 30(%N) – 0.5%C > 47 Note 3. 5 & 15	(a) Better overall corrosion resistance than other Ni-Cr-Mo alloys, e.g., alloy C-276, C-4, 625 (b) For both reducing and oxidizing media excellent resistance to pitting, crevice corrosion & SCC in: – Oxidizing aqueous media, including acids with oxidizing agents, wet chlorine & mixtures containing nitric or oxidizing acids with chlorine – Ferric and cupric chlorides, hot contaminated media (organic and inorganic), chlorine, formic and acetic acids, acetic anhydride, and seawater & brine solutions (c) Where "upset" conditions are likely to occur or in multipurpose plants (d) To resist the formation of grain boundary precipitates in the weld HAZ, thus making it suitable for most chemical process applications in the as-welded condition
Alloy (Inconel) **686** 57Ni- 20Cr- 16Mo- 3.5W-Ti-N	**B575** N06686	43/–	100/45	−198 ~ 450	s.g.: 8.73 *Hardness:* ≤100 HRB	(a) High CCT (critical crevice temperature) (b) For chemical processing, marine, and air pollution control (flue gas desulfurization) industries (c) PRE = %Cr + 1.5(%Mo + %W + %Nb) + 30(%N) – 0.5% C > 51 (d) See Note 15 (e) DIN 17750
Alloy **59** 55Ni- 23Cr- 16Mo-Al	**B575** N06059 Nicrofer ® 5923 hMo	43/–	100/45	−198 ~ 450	s.g.: 8.61 PRE = %Cr + 1.5(% Mo + %W + % Nb) + 30(%N) – 0.5%C > 47 Note 15	(a) Max. 100 HRB (b) Outstanding resistance to a wide range of corrosive media under oxidizing and reducing conditions (c) Excellent resistance to pitting and crevice corrosion and freedom from Cl-SCC. (d) Excellent resistance to mineral acids, such as HNO_3, H_3PO_4, H_2SO_4, and HCl acids and in particular to H_2SO_4 and HCl acid mixtures
Alloy (Hastelloy) **G-3** 47Ni- 22Cr- 7Mo-2Cu	**B582** N06985 Annealed	45/–	90–35 (4.76 mm < *t* ≤ 19.05 mm) 85–30 (19.05 mm < *t* ≤ 63.5 mm	−198~427	*Hardness* ≤100 HRB s.g.: 8.14	(a) Improved corrosion resistance to the welded HAZ (b) Good corrosion resistance in H_2SO_4, H_3PO_4 acid due to 2%Cu (c) In comparison with Hastelloy C 276, more resistance in oxidizing service due to higher Cr (23%) – less resistance in oxidizing service due to lower Mo (23%) (d) For flue gas scrubbers, sulfate compounds, mixed acids
Alloy (Hastelloy) **G-30** 43Ni- 30Cr- 5.5Mo- 15Fe- 2.5W- 2Cu- 0.8Nb-Co	**B582** N06030 Annealed	45/–	85–35 (*t* > 0.51 mm)	−198~427	s.g.: 8.22	(a) Highly resistant to "wet process" phosphoric acid (P_2O_5). P_2O_5 is one of the most important industrial chemicals, being the primary source of phosphorus for agrichemical fertilizers (b) Moderately resistant to chloride-induced localized attack, which can be a problem beneath deposits in the evaporators used to concentrate P_2O_5 (c) Less susceptible to CLSCC than ASS. (d) Highly resistant to other oxidizing acids, such as nitric, and mixtures containing nitric acid. It possesses moderate resistance to reducing acids, such as hydrochloric and sulfuric acids, as a result of its appreciable Mo and Cu
Alloy (Hastelloy) **X** 48Ni -22Cr- 9Mo- 1.5Co	**B435** N06002	45/–	100/45 (solution annealed) 95/35 (hot rolled)	−198 ~ 649	Solution heat treated & quenched at 1177 °C (2150 °F) s.g.: 8.22	(a) Excellent high-temperature strength and oxidation resistance. Highly resistant to SCC (b) All of the product forms are excellent in terms of forming and welding (c) For petrochemical process equipment, aircraft engine and gas turbines in the hot combustor zone sections and structural components in industrial furnace applications because of the excellent oxidation resistance

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Plates and Strips (17/23)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Alloy (Inconel) **725** 57Ni-20Cr-8Mo-3Nb-1.2Ti-Al	**B805** N07725	43/–	110*/45 * After aging solution treated	−198 ~ 649	*Specific aging treatment can be used for higher mechanical properties. Note 15	(a) For bars and wires (b) Age hardenable – -very high strength (c) Good environmental cracking resistance (high H_2S & CO_2 in free S) at high temperatures in deep, extremely hostile, oil and gas production environments (d) High fatigue strength and high corrosion resistance with nonmagnetism, modified heat treatment, and fine grain practice (e) SAE AMS 5589/5590 (f) ASME code case: N-253, 2217
Clad with alloy	**A263** **A264** **A265**	Both materials	Both materials	Both materials	1. A 263: MSS/FSS cladding 2. A264: ASS cladding 3. A265: Nickel alloys cladding	(a) Base metal: carbon & low-alloy steel (b) Specify the thicknesses base metal & clad respectively (c) Consider both materials properties for welding (including peel back design), heat treatment, service temperature (incl. thermal expansion) (d) UT & PT required (e) Clad thickness is normally not considered for strength calculation. (f) Bonding stress: min. 20 ksi (140 MPa) (g) Recommended to use low-carbon-clad materials
Cupro-nickel 90–10 Cu-Ni	**B171** C70600 Annealed	34/–	40/15	−198 ~ 316	*Thick*: ≤63.5 mm s.g.: 8.90	(a) Excellent corrosion resistance, especially in marine environments; moderately high strength, good creep resistance at elevated temperatures; relatively higher cost in comparison with those of Cu-Al and other alloys with similar mechanical properties (b) Where high corrosion resistance is required and where concern over chloride SCC prevents use of stainless steels (c) Service velocity limit: See Sect. 2.6.2.2 pipes and tubes (ASTM B466/B111) (d) See Sect. 2.1.7.2 for more details.
Cupro-nickel 70–30 Cu-Ni	**B171** C71500 Annealed	34/–	50/20 45/18	−198 ~ 371	*Thick*: ≤63.5 mm s.g.: 8.95 *Thick*: ≤125 mm s.g.: 8.95	
Naval rolled brass Copper alloys Annealed	**B171** C46400 C46500 C46000 C46700	31/–	50/*	−198 ~ 204	*Thick*: ≤140 mm s.g.: 8.41 * 20 for thickness 80 mm and under * 18 for thickness above 80 mm and up to 140 mm. C46400: 60Cu-36Zn-1.3Sn	(a) Good corrosion resistance to seawater at even higher than normal temperatures while also assures greater strength and rigidity (b) Excellent capacity for hot working and adapts well for hot forging and pressing (c) Service velocity limit: ≤2 m/s (6 fps) (d) For nuts, bolts, rivets, valve stems, pump shafts and marine (e) Recommended inhibited brass (add Sn, As, Sb, P) to prevent dezincification (f) See Sect. 2.1.7.2 for more details
Inhibited admiralty brass Copper alloys Annealed	**B171** (C44300) (C44400) (C44500)	32/–	45/15	−198 ~ 232	*Thick*: ≤100 mm s.g.: 8.53 C44300: 71Cu-28Zn-1Sn-0.04As C44400: 71Cu-28Zn-1Sn-0.06Sb C44500: 71Cu-28Zn-1Sn-0.06P	(a) Good corrosion resistance to seawater or blackish water at even higher than normal temperatures while also assuring greater strength and rigidity (b) As (arsenic) for C44300, Sb (antimony) for C44400, or P (phosphorous) for C44500 adds to avoid dezincification (c) Susceptible to SCC in Ammonia containing service (d) See Sect. 2.1.7.2 for more details
Aluminum bronze Rod, bar, shapes	**B150** C61300 C61400 C61900 C62300 C62400 C63000 C63020 C63200 C64200 C64210	35/– 35/– 35/– 35/– 35/– 35/– 35/– 35/– 35/– 35/–	70–80/32–50 70–80/30–40 75–90/30–50 75–90/30–50 90–95/35–45 85–100/ 42.5–68 130–135/ 90–100 90/40–50 75–90/25–45 75–90/25–45	−198~343 −198~260 −198~* −198~316 −198~* −198~399 −198~* −198~* −198~316 −198~*	*Composition*: bal = Cu 6–7.5Al, 2-3Fe 6-8Al, 1.5–3.5Fe 8.5-10Al, 3–4.5Fe 8.5-10Al, 2-4Fe 10–11.5Al, 2–4.5Fe 9-11Al, 2-4Fe, 4–5.5Ni 10-11Al, 4–5.5Fe, 4.2-6Ni 8.7–9.5Al, 3.5–4.3Fe, 4–4.8Ni 6.3–7.6Al, 1.5–2.2Si 6.3-7Al, 1.5-2Si	(a) Good corrosion resistance to seawater or blackish water (b) Higher strength than Cu alloys (c) No serious deterioration (d) Low rates of oxidation at high temperatures and excellent resistance to sulfuric acid, sulfur dioxide, and other combustion products (e) C63000,C63020, C63200: excellent cavitation resistance (f) *Per manufacturer's recommendation unless otherwise codes/standards specify

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C — Plates and Strips (18/23)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Aluminum alloys	**B209** 3003 Alclad 3003 5083 5086 6061	 21/– 21/– 25/– 25/– 23/–	 24–30/21 (at H16) 23–29/20 (at H16) 44–56/31 (at H32) 40–47/28 (at H32) 30/16 (at T4)	 −269~204 −269~204 −269~66 −269~66 −269~204	Note 7 1.2Mn-Fe-Si-Fe-bal.Al 3003 clad with 7072 4.4Mg-Mn-Si-Fe-bal.Al 4Mg-Mn-Fe-Si-Fe-bal.Al 1Mg-Fe-0.6Si-Fe-bal.Al	(a) For cold boxes in gas plants and cryogenic service (b) Use at lower temperature is available when the impact test passes (c) See ALPEMA and Table 2.82 (max. design temperature per part and material) in this book for brazed aluminum plate-fin heat exchangers (d) See Sect. 2.1.7.3 for more details (e) Mercury to be controlled at max. 0.01 μg/Nm^3 to avoid LME (liquid metal embrittlement)
Titanium alloys	**B265** Annealed,Gr 1 (R50250) 2 (R50400) 3 (R50550) 7 (R52400) 9 (R56320) 11 (R52250) 12 (R53400) 13 (R53413) 14 (R53414) 15 (R53415) 16 (R52402) 17 (R52252) 18 (R56322)	51/–	 35/25 50/40 65/55 50/40 90/70 35/25 70/50 40/25 60/40 70/55 50/40 35/25 90/70	−59~316	Gr.9 and over grades: consult metallurgist. (s.g., 4.40–4.51) Gr.1–4: Unalloyed Gr.5: 6%Al, 4%V Gr.6: 5%Al, 2.5%V Gr.7: 0.12–0.25%V Gr.9: 3%Al, 2.5%V Gr.11: 0.12–0.25%Pd Gr.12: 0.3%Mo, 0.8%Ni Gr.13, 14, 15: 0.5%Ni, 0.05%Ru Gr.16, 17: 0.04–0.08%Pd Gr.18: 3%Al, 2.5%V, 0.04–0.08%Pd Gr.19: 3%Al, 8%V, 6%Cr, 4%Zr, 4%Mo	(a) Remarkable corrosion resistance in oxidizing acid (HNO_3 except red fuming nitric) by virtue of a passive oxide film; good corrosion resistance in seawater, wet chlorine, organic chlorides, but it is not immune and can be susceptible to pitting and crevice attack at elevated temperatures of 110 °C (230 °F) and higher (b) For H/EX tubes and valves, pump components (c) Titanium can absorb hydrogen from environments containing hydrogen gas At temperatures below 80 °C (176 °F) hydrogen pickup occurs so slowly that it has no practical significance, except in cases where severe tensile stresses are present In the presence of pure hydrogen gas under anhydrous conditions, severe hydriding can be expected at elevated temperatures and pressures. Titanium is not recommended for use in pure hydrogen because of the possibility of hydriding should the oxide film be broken (d) Not recommended in service contacted with methanol (<5% water) (e) See Sect. 2.1.7.4 for more details
	Solution treated, Gr. 19 (R58640) 20 (R58645) 21 (R58210) 23 (R56407)		 115/110 115/110 115/110 120/110		Gr.20: 3%Al, 8%V, 6%Cr, 4%Zr, 4%Mo, 0.04–0.08%Pd Gr.21: 15%Mo, 3%Al, 2.7%Nb, 0.25%Si Gr.23: 6%Al, 4%V with extra low interstitial elements, ELI	
Zirconium alloys	**B551** R60700 R60702 R60704 R60705 R60706	 – 61 – 62 –	Max 55/max.44 55/30 60/35 80/55 74/50	 −59~371* *Max. 316 °C (600 °F) is normally applied due to deterioration	 s.g.: 6.48	(a) High melting point of 1855 °C (3371 °F) (b) Good ductility, easily fabricated (c) Highly resistant to corrosion by acids, high resistance to localized (pitting, SCC and crevice), very good corrosion resistance in most organic acids, exceptional corrosion resistance in mineral acids, good corrosion resistance in strong alkalis (d) High heat transfer efficiency & electricity (e) Very low thermal expansion (f) Characteristics of several types See 2.6.2.1 notes for plates (g) ASTM B351 bars, rod, and wire for nuclear (h) ASTM B352 sheet, strip, and plate for nuclear (i) See Sect. 2.1.7.5 for more details
Tantalum alloys Ta + (W) + (Nb)	**B708** R05200 R05400 R05255 R05252 R05240	 – – – – –	 25–30/15–20 25–30/15–20 70/55–60 40/22–30 35/15–20	 −196~2480* −196~2480* −196~2480* −196~2480* −196~2480* * Maximum temperature should be carefully applied per the design condition.	SMTS and SMYS depend on the thickness or product type. s.g. R05200: 16.6 R05400: 16.6 R05255: 16.9 R05252: 16.7 R05240: 13.6 Melting temperature: 2996 °C for R05200 and 2980 °C for pure tantalum	(a) Tantalum is a dark blue-gray metal that is very heavy, ductile, hard, and easily fabricated. (b) Good conductor of heat and electricity (c) To form extremely thin and protective oxide layers for high-quality capacitors (d) Highly resistant to corrosion by acids below 150 °C and can only be dissolved with HF acid (e) Characteristics of several types R05200, unalloyed Ta R05400, unalloyed Ta, powder-metallurgy R05255, 90% Ta, 10% W, high temperature and high strength in a corrosive environment R05252, 97.5% Ta, 2.5% W, low temperature strength is important as well as high corrosion resistance and good formability. R05240, 60% Ta, 40% Nb (f) See Sect. 2.1.7.6 for more details

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Plates and Strips (19/23)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see general notes & notes at the end of this table)
Niobium alloys	**B393**				*s.g.*	(a) *Type 1* – Reactor grade unalloyed Nb (max. average 90 HBN)
	Type 1	–	18/10.5	−196~*	Type 1 (R04200): 8.57	
	Type 2	–	18/10.5	−196~*	Type 2 (R04210): 8.57	(b) *Type 2* – Commercial grade unalloyed Nb (max. average 125 HBN)
	Type 3	–	28/18	−196~*	Type 3 (R04251): 8.57	(c) *Type 3* – Reactor grade Nb alloy containing 1%Zr (max. average 125 HBN)
	Type 4	–	28/18	−196~*	Type 4 (R04261): 8.57	(d) *Type 4* – Commercial grade Nb alloy containing 1% Zr (max. average 135 HBN)
	Type 5	–	14/7.2	−196~*	Type 5 (R0xxxx): 8.57	(d) *Type 5* – RRR superconducting grade pure Nb
				* Per the design condition	Melting temperature of type 1 & 2: 2468 °C	

General Notes for Plates & Strips

a. Temperature Limits
 (1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards
 (2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. The impact test exemption temperature shall comply with the applicable codes/standards. See Appendix A
 (3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, low-temperature toughness, etc.), and corrosion environment

b. The low strength (low carbon, low Ceq and/or heat treated) P No.1 materials are recommended in environmental cracking conditions

c. P.No.1 materials are not recommended (shall not be used for pressure containing parts) above 427 °C (800 °F) for continuous operation because of the graphitization after several hundred hours. See Sect. 2.3.1 for more details

d. Q-T or N-T Steels in Cr-Mo steels: Traditionally PWHT should be less than the tempering temperature of the base material to sustain the tempered structures. However, API committees in 2013 allowed a break of this rule if all mechanical properties including toughness are satisfied with the requirements after PWHT

e. References for Cr-Mo steels
 (1) See Table 2.37 *for overall reference codes and standards of Cr-Mo steels*
 (2) See Table 2.31 *for ASTM materials standards per product of Cr-Mo steels*
 (3) See Sect. 1.3.6 *references for MPT (minimum pressurizing temperature) of Cr-Mo steels*
 (4) See Sect. 2.1.4.2(f) *references for creep and toughness of 1 1/4CrCr-1/2Mo steels*
 (5) See Table 2.38 *for overall reference codes and standards of 9Cr-1Mo-V steels*
 (6) See Table 2.31a *for European standards of 9Cr-1Mo-V steels*
 (7) WRC 506 for Literature Survey-Half-Bead Temper-Bead of Cr-Mo Steels
 (8) R.A. Swift and J.A. Gulya, Temper Embrittlement of Pressure Vessel Steels-WJ_1973_02_s57
 (9) T. Yakamatsu et al., Temper Embrittlement Characteristics of 2 1/4Cr-1Mo Steels, Transactions ISIJ, Vol. 22, 1982 (435)
 (10) S.P. Ghiya et al., Stress Relief Cracking in Advanced Steel Materials-Overview, Proceedings of the World Congress on Engineering 2009 Vol II, WCE 2009, July 1 – 3, 2009, London, U.K.
 (11) J.G. Nawrocki et al., Mechanism of Stress-Relief Cracking in a Ferritic Alloy Steel, WJ, Feb. 2003, p25-S

f. When austenitic steels/alloys are used in services subject to stress corrosion, they should be supplied as solution-heat treated condition. The purchaser should indicate the additional requirements for thermally stabilized heat treatment for stabilized stainless steel/alloy when they are exposed to polythionic acid SCC (PTASCC) environments. See Sect. 2.1.6.8 for more details

g. See ASTM A123 for Hot Dip Galvanizing

h. Free machining ASS should not be used in seawater service because of poor corrosion resistance of activated surface film

i. When ASS is selected for severe corrosion resistance, the intergranular corrosion cracking (IGC) test per ASTM A262 (Practice A, B, C, E, or F) should be performed. See Table 2.63 for carbides formed per temperatures

j. Specification for General or Common Requirements for all ASTM materials should be applied. See Table 2.100, Note 3

k. CRA material cost comparison (typical – only for reference) – Fig. 2.189

l. Basic Properties of High-Temperature (Refractory) Metals – Table 2.173

m. When CS is used in contact with S over 260 °C (500 °F), it is common to specify silicon-killed grades. Steels with 0.15–0.30% silicon have been shown to be greatly superior to steels with under 0.1% Si in some environments

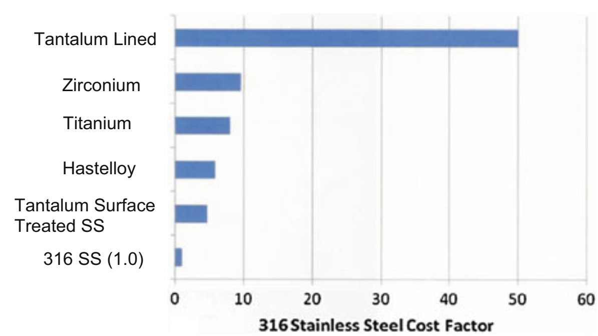


Figure 2.189 CRA material cost comparison. (Source: Special Metals technical reports 2008)

n. Flow Chart of Impact Test Requirements for Base Metal, Weld Metal, and Production of Stainless Steel Pressure Vessel
 See Section VIII, Div.1, Figure JJ-1.2-1 for ASS Base Metal and HAZ Toughness Testing Requirements.
 See Section VIII, Div.1, Figure JJ-1.2-2 for Welding Procedure Qualification with Toughness Testing Requirements for ASS
 See Section VIII, Div.1, Figure JJ-1.2-3 for Welding Consumable Pre-Use Testing Requirements for ASS
 See Section VIII, Div.1, Figure JJ-1.2-4 for Production Toughness Testing Requirements for ASS
 See Section VIII, Div.1, Figure JJ-1.2-5 for DSS, FSS, and MSS Toughness Testing Requirements

o. The permissible lowest temperature to use the material may be somewhat increased or decreased from the specified temperatures in accordance with the material, heat treatment, fine grain practice, thickness, and impact test results per the applicable codes/standards under the consideration of the worst condition in future operations

Plates and Strips (20/23)

Table 2.173 Basic Properties of High-Temperature (Refractory) Metals

Property	Unit	Cr	Hf	Ir	Mo	Nb	Os	Pt	Re	Rh	Ru	Ta	V	W	Zr
Density	g/cm^3	7.2	13.1	22.4	10.2	8.55	22.4	21.4	21	12.4	12.2	16.6	6.1	19.3	6.5
Melting point	°C	1857	2227	2410	2617	2468	3045	1772	3180	1965	2310	2996	1890	3410	1852
CTE	ppm/°C	4.9	5.9	6.4	4.8	7.3	5.1	8.8	6.2	8.2	6.4	6.3	8.4	4.5	5.7
Critical structure		BCC	HCP	FCC	BCC	BCC	HCP	FCC	HCP	FCC	HCP	BCC	BCC	BCC	HCP
Thermal conductivity	W/(cm°C)	0.94	0.23	1.5	1.4	0.54	0.88	0.72	0.48	1.5	1.2	0.52	0.31	1.7	0.23
Specific heat	J/(g°C)	0.45	0.14	0.13	0.25	0.26	0.13	0.13	0.14	0.24	0.24	0.14	0.49	0.13	0.28
Electrical resistivity	Ω.m	12.9	32	5.1	5.4	14.4	9.2	10.4	18.5	4.7	7.3	13.1	20	5.3	42

Source: ASM Metal Handbook, Vol.2 – modified

Notes: *CTE* coefficient of linear thermal expansion, *Ω.m* mW.cm

p. 300 series ASS over 538 °C (1000 °F) of operating temperature: use it only when the carbon content of base metal and welding electrode is 0.04 wt% or higher

q. See Table 2.68 for more details on the properties and development history of Ni base alloys

r. Comparison of TS and PRE of Several DSS and ASS materials – Fig. 2.190

s. See NiDI Publication #10032 for 6% Mo ASS

t. LTCS: carbon steel CVN-impact tested per codes or material standards

Notes for Plates & Strips

1. The temper embrittlement factors (J factor for base metal/X factor for weld metal) are to be applied for heavy wall. (Supplementary requirements in ASTM A 387)
2. See Fig. 2.191 (Critical pitting temperature (CPT) at +400 mV SCE for some different alloys in synthetic seawater (3% NaCl) at different pH values
3. Figure 2.192 shows the corrosion resistance of high-alloy steels and nonferrous metals in oxidation and reduction solution. An oxidizing agent (oxidant, oxidizer), such as hydrogen peroxide (H_2O_2 except analytic chemistry), nitric acid, hot concentrated sulfuric acid (H_2SO_4), or chlorite, is a substance that has the ability to oxidize other substances received the electrons from donator while a reducing agent, such as formic acid (HCOOH), oxalic acid ($C_2H_2O_4$), phosphoric acid (H_3PO_4), cyanides, or sulfite, is an element or substance of compound that loses an electron to another chemical species. See below websites for more detail of oxidizing and reducing agents:
   - Oxidizing Acids, Strong: https://cameochemicals.noaa.gov/react/2
   - Oxidizing Acids, Weak: https://cameochemicals.noaa.gov/react/49
   - Reducing Agents, Strong: https://cameochemicals.noaa.gov/react/45
   - Reducing Agents, Weak: https://cameochemicals.noaa.gov/react/60

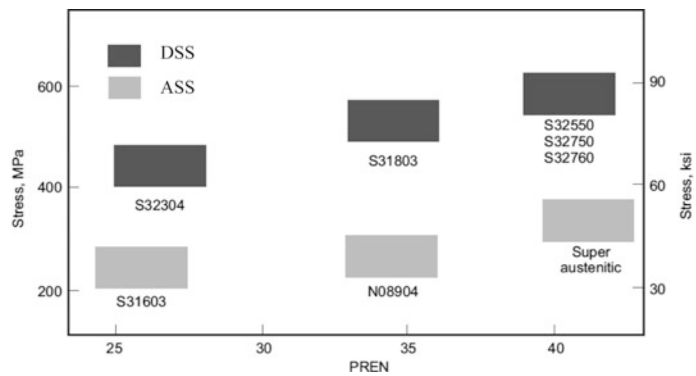


Figure 2.190 Comparison of TS and PRE of Several DSS and ASS materials. (Source: API TR938-C)

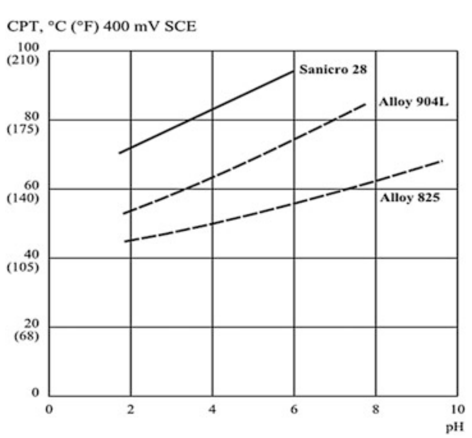


Figure 2.191 CPT at +400 mV SCE for some different alloys in seawater (3% NaCl) at different pH values. (Source: Special Metals technical reports, 2008)

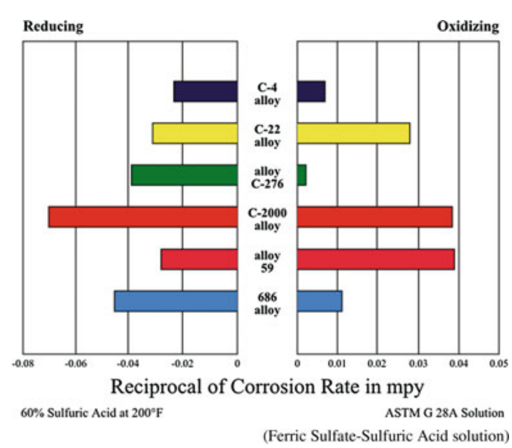


Figure 2.192 Corrosion Rate of CRA in Reduction & Oxidizing Services. (Source: Special Metals technical reports, 2008)

Plates and Strips (21/23)

4. Chloride and pH_2S Limits for Cold-Worked 22%Cr DSS (S31803) and 25%Cr DSS (S32760, pH < 4) – See API TR938-C and Fig. 2.193 below
5. Comparison for corrosion resistance of nickel alloys in several corrosion environments (See Fig. 2.194)
6. High-temperature oxidation resistance of Alloy 600, 601, and 800 (See Fig. 2.195)

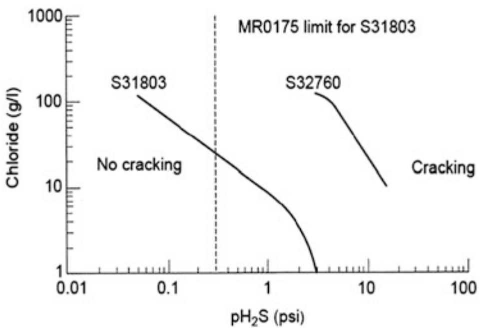


Figure 2.193 For Note 4. (Source: Special Metals technical reports, 2008)

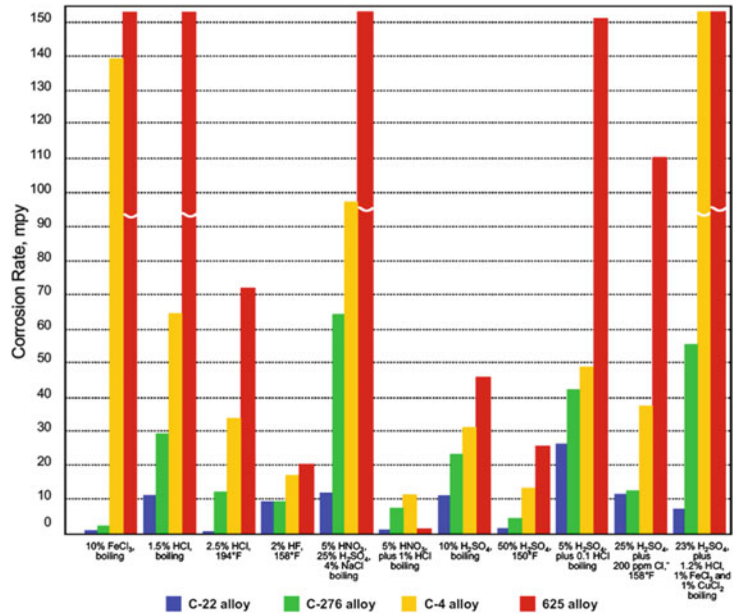
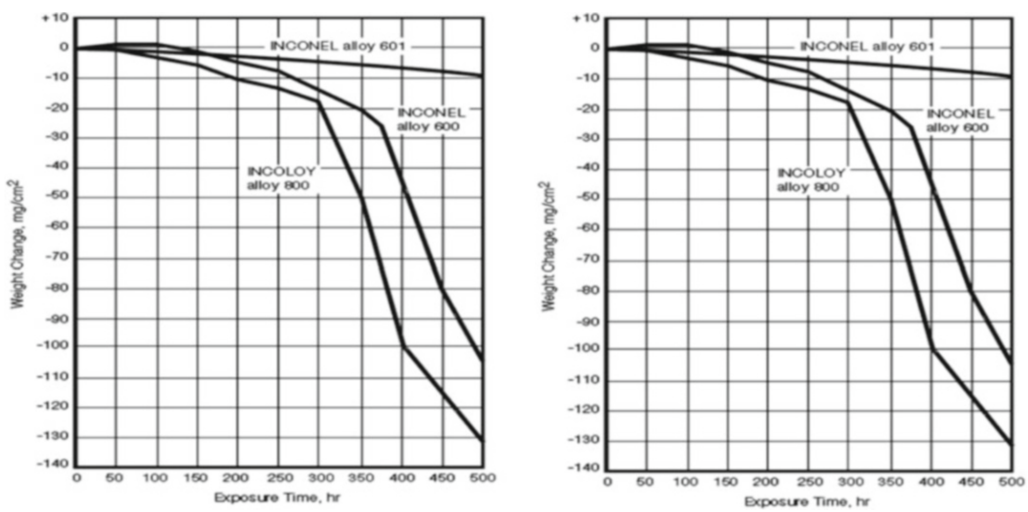


Figure 2.194 For Note 5. (Source: Special Metals technical reports, 2008)



Results of oxidation tests at 1150°C (2100°F). Test cycles consisted of 50 hrs at exposure temperature followed by air cooling to room temperature.

Results of cyclic oxidation tests at 1095°C (2000°F). Cycles consisted of 15 min heating and 5 min cooling in air.

Figure 2.195 For Note 6. (Source: Special Metals technical reports, 2008)

7. The ultrasonic inspection of aluminum alloy plates for pressure vessels shall comply with ASTM B548
8. UNS S82441 (LDX 2404®: 24Cr-3Mn-3.6Ni-1.6Mo-0.27N) and S32101 (LDX2101®: 21.5Cr-5Mn-1.5Ni-0.3Mo-0.22N): Lean DSS may be used as a CRA material between 316L SS and 2205 DSS in chloride-containing service. They are less prone to precipitation of intermetallic phases than other duplex steels. The strength of Lean DSS is similar to that of 2205 DSS. Table 2.174 shows the CPT comparison of 316L SS and several DSS per ASTM G150
9. Iso-Corrosion Curves for SDSS (See Figs. 2.196 and 2.197) and PRE, CPT, and CCT for several DSS (See Figs. 2.198 and 2.199)

Table 2.174 For Note 8

Alloy	CPT, °C	
	Base metal	As welded
316L SS	18	15
Type 2102 Lean DSS	22	15
Type 2003 Lean DSS	35	27
Type 2205 DSS	51	32

Source: API TR938-C – modified

Plates and Strips (22/23)

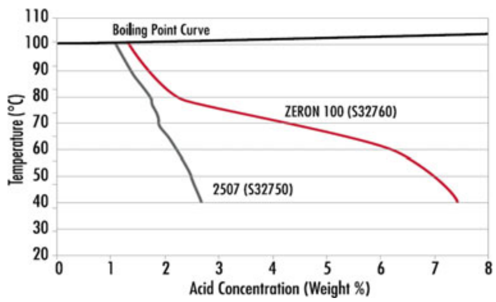


Figure 2.196 Iso-Corrosion Curves 0.1 mm/y (4 mpy) for 25Cr DSS in HCl Acid for Note 9. (Source: Special Metals technical reports, 2008)

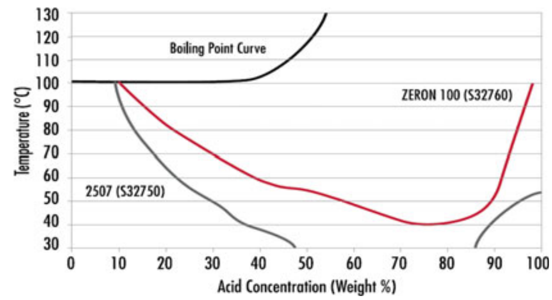


Figure 2.197 Iso-Corrosion Curves 0.1 mm/y (4 mpy) for 25Cr DSS in H_2SO_4 Acid for Note 9. (Source: Special Metals technical reports, 2008)

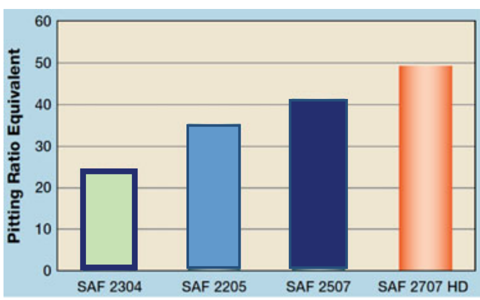


Figure 2.198 Comparison of the pitting resistance equivalent (PRE) value of Sandvik SAF 2707 HD alongside other grades. PRE = %Cr + 3.3 × %Mo + 16 × %N. (Source: Special Metals technical reports, 2008)

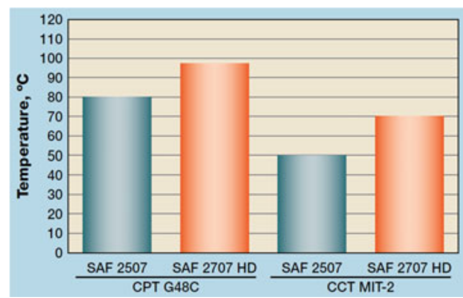


Figure 2.199 Critical pitting temperature (CPT) in modified G-48A and critical crevice corrosion temperature (CCT) obtained in MTI-2 testing. (Source: Special Metals technical reports, 2008)

10. SA387 Old Grade (up to 1971) Conversion: Gr. B = Gr.12, Gr. C = Gr.11, Gr. D = Gr.22, Gr. E = Gr.21
11. Annealed steel should be specified for applications involving high-temperature service where the primary failure mechanism is creep rupture. However, the use of N-T or Q-T heat treatment levels may be more appropriate for which equipment exposed to cyclic service at high temperature or where fatigue is an important factor
12. SA387: NACT instead of N-T may be applicable to improve the toughness
13. API Spec 2Y: The plates shall be quenched and tempered by cooling to a temperature below 538 °C (1000 °F) after rolling, reheating to a temperature between 815 °C (1500 °F) and 925 °C (1700 °F) to produce an austenitic structure, holding a sufficient time to attain uniform temperature throughout the material, quenching in a suitable liquid medium, and tempering at a temperature in the range from 565 to 705 °C (1050–1300 °F)Supplementary Requirements: Low Temperature Drop Weight Test at −55 °C (−67 °F) or CVN Impact Test at −60 °C (−75 °F)/Low S (≤0.006%)/Through Thickness (Z direction) Tensile Test/CTOD test/Gr.50: 131–207 HBN for max. hardness/others
14. Supplementary Requirements: CVN Impact Test from 25 °C (75 °F) up to −60 °C (−75 °F)
15. Alloy 625 (UNS N06625- ERNiCrMo-3) has been widely applied as a corrosion-resistant weld overlay on pressure vessel internal surfaces, clad backfill welding, flange faces, valves, subsea trees, subsea wellheads, and as solid or clad for other piping components and short flowlines (pipelines). Alloy 625 weld overlay on 6% SASS shows inferior crevice corrosion resistance compared to the parent 6% SASS in chlorinated seawater. In this case, Alloy 59 (ERNiCrMo-13), Alloy 22 (ERNiCrMo-10), Alloy 686 (ERNiCrMo-14), and Alloy C-276 (ERNiCrMo-4) weld overlay on 6% SASS shows better crevice corrosion resistance

    When using N06625 welding consumables [E(R)NiCrMo-3:) with N-containing alloys (e.g., DSS, SASS), low Nb variant ERNiCrMo-20 filler (64Ni-22Cr- 9Mo-Nb free: N06660) has been used to reduce the risk of nitride formation and loss of corrosion resistance

    There have been field failures of both Alloy 625 and Alloy 725 (N07725- ERNiCrMo-15) buttering on low-alloy steel piping components in seawater of both the Gulf of Mexico and the Norwegian sector of the North Sea. Hydrogen embrittlement appears to play a role in reducing the fracture toughness in a narrow band adjacent to the fusion line. Many manufacturers are now using alternate designs that avoid the use of these alloys for buttering [See NACE Publ. 24010 for more detail]

    For vessels constructed of UNS N06625, all joints of Categories A and B shall be Joint Type No. (1) or No. (2) of Table 1.54 in this book (ASME Sec. VIII, Div.1, UNF-19). All joints of Categories C and D shall be Joint Type No. (1) or No. (2) of Table 1.54 in this book when the design temperature is 540 °C (1000 °F) or higher (ASME Sec.VIII, Div.1, UNF-19)
16. Alloy C-276 & Alloy 625: After lengthy aging of heavy cold work at approximately 315 °C (600 °F) and higher, they are often detrimental to HE resistance

Plates and Strips (23/23)

17. DSS: At temperatures above 320 °C (608 °F) up to about 550 °C(1022 °F), the ferrite decomposes after long exposure, to precipitate alpha prime. This phase causes a significant loss of ductility; hence, duplex stainless steels are not normally used above 300 °C (572 °F). When used at −29 °C (−20 °F) and colder, an impact test may be required per codes. Several publications report that most DSS materials and the weldments have adequate toughness at −60 °C (−76 °F) and warmer and at −46 °C (−50 °F) and warmer, respectively. UNS 532760 is now available as pipes, fittings, and forgings [e.g., up to 130 mm (5.125 in.), 4000 kg (10,000 lb) hub connectors) with good toughness at −70 °C (−94 °F) and warmer. When toughness at *very* low temperatures is required for cast DSS, the use of a Ni alloy filler is sometimes considered, remembering that the Ni alloy weld commonly has the same strength as the parent DSS. For instance, Alloy C-276 filler (ENiCrMo-4) with specific WPS was used to improve the impact toughness of cast SDSS welds (UNS J93380) at −120 °C (−185 °F)

   In addition, DSS, which is used with cathodic protection for subsea facilities, can cause Hydrogen-Induced Stress Cracking when the DSS has no coating or defective coating. See DNV RP-F112 for more detailed information and guidelines

18. Alloy 718 Bars/Bolts (subsea fasteners failure): The failure susceptibility of Alloy 718 to hydrogen stress cracking is the δ phase (Ni_3Nb), and metallography is the method adopted in API 6A718 to evaluate δ phase. The results of the metallurgical analysis of studs that had failed and studs that had not failed showed that the 95 studs that had δ phase present were almost equally divided between failure and no failure, as shown below

	δ phase present	δ phase absent	Notes
Failure	47	1 *	* Contained a significant imperfection. The single stud with no δ phase that did fail had a significant imperfection in the thread root at the crack initiation location
No failure	48	7	

   Other references for Alloy 718: NACE Paper 19-13025/13057/13359/13453/13531, 18-10650/11171/11297/11382/11387/11478/11535, 17-9068/9669, 16-7901/7459, 14-4165, 12-1263, 05103, 03126, 99332, 86244NACE Corrosion, vol.51, No.6 (1995), p429-435

19. For steam bolier tubes; For hydrocarbon reforming facilities - catalyst tubes, convection tubes, pigtails, outlet manifolds, and quenching-system piping; For ethylene production - both convection and cracking tubes, and pigtails*; For oxy-alcohol production - hydrogenation heater tubes; For hydro-dealkylation units - heater tubes; For vinyl chloride monomer. * See NACE Paper 18-11344, 10361, 05402, 03657, and 03656 for case studies API TR942-A for repair of pigtails.

   Comparison Properties of Alloy 800, 800H, and 800HT are below (Fig. 2.200)

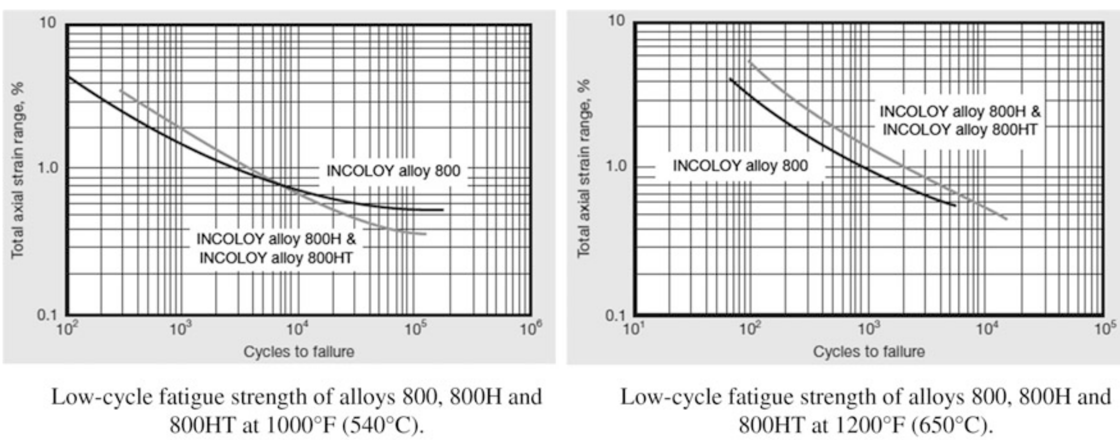


Figure 2.200 Comparison of Alloy 800, 800H, 800HT. (Source: Special Metals, technical report, 2008)

20. See Sect. 2.1.4.7 for more details on TMCP steels and Sect. 2.1.4.9 for QST (of TMCP) steels.
21. Silicon (Si) content of CS exposed to high temperature sulfidation in refinery plants: Minimum 0.10% (minimum 0.13% preferable) Si for operation above 230 °C (450 °F). See API RP939-C.
22. The PWHT of TMCP welds should be avoided unless the mechanical properties and toughness after PWHT proved the requirements.

2.6.2.2 Pipes and Tubes – See General Notes

For Mass Transfer (*w* = welded, *s* = seamless) – Note 7

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T) (1/17)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<P> Seamless (type S) Carbon steel	(s) **A53** A	1/1	48/30	−29 ~ 482 (min. 0.1% Si killed required for >482 °C)	1. PWHT for $t \geq$ 19 mm (¾ in.) 2. Full RT for $t \geq$ 22.5 mm (7/8 in.)	(a) For noncorrosive, mild corrosive, low pressure, medium temperature [≤400 °C (750 °F)] (b) Rimmed or semikilled steel (c) Gr. B is more used than Gr. A due to high strength. (d) Gr. A is more ductile and better weldability than Gr. B. (e) A53-A: Similar to API 5L-L210 (A) seamless A53-B: Similar to API 5L-L245 (B) seamless (f) Recommended to use A106 when MDMT is less than −10 °C (14 °F) (g) Specify "type S" when ordered as seamless (h) Not Si controlled; Note 1
	B		60/35			
<P> ERW Carbon steel (type E)	(w) **A53** A	1/1	48/30	−29 ~ 482 (min. 0.1% Si killed required for >482 °C)	1. PWHT for $t \geq$ 19 mm (¾ in.) 2. Full RT for $t \geq$ 22.5 mm (7/8 in.)	(a) For ≤ #150 lb class, noncorrosive, mild corrosive, low pressure, medium temperature [≤400 °C (750 °F)] (b) Rimmed or semikilled steel (c) Gr. B is more used than Gr. A due to high strength (d) Gr. A is more ductile and better weldability than Gr. B. (e) A53-A: Similar to API 5L-L210 (A) welded A53-B: Similar to API 5L-L245 (B) welded (f) Recommended to use A106 instead of A53 when MDMT is less than −10 °C (14 °F) (g) Specify "type E" when ordered as ERW (h) Not silicon (Si) controlled; Note 1
	B		60/35			
<P> Seamless carbon steel	(s) **A106** A	1/1	48/30	−29 ~ 452	1. PWHT for $t \geq$ 19 mm (¾ in.) 2. Full RT for $t \geq$ 22.5 mm (7/8 in.) Note 1	(a) Si-Killed (b) Graphitization and H_2 attack when temperature > 454 °C (850 °F) (c) QC is more closely controlled than A53 during manufacturing. (d) Carbon (%); Gr. A: 0.25 max Gr. B: 0.30 max Gr. C: 0.35 max (e) In HF service, $C \geq 0.18\%$, $V \leq 0.02\%$, Nb ≤ 0.02%, V + Nb ≤ 0.03%
	B		60/35			
	C	1/2	70/40	−29 ~ 427		
<P> EFW Carbon steel (NPS ≥ 16)	(w) **A134**	1/1	Per mother material	Per mother material	*Max. t*: ≤19 mm (3/4″) Note 1	(a) Electric-fusion (arc)-welded straight seam or spiral seam steel pipe for NPS ≥ 16 (b) Mother materials: A283/A283M (No Si controlled), A285/A285M, A570/A570M, or A36/A36M or to other ASTM specifications for equally suitable weldable material, as specified
<P> Centrifugally cast	(s) **A660** Gr. WCA WCB WCC	1/1 1/2 1/2	60/30 70/36 70/40	−29 ~ 427		(a) Carbon steel pipe for high temperature and high pressure (b) The inner and outer surfaces machined with roughness value no greater than 6.35 μm AARH
<P> Seamless pipe	(s) **A524** I II	1/* 1/*	60–85/35 55–80/30	−29 ~ 427 −29 ~ 427	NPS 1/8 to 26 *1 for SMTS<70ksi *2 for SMTS≥70ksi Note 1	(a) Carbon steel for atmospheric and lower temperatures (b) NPS 1 1/2 and under may be either hot finished or cold drawn (c) NPS 2 and over shall be furnished hot finished
<P> ERW pipe	(w) **A587**	1/1	48/30	−29 ~ 427	NPS 1/2 to 10 plus additional sizes	(a) Killed & Grain Refined (b) Low carbon steel for chemical industry process lines (c) $C \leq 0.15\%$, Al = 0.02–0.10: Note 1
<P> Electrical resistance Welded carbon steel	(w) **A135** A	1/1	48/30	−29 ~ 482	Thickness: NPS 2–30: max. 12.7 mm (0.5 in.) NPS ¾ to 5: 2.11–3.40 mm (0.083–0.134 in.)	(a) Al killed (b) For ≤ #150 lb or for > #150 lb and temperature ≤ 260 °C (500 °F) (c) For noncorrosive, mild corrosive, low pressure, medium temperature [≤400 °C (750 °F)] (d) Note 1
	B		60/35			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in³ (density) = 27.68 g/cm³ (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (2/17)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<P> ERW pipe	(w) **A671** Gr.*	Per mother material	Per mother material	Per mother material	Heat treatment: None, SR, N, N-T, Q-T, Q-precipitation per A671, Table 2	(a) For atmospheric and lower temperatures (b) * Mother materials for each grade: Note 4 (c) Note 1
<P> ERW pipe	(w) **A672** Gr.*	Per mother material	Per mother material	Per mother material	Heat treatment: None, SR, N, N-T, Q-T per A672, Table 2	(a) For high pressure and moderate temperatures (b) * Mother materials for each grade: Note 5 (c) Note 1
Forged and bored pipe	**A369** FPA FPB FP1 FP2 FP5 FP9 FP11 FP12 FP21 FP22 FP91 FP92	 1/1 1/2 3/1 3/1 5B/1 5B/1 4/1 4/1 5C/1 5A/1 15E/1 15E/1	 48/30 60/35 55/30 55/30 60/30 60/30 60/30 60/32 60/30 60/30 85/60 90/64	 −29 ~ 427 −29 ~ 427 −29 ~ 538* −29 ~ 538* −29 ~ 649 −29 ~ 649 −29 ~ 649* −29 ~ 649* −29 ~ 649 −29 ~ 649 −29 ~ 427 −29 ~ 427	* For long-term operation, lower temperature should be applied.	(a) Carbon and ferritic alloy steel forged and bored pipe for high-temperature service (b) Repair welding per ASTM A999 with purchaser's approval
<P> Metal arc welded for high pressure transmission system (16″ and greater) (w)	**A381** Y 35	1/1	60/35	−46 ~ 343	1. Size min. O.D : 406 mm 2. Thickness limit 7.9~38 mm (5/16~1 ½ in.) 3. Welding type – Straight weld – Double submerged Arc weld Note 1	(a) High-pressure line pipe (equivalent of API 5LX series) (b) Rolling from plate (c) Specify the welding type (straight seam or double SAW) when purchasing. (d) Not Si controlled
	42		60/42			
	46		63/46			
	48		62/48			
	50		64/50			
	56		71/56			
	60		75/60			
	65		77/65			
<T> Carbon steel	(s) **A192**	1/1	47/26	−29 ~ 538	Note 1 OD: 12. −177.8 mm (0.5–7 in.)	(a) Boiler tubes for high pressure (b) Equivalent with A53 (seamless) or A106 (c) Carbon: 0.06–0.18% (d) Good weldability
<P> CS (w & s)	**API 5L** PSL 1 A (L210)	1/1	48/30	−29 ~ 538*	API 5L-L210 (A): $C \leq 0.22\%$, Si ≤ 0.03% Similar to A53-A API 5L-L245 (B): $C \leq 0.28\%$, Si ≤ 0.03% Similar to A53-B Note 1	(a) For line pipe (b) Recommended PSL 2 for oil and gas fields (c) See Note 2 for API 5L vs. CSA Z245.1. (d) See Note 3 for comparison between PSL 1 and PSL 2. (e) * Max. 427 °C (800 °F) recommended
	B (L245)		60/35			
<P> CS (w & s)	**API 5L** PSL 2 Bx (L245x)	1/1	60–110/ 35–65	−29 ~ 538*	API 5L-L210 (A): $C \leq 0.22\%$, Si ≤ 0.03% API 5L-L245 (B): $C \leq 0.28\%$, Si ≤ 0.03% Note 1	(a) For line pipe (b) See Note 3 for comparison between PSL 1 and PSL 2. (c) $x = R, N, Q$, or M (d) * Max. 427 °C (800 °F) recommended
	X42x (L290x)		60–110/ 42–71			
<P & T> Seamless (type S)	(pipe) **A333** Gr. 1	1/1	55/30	−46 ~ 343	Impact tested at the temperature in Note 6 Mn: 0.40–1.06% $C \leq 0.30\%$ No Si controlled: Note 1	(a) High Mn and normalized – Good toughness at low temperature
Welded (type W)	(tube) **A334** Gr. 1					
<P> Special LAS	(s) **A333** Gr. 4	4/2	60/35	−100 ~ 343	Ni: 0.47–0.98 Cr: 0.44–1.01 Cu: 0.40–0.75 Al: 0.04–0.30	(a) For low temperature (b) Added A1, Si, Ni ≤1%-normalized steel (c) Low S, P (d) See Note 6
<P> Special LAS	(w & s) **A333** Gr. 6	1/1	60/35	−45 ~ 343	Ni: ≤0.40% Cr: ≤0.30% Cu: ≤0.40% C: ≤0.30% Mn: 0.29–1.06% Si ≥ 0.10%	(a) High Mn and normalized – Good toughness at low temperature (b) See Note 6 (c) For each reduction of 0.01%C below 0.30%, an increase of 0.05% Mn above 1.06% would be permitted to a max. of 1.35% Mn

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (3/17)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<P> Special LAS	(w & s) **A333** Gr. 7	1/1	65/35	−75 ~ 343	Ni: 2.03–2.57% $C \leq 0.19\%$ Mn ≤ 0.90% Si: 0.13–0.32%	(a) High Mn and normalized – Good toughness at low temperature (b) Note 6
<P & T> Seamless (S) and welded (W or E) 3.5 Ni	(pipe) **A333**-Gr.3 (tube) **A334**-Gr.3	9B/1	65/35	−101 ~ 343	Ni: 3.18–3.82% $C \leq 0.19\%$ Mn: 0.31–0.64% Si: 0.18–0.37%	(a) Improved toughness by additional Ni content (b) Killed and normalized steel (c) 3.5%Ni has an intermittent history for hot crack during welding. ASS is a better choice (d) Note 6
<P & T> Seamless (S) and welded (W or E) 9 Ni	(pipe) **A333**-Gr.8 (tube) **A334**-Gr.8	11A/1	100/75	−196 ~ 121 Max. 93 °C (200 °F) for piping	Note 6	(a) For cryogenic service (b) High strength (c) Specify "type S" or "tube W" when purchasing. (d) 9%Ni has an intermittent history for hot crack during welding. ASS is a better choice
<P> C -½ Mo	(s) **A335** P1 (K11522)	3/1	55/30	−29 ~ 538 Max.465 °C (870 °F) preferable for long-term operation due to graphitization.	1. 10% RT for $t \leq 12.7$ mm (½ in.) 2. PWHT & full RT for $t > 12.7$ mm (½ in.) Note 1	(a) Added Mo to improve the high temperature properties and to prevent graphitization because Mo is a strong carbide former (b) It may not be used to resist HTHA in API RP941for new construction. Careful/periodic inspection in HTHA service is required for the existing facilities. (c) Used in noncorrosive or mildly corrosive service (d) May be used in extrusion, forging, and electric fusion welding for NPS > 24
<P> ½ Cr - ½ Mo	(s) **A335** P2 (K11547)	3/1	55/30	−29 ~ 538	1. 10% RT for $t < 22.2$ mm (7/8 in.) 2. Full RT for $t \geq 22.2$ mm (7/8 in.) 3. PWHT required for $t > 12.7$ mm (½ in.)	(a) More resistance to hydrogen attack, graphitization, and high-temperature oxidation than C-0.5Mo (b) This material may not be extensively used (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24 (d) It may not be used to resist HTHA in API RP941for new construction. Careful/periodic inspection in HTHA service is required for the existing facilities
<P> 1 Cr - ½ Mo	(s) **A335** P12 (K11562)	4/1	60/30	−29 ~ 649 Max. 593 °C (1100 °F) for long-term operation	1. 10% RT for $t < 22.2$ mm (7/8 in.) 2. Full RT for $t \geq 22.2$ mm (7/8 in.) 3. PWHT required for $t > 12.7$ mm (½ in.)	(a) More resistance to HTHA, graphitization, and high-temperature oxidation than 0.5Cr-0.5Mo (b) For HTHA/high-temperature oxidation resistance & creep-rupture strength (see API RP941) (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24 (d) Susceptible to severe high-temperature sulfur corrosion [≥316 °C (600 °F)]
<P> 1¼Cr – ½ Mo	(s) **A335** P11 (K11597)	4/1	60/30	−29 ~ 649 Max. 593 °C (1100 °F) for long-term operation	1. 10% RT for $t < 22.2$ mm (7/8 in.) 2. Full RT for $t \geq 22.2$ mm (7/8 in.) 3. PWHT required for $t > 12.7$ mm (½ in.)	(a) More resistance to HTHA, graphitization, and high-temperature oxidation than 1Cr-1/2Mo (b) For HTHA/high temperature oxidation resistance & creep-rupture strength (see API RP941) (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24 (d) Susceptible to severe high-temperature sulfur corrosion [≥316 °C (600 °F)]
<P> 2¼Cr - 1 Mo	(s) **A335** P22 (K21590)	5A/1	60/30	−29 ~ 649	1. Full RT 2. PWHT required for $t > 12.7$ mm (½ in.)	(a) More resistance to HTHA, graphitization, and high temperature oxidation than 1.25Cr-0.5Mo (b) For HTHA/high-temperature oxidation resistance & creep-rupture strength (see API RP941) (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24 (d) Higher creep-rupture strength than 1.25Cr-0.5Mo at 538–649 °C (1000–1200 °F)
<P> 2¼Cr - 0.15 Mo- $S \leq 0.010$	(s) **A335** P23 (K41650)	5A/1	74/58			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (4/17)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<T> Seamless CS & LAS mechanical tubing	**A519** 4130 (G41300)	11B/9	90/70 105/85 75/55 90/60	−29 ~ 538* HR SR A N * Max.465 °C (870 °F) for long-term	[heat treatment] Hot rolled (HR), cold worked (CW), stress relieved (SR), annealed (A), normalized (N), Q-T, (option)	(a) Most AISI grades in A519 are also included (b) When welding is used for joining the weldable mechanical tube grades, the welding procedure shall be suitable for the grade, the condition of the components, and the intended service (c) Only a few grades in A519 listed in ASME sec. II-D and B31.xx for allowable stresses
<P> 3 Cr - 1 Mo	(s) **A335** P21 (K31545)	5C/1	60/30	−29 ~ 649	1. Full RT 2. PWHT required for *t* > 12.7 mm (½ in.)	(a) More resistance to HTHA, graphitization, and high temperature oxidation than 2.25Cr −0.5Mo (b) For HTHA/high-temperature oxidation resistance & creep-rupture strength (see API RP941) (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24
<P> 5 Cr - ½ Mo	(s) **A335** P5 (K41545)	5B/1	60/30	−29 ~ 649	1. Full RT 2. PWHT required for *t* > 12.7 mm (½ in.)	(a) Significantly greater resistance to HTHA, graphitization, and high-temperature oxidation/ sulfidation than 3Cr-1Mo. (b) For HTHA/high-temperature oxidation resistance & creep-rupture strength (see API RP941) (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24 in. (d) Higher creep-rupture strength and erosion resistance than 3Cr-1Mo at high temperature (e) For heater tubes or transfer lines
<P> 9 Cr - 1 Mo	(s) **A335** P9 (S50400)	5B/1	60/30	−29 ~ 649	1. Full RT 2. PWHT required	(a) More resistance to HTHA, graphitization, and high-temperature oxidation/sulfidation than 5Cr-1/2Mo (b) 9Cr-1Mo gives better choice than 5Cr-0.5Mo due to competitive cost and sulfidation resistance. (c) May be used in extrusion, forging, and electric fusion welding for NPS > 24 in (d) Higher creep-rupture strength at high temperature and erosion resistance than 5Cr-0.5Mo (e) For boiler/heater tubes or transfer lines
<P> 9Cr - 1Mo-V -Cb-N- Ni-Al	(s) **A335** P91 (K91560)	15E/1	85/60	−29 ~ 649	1. Full RT 2. PWHT required *UNS no.* P122: K92930 (SMTS/SMYS: 90/58)	(a) More resistance to HTHA, graphitization, and high temperature oxidation/sulfidation than 5Cr-1/2Mo (b) May be used in extrusion, forging, and electric fusion welding for NPS > 24 in (e) Poor weldability – consult a responsible metallurgist (f) Higher creep-rupture strength at high temperature and erosion resistance than 9Cr-1Mo (g) For boiler/heater tubes or transfer lines (h) See API TR938-B. (i) P911 & P122 (11Cr-0.4Mo-V-W-Cu-Cb-B-N) are not registered in ASME Sec. II, Part D and B31.3, Table A-1 & 2 yet. (j) P91: Ni + Mn ≤ 1% for repair welding consumable
<P> 9Cr-0.5Mo-V- Cb-N- Ni-Al-W -B	(s) **A335** P92 (K92460)	15E/1	90/64	−29 ~ 649		
<P> 9Cr-1Mo-V- Cb-N- Ni-Al-W -B	(s) **A335** P911 (K91061)	15E/1	90/64	−29 ~ 649		

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (5/17)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<Pipe and pipe fittings> High Si Cast iron	(s) **A861** Gr.1 Gr.2		Supplementary requirement- mechanical properties: only per the transverse bend test and hydrotest (at ≥40 psig)	−29*~ 800**	1. Gr.1: 0.65–1.10%C Cr ≤ 0.50% Gr.2: 0.75–1.15%C 3.25–5.0%Cr 2. Types- No-bub (MJ type) Hub/plain end Fitting (no-hub: MJ) Fitting (hub/plain end) * For <0 °C, impact test is recommended. ** Normally applied at the boiling point of the service.	(a) 14.5%Si for all grades (b) A861: for corrosion-resistant service – same goals for A518 (c) Heat treatment – All centrifugally cast high-Si iron pipe shall be supplied in the as-cast condition. All other pipe and fittings shall be supplied in the stress-relieved condition. – Stress relieving shall be performed as follows: Hold the casting at 870 °C (1650 °F) min. for 2 hr plus an additional hour per inch of section thickness for castings over 50 mm (2 in.) in thickness Cool the castings to 205 °C (400 °F) maximum at a rate not to exceed 55 °C (100 °F)/15 min. From 205 °C (400 °F) to ambient, the castings shall be permitted to be cooled in still, ambient air
<P> Seamless Ferritic alloy 1.1Ni-0.6Cu-Cb-V-Al	(s) **A335** P36 **A182** F36 (K21001)	*M-no.* 3/1	90/64 At min. 900 °C normalized and min, 595 °C tempered	−29 to 371		(a) For high-temperature service (b) A335-P36: Seamless ferritic alloy-steel pipe for high-temperature service A182-F36: Forged pipe components
<T> 23-27Cr. Mo < 0.25	(w & s) **A268** 446 Gr. 1 Gr. 2	10I/1	70/40 65/40	−29 ~ 343	s.g.: 7.45 Gr.1:C < 0.20, Ni < 0.75 Gr.2:C < 0.12, Ni < 0.50	(a) Corrosion and oxidation resistance (b) Corrosion scaling resistance (c) Sulfidizing atmospheres resistance (d) Abrasion resistance (e) Not suitable for high reducing environments (e.g., hydrochloric acid) (f) Use for boiler tubes, preheaters and heat exchangers, cement kilns, waste heat boilers, molten lead, salt baths, heat-treating incinerators, etc.

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (6/17)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<P> ASS 18Cr – 8Ni	(w & s) **A312**- TP304L TP316L TP321(H)*	8/1	70/25 * For $t > 9.5$ mm (3/8″)		– Seamless, straight-seam welded (ERW), and heavily cold worked (HCW-less than 35% thickness reduction) ASS. – Welded pipe and HCW pipe of NPS 14 and smaller shall have a single longitudinal weld. *s.g.* 304L: 7.94 309S: 7.98 310S: 7.98 316 : 7.98 316L: 7.98 321 : 7.90 347 : 8.02 304H: 7.94 316H: 7.98 *Suffix* *L* = low carbon (good IGC resistance) *H* = high carbon (good creep-rupture strength) Note 10	(a) 304L, 316L, 321: Used at ≤427 °C (800 °F)] and mild acidic service (> pH 4.5). (b) All "H" grades contain 0.04–0.1%C for high-temperature strength, including welding materials. Also, may have average grain size, ASTM no.7 or coarser per ASTM E112. See Note 8 for more details (c) 304, 316 for welded parts: use low-carbon ($C \leq 0.03\%$) or dual grade (304/304L or 316/316L) (d) 309, 310: High-temperature oxidizing resistance (e) 316, 317 (Mo added): More corrosive than 304 in oxidizing acid (HNO_3, conc. H_2SO_4)/good pitting resistance in acidic environment (f) All 300 series SS: Susceptible to Cl-SCC and CUI (g) Large size and thick thickness: economically preferable to use clad materials for corrosion resistance. Some companies want to use clad instead of solid SS because of mitigation effect of SCC propagation. (h) 347 welding material should be used for 321 welding (i) Corrosion test (IGC, SCC, etc.) may be considered for severe corrosion service. (j) Passivation treatment and segregated work (from carbon and low alloy steels) are recommended for corrosive service (k) Max. temperature for low carbon ($C \leq 0.03\%$): 427 °C (800 °F), but 454 °C (850 °F) for ASS with Mo ≥ 2.5%. (l) Due to commercial market, A358 is preferable instead of A312-welded for thickness of NPS >1/2 in. (m) Heavy cold-worked (HCW) pipe should not be used unless approved by the responsible metallurgist
	TP304 TP309S TP310S TP316 TP316LN TP317 TP321(H)* TP347(H) TP347LN TP348(H)		75/30 * For $t \leq 9.5$ mm (3/8″)	−254 ~ 538 (max. 816 for short term)		
	TP304N TP316N		80/35			
	TP304H TP316H*		75/30 Except *95/45 for S31035	−196 ~ 816 Typically not used for cryogenic service only.		
<P> ASS **XM-19** 21Cr-12Ni-2Mo-5Mn-0.2N-0.1Nb-0.1V	(w & s) **A312** S20910	8/3	100/55	−196~649	Brand name: Nitronic 50	(a) HCW pipe should not be used unless approved by the responsible metallurgist. (b) Slightly higher corrosion resistance than those of 316L or 317L SS (c) Higher strength than those of 316L or 317L SS (d) For marine hardware or downhole (e) ASTM A314 for billet, bar, and forging
<P> Lean DSS 21.5Cr-5Mn-1.5Ni-0.3Mo-0.22N	(w & s) **A790** S32101 LDX2101	10H/1	101/77 ($t \leq 5$ mm) 94/65 ($t > 5$ mm)	−29*~316 * For < −29 °C, impact test is required	Note 17 in Plates & Strips	(a) Used as a CRA material between 316L SS and 2205 DSS in chloride-containing service (b) Less prone to precipitation of intermetallic phases than other duplex steels (c) The strength is similar to 2205 DSS. (d) ASME Code Case 2418/NSF Approval Standard 61
<P & T> Lean DSS 20Cr-3.5Ni-1.7Mo-0.17N (w & s)	(tube) **A789/A270** (pipe) **A790** S32003 (AL2003TM)	10H/1	65–70/ 95–100* For A789 65/90 For A270 65/95 For A790	−29**~343 **For < −29 °C, impact test may be required per Sec.VIII-D1	*Hardness:* HRC 30 max. HBW 290 max. *Per thickness Note 8	(a) Exhibits corrosion performance superior to type 317L stainless steel in many environments (b) Lower cost alternative to austenitic type 316L and duplex 2205 alloys (c) ASME Code Case 2503-1 (d) A789 & A790: FSS & ASS (e) A270: seamless & welded sanitary FSS/ASS tube (f) See ASTM A928 for weld filler metal

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (7/17)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<P> Lean DSS **LDX 2404** 24Cr-3Mn-4Ni-1.5Mo-0.25N-Cu	(w & s) **A790** S82441	10H/1	107/78 ($t \leq 10$ mm) 99/70 ($t > 10$ mm)	−29*~316 *For $<$ −29 °C, impact test is required	*Max. Hardness:* 290 BHW s.g.: 7.75 See Note 10	(a) Better corrosion resistance than LDX2010 and 2101 (b) Less prone to precipitation of intermetallic phases than other duplex steels (c) The strength is similar to 2205 DSS. (d) 24Cr-3.7Ni-1.5Mo-0.25N-0.9Cu, PRE≈33 (e) See ASME Sec. VIII, Div.1, Code Case 2780 (f) See NACE Paper 12-1504 (g) See Note 17 in Plates & Strips
<P> DSS SDSS	(w & s) **A790** 2205 (S31803) 2507 (S32750)	10H/1	90/65 116/80	−29* ~ 316 *−40 °C (−40 °F) in ASTM A923 *For$<$−29 °C, impact test is required	*Hardness:* BHN 293max s.g.: 7.88 *Hardness:* BHN 310max s.g.: 7.80 See Note 10.	(a) High strength and good erosion resistance (b) 2205 (22Cr-5Ni-3Mo-0.14N): Strong Cl-SCC and pitting resistance [≤70 °C (158 °F)] (c) 2507 (25Cr-7Ni-4Mo-0.25N): Strong Cl-SCC and pitting resistance [≤85 °C (185 °F)] [Similar SDSS] S32760 (25Cr-7Ni-3.5Mo-0.25N-0.75Cu) S32520 (25Cr-6.7Ni-3.5Mo-0.27N-0.75Cu) (d) Corrosion test per ASTM A923 may be considered (e) Reference: ASTM A923 and API TR938-C (f) See Note 17 in Plates & Strips
<P & T> **DSS** **Safurex** 29Cr-6.5Ni-2Mo	(w & s) Pipe: **A790** Tube: **A789** (S32906)	10H/1	$t \leq 10$ mm ; 116/94 $t > 10$ mm ; 109/80	−29*~316 *For $<$ −29 °C, impact test is required	s.g.: 8.00 See Note 10.	(a) See plate for safurex (b) 29Cr-6.6Ni-2Mo-0.35N-≤0.8Cu (c) X2CrNiMoN 25 22 2 (A4-18005 BC.05) (d) See ASME Code Case 2295-2 (e) See Note 17 in Plates & Strips
Hyper DSS 27Cr-6.5Ni-5Mo	(w & s) Pipe: **A790** Tube: **A789** S32707	10H/1	133/101 138/112 [123/101*]		SAF 2707 HD® & SAF 3207 HD® "HD" stands for hyper-duplex. * $t > 4$ mm	(a) Excellent chlorides SCC resistance (b) 27.5Cr-7.5Ni-4.5Mo-0.4N-1Co-≤1Cu, PRE≈49 (c) See Figs. 2.198 and 2.199 in plates and strips (d) S33207 (31Cr-7.5Ni-4Mo-0.5N-≤1Cu, PRE > 50) is a more advanced hyper DSS than S32707 (e) Max. interpass temperature ≤ 100 °C (212 °F)
<P & T> Alloy **904L** 20Cr-25Ni −4.3Mo-1.5Cu	(w & s) **A312** **A269** TPXM-11 (N08904) (S21904)	45/–	90/50	−196~370	s.g.: 8.05 See Note 10.	(a) Heavy cold-worked (HCW) pipe should not be used unless approved by the responsible metallurgist. (b) A312: Pipe/A269: Tube (c) Good resistance to Cl-SCC (d) Copper gives good corrosion resistance to reducing media (hot phosphoric acid, dilute H_2SO_4, etc.). (e) For seawater, pulp, paper bleach plant, and fertilizer production equipment
<P & T> SASS **AL-6XN** 20Cr-25Ni-6Mo-Cu-N	(w & s) **A312** N08367 (s) **B690** N08367	45/–	95~100/45	−196~427	s.g.: 8.04 See Note 10.	(a) Heavy cold-worked (HCW) pipe should not be used unless approved by the responsible metallurgist (b) Strong Cl-SCC and pitting resistance [≤90 °C (194 °F)] (c) PRE > 40: super austenitic stainless steel (SASS)
<P & T> SASS **254 SMO** **SR 50A** 21Ni-23Cr-6Mo-N	(w & s) **A312** S31254 (CLI-SR50A) Euronorm X S32050	8/4	94/44 99/49	−196~399 −196~538	s.g.: 8.00 SR50A is equivalent with NAS 224N (Nippon Yakin) Seamless or welded (ERW) See Note 10.	(a) Strong Cl-SCC and pitting resistance [≤90 °C (194 °F)] (b) PRE > 40: super austenitic stainless steel (c) Welding electrode: same as alloy C22 or C276 (d) Heavy cold-worked (HCW) pipe should not be used unless approved by the responsible metallurgist

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (8/17)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for Plates)
<P & T> Alloy **25-6Mo** 25Ni-20Cr-6Mo-1Cu-N	(w – pipe) **B673, B804** (s – tube) **B677** (w – tube) **B674** N08926	45/–	94/43	−196~427	See Note 10.	(a) B673, B804: Welded pipe (b) B677: Seamless pipe and tube (c) B674: Welded tube (d) ASME code cases: 2120, N-453/454/455
<P & T> Alloy **330** 19Cr-35Ni-1.2Si-Mn≤2	**B546**(EFW) **B710**(w) **B535**(s) N08330	46/–	70/30	−196~1148	HRB: 70–90 See Note 10.	(a) Good resistance to carburization, nitriding, and/or thermal cycling/shock (b) Fully ASS; not subject to embrittlement from sigma formation (c) Brand name: MISCO RA330
<P & T> Alloy **28** (Sanicro28) 32Ni-27Cr-3.5Mo-1Cu	**B668** N08028	45/–	73/31	−196~454	HRB: 70–90 See Note 10.	(a) Seamless (b) Excellent resistance to sulfide cracking in conditions characterized by high levels of H_2S, CO_2 and chlorides. Examples of applications are production tubing (OCTG) and H/EX used in the processing of sour crude (c) High abrasion resistance
<P> Alloy (carpenter) **20 &20Cb3** 35Ni-20Cr-3Cu-2Mo-Cb **20Mo6** 35Ni-24Cr-6Mo-3Cu	**B464** **B474** Welded (N08020) **B464** (N08026)	45/–	80/35 (annealed)	−196~427	IGC test may be required to prove the corrosion resistance. s.g.: 8.08 See Note 10.	(a) Superior corrosion & stress fracture resistance in non-aerated 10–40% H_2SO_4 acid, below 60~80 °C (140–176 °F) (b) Good corrosion resistance to HF acid at atmosphere and less than 10% HCl acid (c) 20Mo6 (super stainless steel) has been developed from 20Cb3 to improve the pitting & chloride SCC resistance (d) Welding: Use E-320 or ER-320 electrodes (e) PWHT: min. 538 °C (100 °F) for high chloride SCC environment (f) Normally supplied as annealed condition (g) For synthetic rubber, high-octane gasoline, solvents, explosives, plastics, synthetic fibers, heavy chemicals, organic chemicals, pharmaceuticals and foodstuffs h. ASTM B468 for welded tubes
<P> Seamless Cupro-Nickel **90–10** Cu-Ni (C70600) **70–30** Cu-Ni (C71500)	**B466** Temper O60 Temper H55 Temper H80	34/–	38/13 (C70600) 52/18 (C71500) 45/35 (C70600) 50/40 (C70600) 70/45 (C71500)	−198 ~ 316 (C70600) s.g.: 8.95 −198 ~ 371 (C71500) s.g.: 8.90	O60: annealed temper H55: soft drawn temper H80: Hard drawn temper	(a) Excellent corrosion resistance, especially in marine environments; moderately high strength, good creep resistance at elevated temperatures; relatively higher cost in comparison with those of copper-aluminum and other alloys with similar mechanical properties (b) For seawater service as H/EX tubes, forged and machined valve and pump components, fittings, and hardware; where high corrosion resistance is required and where concern over chloride SCC prevents use of stainless steels (c) Seawater velocity limit for piping (NPS ≥ 4): ≤3 m/s (10 fps) for 90:10/ ≤4 m/s (13 fps) for 70:30 (d) Seawater velocity limit for H/EX tubes and small pipe: ≤2 m/s (6 fps) for 90:10/ ≤3 m/s (10 fps) for 70:30 (e) See Sect. 2.1.7.2 for more details on copper alloys (f) Corrosion rates: See Figs. 2.96 and 2.97
<T> Seamless Cupro-Nickel **90–10** Cu-Ni **70–30** Cu-Ni	**B111** Temper O61 Temper H55 Temper HR50	34/–	40/15 (C70600) 52/18 (C71500) 45/35 (C70600) 72/50 (C71500)	−198 ~ 316 (C70600) s.g.: 8.95 −198 ~ 371 (C71500) s.g.: 8.90	O61: annealed temper H55: light drawn temper HR50: drawn, stress relived Hand drawn, end annealed	

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (9/17)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<P & T> Seamless Alloy (Monel) **400** 67Ni-30Cu (N04400)	**B165** N04400 Annealed OD ≤ 5″	45/–	70/28	−198 ~ 816	Specify the heat treatment (see Table A below) See ASTM **B725**. (welded pipe, NPS ≤ 30) Monel cladding (A265) is preferable for NPS ≥ 16.	(a) Pipes in dilute H_2SO_4, dilute HCl including salt deposit (NH_4HS), organic acid, caustic service, and severe acidic solution (b) Severe IGC is expected in H_2S-containing service at >260 °C (500 °F) (c) Not recommended in ammonia and its compound environment (due to SCC) (d) Susceptible to mercury embrittlement (e) See DIN 17751 (Pipe and Tube of Ni alloys)
	Annealed OD > 5”		75/25			
	Stress Relieved		85/55			

※ Table A

Room-emperature mechanical properties (incoloy alloy 400). Valve components: to be annealed.

	Tensile strength	Yield strength	Elongation	Hardness,
Temper	*psi*	*(0.2% offset), psi*	*In 2 in, %*	*Brinell (HBW)*
(a) Hot-finished(rolled)	80,000–100,000	40,000–100,000	60–30	140–241
(b) Cold-drawn stress-relieved	84,000–120,000	55,000–100,000	40–22	160–225
(c) Annealed	70,000–90,000	25,000–50,000	60–35	110–149

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<P> Seamless or welded Ni- Cr alloy **800** (Incoloy) (N08800) & **800 H** (Incoloy) (N08810) 32Ni-21Cr	**B407** Seamless **B514** Welded N08800 Annealed	45/–	60/25	−198 ~ 816	Specify the heat treatment (see Table B below)	(a) Incoloy 800: more resistance chloride SCC, pitting and general corrosion than 300 series stainless steels (b) Recommended solution annealing after cold bending (c) See notes in plates and strips. (d) BS 3072NA15 (Plate & Sheet), BS 3073NA15 (Strip) (e) DIN 17460 (Plate, Sheet, & Strip), EN 10028-7 & EN 10095 (Plate, Sheet, & Strip) (f) ASME Code Case 2339 (g) See API TR942-A for hydrogen reformer furnace outlet pigtails and manifolds (h) See Note 19 for plates and strips
	N08810 Annealed		75/30			

※ Table B

Room-temperature mechanical properties (incoloy alloy 800 & 800H)

	Tensile strength	Yield strength	Elongation	Hardness,
Temper	*psi*	*(0.2% offset), psi*	*In 2 in, %*	*Brinell (HBW)*
(a) Hot-finished (rolled)	80,000–120,000	35,000-90,000	50–25	140–217
(b) Annealed	75,000–100,000	30,000–60,000	60–30	120–184
(c) Cold-drawn	100,000–150,000	75,000–125,000	30–10	180–300

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Alloy (Incoloy) **825** 42Ni–21Cr-3Mo	**B423** Welded/Seamless **B705** Welded N08825	45/–	85/35* 75/ 25**	−198 ~ 816 (normally recommended <540 °C (1000 °F)	s.g.: 8.14 *Hot-finished annealed in B423 & B705 **Cold worked annealed in B423	(a) Good corrosion resistance to sulfuric, phosphoric acids, and neutral chloride media (except $MgCl_2$). See Note 2 in plates and strips (b) Phosphoric acid evaporators; pickling-tank heater & hooks and equipment; chemical process equipment; tank trucks; propeller shafts, pollution-control equipment, and spent nuclear fuel element recovery
<P & T> Alloy (Incoloy) **945** 50Ni–21Cr-3Mo-3Nb-2Cu-1Ti-bal.Fe	**B983** Seamless Alloy 945 (N09945)	43/–	Type 1: 150/ 130 Type 2: 165/ 140	−60* ~ 650** *For lower temperature, impact test required **Normally used at <540 °C (1000 °F) for age hardened material	s.g.: 8.2 Precipitation hardened or cold worked, seamless	(a) High strength and corrosion resistance in aggressive sour wells containing high levels of H_2S and chlorides (b) For downhole and surface gas-well components, including tubular products, valves, hangers, landing nipples, tool joints, packers, fasteners, pump shafting, high fatigue top tension riser components, and high strength piping systems (c) Annealing: at 1010–1066 °C (1850–1950 °F) for 0.5–4 hrs (per thickness), water quench (d) Age hardening: at 704–732 °C (1300–1350 °F) for 6–8 hrs, furnace cooled at 26–56 °C/hr to 607–635 °C (1125–1175 °F), hold for 6–8 hrs, air cooled

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (10/17)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<P & T> Alloy (Inconel) **686** 57Ni-20Cr-16Mo-3.5W-Ti-N	**B619** **B622** **B626** N06686	43/–	100/45	−198 ~ 450	s.g.: 8.73 PRE ≈ 51 B619: welded pipe B622: seamless pipe & tube B626: welded tube	(a) High CCT (critical crevice temperature) (b) For chemical processing, marine, and air pollution control (flue gas desulfurization) industries (c) See Note 15 in Plates & Strips (d) See DIN 17751
<P & T> Alloy (Nicrofer) **59** 55Ni-23Cr-16Mo-Al	**B619** **B622** **B626** N06059	43/–	100/45	−198 ~ 450	s.g.: 8.61 PRE ≈ 47 B619: welded pipe B622: seamless pipe & tube B626: welded tube	(a) Excellent resistance to pitting and crevice corrosion and freedom from Cl-SCC (b) Excellent resistance to mineral acids, such as HNO_3, H_3PO_4, H_2SO_4 and HCl acids and in particular to H_2SO_4 and HCl acid mixtures (c) See Note 15 in Plates & Strips
<P & T> Alloy (Inconel) **718** 52Ni-19Cr-5Nb-3Mo-1Ti-Al-Ta	**B619** **B622** **B626** N07718	43/–	185/170 Aged after cold rolling	−254 ~ 700	SAE AMS 5589/ 5590 ASME code case: N-253 DIN 17751 Note 18 in Plates & Strips.	(a) Age hardenable – Very high strength (b) Good environmental cracking resistance (high H_2S & CO_2 in free S) at high temperatures in deep, extremely hostile, oil and gas production environments (c) High fatigue strength and high corrosion resistance with nonmagnetism, modified heat treatment, and fine grain practice (d) For oil & gas drilling and production facilities
<P & T> Seamless or welded Alloy (Inconel) **600** 72Ni-15Cr-8Fe	**B167** (seamless) **B-517** (welded pipe) N06600	43/–	Hot 80/30 75/25 Cold 80/35 80/35	−198 ~ 649	s.g.: 8.47 OD ≤ 5 inch OD > 5 inch OD ≤ 5 inch OD ≥ 5 inch SAE/AMS 5580 DIN 17751, ISO 6207 MIL-DTL-23227 Note 6 for plates and strips.	(a) Good corrosion resistance in oxidizing, reducing, and Cl-SCC environment (b) Oxidation resistance up to 1100 °C (2010 °F) in atmospheric and carburization resistance [≤1177 °C (2150 °F)], but normally limited max. 649 °C (1200 °F) due to strength (c) Not recommended in high temperature salt water/caustic alkalis/mercury due to pitting/SCC/IGSCC above 540 °C (Cr_7C_3 below 760 °C/$Cr_{23}C_6$ below 760 °C). Solution heat treatment is required to minimize them (d) Good corrosion resistance in sulfur-free gas environment (e) ASME Code Cases 1827, N-20, N-253, and N-576
<P & T> Seamless or welded Alloy (Inconel) **601** 60Ni-23Cr-12Fe	**B167** (seamless) (N06601)	43/–	80/30 Annealed	−198~1200* * 1095 °C for long term or cyclic oxidation environment	s.g.: 8.11	(a) Good high temperature oxidation resistance [≤1200 °C (2200 °F) for short exposure]. Better resistance than alloy 600 good for fired heater refractory anchor material (b) Unique resistance to oxide spalling under cyclic thermal conditions (c) Modified grade (GC): grain size control to inhibit the grain growth by Zr and Nitrogen (d) See Note 6 for plates and strips
<P> Alloy (Inconel) **625** 60Ni-22Cr-9Mo-3.5Cb	Seamless **B444** Welded **B705** (N06625) Annealed	43/–	Gr.1 120/60 Gr.2 100/40	−198 ~ 871	Gr.1: Anneal Gr.2: Solution anneal	(a) Gr. 1: service temperatures up to 593 °C (1100 °F) (b) Gr. 2: service temperatures above 593 °C (1100 °F) when the resistance to creep and rupture is required (c) See Note 15 in Plates & Strips
<P & T> Alloy (Hastelloy) **B-2** 69Ni-28Mo-1Cr-1Co-1Mo-2Fe	**B622** Seamless pipe & tube (N10665) **B619** Welded pipe (N10665)	44/–	110/51	−198 ~ 427	Solution heat treated & quenched at 1066 °C (1951 °F) ※ In order to prevent Cr-depletion (IGC-knife line attack) on weld HAZ: Fe ≤ 2.0%, $C \leq 0.025\%$, Si ≤ 0.1% ※ s.g.: 9.22	(a) H_2SO_4, H_3PO_4 (phosphoric), CH_3COOH (acetic), formic acid, HCl acid (at all concentrations and temperatures) – good reducing acid corrosion resistance (b) Good pitting and SCC resistance in nonoxidizing salt or halogen compound (c) Poor corrosion resistance in oxidizing environment due to a little Cr (d) Nonmagnetic, high strength, low thermal expansion coefficient (e) Cr-depletion (IGC- knife line attack) can appear at weld HAZ. (f) Rapidly corrode in ferric & cupric salts (from normally dissolved Fe, Cu in HCl acid) (g) Physical & metallurgical properties: similar to 300 series ASS

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (11/17)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<P & T> Alloy (Hastelloy) **C-276** 57Ni-16Mo -15Cr-2.5Co-4W	**B622** Seamless pipe & tube (N10276) **B619** Welded pipe (N10276)	44/–	100/41	−198 ~ 676	Solution heat treated & quenched at 1120 °C (2048 °F) ※ s.g.: 8.89	(a) Good corrosion resistance in ferric & cupric chlorides, HCl acid, hot contaminated media (organic and inorganic), chlorine, formic and acetic acids, acetic anhydride, and seawater (b) Corrosion resistance is better than Alloy B-2 if oxidizing salts, such as ferric chloride, are present in the acid (c) Corrosion resistance and mechanical properties can be decreased after long-time aging at 650–1090 °C (1200–1995 °F) due to the precipitation of metallic compound (d) For chemical process equipment and desulfurization of flue gas equipment (e) Physical & metallurgical properties: similar to 300 series ASS (f) See Note 15 in Plates & Strips
<P & T> Alloy (Hastelloy) **C-22** 55Ni-21Cr −13.5Mo-2.5Co-3W	**B622** Seamless pipe & tube (N06022) **B619** Welded pipe (N06022)	44/–	100/45	−198~427	s.g.: 8.69	(a) Better overall corrosion resistance than other Ni-Cr-Mo alloys available, including Hastelloy C-276, C-4, A625. See Note 15 in Plates & Strips (b) For both reducing and oxidizing media. Outstanding resistance to pitting, crevice corrosion and stress-corrosion cracking in: – Oxidizing aqueous media, including acids with oxidizing agents, wet chlorine, and mixtures containing nitric or oxidizing acids with chlorine ions – Ferric and cupric chlorides, hot contaminated media (organic and inorganic), chlorine, formic and acetic acids, acetic anhydride, and seawater & brine solutions (c) To resist the formation of grain boundary precipitates in the weld heat affected zone, thus making it suitable for most chemical process applications in the as-welded condition
Alloy (Hastelloy) **C-4** 65Ni-16Cr −15.5Mo-2Co −0.7Ti	**B622** Seamless Pipe & Tube (N06455) **B619** Welded pipe (N06455)		100/40		s.g.: 8.64	
<P & T> Seamless Aluminum alloys	**B241/B345** 3003 5083* 6061 6063 6351	21/– 25/– 23/– 23/– 23/–	27/24 (at H18) 40/24 (at H111) 38/35 (at T6) 30/25 (at T6) 42/37 (at T6)	−269~204	*B241 only.	(a) Extruded pipe & tubes (b) For cold boxes in cryogenic service (c) Use at the lower temperature is available when the impact test passes (d) See ALPEMA and Table 2.82 (max. design temperature per part and material) in this book for brazed aluminum plate-fin heat exchangers (e) See Sect. 2.1.7.3 for more details
<P> Titanium Alloy	**B861** **B862** 1 (R50250) 2 (R50400) 3 (R50550) 7 (R52400) 9 (R56320)* 11 (R52250) 12 (R53400)	51/–	35/20 50/40 65/55 50/40 90/70 35/20 70/50	−59 ~ 316	s.g.: 4.40–4.51 Gr.1–4: unalloyed Gr.5: 6%Al, 4%V Gr.6: 5%Al, 2.5%V Gr.7: 0.12–0.25%V Gr.9: 3%Al, 2.5%V Gr.11: 0.12–0.25%Pd Gr.12:0.3%Mo-0.8% Ni B861: seamless B862: welded *Annealed or transformed-beta condition.*	(a) Remarkable corrosion resistance in oxidizing acid (HNO_3 except red fuming nitric) by virtue of a passive oxide film. Good corrosion resistance in seawater, wet chlorine, organic chlorides, but it is not immune and can be susceptible to pitting and crevice attack at elevated temperatures. Example, not immune to seawater corrosion if the temperature is greater than about 110°C (230°F) (b) Titanium can absorb hydrogen from environments containing hydrogen gas. At temperatures below 80°C (176°F) hydrogen pickup occurs so slowly that it has no practical significance, except in cases where severe tensile stresses are present. In the presence of pure hydrogen gas under anhydrous conditions, severe hydriding can be expected at elevated temperatures and pressures. Titanium is not recommended for use in pure hydrogen because of the possibility of hydriding should the oxide film be broken (c) Not recommended in aeration condition 250°C (482°F) and over. (d) See Sect. 2.1.7.4 for more detail.
	B861 Cold worked and stress relieved 9 (R56320)		125/105			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Pipes and Tubes (P & T)–For Mass Transfer (12/17)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS , ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<P> Zirconium Alloys	**B658** R60702 R60704 R60705	61 – 62	55/30 60/35 80/55	−59~371* *Max. 316 °C (600 °F) is normally applied deterioration.	s.g.: 6.48	(a) ASTM B353 seamless and welded tubes for nuclear (except nuclear fuel cladding) (b) ASTM B811 seamless tubes for nuclear reactor fuel cladding (c) See the notes of zirconium alloys in Plates & Strips
<T> Tantalum alloys Seamless	**B521** R05200 R05400 R05255 R05252 R05240		30/20 30/20 70/60 40/28 40/28	−196~2480* −196~2480* −196~2480* −196~2480* −196~2480* * Per design condition	*s.g.* R05200: 16.6 R05400: 16.6 R05255: 16.9 R05252: 16.7 R05240: 13.6	(a) Tantalum (Ta) is ductile, easily fabricated, highly resistant (refractory metal) to corrosion by acids, and a good conductor of heat and electricity and has a high melting point (b) Characteristics of several types See Sect. 2.6.2.1 general notes and notes for plates (c) Maximum temperature should be carefully applied per the design condition

General Notes for Pipes

a. Temperature Limits
   (1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards.
   (2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. The impact test exemption temperature shall comply with the applicable codes/standards. See Appendix A.
   (3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, low temperature toughness, etc.), and corrosion environment.

b. The low strength (low carbon, low Ceq and/or heat treated) P No.1 materials are recommended in environmental cracking condition.

c. P.No.1 materials are not recommended above 427 °C (800 °F) for continuous operation because of the graphitization after several hundred hours. See Sect. 2.3.1 for more details.

d. Induction bending procedure of constructor/manufacturer should be carefully reviewed by a responsible metallurgist.

e. Table 2.175 shows the Standards of API Tubular Goods-OCTG and Line Pipes [RP: Recommended Practice, Spec: Specification, TR: Technical Report, Std: Standard]. See (10) OCTG in page xviii in this book for Definitions and Comparison.

Table 2.175 Standards of API tubular goods-OCTG and line pipes

API standard no.	Title
API RP 5A3	Thread compounds for casing, tubing, and line pipe
API RP 5A5	Field inspection of new casing, tubing, and plain-end drill pipe
API Spec 5B	Threading, gauging, and thread inspection of casing, tubing, and line pipe threads
API RP 5B1	Gauging and inspection of casing, tubing, and line pipe threads
API RP 5C1	Care and use of casing and tubing
API TR 5C3	Formulas and calculations for casing, tubing, drill pipe, and line pipe properties
API RP 5C5	Procedures for testing casing and tubing connections [ISO 13679]
API RP 5C6	Welding connections to pipe
API RP 5C7	Coiled tubing operations in oil and gas well services
API Spec 5CT	Casing and tubing, petroleum and natural gas industries-steel pipes for wells [ISO 11960]
API Spec 5D	Drill pipe
API Spec 5DP	ISO 11961:2008 (identical), petroleum and natural gas industries—steel drill pipe
API Spec 5L	Line pipe, petroleum and natural gas industries – steel pipe for pipeline transportation systems [ISO 3183]
API RP 5L1	Railroad transportation of line pipe
API RP 5L2	Internal coating of line pipe for non-corrosive gas transmission service
API RP 5L3	Conducting drop-weight tear tests on line pipe
API RP 5L7	Unprimed internal fusion bonded epoxy coating of line pine
API RP 5L8	Field inspection of new line pipe
API RP 5L9	External fusion bonded epoxy coating of line pipe
API Spec 5LC	CRA line pipe
API Spec 5LCP	Coiled line pipe
API Spec 5LD	CRA clad of lined steel pipe
API RP 5LW	Transportation of line pipe on barges and marine vessels
API RP 5SI	Purchaser representative surveillance and/or inspection at the supplier
API Std 5T1	Imperfection terminology
API TR 5TRSR22	SR22 supplementary requirements for enhanced leak resistance LTC
API RP 5UE	Ultrasonic evaluation of pipe imperfections

Pipes and Tubes (P & T)–For Mass Transfer (13/17)

f. Specify "Type S" or "Tube W" on purchasing order document if it is a dual-type manufacturing material (e.g., A53, A321, etc.). Many end-users want to use seamless type up to NPS 18 or 20 for hydrocarbon processing, cyclic service, flammable service, lethal service, high pressure, or hydrogen service.

g. Mill under-tolerance of thickness should be complied with the following unless otherwise specified in the material standards.:

Pipe identified as only "seamless" or pipe identified as duel grade, such as "seamless or welded": 12.5% – The actual minimum thickness shall be added 12.5% on the thickness required by design calculation.

Pipe identified as only "welded": 0.3 mm (0.01 in.) – The actual minimum thickness shall be added 0.3 mm on the thickness required by design calculation.

h. The permissible lowest temperature to use the material may be somewhat increased or decreased from the specified temperature in accordance with material, heat treatment, fine grain practice, thickness, and impact test results per the applicable codes/standards at the worst condition of future operation.

i. Weld Factors – Table 2.176.

Table 2.176 Weld Factors

Type of weld process and NDT	ASME B31			EN 13480-3	
	A789	A790	A928	EN 10217-7/EN 10253-4	EN 10296-2/EN 10253-3
EFW, 100% ET	0.8	0.8	0.8	1.0	–
EFW, 100% RT	1.0	1.0	1.0	1.0	–
EFW, spot RT	–	–	0.9	–	0.85
EFW, double butt	0.85	0.85	0.85	–	0.7
EFW, single butt	0.8	0.8	–	–	0.7

EFW electrical fusion welded, *ET* Eddy current rtested, *RT* radiographic tested

The Joint Quality Factor (Ej used in ASME/ASTM standards) or Joint Coefficient (z used in EN standards) is used for the calculation of the wall thickness for welded tubes.

The type of welding process, amount, and type of NDE decide the factor.

j. Control rolled and thermomechanical control process (TMCP) steels are considered equivalent and both are subject to strain aging tests because they are susceptible to strain aging due to their precipitation-hardened microstructures. Meanwhile normalized and quenched and tempered pipes do not have these microstructures and, therefore, do not require strain aging tests.

k. References for Cr-Mo steels: See General Note e. for Plates and Strips.

l. Large size and thick wall: Economically preferable to use clad materials for corrosion resistance. Some companies want to use clad instead of solid SS because of mitigation effect of SCC propagation.

m. When austenitic steels/alloys are to be used in services where they will be subject to stress corrosion, they should be supplied as solution-heat treated condition. The purchaser should indicate the additional requirements for thermally stabilized heat treatment for stabilized stainless steel/alloy when they are exposed to polythionic acid SCC environment. See Sect. 2.1.6.8 for more details.

n. See Table 2.68 for more details on the properties and development history of Ni-based alloys.

o. Oil Country Tubular Goods (OCTG) Pipe (other than drilling pipe) vs. Line Pipe – Table 2.177.

Table 2.177 Oil country tubular goods (OCTG) pipe (other than drilling pipe) vs. line pipe

Items	OCTG pipe (API Spec 5CT)	Line pipe (API Spec 5L)	Remark
Purpose	Casing, drill, and tubing	Oil and gas transfer	
Materials type	CS, low alloy steels, SS	CS	
Main requirements	Strength, toughness, corrosion (major)/ erosion (minor) resistance	Strength, toughness, corrosion resistance (if required)	OCTG requires more wide characteristics.
Connection	Mainly thread (API spec 5B), partially coupling	Mainly weld (flange partially for aboveground)	
Manufactured by	Seamless, welded (mostly ERW) for pipe	Seamless, welded (EFW & ERW)	
Covered products	Pipe, coupling stock, coupling, and accessory materials	Pipe	
Quality levels	PSL-1, 2, and 3	PSL-1 and 2	PSL-1, 2, 3, 3G, and 4 in API spec. 6A (wellhead and Christmas tree equipment)
Size	Medium size OD = 114–508 mm (4″ to 20″)	Small to large size OD = 10–3239 mm(3/8–128″)	
Standard (OD, ID) dimension	Different from ASME B36.10 (pipe)	Same as ASME B36.10 (pipe)	
Strength levels	Several types (SMYS = 517–1138 MPa, SMTS = 689–1000 MPa)	Several types	
Chemical composition	Higher carbon	Lower carbon	Line pipe requires more strength and hardness because OCTG is not for weldable
Impact test	Mandatory as sampling	Mandatory only for PSL-2	OCTG requires more toughness
Hardness test	Most grades in Table C.40 (for through-wall)	For cold formed welded pipe (for surface)	OCTG requires more hardened surfaces

Pipes and Tubes (P & T)–For Mass Transfer (14/17)

p. Types of OCTG (Oil Country Tubular Goods) Pipes in Petroleum and Natural Gas Industries – Table 2.178

Table 2.178 Types of OCTG (Oil Country Tubular Goods) Pipes in Petroleum and Natural Gas Industries

Items	Drill pipe	Casing pipe	Tubing
Purpose	Drilling	Borehole	The oil or gas is transported from the wellbore
Applicable code	API spec 5DP	API spec 5CT	API spec 5CT
Materials type	CS	CS, low-alloy steels, SS	CS, low-alloy steels, SS
Applicable components	Pipe body [around 9 m (30 ft) long are coupled with tool joints], tool joint	Pipe [around 9 m (30 ft) long] with a threaded connection on each end	Pipe [around 9 m (30 ft) long] with a threaded connection on each end
Target to design	– High torque by drilling, – Axial tension by its dead weight, – Internal pressure by purging of drilling fluid – Bending loads due to non-vertical or deflected drilling	Axial tension by its dead weight – Internal pressure by fluid purging emulsion – External pressure by surrounding rock formations	– Axial tension by its dead weight – Internal pressure by fluid purging emulsion – Corrosion resistance
OD	60.3–168 mm (2 3/8″–6.6″)	114.3–508 mm (4.5–20″)	60.3–114.30 mm (2.375–4.5″)
Grade	Gr. E: $P \leq 0.030\%$, $S \leq 0.020\%$ YS = 517–724 MPa, TS:≥687 MPa Gr. *X, G, S*: $P \leq 0.020\%$, $S \leq 0.015\%$ *X*: YS = 655–862 MPa, TS:≥724 MPa, *G*: YS = 724–931 MPa, TS:≥793 MPa, *S:* YS = 931–1138 MPa, TS:≥1000 MPa Tool join *t*: $P \leq 0.020\%$, $S \leq 0.015\%$ YS = 827–1138 MPa, TS:≥965 MPa	H40, J55, K55, N80, M65, L80, L8013CR, C90, C95, T95, P110, Q125, V150 Note (1)	H40, J55, K55, N80, M65, L80, L8013CR, C90, C95, T95, P110, Q125, V150
Type	Seamless for body, fine grain practice	Seamless or welded	Seamless or welded

Notes

(1) See below for characteristics and strength of API Spec 5CT (Casing, Drill, and Tubing), several grades.

- Gr. H40 – YS = 40 – 50ksi and TS ≥ 60 psi; general purpose.
- Gr. J55 – YS = 55–80ksi and TS ≥ 75 psi; general purpose pipes for tubing applications, similar to specification K55.
- Gr. K55 – YS = 55–80ksi and TS ≥ 95 psi; general purpose pipes used primarily in casings.
- Gr. L80 – YS = 80–95ksi and SMTS≥95 psi, and hardness test requirement of 23 HRC max.; usually used in wells with sour (H_2S) environments or deep sour wells.
- Gr. N80 or N80 Q&T (Quenched and Tempered) – YS = 80–95ksi and TS ≥ 95 psi; general purpose.
- Gt. N80 (Normalized) – Lower-cost alternative to standard Q&T N80; pipe walls less than 12.7 mm (0.5 in.); CVN impact test absorbed energy results conform to API SR16 and are lower Q&T N80.
- Gr. C90 – YS = 90–105ksi and TS ≥ 100 psi with hardness of 25.4 HRC max.; generally used in sour condensate wells; with required extensive hardness testing, SSC testing per NACE Standard TM-0177-Method A; minimum threshold stress required is 80% of SMYS (90 ksi).
- Gr. C95 –YS = 95–110ksi and TS ≥ 105 psi, but without a hardness requirement; generally not used in sour wells.
- Gr. T95 –YS = 95–110ksi and TS ≥ 105 psi with hardness of 25.4 HRC max.; generally for use in sour condensate wells; extensive hardness testing is required including SSC testing per NACE Standard TM-0177-Method A; minimum threshold stress required is 80% of SMYS (95 ksi).
- Gr. P110 – YS = 110–140ksi and TS ≥ 125 psi; generally used in deep wells; this grade is not suitable for most sour condensate wells.
- Gr. Q125 – YS = 125–150ksi, SMTS≥135 psi; generally used in deep wells; this grade is not suitable for most sour condensate wells; quadrant hardness testing is required (no specified hardness limits other than the variation between readings); impact testing required for each heat and/or lot; typically EMI and UT NDT inspections are required.

Notes for Pipes and Tubes

1. Silicon (Si) content of CS exposed to high temperature sulfidation corrosion in refinery plants: Minimum 0.10% (minimum 0.13% preferable) Si for operation above 230 °C (450 °F). See API RP939-C.
2. Equivalent grades of API 5L-PSL 1 and CSA Z245.1 – Table 2.179

Table 2.179 Equivalent grades of API 5L-PSL 1 and CSA Z245.1

Grade equivalents		Grade equivalents		Grade equivalents	
API 5L	CSA Z245.1	API 5L	CSA Z245.1	API 5L	CSA Z245.1
A25 (L175)	172	X46 (L320)	317	X65 (L450)	448
A (L210)	207	X52 (L360)	359	X70 (L485)	483
B (L245)	241	X56 (L390)	386	X80	550
X42 (L290)	290	X60 (L415)	414		

3. Comparison between PSL 1 and PSL 2 in API 5L Pipe – Table 2.180

Table 2.180 Comparison between PSL 1 and PSL 2 in API 5L Pipe

Parameter	PSL 1	PSL 2
Grade range	A25 through X70	BR through X80Q
Size range (OD, inch)	1/8 *[1] through 84	4 *[1] through 84
Type of pipe ends	Plain-end, threaded end	Plain-end
Acceptable processes of manufacture and product specification levels	See Table 2	See Table 2
Acceptable manufacturing routes	NS	See Table 3
Killed and made according to fine grain practice for starting material.	NS	Required
DWT (drop weight tear) test	NS	Required for welded pipe (see Para. 9.9)
Repair by welding of pipe body, plate by skelp	Permitted	Prohibited
Repair by welding of weld seams without filler metal	Permitted by agreement	Prohibited
Traceability	See Para. 8.13.1	See Para. 8.13.2
Inspection frequency	See Table 17	See Table 18
Inspection documents	See Para. 10.1.2	See Para. 10.1.3
Number, orientation and location of test pieces per sample for mechanical tests for mechanical tests	See Table 19	See Table 20
Manufacturing procedure qualification	NS	Required per Annex B
SMLS pipe body nondestructive inspection for other than sour service or offshore service	See Table E.2	See Table E.2

General Notes:
G1. The specified Tables, paragraphs are in API 5L.
G2. Common requirements of PSL 1 & PSL 2 are not described in this comparison table.
G3. NS: Not Specified.
Notes: *[1] NPS (nominal pipe size as inch) per manufacturing practice
Legend:
– COW = tubular product having one or two longitudinal seams or one helical seam, produced by a combination of gas metal-arc and submerged-arc welding wherein the gas-metal arc weld bead is not completely removed by the submerged-arc welding passes.
– LW = tubular product having one longitudinal seam produced by laser welding.

4. ASTM A671 ERW Steel Pipe for Atmospheric and Lower Temperature – Table 2.181

Table 2.181 A671 ERW Steel Pipe for Atmospheric and Lower Temperature

Pipe grade	Type of steel	ASTM specification		Pipe grade	Type of steel	ASTM specification	
		No.	Grade			No.	Grade
CA55	Plain carbon	A285/A285M	C	CFE70	Ni steel	A203/A203M	E
CB60	Plain carbon, killed	A515/A515M	60	CG100	9% nickel	A353/A353M	–
CB65	Plain carbon, killed	A515/A515M	65	CH115	9% nickel	A553/A553M	Type 1
CB70	Plain carbon, killed	A515/A515M	70	CJA115	Alloy steel and Q-T	A517/A517M	A
CC60	Plain carbon, killed, fine grain	A516/A516M	60	CJB115	Alloy steel and Q-T	A517/A517M	B
CC65	Plain carbon, killed, fine grain	A516/A516M	65	CJE115	Alloy steel and Q-T	A517/A517M	E
CC70	Plain carbon, killed, fine grain	A516/A516M	70	CJF115	Alloy steel and Q-T	A517/A517M	F
CD70	Mn-Si and normalized	A537/A537M	Cl-1	CJH115	Alloy steel and Q-T	A517/A517M	H
CD80	Mn-Si and Q-T	A537/A537M	Cl-2	CJP115	Alloy steel and Q-T	A517/A517M	P
CFA65	Ni steel	A516/A516M	A	CK75	C-Mn-Si	A299/A299M	A
CFB70	Ni steel	A203/A203M	B	CP85	Alloy steel and age-hardening, Q-precipitation	A736/A736M	A-Cl.3
CFD65	Ni steel	A203/A203M	D				

Notes: *Q & T* quenched and tempered, [A] Any grade may be furnished

5. Plate Specification of ASTM A672 (EFW CS Pipe) – Table 2.182

Table 2.182 Plate Specification of ASTM A672 (EFW CS Pipe)

Pipe grade	Type of steel	ASTM specification		Pipe grade	Type of steel	ASTM specification	
		No.	Grade			No.	Grade
A45	Plain carbon	A285/A285M	A	H75	Mn-Mo and normalized	A302/A302M	A
A50	Plain carbon	A285/A285M	B	H80	Mn-Mo and normalized	A302/A302M	B, C, D
A55	Plain carbon	A285/A285M	C	J80	Mn-Mo and Q-T	A533/A533M	Cl-1[A]
B60	Plain carbon, killed	A515/A515M	60	J90	Mn-Mo and Q-T	A533/A533M	Cl-2[A]
B65	Plain carbon, killed	A515/A515M	65	J100	Mn-Mo and Q-T	A533/A533M	Cl-3[A]
B70	Plain carbon, killed	A515/A515M	70	K75	Cr-Mn-Si	A202/A202M	A
C55	Plain carbon, killed, fine grain	A516/A516M	55	K85	Cr-Mn-Si	A202/A202M	B
C60	Plain carbon, killed, fine grain	A516/A516M	60	L65	Mo	A204/A204M	A
C65	Plain carbon, killed, fine grain	A516/A516M	65	L70	Mo	A204/A204M	B
C70	Plain carbon, killed, fine grain	A516/A516M	70	L75	Mo	A204/A204M	C
D70	Mn-Si and normalized	A537/A537M	Cl-1	N75	Mn-Si	A299/A299M	
D80	Mn-Si and Q-T	A537/A537M	Cl-2				

Notes: *Q & T* quenched and tempered, [A] Any grade may be furnished

6. Impact Test Absorbing Energy and Temperature of A333 & A334 (unless otherwise specified by purchaser) (Tables 2.183 and 2.184)

Table 2.183 Impact temperature of A333 and A334 (LTCS)

Grade	Minimum impact test temperature	
	°F	°C
1	−50	−45[(2)]
3	−150	−100
4	−150	−100
6	−50	−45[(2)]
7	−100	−75
8	−320	−200
9	−100	−75
10	−75	−60

Table 2.184 Impact requirements for grades 1, 3, 4, 6, 7, 9, 10 of A333 and A334 (LTCS)

Size of specimen,	Minimum average notched bar impact value of each set of three specimens[(1)]		Minimum notched bar impact value of one specimen only of a set[(1)]	
mm	ft-lbf	J	ft-lbf	J
10 by 10	13	18	10	14
10 by 7.5	10	14	8	11
10 by 6.67	9	12	7	9
10 by 5	7	9	5	7
10 by 3.33	5	7	3	4
10 by 2.5	4	5	3	4

Notes

(1) Straight line interpolation for intermediate values is permitted.

(2) Currently MTI technical committee for impact test requirement of LTCS suggested to ASTM committees to change −45 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME requirements.

7. Materials-Pressure Rating-Size-Minimum Thickness (excluded corrosion allowance) for Piping Materials Classes (Recommendation) – Table 2.185[(1)]

Table 2.185 Materials-Pressure Rating-Size-Minimum Thickness (excluded corrosion allowance) for Piping Materials Classes (Recommendation)

Material	ASME class (standard rating, Lb)	Piping thickness for NPS ½ to (in.)	Piping thickness for NPS 1–1 ½ (in.)	Piping thickness for NPS 2–4 (in.)
CS	150–300	Sch. 160	Sch. 80	Sch. 80
	600	Sch. 160	Sch. 160	Sch. 160
	900	Sch. XXS	Sch. 160	Sch. 160
	1500	Sch. XXS	Sch. XXS	Sch. XXS
	2500	Sch. XXS	Sch. XXS	Sch. XXS
316 SS	150–900	Sch. 80S	Sch. 80S	Sch. 80S
	1500	Sch. 160	Sch. 160	Sch. 160
	2500	Sch. XXS	Sch. XXS	Sch. XXS
Duplex SS	150–900	Sch. 80S	Sch. 80S	Sch. 80S
Super Duplex SS	150–900	Sch. 80S	Sch. 80S	Sch. 80S
90/10 Cu-Ni	16 & 20 barg	2.0 mm	2.5 mm or per EEMUA 144	3.0 mm or per EEMUA 144
PE or PP	150			
PVC	150			
CPVC	150	12.7–38 mm (1/2–1½ in.)	Sch. 80 per ASTM F441	Sch. 80 per ASTM F441
Fiberglass	150	25–38 mm (1–1 1/2 in.)	Per manufacturer specification	Per manufacturer specification

Notes: [(1)]Per the strength calculation for pipe of NPS 6 and above (in.),

8. ASTM A312-Grain Size Requirements – Table 2.186

Table 2.186 A312-Grain Size Requirements

Grade	UNS designation	ASTM grain size	Grade	UNS designation	ASTM grain size
–	N08810	5 or coarser	TP310HCb	S31041	6 or coarser
–	N08811	5 or coarser	TP316H	S31609	7 or coarser
TP304H	S30409	7 or coarser	TP321H	S32109	7 or coarser
TP309H	S30909	6 or coarser	–	S32615	3 or finer
TP309HCb	S30940	6 or coarser	TP347H	S34709	7 or coarser
TP310H	S31009	6 or coarser	TP348H	S34809	7 or coarser
–	S31035	7 or coarser			

9. Recommended Maximum Fluid Velocities of CS Piping in Refinery Plants – Table 2.187

Table 2.187 Recommended Maximum Fluid Velocities of CS Piping in Refinery Plant

Service and size for carbon steel piping		Recommended maximum fluid velocity, m/sec (ft/sec)[(1)]
100% gas or vapor piping (including superheated steam)		38 (125)[(2)]
Amine (rich) piping		3.5 (5)
Amine (lean) piping		6 (20)
Brine or seawater piping		2.4 (8)
Fired heater transfer line, TAN ≥0.5		18 (60)
Fired heater transfer line, TAN <0.5		23 (75)
Letdowm valve upstream		2 (6)
Liquid-gas (or liquid-vapor) mixture piping, except heater transfer and thermosiphon reboiler outlet piping		23 (75)[(2)]
Paraxylene slurry lines		3.4 (11)
Pump suction piping		2.7 (9)[(3)]
Pump discharge piping	NPS: ≤4	3.0 (10)
	NPS: 6–8	4.6 (15)
	NPS: 10–12	5.8 (19)
	NPS: 14–16	6.4 (21)
	NPS: ≥18	7.3 (24)
Pulverized catalyst carrier piping (dilute phase flow) for densities >8.0 kg/m^3 (0.5 lb/ft^3)		12 (40)
Pulverized catalyst standpipe (dense phase flow)		1.8 (6)
Sulfuric acid piping		0.9 (3)
Slurry piping, except as noted below		4.6 (15)
Slurry piping where erosion or crystal breakage is of concern		2.7 (9)
Thermosiphon reboiler outlet piping		12 (40)[(2)]
Pulverized catalyst standpipe (dense phase flow)		1.8 (6)
Pulverized catalyst carrier piping (dilute phase flow) for densities >8.0 kg/m^3 (0.5 lb/ft^3)		12 (40)
Sour water		4.6 (15)
Steam piping (other than superheated steam)		23 (75)[(2)]

Notes

[(1)] Minimum velocity for slurry or liquid water containing service should be also considered to avoid MIC.Based on the mixed velocity for multiphase (gas + liquid) and liquid velocity in single liquid phase except 100% Gas or Vapor piping, Thermosiphon reboiler outlet piping and steam piping.
See API RP14E, 2.4(a), ISO 13703, 5.5.1, or Sect. 2.4.5.2 in this book for more details on maximum velocity limit.Once CRA material is selected, typically the velocity limits will be increased.

[(2)] Gas/Vapor Lines: The maximum velocity should also consider the following erosion velocity limits as a minimum.V (erosional velocity limit) = $180\ \rho^{-0.5}$ m/sec where: ρ = bulk flowing density, (kg/m^3)

[(3)] Sufficient NPSHA shall be provided for pumps handling liquids that contain absorbed gases such as lean and rich amine and sour water to prevent more than 1% by volume gas leaving solution at the impeller eye of the first stage pump suction.

10. Solution heat treatment or stabilizing heat treatment (only for stabilizing elements, Nb- or Ti- containing SS or nickel alloys) is recommended after cold bending or forming unless otherwise exempted from the applicable codes or standards

For Heat Transfer (Heat Exchanger Tubes: (w = welded, s = seamless) – See General Notes

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (1/9)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> Seamless Carbon steel	**A179**	1/1	47/26	−29 ~ 482	Size limit OD): 3.2 mm (1/8″) to 76.2 mm (3 in.) *Hardness*: ≤72 HRB	(a) For steam, but is normally used in coolers and condensers when clean water is used as the coolant (b) Recommended to specify "killed condition" when the service temperature is −29 °C (−20 °F) or colder (c) C = 0.06–0.18%, Mn = 0.27–0.63%, P ≤ 0.035%, S ≤ 0.035%, not Si controlled
<Tube> ERW Carbon steel	**A214**	1/1	47/26	−29 ~ 538	OD: ≤76.2 mm (3 in.) *Hardness*: ≤72 HRB	(a) For steam, but is normally used in coolers and condensers when clean water is used as the coolant (b) Recommended to specify "killed condition" when the service temperature is −29 °C (−20 °F) or colder (c) C ≤ 0.18%, Mn = 0.27–0.63%, P ≤ 0.035%, S ≤ 0.035%, not Si controlled (d) The allowable stress is 15% less than that of A179 (e) More preferable than A179 for economic reason in noncorrosive and non-high pressure service
<Tube> Seamless Carbon steel	**A210** A-1	1/1	60/37	−29 ~ 538	Size limit OD): 12.7 mm (0.5 in.) to 127 mm (5 in.) *Hardness*: ≤79HRB for Gr.A-1 ≤89HRB for Gr.C	(a) For boiler and superheater (b) Killed (c) High strength due to medium carbon (d) C & Mn (%) Gr A-1: C ≤ 0.27%C, Mn ≤ 0.93%, Si ≥ 0.10% Gr C: C ≤ 0.35%, Mn = 0.29~1.06%, Si ≥ 0.10%
	C	1/2	70/40			
<Tube> Seamless or welded Carbon steel	**A334** 1	1/1	60/37	−45 ~ 343	1. Impact tested at the temperature : see below for A334.	(a) Good low temperature toughness due to high Mn, and normalized condition (b) Specify "seamless" or "welded" when purchasing
	6		60/35			

Impact temperature (plate, pipe, tube) A334/334M

	Grade	Impact test temperature		Max. Hardness
		°F	**°C**	
	1	−50	−45*	85 HRB (106 BHN)
	3	−150	−100	90 HRB (190 BHN)
	6	−50	−45*	90 HRB (190 BHN)
	7	−199	−75	90 HRB (190 BHN)
	8	−320	−195	–
	9	−100	−75	90 HRB (190 BHN)

* Currently MTI technical committee for impact test requirement of LTCS suggested to ASTM committees to change −45 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME requirements

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> Seamless and low alloy steel	**A423** Gr.1 Gr.2 Gr.3	4/2 4/2	60/37 60/37 55/33	−29 ~ 343	*Size limit OD:* 12.7 mm (1/2″) to 127 mm (5″) *Thickness limit:* 0.9 mm (0.035″) to 12.7 mm (0.5″) *Hardness:* ≤170 HB (or 87 HRB)	(a) For economizers or other applications where corrosion resistance is important (b) Required mechanical tests: Tension test, flattening test, flaring test (seamless), flange test (welded), hardness test, reverse flattening test (welded), hydro- or nondestructive electric test. (c) Gr.1: 0.75Cr–0.5Ni–Cu/Gr.2: 0.75Ni–0.5Cu–Mo Gr.3: 0.35Cu-0.10Sb
<Tube> Seamless C – ½ Mo	**A209** T1	3/1	55/30	−29 ~ 538	*Size limit OD:* 12.7 mm (1/2″) to 127 mm (5″) *Hardness:* ≤80HRB for Gr.T1 ≤81HRB for Gr.T1a ≤77HRB for Gr.T1b	(a) For boiler and superheater (b) Killed (c) Advanced high-temperature strength, graphitization resistance, HTHA resistance than carbon steels (d) It may not be used to resist HTHA in API RP941for new construction. Careful/periodic inspection in HTHA service is required for the existing facilities
	T1a		60/32			
	T1b		53/28			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (2/9)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> Seamless 1 Cr-0.5Mo	**A213** T12	4/1	60/32	−29 ~ 649	*Size limit*: 3.2 mm (1/8″) for ID to 127 mm (5″) for OD. *t*: 0.4–12.7 mm (0.015–0.5 in.) *Hardness*: ≤85HRB for Gr.T11 ≤85HRB for Gr.T12/T22	(a) For HTHA/high-temperature oxidation resistance & creep-rupture strength (see API RP941) (b) Q-T: Purchaser's option
<Tube> Seamless 1.25Cr-0.5 Mo	**A213** T11	4/1	60/25	−29 ~ 649		(a) For boiler, superheater, and H/EX (b) For HTHA/high-temperature oxidation resistance & creep-rupture strength (see API RP941) (c) Q-T: Purchaser's choice
<Tube> Seamless cold drawn 2.25Cr-1Mo	**A213** T22	5A/1	60/25	−29 ~ 649		(a) For boiler, superheater, and H/EX (b) For HTHA/high temperature oxidation resistance & creep-rupture strength (see API RP941) – better than 1 Cr-0.5Mo (c) Q-T: purchaser's choice
<Tube> Seamless 9Cr-1Mo	**A213** T 9	5B/1	60/25	−29 ~ 649	*Size limit OD)*: 3.2 mm (0.125 in.) to 76.2 mm (3 in.) *Hardness:* ≤179HBW for Gr.T9 190-250HBW for Gr. T91 196-265HBW for Gr. T92	(a) For boiler, superheater, and H/EX (b) For high temperature sulfur corrosion environment (c) Recommended for pipe and tubes materials (d) Reference for Gr.91: API TR 938-B (e) T9: annealed or N-T T91 & T92: N-T (f) T92: not registered in ASME allowable stress tables yet
<Tube> Seamless 9Cr-1Mo-V	**A213** T 91	15E/1	85/60	−29 ~ 649		
<Tube> Seamless 9Cr-1Mo-V	**A213** T 92	15E/1	90/64	−29 ~ 649		
<Tube> Seamless or welded 3.5Ni	**A334** 3	9B/1	65/34	−101 ~ 343	Impact tested at the temperature: see above for A334.	(a) Grain refined by 3.5%Ni added, and normalized condition (b) Good toughness due to low carbon (≤0.19%) (c) Specify "seamless" or "welded" when purchasing (d) 3.5%Ni has an intermittent history for hot crack during welding. ASS is a better choice when welding is required
Tube ERW Standard low carbon steel	**A513** MT1010 MT1015 MT X1015 MT1020 MT X1020	1/1	–	−29 ~ 427	Rimmed or capped steel may be used unless otherwise required.	(a) ERW CS and LAS mechanical tubing (b) Two types: hot rolled and cold rolled (c) Size range *t* for hot-rolled OD 12.7–381 mm (0.5–15 in.) 1.65–16.5 mm (0.065–0.65 in.) *t* for cold-rolled OD 9.5–305 mm (3/8–12 in.) 0.56–3.40 mm (0.022–0.134 in.) (d) "MT" stands for mechanical tubing (e) If no grade is specified, MT1010 to MT1020 may be furnished
Tube ERW Standard low carbon steel	**A513** Various AISI series	*	* *Per base metal	−29 ~ ** **Per design condition		
<Tube> Seamless or welded (MSS) 12Cr	**A268** TP 410 (S41000) 12Cr F6NM (S41500) 12Cr-4Ni-0.7Mo	 6/1 6/4	 60/30 115/90	−29 ~ 649* *Max. 400 °C (750 °F) for long-term operation	*Hardness:* ≤207 HBW for 410 ≤295 HBW for F6NM	(a) Carbon content is within 0.12~1.2% which is higher than that of FSS. Air-hardening materials (b) Highly decreased toughness after several hundred hours at 400~550 °C [called as 475 °C (885 °F) embrittlement)] (c) Good corrosion resistance in high-temperature sulfur and H_2, H_2S services (d) Poor corrosion resistance in low-temperature oxidation environment than carbon steels (e) Poor weldability (f) Specify "seamless" or "welded" when purchasing (g) F6NM has greatly higher TS and erosion resistance compared to 410 SS (h) All tubes in ASTM A268 shall be reheated to a temperature of 650 °C (1200 °F) except 510 °C (950 °F) for S41500 or higher and cooled
<Tube> Seamless or welded 405 SS (FSS) 12Cr-Al-Ni	**A268** TP 405 (S40500)	7/1	60/30	−29 ~ 538* *Max. 400 °C (750 °F) for long-term operation	*Hardness:* ≤207 HBW	(a) Highly decreased toughness after several hundred hours at 400~550 °C [475 °C (885 °F) embrittlement)] (b) Good corrosion resistance in high-temperature sulfur and H_2, H_2S services (c) Poor corrosion resistance in low-temperature oxidation environment than carbon steels (d) Weldability: better than 410 SS

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (3/9)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> Seamless or welded 26-3-3 Sea-cure 26Cr-3Ni-3Mo (SFSS)	**A268** 26-3-3 (S44660)	10K/1	85/65	−40 ~ 371* *Max. 300 °C (570 °F) for long-term operation.	*Hardness:* ≤265 HBW	(a) Super ferritic stainless steel (SFSS). (b) Excellent corrosion resistance in blackish water and seawater, erosion resistance (max. 100 fps in water), good thermal conductivity, and superior mechanical and physical properties (c) For power plant condensers, heat exchangers, and desalination plants
<Tube> Seamless or welded Lean DSS LDX2101 21Cr-5Mn-1.5Ni-0.3Mo-0.22N-0.2Cu	**A789** S32101	10H/1	101/77 ($t \le 5$ mm) 94/65 ($t > 5$ mm)	−29*~316 *For < −29 °C, impact test is required	*Hardness:* ≤290 BHW s.g.: 7.80	(a) Used as a CRA material between 316L SS and 2205 DSS in chloride-containing service (b) Less prone to precipitation of intermetallic phases than other duplex steels (c) The strength is similar to 2205 DSS (d) ASME Code Case 2418/NSF Approval STD 61 (e) See Note 8 & 17 in plates and strips
<Tube> Seamless or welded DSS 22Cr-5Ni	**A789** 2205 (S31803)	10H/–	90/65	−29* ~ 316 *−40 °C (−40 °F) In ASTM A923 *For < −29 °C, impact test is required	*Hardness:* ≤290 HBW s.g.: 7.88 Note 2	(a) High strength and good erosion resistance (b) Strong Cl-SCC and pitting resistance [≤70 °C (158 °F)] (c) N = 0.14–0.20 wt% (d) See Note 8 & 17 in plates and strips
<Tube> Seamless or welded SDSS 25Cr-7Ni	**A789** 2507 (S32750)		116/80		*Hardness:* ≤300 HBW s.g.: 7.80 Note 2	(a) High strength and good erosion resistance (b) Strong Cl-SCC and pitting resistance [≤85 °C (185 °F)] (c) Corrosion test per ASTM A923 may be applied (d) N = 0.24–0.32 wt% (e) See Note 8 & 17 in plates and strips
<Tube> Seamless or welded ASS	**A269** 304 304L	8/1	70/25	−196 ~ 816 *Min. temperature* for 304, 304L, 316, 316L, 347 in B31.3: −254 °C (−425 °F)	*s.g./Max. Hardness:* 304L: 7.94/192HBW 304H: 7.94/192 HBW 309S: 7.98/192 HBW 310S: 7.98/192 HBW 316: 7.98/192 HBW 316L: 7.98/192 HBW 316H: 7.98/192 HBW 321: 7.90/192 HBW 347: 8.02/192 HBW *Suffix* L = low carbon (good IGC resistance) H = high carbon (good creep-rupture strength) 321: Ti added, 347: Nb added	(a) 304L, 316L, 321: in low temperature [≤427 °C (800 °F)] and mild acidic service (pH > 4.5) (b) All "H" grades contain 0.04–0.1%C for high-temperature strength, including welding materials. Also, have average grain size of ASTM no.6 or coarser per ASTM E112. See note 8 in Pipes & Tubes for reference (c) 304, 316 for welded parts: use low carbon ($C \le 0.03\%$) or dual grade (304/304L or 316/316L) (d) 309S (23Cr-13Ni), 310S (25Cr-20Ni): High-temperature oxidizing resistance grain size to be ASTM 6 or coarse for the service at 565 °C (1050 °F) and warmer (e) 316 (2%Mo), 317 (3%Mo): More corrosive than 304 in oxidizing acid (HNO_3, conc. H_2SO_4)/ good pitting resistance in acidic environments (f) all 300 series: Susceptible to cl-SCC and CUI (g) 347 welding material should be used for 321 welding (h) Corrosion test (IGC, SCC, etc.) may be considerable for severe corrosion service. (i) Passivation treatment and segregated work (from carbon and low alloy steels) are recommended for corrosive service. (j) Max. temperature for low carbon ($C \le 0.03\%$): 427 °C (800 °F) [454 °C (850 °F) for ASS with Mo ≥ 2.5%] (k) 321/347: stabilized annealing recommended for the service at 400 °C (750 °F) and warmer (l) A213: Seamless A249: Welded m. See note 3 (o) See ASTM A632 for small-diameter (1.27–12.7 mm) ASS tubing for general service
	304LN 316 316L 316LN 317 321 347		75/30			
<Tube> Seamless or welded ASS	**A213/A249** 304 304H 309Cb 309H 309HCb 309S 310Cb 310H 310HCb 316 316H 317 321 321H 347 347H 348 348H		75/30 Except 65/29 For 310S (S31272)	−196 ~ 816 *Min. Temperature* for 304, 304 L, 316, 316 L, 347 in B31.3: −254 °C (−425 °F)		
	304N 316N		80/35	−196 ~ 816		
	304L 316L		70/25	−196 ~ 427 −196 ~ 454		
	304LN 316LN 317L		75/30	−196 ~ 427 −196 ~ 454 −196 ~ 454		
	347HFG		80/30	−196 ~ 816		
	310HCbN		95/43	−196 ~ 816		

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (4/9)

Material/ brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> SASS **AL-6XN** 20Cr-25Ni-6Mo-0.25Cu-0.2N	**B690** **B676** N08367	45/–	95/45	−196~427	B690: seamless B676: welded s.g.: 8.06	(a) Strong Cl-SCC and pitting resistance [≤90 °C (194 °F)] (b) PRE ≥ 40; super austenitic stainless steel
<Tube> SASS **254SMO** 20Cr-18Ni-6Mo-0.7Cu-0.2N	**A213** **A249** S31254	8/4	*t* ≤ 5 mm 98/45 *t* > 5 mm 95/45	−196/399	B213: seamless B249: welded *Hardness:* ≤220 HBW s.g.: 8.0	(a) Strong Cl-SCC and pitting resistance [≤90 °C (194 °F)] (b) PRE ≥ 40; super ASS
<Tube> SASS **CLI-SR 50A** 23Cr-22Ni-6Mo-<0.4Cu-0.25N	**A213** **A249** S32050 Euronorm X1NiCrMoN 21.22.7	45/–	98/48	−196~538	B213: seamless B249: welded *Hardness:* ≤256HBW s.g.: 8.06	(a) Strong Cl-SCC and pitting resistance [≤90 °C (194 °F)] (b) PRE ≥ 40; super austenitic stainless steel (c) Welding electrode: same as alloy C22 or C276 (d) CLI is a brand of ArcelorMittal
<Tube> Alloy (carpenter)20 **20Cb3** 35Ni-35Fe-20Cr-3Cu-2Mo-Cb	**B729** Seamless **B468** Welded (N08020)	45/–	80/35 (annealed)	−196 ~ 427	IGC test may be required for max. corrosion resistance s.g.: 8.08	(a) Superior corrosion & stress fracture resistance in non-aerated 10–40% H_2SO_4 acid, below 60–80 °C (140–176 °F) (b) Good corrosion resistance in HF acid at atmosphere and less than 10% HCl acid (c) 20Mo6 (super stainless steel) is developed from 20Cb3 to improve pitting and chloride SCC resistance. (d) Welding: Use E-320 or ER-320 electrodes (e) PWHT: min. 538 °C (1000 °F) in severe chloride SCC environment (f) Normally supplied in the as-annealed condition (g) See Note 3
20Mo6 35Ni-30Fe-24Cr-6Mo-3Cu	**B729** Seamless (N08026)				s.g.: 8.13 ; Better pitting and crevice corrosion resistance than 20Cb3	
<Tube> Alloy (Hastelloy) **C-276** 57Ni-16Mo-15Cr-2.5Co-4W	**B690** (s) **B676** (w) **B626** (w) **B622** (s) Seamless (s) or welded (w) tube (N10276)	44/–	100/41	−198 ~ 676	Solution heat treated & quenched at 1120 °C (2048 °F) ※ s.g.: 8.89	(a) Good corrosion resistance in ferric & cupric chlorides, HCl acid, hot contaminated media (organic and inorganic), chlorine, formic, and acetic acids, acetic anhydride, and seawater (b) Corrosion resistance is better than B-2 if oxidizing salts such as ferric chloride are present in the acid (c) Corrosion resistance and mechanical properties can be decreased after long-time aging at 650–1090 °C (1200–1995 °F) due to the precipitation of metallic compound (d) For chemical process equipment and desulfurization of flue gas equipment (e) Physical & metallurgical properties: similar to 300 series ASS (f) See Note 15 in Plates & Strips
<Tube> Alloy **330** 19Cr-35Ni-1.2Si-max.2 Mn	**B535** (s) **B739** (w) N08330	46/–	70/30	−196~1148	*Hardness:* 70–90 HRB	(a) Good resistance to carburization, nitriding, and/or thermal cycling/shock (b) Fully ASS. Not subject to embrittlement from sigma formation (c) Brand name: MISCO RA330
<Tube> Seamless alloy (Incoloy) **800**	**B163** 32Ni-bal.Fe-21Cr (N08800)	45/–	75/30	−198 ~ 816	s.g.: 7.98	(a) Incoloy 800: more resistance chloride SCC, pitting and general corrosion than 300 series stainless steels (b) Recommended solution annealing after cold bending (c) Incoloy 800 H: more creep-rupture strength than Incoloy 800 (d) Solution annealed grade: increased high temperature strength (e) Incoloy 825: More resistance for Cl-SCC than 800/800H (f) See ASTM B515 for alloy 800/800H welded tubes (g) BS 3074NA15 (Seamless) (h) DIN 17459 (Seamless), ISO 6207 (Seamless) (i) ASME Code Case 1325 (All products), 1983 (Seamless)
800H	32Ni-bal.Fe-21Cr (N08810)		65/25			
825	42Ni-bal.Fe-21Cr-3Mo-2Cu (N08825)		85/35			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (5/9)

Material/ brand	ASTM no. &Gr.	P no/Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> Seamless Alloy **686** 57Ni-20Cr-16Mo-3.5W-Ti-N	**B163** N06686	43/–	100/45	−198 ~ 450	s.g.: 8.73 PRE ≈ 51	(a) Seamless tubes (b) High CCT (critical crevice temperature) (c) For chemical processing, marine, and air pollution control (flue gas desulfurization) industries (d) See Note 15 in plates and strips (e) DIN 17751
<Tube> Seamless Alloy (Monel) **400** 67Ni-30Cu	**B163** (N04400) 67Ni-30Cu Annealed Stress Relief	42/1	70/28 (Annealed) 85/55 (Stress Relief)	−198 ~ 816	s.g.: 8.80 *Size limit*; ≤3 in. OD	(a) Wide temperature range (b) Equipment in dilute H_2SO_4, dilute HCl including salt deposit (NH_4HS), organic acid, caustic service, and severe acidic solution (c) Not recommended in high temperature [>260 °C (500 °F)] sulfidation environment (d) Not recommended in ammonia and its compound environment (due to SCC) (e) For fractionator's top section or OVHD equipment (f) U-tubes in HF acid solution: required stress relieving at 593–649 °C (1100–1200 °F), slow cooling in sulfur-free environment (g) Susceptible to mercury embrittlement (h) ASTM B730 (welded tube), B829 (seamless pipe and tube) (i) BS3074NA13 (Tube), DIN 17751 (Pipe and Tube)
<Tube> Seamless & welded Alloy (Inconel) **600**	**B163** **B516** (N06600) 72Ni-15Cr-8Fe Annealed	43/–	80/35	−198 ~ 649	B163: seamless B516: welded s.g.: 8.47	(a) Wide temperature range (b) Good corrosion resistance to Cl-SCC (c) Good high temperature oxidation resistance [<1177 °C (2150 °F)], but normally limited max. 649 °C (1200 °F) due to strength (d) Not recommended in high temperature salt water due to pitting
<Tube> Alloy (Inconel) **625**	**B444** **B704** (N06625) 60Ni-22Cr-9Mo-3.5Cb	43/–	Gr.1 (anneal) 120/60 Gr.2 (solution anneal) 100/40	−198 ~ 871	B444: seamless B704: welded	(a) See notes on plates of alloy 625 (b) Gr.1: service temperatures up to 593 °C (1100 °F) (c) Gr. 2: service temperatures above 593 °C (1100 °F) when the resistance to creep and rupture is required (d) Solution heat treatment for U-tubes is not required unless codes and end-user require
<Tube> Seamless Alloy **28/29**	**B668** N08028* N08029	45/–	73/31 73/31	−198 ~ 454	s.g.: 8.0 *Brand: Sanicro 28	(a) Excellent resistance to both reducing and oxidizing acids, to SCC and pitting and crevice corrosion. Especially resistant to sulfuric and phosphoric acid (b) N08028: 27Cr-32Ni-3.5Mo-1Cu (c) N08029: 27Cr-32Ni-4.5Mo-1Cu (d) ASME code case: 1325-18
<Tube> Seamless **Cupro-Nickel** Annealed	**B111** C70600 (90-10 Cu-Ni) **B111** C71500 (70–30 Cu-Ni)	34/–	40/15* 45/35** 52/18* 72/50***	−198 ~ 316 (C70600) −198 ~ 371 (C71500)	s.g.: 8.95 for 90–10 8.90 for 70–30 * O61: annealed temper ** H55: light drawn temper *** HR50: drawn, stress relived hand drawn, end annealed	(a) Good corrosion resistance to seawater or blackish water at even higher than normal temperatures while also assuring greater strength and rigidity. See Sect. 2.1.7.2 for more details (b) Susceptible to SCC in ammonia-containing service (c) Size limit: ≤3 1/8 in. OD (d) Service velocity limit of H/EX tubes in seawater: ≤2 m/s (6 fps) for 90:10/ ≤3 m/s (10 fps) for70:30 (e) See Sect. 2.1.7.2 for more details on copper alloys (f) Corrosion rates: See Figs. 2.96 and 2.97 (g) See EEMUA Publ. 144 for offshore application of C70600 tubes
<Tube> Seamless **Inhibited admiralty brass** Annealed	Straight **B111** (C44300) (C44400) *(C44500)* U-bend **B395** (C44300) (C44400) (C44500)	32/–	45/15	−198 ~ 232	s.g.: 8.53 C44300: 71Cu-28Zn-1Sn-0.04As C44400: 71Cu-28Zn-1Sn-0.06Sb C44500: 71Cu-28Zn-1Sn-0.06P	(a) Good corrosion resistance to seawater or blackish water at even higher than normal temperatures while also assuring greater strength and rigidity (b) As (arsenic) for C44300, Sb (antimony) for C44400, or P (phosphorous) for C44500 is added to avoid dezincification. (c) Susceptible to SCC in ammonia-containing service (d) Stress relieving at 427 °C (800 °F), 1 hr for U bends (e) Service velocity limit in seawater: ≤2 m/s (6 fps) (f) B111: Seamless copper alloy condenser tube & ferrule stock B395: U-bend seamless copper alloy H/EX and condenser tube (g) See Sect. 2.1.7.2 for more details

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (6/9)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> Seamless **Aluminum brass** -As added Annealed	Straight **B111** (*C68700*) U-bend **B395** (C68700)	32/–	50/18 O61 annealed	−198 ~ 260	s.g.: 8.33 C68700: 77Cu-20Zn-2Al-0.04As	(a) Good corrosion and erosion (impingement) resistance to seawater or blackish water (due to 2% Al contains). However, it should be carefully used after fully evaluating the risk of MIC, fouling, and erosion (b) P (phosphorous), as (arsenic), or Sb (antimony) should be added to avoid dezincification (c) Susceptible to SCC in ammonia-containing service (d) Stress relieving at 427 °C (800 °F), 1 hr for U bends (e) Service velocity limit in seawater: ≤2 m/s (6 fps) (f) B111: Seamless copper alloy condenser tube & ferrule stock B315: Seamless copper alloy pipe & tube B395: U-bend seamless copper alloy H/EX and condenser tube (g) See Sect. 2.1.7.2 more detail
<Tube> Seamless **Aluminum bronze** Annealed	Straight **B111** C60800 U-bend **B395** (C60800)	35/–	50/19 O61 annealed	−198 ~ 260	s.g.: 8.54 C60800: 71Cu-22Zn-6Al-0.03As	
	B315 C61300 C61400	35/–	65/28 M30 extruded or O61 annealed	−198 ~ 260	s.g.: 8.50 C61300: 89Cu-7Al-2.5Fe-P ≤ 0.015 C61400: 89Cu-7Al-2.5Fe-Mn ≤ 1.0-*P* ≤ 0.015	
<Tube> Seamless **Tungum** (modified copper Brass)	**B706** TB00 TF00 HR50 (C69100)	32/–	55/16.5 60/31 79/48 (Note 1)	−198 ~ 260	s.g.: 8.60 TB00-soft annealed TF00 -precipitation hardened HR50 – drawn-stress relieved	(a) Good SCC and crevice corrosion resistance in seawater (b) For non-process gas and liquid services below 4000 psi (c) For cryogenic service (d) Use not recommended for H_2S, mercury, ammonia, or unqualified production chemicals (e) The cost is approximately 2 times 316L SS cost (f) See Sect. 2.1.7.2 more detail
<Tube> **Aluminum alloys**	**B210** Seamless 3003 Alclad 3003 5083 5086 6061	21/– 21/– 25/– 25/– 23/–	24/21 (at H18) 26/23 (at H18) 39–51/16 (at O) 35–46/ 14(at H32) 30/16 (at T4)	−269~204 −269~204 −269~66 −269~66 −269~204	s.g.: 2.73 s.g.: 2.73 s.g.: 2.65 s.g.: 2.66 s.g.: 2.70	(a) For cold boxes in gas plants and cryogenic service (b) Use at lower temperature is available when the impact test is passed (c) See Sect. 2.1.7.3 for more details (d) See ALPEMA and Table 2.82 (max. design temperature per part and material) in this book for brazed aluminum plate-fin heat exchangers
<Tube> Seamless or welded **Titanium alloy**	**B338** Annealed 1 (R50250) 2 (R50400) 3 (R50550) 7 (R52400) 9 (R56320) 11 (R52250) 12 (R53400) 13 (R53413) 14 (R53414) 15 (R53415) 16 (R52402) 17 (R52252) 18 (R56322)	51/–	35/25 50/40 65/55 50/40 90/70 35/25 70/50 40/25 60/40 70/55 50/40 35/25 90/70	−59 ~ 316	s.g.: 4.40–4.51 Gr.9 and over grades: consult metallurgical engineer Gr.1–4: Unalloyed Gr.5: 6%Al, 4%V Gr.6: 5%Al, 2.5%V Gr.7: 0.12–0.25%V Gr.9: 3%Al, 2.5%V Gr.11: 0.12–0.25%Pd Gr.12: 0.3%Mo, 0.8% Ni Gr.13, 14, 15: 0.5% Ni, 0.05%Ru Gr.16, 17: 0.04–0.08%Pd Gr.18: 3%Al, 2.5%V, 0.04–0.08%Pd	(a) Remarkable corrosion resistance in oxidizing acid (HNO_3 except red fuming nitric) by virtue of a passive oxide film. Good corrosion resistance in seawater, wet chlorine, organic chlorides, but it is not immune and can be susceptible to pitting and crevice attack at elevated temperatures. Example, not immune to seawater corrosion if the temperature is greater than about 110 °C (230 °F) (b) Titanium can absorb hydrogen from environments containing hydrogen gas. At temperatures below 80 °C (176 °F) hydrogen pickup occurs so slowly that it has no practical significance, except in cases where severe tensile stresses are present. In the presence of pure hydrogen gas under anhydrous conditions, severe hydriding can be expected at elevated temperatures and pressures. Titanium is not recommended for use in pure hydrogen because of the possibility of hydriding should the oxide film be broken. (c) Not recommended in aeration condition at 250 °C (482 °F) and over. (d) See Sect. 2.1.7.4 for more details.
	Cold worked and stress Relieved 9 (R56320) 18 (R56322)		125/105 125/105			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes of H/EX for Heat Transfer (7/9)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Tube> **Niobium alloys** Seamless or welded	**B394** R04200-type 1 R04210-type 2 R04251-type 3 R04261-type 4		 18/8.5–10.5* 18/8.5–10.5* 28/18 28/18 *8.5 ksi for seamless	 −196~** ** Per the design condition. Melting temperature: 2468 °C	*s.g.* R04200: 8.57 R04210: 8.57 R04251: 8.57 R04261: 8.57	(a) *Type 1* – Reactor grade unalloyed Nb *Type 2* – Commercial grade unalloyed Nb *Type 3* – Reactor grade Nb alloy containing 1%Zr *Type 4* – Commercial grade Nb alloy containing 1%Zr
<Tube> **Zirconium alloys**	**B523** R60702 R60704	 61 –	 55/30 60/35	 −59~371*	s.g.: 6.48 *Max. 316 °C (600 °F) is normally applied due to deterioration	(a) ASTM B353 seamless and welded tubes for nuclear (except nuclear fuel cladding) (b) ASTM B811 seamless tubes for nuclear reactor fuel cladding (c) See the notes of zirconium alloys in Plates & Strips
<Tube> **Tantalum alloys** Seamless	**B521** R05200 R05400 R05255 R05252 R05240		 30/20 30/20 70/60 40/28 40/28	 −196~* −196~* −196~* −196~* −196~*	*s.g.* R05200: 16.6 R05400: 16.6 R05255: 16.9 R05252: 16.7 R05240: 13.6	(a) Tantalum (Ta) is ductile, easily fabricated, highly resistant (refractory metal) to corrosion by acids, and a good conductor of heat and electricity and has a high melting point (b) Characteristics of several types: See 2.6.2.1 general notes and notes for plates and strips (c) Melting temperature: 2996 °C for R05200 and 2980 °C for pure tantalum * Maximum temperature should be carefully applied per the design condition

General Notes for Tubes

a. Temperature Limits

(1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards.

(2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. The impact test exemption temperature shall comply with the applicable codes/standards. See Appendix A.

(3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, etc.), and corrosion environment. CVN impact test may be exempt per codes and standards for thin wall tubes.

b. Specify the following suffix:

– S: Seamless Type
– W: Metal Arc Welded Type (Straight Welded Type, Double Submerged Arc Welded Type or Electric Fusion Welded Type, etc.)
– E: Electric Resistant Welded Type

c. Specify "Type S" or "Tube W" on purchasing order document if it is a dual type manufacturing material (e.g., A334, A268, etc.). Many end-users want to use seamless type for flammable service, lethal service, high pressure, or hydrogen service.

d. Comparison of Materials used for Cooling Water Handling H/EXs – Table 2.188

Table 2.188 Comparison of Materials used for Cooling Water Handling H-EXs

Material	Advantages	Limitations
Carbon steel	Low cost, easy to fabricate and repair, readily available	Must have good cooling water treatment system in order to get economical life. Not used in seawater
Admiralty Brass/UNS C44300 (seamless)	Economical for fresh water cooling service where carbon steel has relatively short life. Reasonably good corrosion resistance to streams that contain wet H_2S	If the pH is outside the 4–7 range, pitting, stress corrosion cracking or dealloying (loss of zinc) can occur, especially at high temperatures. Sulfates and phosphates have also been reported to cause stress corrosion cracking. Limited life in seawater.
316 SS∗ UNS S31600	Good resistance to chloride pitting and general corrosion up to 1000 ppm chlorides in water. Good resistance to organic acids and limited resistance to sulfuric acid. Readily available and weldable	*Low carbon grade (UNS S31603∗) must be used if used in welded fabrication. Poor resistance to microbiologically influenced corrosion. Residual chlorine must be less than 2 ppm. Limited to 49 °C (120 °F) when aqueous chlorides are present due to susceptibility to ClSCC. Not suitable for seawater
2205 DSS, UNS S32205 (welded)	Good resistance to chloride pitting and SCC. High strength compared to 300 series stainless steels	Not used for seawater, except in thick sections at low temperatures. Not suitable for crude unit overhead exchangers. Multiple weld repairs can destroy corrosion resistance. Usefulness in H_2S and chlorides depends on concentrations of these species
2507 DSS, UNS S32750 (welded)	Excellent resistance to chloride pitting and to SCC. Expected to have good resistance to crude unit overhead corrosion; however, only limited experience to date. High strength compared to most alloys used for seawater	Welding requires careful heat input control to avoid destroying corrosion resistance. Limited to areas where 2205 is not suitable because of higher cost. Usefulness in H_2S and chlorides depends on concentrations of these species

Tubes of H/EX (8/9)

90Cu-10Ni, UNS C70600 (seamless)	Excellent resistance to seawater. Relatively low cost to other materials used for seawater. Good resistance to corrosion and SCC from ammonia	Very susceptible to attack from sulfides if sulfides exceed 0.007 mg/l. For this reason, not good in polluted water or in refinery streams containing H_2S. Subject to erosion if velocity exceeds 2.4 m/s (8 fps) in seawater. Can be dealloyed at low & high pH and high temperatures
70Cu-30Ni, UNS C71500 (seamless)	Excellent resistance to seawater. Better erosion resistance than 90–10 Cu Ni. Excellent resistance to corrosion and stress corrosion from ammonia	Very susceptible to attack from sulfides if sulfides exceed 0.007 mg/l. For this reason, not good in polluted water and very limited use in refinery streams containing H_2S. Subject to erosion if velocity exceeds 4.5 m/s (15 fps) in seawater. Can be dealloyed at low & high pH and high temperatures
Titanium Gr. 2 SB-338, UNS R50400	Excellent resistance to corrosion and chloride pitting in seawater. Immune to chloride SCC. Suitable for crude and vacuum unit overhead exchangers	Embrittlement due to hydriding can occur above 71–80 °C (160–176 °F) if hydrogen is present. Subject to fatigue failure if baffle spacing is too long. Can be crevice-corroded in extreme conditions where salt concentrates

e. The low strength (low carbon, low Ceq and/or heat treated) P No.1 materials are recommended in environmental cracking condition.

f. General requirements for U-Bends in API RP660 (Shell and Tubes Type H/EXs). Otherwise, see Sects. 3.1.7 and 4.12.3.16.

(1) The mean radius of U-bends shall not be less than 1.5 times the nominal outside diameter of the tube. For martensitic stainless steels, super ASS (>6 wt % Mo) DSS, titanium, and high nickel alloys (>30 wt % Ni), the mean radius of U-bends shall not be less than 2.0 times the nominal outside diameter of the tube.

(2) For U-tubes, design calculations shall be based on the reduction in wall thickness associated with bending. The thickness of the tubes need not be increased to meet the requirements in Table 1.11 in this book provided the wall thickness in the U-bends meet the minimum requirements of the pressure design code and any specified tube corrosion allowance.

(3) For U-tube and floating head type exchangers, the minimum clearance between any part of the U-bend or floating head cover, and the shell rear head, shall be 38 mm (1.5 in.), to accommodate thermal expansion of the tube bundle. Both the crown and knuckle of the head shall be considered.

g. Heat Treatment Requirements for U-Bends in API RP660 (Shell and Tubes Type H/EXs): See Sect. 4.12.3.16. In addition, see Sect. 3.1.7 for other fabrication requirements of U-Bends.

h. Recommended MOC for Offshore (Gulf of Mexico) Topside Tubing in Consideration of External Corrosion (Marine Environment) – Table 2.189

Table 2.189 Recommended MOC for Offshore (Gulf of Mexico) Topside Tubing in Consideration of External Corrosion (Marine Environment)

Pressure	Max. operating temperature	Recommended materials[(1),(2),(3),(4)]	Internal service[(5)]	Remarks
≤350 barg (5000 psig) (pH > 6.0)	≤60 °C (140 °F)	316(L) SS, 317(L) SS, 2205 DSS, Alloy 825, Alloy 904L, 6%Mo SS (254SMO, AL-6XN, etc.)	Fuel gas, heat media, chemical injection, process oil & gas, seawater, and produced & potable water	316(L) SS & 317(L) SS may be acceptable for tubing and associated components for nonmarine sites
	≤75 °C (167 °F)	2205 DSS, alloy 825, alloy 904L, 6%Mo SS	Diesel, air, nitrogen, wet CO_2, hydraulic and lube oil, hot oil, chemical injection, potable water	=
	≤100 °C (212 °F)	2507 SDSS, alloy 825, alloy 904L, 6%Mo SS		=
	≤121 °C (250 °F)	6%Mo SS		=
	≤200 °C (392 °F)	Tungum (hydrotest up to 7500 psig/ operation up to 4000 psig), alloy 625		Tungum: Only for utility Alloy 625: For process
	≤260 °C (500 °F)	Alloy 625	Diesel, glycol and hot oil	For high strength and corrosion resistance
≤700 barg (10,000 psig)	≤60 °C (140 °F)	2205 DSS, alloy 825, alloy 904L, 2507 SDSS. 6%Mo SS	Sweet to mildly sour service (pH > 3.5)	=
	≤75 °C (167 °F)	Alloy 825, alloy 904L, 2507 SDSS		=
	≤100 °C (212 °F)	2507 SDSS, 6%Mo SS, alloy 625	More severe corrosive Process service (pH > 2.0)	6%Mo SS: Up to 406 barg (5800 psig)
	≤200 °C (392 °F)	Alloy 625		=
> 700 barg (10,000 psig)	≤60 °C (140 °F)	2205 DSS, 2507 SDSS	Sweet to mildly sour service (pH > 3.5)	=
	≤75 °C (167 °F)	2507 SDSS, alloy 625		=
	≤200 °C (392 °F)	Alloy 625	More severe corrosive Process service (pH > 2.0)	For high strength and corrosion resistance

Sub-Notes:

(1) Pressure/temperature for super duplex SS (SDSS), Tungum, Alloy 625, and 6Mo SS (AL-6XN, 254SMO, etc.) should be established to ensure the tubing size and wall thickness selected should meet or exceed the application pressure and temperature.

(2) When joining Alloy 625 tubing with SDSS, 2507 SDSS compression fittings should be used, due to the higher hardness property of SDSS.

(3) Some experiences report that (a) the corrosion resistance of Alloy 825 may not be better than that of 316L SS, (b) 317LMN shows not much remarkable corrosion resistance compared to 316L SS, so that is not recommended; (c) 254SMO has good corrosion resistance in North Sea; and (d) all tubes should be seamless.

(4) Fitting and clamps should be used of the same material as the tubing or of similar corrosion resistance (including nonmetallic materials) to avoid galvanic corrosion at these locations as well as to avoid these sites becoming initiation points for pitting or crevice corrosion.

(5) Consult chemical supplier and end-user's or responsible corrosion engineer for consideration of internal corrosion.

Tubes of H/EX (9/9)

i. When austenitic steels/alloys are used in services subjected to stress corrosion, the material with solution or stabilized-heat treatment should be used. For material purchasing, the buyer should indicate the additional requirements for thermally stabilized heat treatment for stabilized stainless steel/alloy when they are exposed to polythionic acid SCC or other severe SCC environment. See Sect. 2.1.6.8 for more details.

j. Tube hole diameter and tolerance on tubesheets of heat exchangers including air coolers.
If ASS, DSS, titanium, Cu-Ni or Ni-alloy tubes are used, the tube holes on tubesheets shall be machined in accordance with TEMA (9th edition), Table RCB-7.21/2M, column (b) (Special Close Fit). See TEMA, API 660, and API 661.

k. P.No.1 materials are not recommended above 427 °C (800 °F) for continuous operation because of the graphitization after several hundred hours. See Sect. 2.3.1 for more details.

l. See Table 2.68 for more details on the properties and development histories of Ni base alloys.

Notes for Tubes

1. Strength (TS) comparison of Copper Alloys (source: Tungum catalog): See Fig. 2.97.
2. Some users prohibit tube-to-tubesheet (TTT) joints except light rolling (<2%) for positioning due to possible high hardness, and require strength welds with filler metal.
3. Solution heat treatment or stabilizing heat treatment (only for stabilizing elements, Nb or Ti containing SS or nickel alloys) is recommended after cold bending or forming unless otherwise exempted from the applicable codes or standards.

2.6.2.3 Tubes/Supports for Fired Heaters and Boilers (*w* = welded, *s* = seamless) – See General Notes

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes/Support for Fired Heater/Boiler (1/7)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Boiler & superheater tubes> carbon steel Welded	**A178** A C D	 1/1 1/1 1/2	 47*/26* 60/37 70/40	~ 540	*C%/Mn% for Gr. A*: 0.06–0.18/ 0.27–0.63 *C*: ≤0.35/≤0.80 *D*: ≤0.27/ 1.00–1.50	(a) ERW tubes (b) Grade D: Killed (c) Gr. C & D: Similar to the characteristics and cautions for pipe, A106 Gr. A * Only assumed values for design purpose
<Boiler tubes> carbon steel	**A192** Low carbon	1/1	47*/26*	~ 540	*C*: 0.06~0.18%	(a) Seamless tubes (b) For high pressure service * Only assumed values for design purpose
<Boiler & superheater tubes> carbon steel Seamless-killed	**A209** T1 T1a T1b	 1/1	 55/30 53/28 60/32	~ 540	*C, %* Gr.T1: 0.10–0.20 Gr.T1a:0.15–0.25 Gr.T1b: ≤0.14	(a) Hardness limits: Gr.T1: 146 BHN (80 HRB) Gr.T1a: 153 BHN (81 HRB) Gr.T1b: 137 BHN (77 HRB)
<Heater tubes> C-1/2Mo (K11522)	**A335** P1	3/1	55/30	~ 566		(a) Seamless pipes for high temperature (b) Similar to the characteristics and cautions for A335 Gr. P1
<Heater tubes> ¼Cr-½Mo (K11597)	**A335** P11	4/1	60/30	~ 650		(a) Seamless pipes for high temperature (b) Similar to the characteristics and cautions for A335 Gr. P11
<Heater tubes> 2¼Cr-1Mo (K21590)	**A335** P22	5A/1	60/30	~ 650		(a) Seamless pipes for high temperature (b) Similar to the characteristics and cautions for A335 Gr. P22
<Heater tubes> 5Cr-½Mo (K41545)	**A335** P5	5B/1	60/30	~ 650		(a) Seamless pipes for high temperature (b) Similar to the characteristics and cautions for A335 Gr. P5
<Heater tubes> Seamless pipes for High temperature 9Cr-1Mo (S50400) 9Cr-1Mo-V-Cb-N-Ni-Al-Ti-Zr (K91560) 9Cr-1Mo-V-Cb-N-W-B-Ni-Al-Ti-Zr (K91061)	**A335** P9 P91 P911	 5B/1 15E/1 15E/1	 60/30 85/60 90/64	~ 705	Full RT PWHT required Size: ≤NPS 12 in.	(a) More resistance to hydrogen attack than 5Cr-0.5Mo (b) More resistance to graphitization than 5Cr-0.5Mo (c) More resistance high-temperature sulfur & oxidation than 5Cr-0.5Mo (d) When extrusion, forging, or EFW type for NPS > 12. is selected, consult metallurgical engineer (e) Higher creep-rupture strength at high temperature and erosion resistance than 5Cr-0.5Mo. (P911 > P91 > p9)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes/Support for Fired Heater/Boiler (2/7)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Heater tubes> Seamless pipes for High temperature 9Cr-1Mo- 1.7W-V-Cb- N-Ni-Al-Ti-B -Zr (K92460)	**A335** P92	15E/1	90/64	~ 705	Full RT PWHT required Size: ≤NPS 12 in.	(a) More resistance to hydrogen attack than 5Cr-0.5Mo (due to Cr) (b) More resistance to graphitization than 5Cr-0.5Mo (due to Cr & Mo) (c) More resistance high temperature sulfur & oxidation than 5Cr-0.5Mo (d) When extrusion, forging, or EFW type for NPS > 12. Is selected, consult metallurgical engineer (e) Higher creep-rupture strength at high temperature and erosion resistance than 9Cr-1Mo and gr.P91
<Boiler, superheater, H/EX tubes> Seamless Tubes	**A213** T2 T12 T11 T22 9 91 92 911	 3/1 4/1 4/1 5A/1 5B/1 15E/1 15E/1 15E/1	 – 60/32 – – 60/30 85/60 90/64 90/64	 ~ 540 ~ 650 ~ 650 ~ 650 ~ 705 ~ 705 ~ 705 ~ 705	*Max hardness:* T12: 163BHN T9: 179BHN T91: 250BHN T92: 250BHN T911: 250BHN	(a) See the same grade in ASTM A335 (b) See A209 in Sect. 2.6.2.2.2 heat transfer for Gr. T1, T1a, and T1b
<Boiler, superheater, H/EX tubes> Seamless ASS	**A213** TP 304(H) TP 316(H) TP316Cb TP 317(L) TP 321(H) TP 347(H) TP309H TP309Cb TP309HCb	8/1	75/30	~ 815 (for 304/304H/316/316H/321/321H/347/347H) ~ 677 for 304L ~ 704 for 316L/316Cb, 317L/ 309 series	Stabilized annealed See Note 8 in Pipes & Tubes for reference	(a) Similar to the characteristics and cautions for the same grade in ASTM A312 (b) All “H” grades contain 0.04–0.1%C for high-temperature strength, including welding materials. Also, may have average grain size, ASTM no.7 or coarser per ASTM E112 if required (c) TP309LMoN: 93/38 for SMTS/SMYS
<Heater tubes> HF 19Cr – 9Ni Casting Note 7	**A297** Gr. HF (J92603)	8/1	70/35	~ 1093	As cast See Note 3 & 5. See NiDI publication #10058.	(a) More added Ni than “HN” and more added Cr than “HT” (b) Good rupture stress at 982–1093 °C (1800–2000 °F) and high temperature oxidation and decarburization resistance (c) For ethylene pyrolysis tubes, ammonia plant steam methane reformer tubes, heat treating fixtures (d) HP modified (added Nb, W) has better creep rupture strength and oxidation resistance
<Heater tubes> HK-40 25Cr – 20Ni Centrifugally casted Note 7	**A608** Gr.HK-40 (J94204)*	8/2	65/35	~ 954 (max. 100,000 hours design life unless specified.)	*Specify chemical requirements; Pb: ≤200 ppm *C*: 0.38–0.45% Thickness variation ≤6.4 mm for OD 2–12″ ≤13–25 mm for OD >12” See Note 3 & 4.	(a) For hydrogen reforming service (b) Better strength/oxidation resistance than HH (c) Hydrotest: 3 times of design pressure, for min. 5 minutes (recommended) (d) Tensile test at 954 °C (1750 °F) per A608, S2 – YS, 9ksi/TS, 12.5ksi (recommended) (e) Production chemical analysis of metal: per ASTM A608, S1 (recommended) (f) Etching test per ASTM A608, S7 (recommended) (g) RT for the turned and bored tubing 100%RT for major repair welds
	A608 Gr.HK-40 (J94204)*	8/2	65/35	~ 954	*Specify chemical requirements; Pb: max.200 ppm Si: 1.5–2.00% Thickness variation ≤2 mm for OD 2–6″ ≤2.5–3.3 mm for OD >6″ See Note 3 & 4.	(a) For ethylene pyrolysis service (b) Better strength/oxidation resistance than HH (c) None or machine ID to remove unsoundness a min. of 1.14 mm (0.045 in.) from the thickness (to minimize carburization) (d) Machine surfaces shall be free of defects (e) Production chemical analysis of metal: per ASTM A608, S1 (recommended) (f) Etching test per ASTM A608, S7(recommended) (g) RT for the turned and bored tubing 100%RT for major repair welds

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes/Support for Fired Heater/Boiler (3/7)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Heater tubes> HK(-40) Static casting 25Cr – 20Ni Return Bend & fittings Note 7	Pressure part **A351** Gr. HK40 (J94204) General **A297** Gr. HK (J94224)	8/2	62/35 65/35	~ 954	As cast Specify chemical requirements; Pb: $\leq$200 ppm *C*: 0.38–0.45% See Note 3 & 4.	(a) For hydrocarbon reforming & ethylene Pyrolysis service (b) Better strength/oxidation resistance than HH (c) RT per ASTM A351, S5 (d) PT per ASTM A351, S6 (e) No defects on machining surface (f) 100% RT – acceptance per ASTM E-94 (recommended). 100% RT for major repair welds
<Heater tubes> HP 25Cr – 35Ni Casting Note 7	**A297** Gr. HP (N08705 former J95705)	45/–	62.5/34	~ 1093	As cast See Note 3 & 5. See NiDI publication #10058.	(a) More Ni than "HN" and more Cr than "HT" (b) Good rupture stress at 982–1093 °C (1800–2000 °F) and high-temperature oxidation and decarburization resistance (c) For ethylene pyrolysis tubes, ammonia plant steam methane reformer tubes, heat treating fixtures (d) HP modified (added Nb, W) has better creep-rupture strength and oxidation resistance
<Heater tubes> 20Cr – 32Ni 800 800H 800HT	**B407** **B515** (N08800) (N08810) (N08811)	 45/– 45/– 45/–	At annealed 75*/30* 65/25 65/25	Note 2 ~815 ~900 ~900	B407: seamless B515: welded *At annealed (B407) 65/25 ksi Note 1	(a) Highly resistant both to chloride SCC and to embrittlement from precipitation of sigma phase (b) General corrosion resistance is excellent (c) In the solution annealed condition, 800H and 800HT have superior creep and stress rupture properties
<Heater tube> IN-519 24Cr-24Ni-1.5Cb	–	45/–	75/35	~ 982	See Note 3.	(a) Developed type of HK (J94224) – developed creep-rupture strength due to reduced C and added Cb (b) Centrifugally cast catalyst tubes in steam-hydrocarbon reformer furnaces (c) See NiDI publication #4383
<Heater tube> IN-787 16Cr-60Ni-8.5Co-7.0(Al+Ti)-2.6W-1.7Mo-1.7Ta-0.85Cb	–	43/–	159/138 150/130	~ 982	See Note 3. IN 738C: 0.17C-0.1Zr IN 738LC: 0.11C-0.05Zr s.g: 8.11	(a) Vacuum meted, vacuum cast, precipitation hardenable (b) For high-temperature gas turbines (c) See NiDI publication #1278
<Heater tube/ support> Casting HT 17Cr – 35Ni Note 7	**A297** Gr. HT (N08605) **A351** Gr. HT30 (N08030)	45/–	65/– 65/28	~ 1150	As cast See Note 3.	(a) Thermal shock, high-temperature oxidation and decarburization resistance (b) Max. recommended temperature – Oxidizing environment: 1149 °C (2100 °F) – Reducing environment: 1093 °C (2000 °F) (c) Weak in high-sulfur gas (d) For load-bearing components, rotors, radiant tube, cyanide & salt pots, hearth plates, quenched trays
<Heater tube> IN-657 50Cr-48Ni-1.5Cb	–	43/–	87/54	~ 871	See Note 3.	(a) Developed type of 50Cr-50Ni (R20500)- developed creep-rupture strength and kept corrosion resistance be degraded by fuel oil ash due to reduced Ni, and added Cb (b) For tubesheets of convection section in refinery heaters, boilers
<Heater tube> IN-738C IN-738LC 16Cr-60Ni-8.5Co-7.0(Al+Ti)-2.6W-1.7Mo-1.7Ta-0.85Cb	-	43/–	159/138 150/130	~ 982	See Note 3. IN 738C: 0.17C-0.1Zr IN 738LC: 0.11C-0.05Zr s.g: 8.11	(a) Vacuum meted, vacuum cast, precipitation hardenable (b) For high-temperature gas turbines (c) See NiDI publication #497
<Tube support> Casting 25Cr-12Ni(HH) Note 7	**A447** Type II (formerly B-190) J93503	45/–	80/1 At atm 20/– After aging At 871 °C	~ 1093	Magnetic test (to confirm the microstructure) Short time High temperature Tensile test See Note 3.	(a) For most refinery heater components (b) The creep-rupture strength and ductility of type II is more superior than those of type I. Type II is preferable (c) The purchaser should inform the manufacturer when the service temperatures are to exceed 980 °C (1796 °F)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Tubes/Support for Fired Heater/Boiler (4/7)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Heater tube/ supports> casting 29 Cr-9Ni 25 Cr-12Ni Note 7	**A297** Gr. HE (J93403) Gr. HH (J93503)	45/–	85/40 75/35	~ 1093	See Note 3.	(a) Gr. HE: Good high-temperature sulfur corrosion resistance due to low Ni It may be used instead of ASTM A447 type II when fuel oil is including high sulfur (b) The high-temperature oxidation resistance of 29Cr-9Ni is similar to that of 25Cr-12Ni (c) The high-temperature strength of 29Cr-9Ni is less than that of 25Cr-12Ni
<Heater tube/ supports> casting 35Cr-45Ni-1Nb	35/45	45/–	87*/42 89 @1000 °C	~ 1130	s.g: 8.22	(a) Ethylene pyrolysis outlets and fittings, direct reduction furnace assemblies (b) Excellent carburization resistance (c) See NACE TM0498 for the evaluation of carburization
<Heater tube/ supports> casting 50/60Cr-50/40Ni	**A560** 50Cr-50Ni (R20500) 60Cr-40Ni (R20600) 50Cr-50Ni-Cb(R20501)	43/–	80/50 110/85 80/50	~ 1093	Specify T.S & CVN Impact test See Note 3.	(a) Good vanadium attack resistance in fuel oil (b) High melting point/electrical resistivity/ emissivity (c) Good oxidation resistance/creep-rupture strength/thermal shock resistance (d) Good strength and ductility of fabrication temperature (e) Low thermal expansion/modulus (both of which help minimize thermal fatigue) (f) A560 is designated as "A" even though it is for nonferrous alloys

General Notes for Heaters

a. Temperature Limits
   (1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards
   (2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. The impact test exemption temperature shall comply with the applicable codes/standards. See Appendix A
   (3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, low temperature toughness, etc.), and corrosion environment

b. Heat Resistant Cast Grades: HK, HP, HA, HC, HB, HE, HF, HH, HZ, HL, HN, HU, HW, HX
   'H': Heat Resistance at ≥649 °C (1200 °F)

c. Group per Chemical Components-See Sect. 2.1.7(f) for more details
   (1) Cr-Fe Alloys: HA, HC, HD
   (2) Cr-Ni-Fe Alloys: HE, HF, HH, HI, HK; IN-519, HL
   (3) Ni-Cr-Fe Alloys: HN, HP, HT, HU, HW, HX

d. See Sect. 1.2.3.4 tube thickness calculation, 1.3.3.2 creep-rupture stress, 2.17 (f), Table 1.8 mill tolerance, Table 1.11 minimum thickness, Table 1.16, Table 1.70 design metal temperatures, Table 2.31a & fig. 2.24 Gr. 91 tube materials, and Table 2.143 tube inspection for other detail of heater tube materials.

e. Metal skin temperatures, rather than stream temperatures, should be used to design creep-rupture as well as predict corrosion rates. For example, metal temperatures of furnace tubes are typically 85 to 110 °C (150 to 200 °F) higher than the bulk temperature of the hydrocarbon stream passing through the tubes. Furnace tubes normally corrode at a higher rate on the hot side (fire side) than on the cool side (wall side) if it is exposed to corrosive elements (e.g., S, H_2S, O_2, etc.). Convection tubes often show accelerated corrosion at contact areas with tube hangers because of locally increased temperatures. Similarly, replacement of bare convection tubes with finned or studded tubes can further increase tube metal temperatures by 85 to 110 °C (150 to 200 °F). See Metal Handbook vol.13

f. See Sect. 2.6.2.1 Plates and Shapes for tube supports, but API 560 allows to use at higher temperature for refractory anchor tips as Table 2.190

Table 2.190 Typical Tube Temperatures to Avoid Deterioration

Anchor material	Maximum anchor temperature, °C (°F)
CS	455 (850)
304 SS	760 (1400)
316 SS	760 (1400)
309 SS	815 (1500)
310 SS	927 (1700)
330 SS	1038 (1900)
Alloy 601 (N06601)	1093 (2000)
Ceramic studs and washers	>1093 (>2000)

g. Table 2.191 shows typical tube deterioration mechanisms in specific services in refinery plants

Table 2.191 Typical tube deterioration mechanisms in specific services in refinery plants

Process unit	Tube materials	Deterioration mechanism	Comments (caused by)
Crude unit Atmospheric section	5Cr-0.5Mo 9Cr-1Mo 316 SS 317 SS	Creep, external oxidation	Abnormal operation, low flow, or flame impingement
		Sulfidic corrosion	Alloy content, inadequate to resist attack by the level of sulfur compounds and naphthenic acid
		Naphthenic acid corrosion	Alloy content, inadequate to resist attack by the level of sulfur compounds and naphthenic acid
Crude unit Vacuum section	5Cr-0.5Mo 9Cr-1Mo 316 SS 317 SS	Creep, external oxidation	Abnormal operation, low flow, or flame impingement
		Sulfidic corrosion	Alloy content, inadequate to resist attack by the level of sulfur compounds and naphthenic acid
		Naphthenic acid corrosion	Alloy content, inadequate to resist attack by the level of sulfur compounds and naphthenic acid
Delayed cokers	5Cr-0.5Mo 9Cr-1Mo 347 SS	Carburization	Common problem in this service; can be detected by chemical spot tests
		Creep, external oxidation	Excessive metal temperatures from internal coke formation, high duty, low flow, or flame impingement
		Sulfidic corrosion	Alloy content inadequate to resist attack by the level of sulfur compounds
		PTASCC(1) (347 to be used)	PTASCC(1) of sensitized stainless steel
		Erosion	Coke particles during steam-air decoking and thermal spalling
Catalytic hydrodesulfurizer	5Cr-0.5Mo 9Cr-1Mo 321/347 SS	Creep, external oxidation	Abnormal operation, low flow, or flame impingement
		PTASCC(1)	PTASCC(1) of sensitized stainless steel
		Hydrogen/H2S corrosion	Alloy content inadequate to resist attack by the level of hydrogen/hydrogen sulfide
Catalytic reformer	1.25Cr-0.5Mo 2.25Cr-1Mo 5Cr-0.5Mo 9Cr-1Mo	Creep, external oxidation	Abnormal operation, low flow, or flame impingement
		Hydrogen attack	Operation of tube materials above API RP 941 Nelson curves
		Metal dusting	High carbon activity and high-temperature operation Occurs under specific conditions
		Spheroidization	Probable in 1.25Cr-0.5Mo after long-term service
Catalytic cracking Waste heat boiler	CS 1.25Cr-0.5Mo 2.25Cr-1Mo	Internal corrosion	Inadequate or improper water quality
		Creep, external oxidation	Abnormal operation, low flow, or flame impingement
		External dew point corrosion(2)	Tube metal temperatures operating below the flue gas dew point
		Erosion	Entrained catalyst in the flue gas
Steam methane reformer Ethylene pyrolysis	HK-40 HP-modified	Creep	Abnormal operation, low flow, or flame impingement
		Metal dusting, carburization	High carbon activity and high-temperature operation Occurs under specific conditions
		Creep, external oxidation	Abnormal operation, low flow, or flame impingement
Utilities-boilers	CS 1.25Cr-0.5Mo 2.25Cr-1Mo	Internal corrosion	Inadequate or improper water quality
		Creep	Abnormal operation, low flow, or flame impingement
		External oxidation	Abnormal operation, low flow, or flame impingement

Source: API RP573

Notes:

(1) PTASCC = Polythionic Acid Stress Corrosion Cracking

(2) Dew point corrosion is not common to catalytic cracking alone; however, it is common for air preheaters, boiler feedwater (economizer) coils, and is periodically seen in stacks

h. P.No.1 materials are not recommended above 427 °C (800 °F) for continuous operation because of the graphitization after several hundred hours. See Sect. 2.3.1 for more details

i. 310 SS is a typical material for tube support except the heaters with P-No.1 tube material

j. See Table 2.68 for more details on the properties and development history of Ni-based alloys

k. As close to the higher temperature (up to maximum temperature) for normal operation, the lifetime of the material typically decreases

l. Table 2.192 shows Larson-Miller Constants (CLM), which are listed in API 530 Table 4

Tubes/Support for Fired Heater/Boiler (6/7)

Table 2.192 Larson-Miller constants (CLM) (API 530. Table 4)

Material	Grade or type	Larson-Miller constants (CLM), rounded up	
		Minimum values	Average values
Low-carbon steel	–	18.15	17.70
Moderate-carbon steel	B	15.60	15.15
C-0.5Mo steel	T/P1	19.01	18.73
1.25Cr-0.5Mo steel	T11 or P11	22.05	21.55
2.25Cr-1Mo steel	T/P22	19.57	18.92
3Cr-1Mo steel	T/P21	15.79	15.38
5Cr-0.5Mo steel	T/P5	16.03	15.59
5Cr-0.5Mo-Si steel	T/P5b	16.03	15.59
9Cr-1Mo steel	T/P9	26.22	25.86
9Cr-1Mo-V steel	T/P91	30.89	30.36
18Cr-8Ni steel	304(H)	16.15	15.52
18Cr-8Ni steel, $C \leq 0.3\%$	304L	18.29	17.55
16Cr-12Ni-2Mo steel	316(H)	16.76	16.31
16Cr-12Ni-2Mo steel, $C \leq 0.3\%$	316L	15.74	15.20
16Cr-12Ni-3Mo steel, $C \leq 0.3\%$	317L	15.74	15.20
18Cr-10Ni-Ti steel	321	13.32	12.80
18Cr-10Ni-Ti steel, $C = 0.4–1.0\%$	321H	15.29	14.76
18Cr-10Ni-Nb steel	347	14.89	14.25
18Cr-10Ni-Nb steel, $C = 0.4–1.0\%$	347H	14.17	13.65
Ni-Fe-Cr alloy	Alloy 800	17.01	16.51
Ni-Fe-Cr alloy	Alloy 800H	16.56	16.04
Ni-Fe-Cr alloy	Alloy 800HT	13.61	13.23
25Cr-20Ni	HK-40	10.86	10.49

m. See the following references for heater/furnace/boiler components
  – API TR942-A Materials, Fabrication, and Repair Considerations for Hydrogen Reformer Furnace Outlet Pigtails and Manifolds
  – NiDI Publication #14053 Ni Alloys and SS for Elevated Temperature Service and Weldability Considerations
  – NiDI Publication #10071 Wrought and Cast Heat Resistant SS Ni Alloys Refining Petrochemical
  – NiDI Publication #10058 HP-modified Furnace Tubes for Steam Reformers
  – NiDI Publication #10031 Repair Welding High Alloy Furnace Tubes
  – NiDI Publication #10001 High Temperature Problem in Refinery and Petrochemical
  – NiDI Publication #9004 High Temperature characteristics of SS
  – NiDI Publication #1205 The Role of Nickel in Carburizing Steels
  – NiDI Publication #1196 Cast Heat-Resistant Alloys
  – NiDI Publication #406 Nickel Alloy Steel Castings
  – NiDI Publication #393 High Temperature High Strength Nickel Base Alloys
  – NiDI Publication #266 Heat-Resistant Castings Corrosion Resistant Castings: Their Engineering Properties and Applications
  – NACE Paper 17-9351, 11155, 10347, 07427, 06239, 06467, 05404, 05419, 05427, 05439, 04641, 03657, 02481, 01238, 99387, 99386, 98443, 98429, 97493, 97403, 96140, 95332, 94520, 94396, 93239, 92311
  – NACE MP 2014-12 (p9-10), 2012-10 (p158), 2009-04 (p66), 2005-12 (p56-59)
  – NACE Corrosion Journal 2006-01 (p54-63),
  – ASM, Metal Handbook, Vol.2

n. *Repair by welding for casting*: Repair of injurious defects by welding should be permitted and major weld repairs should be permitted only subject to the approval of the purchaser. Unless otherwise specified by purchaser or material standard, weld repairs should be considered major if the depth of the cavity prepared for welding exceeds 20% of the required minimum wall thickness or if the total surface area exceeds 65 cm^2 (10 in^2). Defects shall be completely removed before welding. If defects are linear, complete removal should be checked by liquid penetrant inspection (Practice of ASTM E165). Only qualified operators and procedures in accordance with Practice of ASTM A488(M) should be used. All weld repairs shall be subjected to the same inspection standard as the tubing.

o. When austenitic steel/alloy castings are to be used in services where they will be subject to stress corrosion, the purchaser should so indicate in his order, and such castings should be solution-heat-treated following all weld repairs.

p. See Note 1 in Sect. 2.6.2.2(1) Pipe and tubes-mass transfer in high temperature sulfidation corrosion environment.

q. Typical PFDs of Reformers and Furnaces – Fig. 2.201

r. See API STD 560 Revision History (prepared by Furnace Improvements) for all history and comparison between 1986 and 2016

Tubes/Support for Fired Heater/Boiler (7/7)

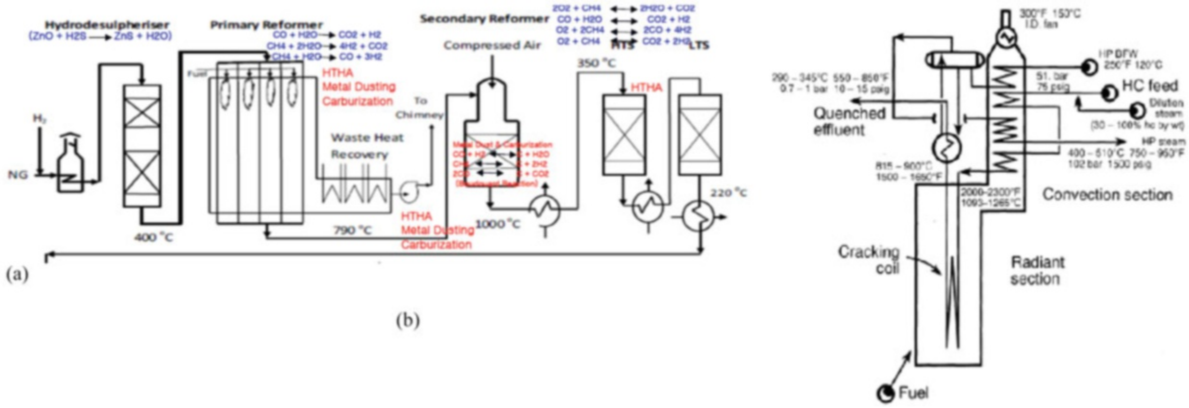


Figure 2.201 Typical PFDs of reformers and furnaces. (**a**) Ammonia Plat Methane Reformer (↑). (**b**) Ethylene Thermal Cracking Furnaces (→)

Notes for Heaters

1. 100 Hour Still Air Continuous Oxidation (Simplified) Tests (Only Reference) – Table 2.193

Table 2.193 100 Hour Still Air Continuous Oxidation Tests

Alloy	Sample weight gain (mg/cm^2)					Remark
	927 °C (1700 °F)	982 °C (1800 °F)	1038 °C (1900 °F)	1093 °C (2000 °F)	1149 °C (2100 °F)	
Alloy 800	0.77	1.8	2.1	2.1	5.1	21Cr-31Ni
Type 309	0.80	1.2	2.1	2.5	4.0	23Cr-13Ni
Type 310	0.80	1.1	2.6	3.2	5.2	25Cr-20Ni

2. They may be used up to 985 °C (1800 °F) in application where the internal pressure is so low that rupture strength does not govern the design
3. Ductility test may be required after aging in accordance with project specification, e.g., the minimum elongation to be 15% (or 10%) after 1000 (or 100) hours aging at the design temperature
4. Some damage mechanisms such as carburization, oxidation, and creep can appear during high temperature operation, requiring the tubes to be replaced at intervals of approximately five or 6 years. Solution-annealing prior to repair welding is considered to be an important issue to recover the ductility of parent metal. However, if the annealing temperature is too high, this may not be acceptable from the viewpoint of high-temperature strength. Solution annealing temperature should be at least 100 °C higher than the solvus temperature in order to solute carbides on grain boundaries and intermetallic phases, which will be suitable for materials ductility. Solution annealing procedure for HK-40 may be conducted at a temperature of 1050 °C (HP at 1100–1200 °C) for 2 hours and cooled by compressed air
5. If field repairs are required on HP-40 Mod Nb after aging, a solution anneal for minimum 2 hours is recommended, which will restore much of the elongation
6. Solution heat treatment or stabilizing heat treatment (only for stabilizing elements, Nb or Ti containing SS or nickel alloys) is recommended after cold bending or forming
7. See Table 2.71 for more various (centrifugally) cast alloy tubes

2.6.2.4 Forgings & Wrought (Fittings) – See General Notes

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (1/13)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging> C–Si Carbon Steel	**A181** Cl. 60 Cl. 70	1/1 1/2	60/30 70/36	−29 ~ 538	Used with CS seamless, welded, or fabricated pipes. Applicable weight ≤ 4540 kg (10,000Lb)	(a) General forging (b) Recommended for ≤ #300Lb Class (preferable ≤ #150Lb) In low pressure, medium temperature, nonflammable, and nontoxic service
<Forging> C-Si Carbon steel	**A105**	1/2	70/36	−29 ~ 538 Max 427 °C (800 °F) for long-term operation	*Heat treatment*: – Annealing – Normalizing – Normalizing + tempering (N-T) – Quenching + tempering (Q-T) *C*: ≤0.35% Mn: 0.60–1.05% *Hardness*: 137–197 HBW Former: to 187 HBW See Note 4	(a) Forging for piping and nozzles in most pressure containing parts (b) Applicable weight ≤ 4540 kg (10,000Lb) larger forgings may be ordered to A266/A266M (c) Standard forging and fittings per ASME B31series (d) Recommended normalizing for > NPS 4 in. and > #300Lb (e) Impact test is required and normalizing may be required for the MDMT < −29 °C (−20 °F). Some end-users use A105 at −10 °C (14 °F) and warmer because of its bad toughness (f) For each reduction of 0.01% below the specified carbon max. 0.35%, an increase of 0.06% Mn above the specified max. 1.05% will be permitted up to a max. of 1.35% (g) MR0175/ISO15156 (wet H2S): max. 187 HBW (h) A/SA-105 is designated as Curve A for as-forged and Curve B for forging produced by fine grain practiced and N, N-T, or Q-T from ASME BPVC 2019 edition-Impact Test Exemption Curves
<Forging> Low Temp. Carbon Steel	A350 LF1/5 LF2-all LF3-cl.1 LF5-cl.2 LF6-cl.1 LF6-cl.2,3 LF-9 LF787-cl.2 LF787-cl.3	1 / 1 1 / 2	60-85/30 70-95/36 70-95/37.5 70-95/37.5 66-91/52 75-100/60 63-88/46 65-85/55 75-95/65	* ~ 538 * See Note 2 Max 427°C (800°F) for long-term operation	*Heat treatment for 787*: - Normalizing +Precipitation (N-P) - Quenching +Precipitation (Q-P)** ** only for cl.3 *Heat treatment for others: N, N-T, or Q-T*	a. For LTCS (impact tested).
<Forging> C-Mn	**A266** Gr.1 Gr.2/4 Gr.3	1/1 1/2 1/2	60–85/30 70–95/36 75–100/37	−29 ~ 538 Max 427 °C (800 °F) for long-term operation	*Heat treatment*: Annealing Normalizing Normalizing + tempering (N-T) Quenching + tempering (Q-T) See Note 4	(a) Applicable weight > 4540 kg (10,000Lb) or Nonstandard forging/fittings for pressure vessels (i.e., tubesheets and hollow cylindrical forgings) (b) Si ≥ 0.1% for service temperature ≥ 454 °C (850 °F) (c) Impact test may be required for ≤ −29 °C (−20 °F) (d) Specify the type of heat treatment on purchasing (e) Carbon contents: max. 0.30% for Gr. 1, 2 & 4, and 0.35% for Gr. 3
<Fitting> Carbon steel	**A234** Gr. WPB Gr. WPC	1/1 1/2	60/35 70/40	−29 ~ 538 Max 427 °C (800 °F) for long-term operation	*Heat treatment*: – Annealing – N-T *Hardness:* ≤197 HBW	(a) Killed (b) It is made from pipe A-106 Gr. B, plate A516 Gr. 65, 70 or forging A-181 Gr. 70, etc. (c) WPB has better weldability and lower strength, and is more popular than WPC (70/40 ksi) (d) Fittings made from forgings may have 0.35 max carbon and 0.35 max silicon with no minimum
<Forging> Carbon steel	**A727**	1/1	60–85/36	−29 ~ 343	(Cu + Ni + Cr + Mo) in heat analysis ≤1.0% (Cr + Mo) in heat analysis ≤0.32%	(a) For pressure piping components with inherent notch toughness (b) Maximum finished section thicknesses no larger than 51 mm (2 in.) (c) Killed, fine-grain practice, and also shall heat treat the forgings by normalizing, or N-T or Q-T

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (2/13)

Material/brand	ASTM no.&Gr.	P no/Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Forging> Carbon steel	**A836**	1/1	55/25	Per glass-coating limits	Ti contains min. 4 × C %, and max. 1.0%. Si ≤ 0.35%	(a) For titanium-stabilized carbon steel forgings for glass-lined piping and pressure vessel service (b) Mechanical properties are certified on the basis of test material subjected to heat treatments to simulate glass-coating operations (c) The repair-welded test plate used to qualify the procedure shall be normalized three times at 845 °C (1550 °F) prior to testing to simulate glass-coating operations
<Fitting> C-0.5Mo	**A234** WP1	3/1	55/30	−29 ~ 538 Max.465 °C (870 °F) for long-term operation due to graphitization	*Heat treatment*: – Anneal (full or isothermal) – N-T – Q-T *Hardness:* ≤197 HBW	(a) Made by pipe, killed plate, or forging (b) Added Mo to improve the high-temperature properties and to prevent graphitization because Mo is strong carbide former (c) Good resistance to hydrogen attack than CS however, it may not be used to resist HTHA in API RP941for new construction careful/periodic inspection in HTHA service is required for the existing facilities (d) For noncorrosive or mildly corrosive service (e) To be made by A335 Gr. P1 for *t* ≤ 25.4 mm (1 in.) (f) Specify "do not be made by A182-F1" recommended
<Forging> C-0.5Mo	**A182** Gr. F1 **A336** Gr. F1	3/2	70/40	−29 ~ 538 Max.465 °C (870 °F) for long-term operation due to graphitization.	*Heat treatment*: – Annealing – N-T *A182*: forged or rolled alloy and stainless steel pipe flanges, forged fittings, and valves and parts for high-temperature service *A336*: alloy steel forgings for pressure and high-temperature parts	(a) Added Mo to improve the high temperature properties and to prevent graphitization because Mo is a strong carbide former (b) Better resistance to hydrogen attack than carbon steel. But, it may not be used to resist HTHA in API RP941for new constructions. Careful/periodic inspection in HTHA service is required for the existing facilities (c) Used in noncorrosive or mildly corrosive service (d) Susceptible to cracking due to high carbon (e) Note 6
<Forging> 1Cr – 0.5Mo	**A182** F12- Cl. 1 Cl. 2*	4/1	60/30 70/40	−29 ~649 Max. 538 °C (1000 °F) for long-term operation preferable	*Heat treatment:* – Anneal – N-T See Note 6	(a) See plates/pipes for 1Cr–1/2Mo (b) A234-WP12: made by pipe A335 Gr P12, plate A 387 Gr 12, or forging A 182 Gr F12 (c) Specify the specific heat treatment (d) Alternative forging: A336-F12 (e) A182, F12-Cl.2: to be N-T (heat treated) for flange (ASME B16.5) (f) Note 6
<Fitting> 1Cr – 0.5Mo	**A234** WP12- Cl. 1 Cl. 2	4/1	60/32 70/40	−29 ~ 649 Max. 593 °C (1100 °F) for long-term	*Heat treatment:* – Anneal (full or isothermal) – N-T – Q-T	(a) See plates/pipes for 1Cr–1/2Mo (b) Hardness ≤197 HBW
<Forging> 1.25Cr – 0.5Mo	**A182** F11- Cl. 1 Cl. 2 Cl. 3	4/1	60/30 70/40 75/45	−29 ~649 Max. 593 °C (1100 °F) for long-term	*Heat treatment*: – Anneal – N-T	(a) See plates/pipes for 1.25Cr–0.5Mo (b) A234-WP11: made by pipe A335 Gr P11, plate A 387 Gr 11, or forging A 182 Gr. F11 (c) Hardness of F11, Cl.1: 121–174 HBW Hardness of F11, Cl.2: 143–207 HBW Hardness of F11, Cl.3: 156–207 HBW Hardness of WP11 ≤ 197 HBW (d) Alternative forging: A336-F11 (e) A182-F11, cl.2: To be N-T (f) Note 6 for A182
<Fitting> 1.25Cr – 0.5Mo-Si	**A234** WP11- Cl. 1 Cl. 2 Cl. 3	4/1	60/30 70/40 75/45	−29 ~ 649 Max. 593 °C (1100 °F) for long-term	*Heat treatment*: – Anneal (full or isothermal) – N-T – Q-T	

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (3/13)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging> 2.25Cr – 1Mo	**A182** F22- Cl. 1 Cl. 3	5A/1	60/30 75/45	−29 ~ 649	*Heat treatment*: – Anneal – N-T	(a) See plates/pipes for 2.25Cr-1Mo. (b) A234-WP22: made by pipe A335 Gr. P22, plate A387 Gr. 22, or forging A182 Gr. F22 (c) Hardness of F22, Cl.1 ≤ 170 HBW Hardness of F22, Cl.3: 156–207 HBW Hardness of WP22 ≤ 197 HBW (d) Specify the specific heat treatment. (e) Alternative forging: A336-F22-Cl.1 & 3 (f) Note 6 for A182
<Fitting> 2.25Cr-1Mo	**A234** WP22- Cl. 1 Cl. 2	5A/1	60/30 75/45	−29 ~ 649	*Heat treatment*: – Anneal (full or isothermal) – N-T – Q-T	
<Forging> 2.25Cr-1Mo Enhanced	**A508** 22-Cl. 3	5A/1	85/55	−29 ~ 649	*Heat treatment*: – Q-T	(a) Same as characteristics and caution to select plates/pipes, 2.25Cr–1Mo-enhanced (b) Alternative forging: A541-22-Cl.3
<Forging> 2.25Cr – 1Mo-0.25V Advanced	**A182** F22V	5C/1	85/60	−29 ~ 649	*Heat treatment*: – N-T or Q-T Note 6	(a) See plates/pipes for 2.25Cr–1Mo-advanced (b) Alternative forging: A336-Gr. F22B and A541-Gr.22V (c) Hardness of F22V: 174–237 HBW
<Forging> 3Cr-1Mo	**A182** F21	5A/1	75/45	−29 ~ 649	*Heat treatment*: – Anneal Note 6	(a) See plates/pipes for 3Cr -1Mo (b) Alternative forging: A336-Gr.F21-Cl. 3 (c) Hardness of F21: 156–207 HBW
<Forging> 3Cr-1Mo-0.25V-B advanced	**A182** F3V	5C/1	85/60	−29 ~ 649	*Heat treatment*; – Anneal Note 6	(a) See plates/pipes for 3Cr–1Mo-0.25V-B advanced (b) Alternative forging: A336-Gr.F3V, A508-Gr.3V, and A541-Gr.3V (c) Hardness of F3V: 174–237 HBW
<Forging> 3Cr-1Mo-0.25V-Cb-Ca Advanced	**A182** F3VCb	5C/1	85/60	−29 ~ 649	*Heat treatment*; – Anneal Note 6	(a) See plates/pipes for 3Cr–1Mo-0.25V-Cb-Ca advanced (b) Alternative forging: A336-Gr.F3VCb, A508-Gr.3VCb, and A541-Gr.3VCb (c) Hardness of F3VCb: 174–237 HBW
<Forging> 5Cr-0.5Mo	**A-182** F5 F5a	5B/1	70/40 90/65	−29 ~ 649	*Heat treatment*; – Anneal – N-T *Hardness* F5: 143–217 HBW F5a: 187–248 HBW Note 6	(a) See plates/pipes for 5Cr–0.5Mo (b) A234-WP22: made by pipe A335 Gr P5, plate A387 Gr 5, or forging A182 Gr F5 (c) Gr F5a: Bad weldability due to high carbon (d) Specify the specific heat treatment. (e) Alternative forging: A336-F5 (TS 60ksi/YS 36ksi) & F5A (TS 80ksi/YS 50ksi)

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (4/13)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging> Low alloy steel	**A592** Gr. A Gr. B Gr. F	 11B/1 11B/2 11B/3	*t ≤ 65 mm (2.5 in.)* 115–135/100 *t > 65 mm (2.5 in.)* 105–135/90	−29 ~ 649	*Max.t:* Gr. A: 38 mm (1.5 in.) Gr. E/F: 100 mm (2 in.) Alloy elements: Ni, Mo, V, Ti, Zr, Cu, B	(a) For high-strength Q-T low-alloy forged parts of pressure vessels (b) The impact test temperature if a test temperature lower than 0 °C (32 °F) is required (c) Fully killed & fine grain (ASTM no.5 or finer) (d) Tempering temperature ≥ 900 °C (1650 °F)
<Forging>	**A372 Gr.**					(a) Carbon and alloy steel forgings for thin-walled pressure vessels including gas bottles
	A	1/1	60–85/35	See the same P no. in plates and strips and/or forgings.	CS	(b) Provision is made for integrally forging the ends of vessel bodies made from seamless pipe or tubing
Carbon and low alloy steel	B	1/2	75–100/45		CS	(c) At the option of the manufacturer, Gr. A, B, C, and D and classes 55, 65, and 70 of Gr. E, F, G, H, and J forgings shall be normalized, normalized and tempered, liquid quenched and tempered, or normalized followed by liquid quench and temper
	C	1/4*	90–115/55		CS	(d) Gr. K, L, M, N, and P and classes 90 and 110 of Gr. J forgings shall be liquid quenched and tempered, or normalized followed by liquid quench and temper
	D	1/4*	105–130/65		CS	*The close P and Gr. Numbers when welded. Careful consideration is required for welding
	E-Cl.55	3/3*	85–110/55		1Cr-0.2Mo	
	E-Cl.65	3/3*	105–130/65		1Cr-0.2Mo	
	E-Cl.70	3/3*	120–145/70		1Cr-0.2Mo	
	F-Cl.55	3/3*	85–110/55		1Cr-0.2Mo	
	F-Cl.65	3/3*	105–130/65		1Cr-0.2Mo	
	F-Cl.70	3/3*	120–145/70		1Cr-0.2Mo	
	G-Cl.55	3/3*	85–110/55		0.5Cr-0.2Mo	
	G-Cl.65	3/3*	105–130/65		0.5Cr-0.2Mo	
	G-Cl.70	3/3*	120–145/70		0.5Cr-0.2Mo	
	H-Cl.55	3/3*	85–110/55		0.5Cr-0.2Mo	
	H-Cl.65	3/3*	105–130/65		0.5Cr-0.2Mo	
	H-Cl.70	3/3*	120–145/70		0.5Cr-0.2Mo	
	J-Cl.55	3/3*	85–110/55		1Cr-0.2Mo	
	J-Cl.65	3/3*	105–130/65		1Cr-0.2Mo	
	J-Cl.70	3/3*	120–145/70		1Cr-0.2Mo	
	K	9A/3*	110–125/80		2.5Ni-1.3Cr-0.4Mo	
	L	9A/3*	155–180/135		1.8Ni-0.8Cr-0.2Mo	
	J-Cl.90	3/3*	120–145/90		1Cr-0.2Mo	
	J-Cl.110	3/3*	135–160/110		1Cr-0.2Mo	
	M-Cl.85	9B/3*	105–130/85		3.2Ni-1.7Cr-0.5Mo	
	M-Cl.100	9B/3*	120–145/100		3.2Ni-1.7Cr-0.5Mo	
	N-Cl.100	9A/3*	115–140/100		1.8Ni-1.2Cr-0.3Mo	
	N-Cl.120	9A/3*	135–160/120		1.8Ni-1.2Cr-0.3Mo	
	N-Cl.140	9A/3*	155–180/140		1.8Ni-1.2Cr-0.3Mo	
	P-Cl.100	9A/3*	115–140/100		2.7Ni-1.3Cr-0.4Mo	
	P-Cl.120	9A/3*	135–160/120		2.7Ni-1.3Cr-0.4Mo	
	P-Cl.140	9A/3*	155–180/140		2.7Ni-1.3Cr-0.4Mo	

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (5/13)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging> Carbon and low alloy Q-T steel	**A508/ 541 Gr.** 1 & 1A 2-Cl.1 2-Cl.2 3-Cl.1 3-Cl.2 3V 3VCb 4N-Cl.1 4N-Cl.2 4N-Cl.3 5-Cl.1 5-Cl.2 6-Cl.1 6-Cl.2 6-Cl.3 6-Cl.4 22-Cl.3 22-Cl.4 22-Cl.5 22-Cl.6 22-Cl.7	 1/2 3/3 3/3 3/3 3/3 5C/1 5C/1 11A/5 11B/10 3/3 11A/1 11B/10 3/3 3/3 3/3 3/3 5C/1 5C/1 5C/1 5C/1 5C/1	 70–95/36 80–105/50 90–115/65 80–105/50 90–115/65 85–110/60 85–110/60 105–130/85 115–140/100 90–115/70 105–130/85 115–140/100 85–110/60 95–120/75 100–125/80 105–130/85 85–110/55 85–110/60 95–120/75 100–125/80 105–130/85	See the same P no. in plates and strips and/or forgings.	*t.: trace* CS 0.3Cr-0.6Mo-0.7Ni 0.3Cr-0.6Mo-0.7Ni 0.5Mo-0.7Ni-t.Cr 0.5Mo-0.7Ni-t.Cr 3Cr-1Mo-0.2V 3Cr-1Mo-0.2V-0.02Cb 3.5Ni-1.7Cr-0.5Mo 3.5Ni-1.7Cr-0.5Mo 3.5Ni-1.7Cr-0.5Mo 3.5Ni-1.7Cr-0.5Mo 3.5Ni-1.7Cr-0.5Mo 0.8Ni-0.8Cr-0.4Mo 0.8Ni-0.8Cr-0.4Mo 0.8Ni-0.8Cr-0.4Mo 0.8Ni-0.8Cr-0.4Mo 2.25Cr-1Mo-t.V 2.25Cr-1Mo-t.V 2.25Cr-1Mo-t.V 2.25Cr-1Mo-t.V 2.25Cr-1Mo-t.V	(a) A541: For pressure vessel (b) A508: For pressure vessel components, such as forgings for vessel closures, shells, flanges, tube sheets, rings, heads, and similar parts (c) CVN impact tests are required as below unless otherwise required by purchaser. See A508 & A541 Table 3 for the required minimum absorbing energy values At 21 °C for Gr.2-Cl.2, Gr.3-Cl.2, At 4 °C for Gr. 1 & 1A, Gr.2-Cl.1, and Gr.3-Cl.1, At 21 °C for Gr.2-Cl.2, Gr.3-Cl.2, At −18 °C for Gr.22-Cl.3 and Gr.3V & 3VCb, At −29 °C for Gr.4N & 5 (all classes), At −59 °C for Gr.6-Cl.1,2,3 & 4 and Gr.22-Cl.4,5,6,7 (d) Multiple forgings in A508 are those which will be separated after the quench and temper treatment (e) The tension test specimens shall be positioned so that the longitudinal axis and mid-length is in accordance with one of methods 1, 2, 3, and 4
<Forging> Low alloy steel	**A592** Gr. A Gr. B Gr. F	 11B/1 11B/2 11B/3	*t ≤ 65 mm (2.5 in.)* 115–135/100 *t > 65 mm (2.5 in.)* 105–135/90	−29 ~ 649	*Max.t:* Gr. A: 38 mm (1.5 in.) Gr. E/F: 100 mm (2 in.) Alloy elements: Ni, Mo, V, Ti, Zr, Cu, B	(a) For high-strength Q-T low-alloy forged parts of pressure vessels (b) The impact test temperature if a test temperature lower than 0 °C (32 °F) is required (c) Fully killed & fine grain (ASTM no.5 or finer) (d) Tempering temperature ≥ 900 °C (1650 °F)
<Forging> Low alloy steel	**A859** Gr. A Gr. B	 11B/1	*Gr. A. Cl.1* 65–85/55 *Gr. A. Cl.2* 75–95/65 *Gr. B* 105/110–115	−29 ~ 649	*Heat treatment* Gr. A-Cl.1: N+PH [540–665 °C] Gr. A-Cl.2: Q+PH [540–665 °C] Gr. B: Double Q+PH [540–700 °C]	(a) For age-hardening alloy steel for pressure vessel components (b) The CVN impact test temperature: Gr. A-Cl.1 & 2: −45 °C (−50 °F) Gr. B: 18 °C (0 °F) min. 110/100 J (ave./min.) Gr. B: −85 °C (−120 °F) min. 80/75 J (ave./min.) Purchaser should select the sampling method of impact test coupons, method 1 to method 4. (c) Fully killed & fine grain (d) Gr. B: double Q-T; may not be weldable (e) *Alloy elements* Gr. A: 0.75Cr, 0.85Ni, 0.2Mo, 1.15Cu Gr. B: 0.6Cr, 3.65Ni, 0.6Mo, 1.45Cu, 0.04Cb

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (6/13)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging> 9Cr-1Mo	**A182** F 9	5B/1	85/55	−29 ~ 649	*Heat treatment*; – Annealing – N-T	(a) See plates/pipes for 9Cr–1Mo (b) A234-WP9: made by pipe A335 Gr P9, forging A182 Gr. F9 (c) Specify the specific heat treatment. (d) Alternative forging: A336-F9 (TS 85ksi/YS 55ksi) (e) Hardness of F9: 179–217 HBWHardness of WP9 ≤ 217 HBW (f) Note 6 for A182
<Fitting> 9Cr-1Mo	**A234** WP9- Cl. 1 Cl. 2	5B/1	60/30 75/45	−29 ~ 649	*Hardness*: 217 HBW max. *Heat treatment*; – Anneal (full or isothermal) – N-T or Q-T	
<Forging> 9Cr-1Mo-V -Cb-N-Al	**A182** F 91	15E/1	90/60	−29 ~ 649	*Heat treatment*; – N-T – Q-T Note 6	(a) Same as characteristics and cautions to select plates/pipes, 9Cr-1Mo-V-Cb-N-Al (b) A234-WP91: made by pipe A335 Gr P91, forging A182 Gr F91 (c) Specify the specific heat treatment if needs low temperature toughness (d) Alternative forging: A336-F91 (e) Hardness of F91: 190–248 HBWHardness of WP91: 190–250 HBWHardness of WP92: 269 HBW max (f) To be normalized for supplementary requirement S1
<Fitting> 9Cr-1Mo-V -Cb-N-Al	**A234** WP91				*Heat treatment*; – N-T – Q-T	
<Forging> 9Cr-1 Mo-V-Cb-N-Al-B-W	**A182** WP911	15E/1	90/64	−29 ~ 649	*Heat treatment*; – N-T – Q-T Note 6	(a) See plates/pipes for 9Cr-1Mo-V-Cb-N-Al- B-W (b) A234-WP911: made by pipe A335 Gr P911, forging A182 Gr F911 (c) Specify the specific heat treatment if needs low temperature toughness (d) Alternative forging: A336-F911 (e) Hardness of F911: 187–248 HBWHardness of WP911 ≤ 248 HBW
<Fitting> 9Cr-1Mo-V-Cb -N-Al-B-W	**A234** WP911		90–120/64		*Heat treatment*; – N-T – Q-T	
<Forging> Carbon and low alloy steel	**A707** L1 L2 L3 L4 L5 L6 L7 L8	1/*	60/42-Cl.1 66/52-Cl.2 75/60-Cl.3 90/75-Cl.4	 −29 −46 −46 −62 −62 −62 −73 −73	[Product analysis] L1: Ni ≤ 0.43% L2: Ni ≤ 0.43% L3: Ni ≤ 0.43% L4: 1.60–2.05Ni% L5: 0.67–1.03Ni% L6: Ni ≤ 0.43% L7: 3.18–3.82Ni% L8: 2.68–3.97Ni% * See AWS B2.1.	(a) Forged carbon and alloy steel flanges for low-temperature service (b) Mostly to use petroleum and gas pipelines for low temperature (c) Hardness: 60/42-Cl.1: 149–207 HBW 66/52-Cl.2: 149–217 HBW 75/60-Cl.3: 156–235 HBW 90/75-Cl.4: 179–265 HBW (d) See Note 1 for 3.5Ni.
<Forging> Carbon and low alloy steel	**A765** Gr. I Gr. II Gr. III Gr. IV Gr.V-Cl.1 Gr.V-Cl.2	 1/1 1/2 9B/1 1/3 9A/11 9A/11	 60–85/30 70–95/36 70–95/37.5 80–105/50 60–85/30 70–95/37.5	 −29 ~ 538 −45 ~ 538 −100 ~343 −29 ~ 371 −60 ~ 343* −60 ~ 343*	Gr. I: CS Gr. II: CS Gr. III: 3 1/2Ni Gr. IV: CS Gr. V: 1.5Ni	(a) For pressure vessel components (b) Impact tested (c) They are more preferable than A350 in heavy wall (d) See note 5 (e) See Note 1 for 3.5Ni. * recommended
<Forging> 9Ni 8Ni	**A522** **Type** **I** **II**		100/75 100/75	−196 ~ 343 −170 ~ 343	Type I: 8.5–9.5Ni Type II: 7.5–8.5Ni	(a) Impact tested (b) Maximum section thickness of 3 in. [75 mm] in the double normalized and tempered condition and 5 in. [125 mm] in the Q-T condition

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (7/13)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Forging> PHSS **XM-16** 12Cr-9Ni -2Cu-1Ti	**A705** S45500		205*/ 185*	−29 ~ 343^ ^Recommended	*H1000 tempered	(a) Martensitic age-hardenable PHSS (b) Good corrosion resistance (similar to 304 SS) (c) A single-step aging treatment develops exceptionally high-yield strength with good ductility and toughness (d) Brand name: Custom 455 (e) *Up to 13 mm (0.5 in.) (f) Specify SMTS/SMYS for A693 recommended
<Forging> PHSS **XM-25** 15Cr-6Ni −0.7Mo- 1.5Cu- 1Mn	**A705** S45000		125*/ 75*	−29 ~ 343^ ^Recommended	*Hardness*: ≤311 HBW s.g.: 7.80 * H1150 tempered	(a) Martensitic age-hardenable PHSS (b) Good corrosion resistance (similar to 304 SS), YS is higher than 304 SS (c) Brand name: Custom 450 (d) *Up to 13 mm (0.5 inch) (e) Specify SMTS/SMYS for A693 recommended
<Forging> ASS	**A182**					(a) L = low carbon (good IGC resistance) (b) H = high carbon (good creep-rupture strength) (c) 304L, 316L, 321: In low temperature [≤427 °C (800 °F)] and mild acidic service (> pH 5) (d) All "H" grades; contain 0.04–0.1%C for high temperature strength, including welding materials. Also, have an average grain size of ASTM no.6 or coarser per ASTM E112. See Note 8 in Pipes & Tubes for reference (e) 304, 316 for welded parts: use low carbon ($C \leq 0.03\%$) or dual grade (304/304L or 316/316L) (f) 309S (23Cr-13Ni), 310S (25Cr-20Ni): High-temperature oxidizing resistance. Grain size to be ASTM 6 or coarse for the service at 565 °C (1050 °F) and warmer (g) 316 (2%Mo), 317 (3%Mo): More corrosive than 304 in oxidizing acid (HNO3, conc. H2SO4)/good pitting resistance in acidic environment (h) All 300 series: Susceptible to Cl-SCC and CUI (i) 347 welding material should be used for 321 welding (j) Corrosion test (IGC, SCC, etc.) may be considerable for severe corrosion service (k) Passivation treatment and segregated work (from carbon and low alloy steels) are recommended for corrosive service (l) Max. temperature for low carbon ($C \leq 0.03\%$): 427 °C (800 °F) [454 °C (850 °F) for ASS with Mo ≥ 2.5%] (m) Max. Temperature for F321/347: 538 °C (1100 °F) (n) F321H/347H: Solution heat treated at min. 1095 °C (1995 °F) for service of 538 °C (1100 °F) and warmer (o) 321/347: Stabilized annealing recommended for the service at 400 °C (750 °F) and warmer (p) min. Temperature for 304, 304 L, 316, 316 L, 347 in B31.3: −254 °C (q) A182-F310: Grain size not to be finer than ASTM 6 for the service at 565 °C (1050 °F) and warmer (r) A965: Steel forgings, austenitic, for pressure and high temperature parts (s) ** alloy 24, DIN 1.4565 (t) ^ brand name: Nitronic 50 (u) Note 6 for A182
	F310MoLN	8/1	78/37	−198 ~ 816		
	F45		87/45		F45: S30815	
	F47		75/30		F47: 317LM	
	F48		80/35		F48: 317LMN	
	F49		115/60		F49: S34565**	
	F56		73/27		F56: S33228	
	F58		109/61		F58: S31266	
	F62		95/45		F62: N08367	
	F63		80/32		F63: S32615	
	F64		90/40		F64: S30601	
	F904L		71/31			
	A965/A182				*For A182 70 → 75 65 → 70 32 → 35	
	F304	8/1	70*/30	−198 ~ 816		
	F304H		70*/30			
	F304L		65*/25			
	F304N		80/35			
	F304LN		70*/30			
	F309H		70*/30			
	F310		75/30			
	F310H		70*/30			
	F316		70*/30			
	F316H		70*/30			
	F316L		65*/25			
	F316N		80/35			
	F316LN		70*/30			
	F321		70*/30			
	F321H		70*/30			
	F347		70*/30			
	F347H		70*/30			
	F348		70*/30			
	F348H		70*/30			
	FXM-19		100/55		FXM-19^: S20910	
	FXM-11		90/50		FXM-11: S21904	
	F46		78–100/ 32*		F46: S30600	
<Fitting> ASS	**A403** 304L 316L 304H 316H 321 310	8/1	75/30	−198 ~ 816	Note 7	
<Forging> DSS	**A182** 2205 F51- S31803 F60- S32205	10H/–	90/65	-29* ~ 316 *For<−29 °C, impact test is required.	Note 6	(a) High strength and good erosion resistance (b) Good resistance to Cl-SCC and pitting [≤70 °C (158 °F)] (c) S32205 has slightly more pitting corrosion resistance and higher allowable strength than those of S31803

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (8/13)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging> SDSS	**A182** 2507 F53- S32750	10H/1	116/80	*−40 °C (−40 °F) In ASTM A923	*Hardness*: ≤310 HBW s.g.: 8.00 Note 6	(a) High strength and good erosion resistance (b) Good resistance to Cl-SCC& pitting [≤85 °C (185 °F)] (c) Corrosion test considerable per ASTM A923
<Forging>DSS 25Cr-7Ni-3.5Mo-0.7Cu-0.5W-0.25N	**A473** S32760	10H/1	109/80	−29*~316 *−40 °C (−40 °F) In ASTM A923 *for < −29 °C, impact test Is required.	*Hardness*: ≤290 HBW s.g.: 7.80 *N* = 0.24–0.32 wt% PRE ≥40 Brand: Zeron 100 Note 4 & 8	(a) Good Cl-SCC & pitting resistance [≤85 °C(185 °F)] (b) Better crevice corrosion resistance than 2507 DSS (c) Excellent corrosion resistance in nonoxidizing and mineral acids like HF acid, sulfuric acid, and hydrochloric acid. (d) Used in sour service at ≤34 HRC, Cl- ≤ 120,000 ppm, ppH_2S ≤ 0.02 MPa.a (3 psia), or at Cl- ≤ 15,000 ppm, pH in aqueous phase >5.6, and ppH_2S ≤ 0.10 MPa,a (15 psia) (e) Reference: ASTM A923, API TR938-C
<Fitting> DSS	**A815** WPS31803 WPS32205 WPS32750	10H/1	 90/65 95/65 116/80	−29* ~ 316 *−40 °C (−40 °F) In ASTM A923	*Hardness*: ≤290 HBW ≤290 HBW ≤310 HBW	(a) See above notes for A182-2205/2507 (b) The prefix WP should be changed to CR for corrosion service. To be CRS31803/CRS32205/CRS32750.
<Fitting> ASS XM-19 21Cr-12Ni-2Mo-5Mn-0.2N-0.1Nb-0.1V	**A403** S20910	8/3	100/55	−196~816	Note 7	(a) Slightly higher corrosion resistance than those of 316L or 317L SS (b) Higher strength than those of 316L or 317L SS (c) For marine hardware or downhole (d) ASTM A314 for billet, bar and forging (e) Brand name: Nitronic 50
<Forging & Fitting> SASS AL-6XN 20Cr-25Ni-6Mo-0.25Cu-0.2N	**B462** N08367	45/–	95/45	−196~427		(a) B462: Alloy pipe flanges, forged fittings, and valves and parts for corrosive high-temperature service (b) Good resistance to Cl-SCC and pitting [≤90 °C (194 °F)] (c) PRE > 40; super austenitic stainless steel
<Fitting> Alloy 904L (ASS) 20Cr-25Ni-4.3Mo-1.5Cu	**A403** WP904L* (N08904)	45/–	71/31	−196~370	s.g.: 8.05 PRE: 35 *The prefix WP should be changed to CR for corrosion service. To be CR904L. Note 7	(a) Good resistance to Cl-SCC. Copper gives a good corrosion resistance to reducing media (hot phosphoric acid, dilute H_2SO_4, etc.) (b) Offshore, seawater, chemical industry, good stability against reducing acids of medium strength like sulfuric acid, phosphoric acid and various chloric media in refinery, paper, bleach, pulp, and fertilizer industry. (c) Sandvik 2RK66
<Forging> SASS 254 SMO	**A182** F44 (S31254)	8/4	94/44	−196~399	Note 6	(a) Good resistance to Cl-SCC and pitting [≤90 °C (194 °F)] (b) PRE > 40; super austenitic stainless steel
<Forging & fitting> Alloy 20 (carpenter 20Cb3) 35Ni-35Fe-20Cr-3Cu-2Mo-Cb)	<Forging> **A182** F20 (N08020) **B462** N08020 <Fittings> **B366** WP20CB	45/–	80/35	−196~427	*Heat treatment* Stabilized anneal *IGC test* preferable for sound corrosion resistance. s.g.: 8.08 for 20Cb3 Note 3 for B366 s.g.: 8.13 for 20Mo6 Note 6 for A182	(a) Superior corrosion & stress fracture resistance in non-aerated 10–40% H_2SO_4 acid, below 60–80 °C (140–176 °F). (b) Good corrosion resistance in HF acid at atmosphere and less than 10% HCl acid (c) 20Mo6 (super stainless steel) is developed from 20Cb3 to improve the pitting and chloride SCC resistance (d) Welding: Use E-320 or ER-320 electrodes (e) PWHT: min. 538 °C (1000 °F) when severe chloride SCC environment (f) For synthetic rubber, high-octane gasoline, solvents, explosives, plastics, synthetic fibers, heavy chemicals, organic chemicals, pharmaceuticals and foodstuffs (g) 20Cb3: Cb = 8 × % C to 1.00 max. (h) B462: pipe flanges, forged fittings, valves and parts for high-temp corrosive service
<Forging & fitting> Alloy (carpenter) 20Mo6 35Ni-30Fe-24Cr-6Mo-3Cu	**B462** N08026	45/–	80/35			

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (9/13)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Forging & wrought> Alloy 925 42Ni-21Cr-3Mo-2Cu-2Ti-min. 22Fe-0.2 Al	<Forging, bar> **B637** N09925	45/–	140/110	−198~650 °C (1200 °F) Normally recommended <540 °C (1000 °F)	Solution anneal + precipitation hardening	(a) High strength, and pitting/SCC/SSC resistance (b) Oil and gas down-hole, surface gas well components, valves, hangers, landing nipples, fastener, pump shaft for high-strength and/or marine service. (c) See Code Case 2218 for ASME Sec.VIII, Div.1 (d) Tube is also available
<Forging> Alloy (Incoloy) 945 50Ni–21Cr-3Mo-3Nb-2Cu-1Ti-bal.Fe	<Forging, bar> **B637** N09945	43/–	85/35	−60 ~ 704 Preferable range (normally recommended <540 °C (1000 °F)	s.g.: 8.2 Precipitation hardened or cold worked, seamless	(a) High strength and corrosion resistance in aggressive sour wells containing high levels of H_2S and chlorides (b) For downhole and surface gas-well components including tubular products, valves, hangers, landing nipples, tool joints, packers, fasteners, pump shafting, high fatigue top tension riser components, and high-strength piping systems
<Forging & wrought> Alloy (Monel) 400 67Ni-30Cu	<Forging> **B564** N04400 <Rod, bar & wire> **B164** N04400 <Fittings> **B366** WPNC	42/–	70/25 Annealed	−198~482	*Heat treatment*; – As worked – Stress relieve – Anneal Valve components: to be annealed.	(a) The strength of B164 depends on the shape, work, and heat treatment (b) Pipes in dilute H_2SO_4, dilute HCl including salt deposit (NH4HS), organic acid, caustic service, and severe acidic solution. (c) Severe IGC is expected in H_2S-containing service, >260 °C (500 °F) (d) Not recommended in ammonia and its compound environment (due to SCC) (e) Susceptible to mercury embrittlement (f) See Note 3 for B366 (g) SAE AMS 4675 (Bars and Forgings) (h) DIN 17754 (Forgings)
<Forging, bar & wrought> Alloy (Incoloy) 800 (N08800) /800H (N08810) 32Ni-20Cr	<Forging> **B564** N08800 N08810 <Rod&bar> **B408** N08800 N08810 <Fitting> **B366** CRNIC &WPNIC (N08800) CRNIC10 & WPNIC10 (N08810)	45/–	75/30 65/25 75/30 * 65/25 ** Per base metal, e.g., ASTM B407, 514, 515, 409, 408, 564	−198~593 For N08800 −198~816 For N08810	*Heat treatment* – Anneal *Heat treatment* * Anneal ** Cold or hot worked and anneal ; Anneal	(a) Incoloy 800: more resistance chloride SCC, pitting and general corrosion than 300 series stainless steels (b) Recommended solution annealing after cold bending (c) See Note 3 for B366
<Forging> Alloy **825** 42Ni–21Cr-3Mo	**B564** N08825	45/–	85/35	−198 ~ 816 (normally recommended <540 °C(1000 °F)	s.g.: 8.14	(a) Good corrosion resistance to sulfuric, phosphoric acids, and neutral chloride media (except $MgCl_2$) (b) See alloy 825 in plates and strips
<Forging, rolled, bar & fittings> Alloy 686 57Ni-20Cr-16Mo-3.5W-Ti-N	**B462** **B564** N06686 **B366** WPIN686/ CRIN686	43/–	100/45	−196 ~ 450	s.g.: 8.73 PRE ≈ 47 See Note 3 for B366	(a) B462: Forged or rolled B564: Forging B366: Fitting (b) High CCT (critical crevice temperature) (c) For chemical processing, marine, and air pollution control (flue gas desulfurization) industries (d) See Note 15 in plates and strips (e) DIN 17750 for Forgings
<Forging> Alloy 59 55Ni-23Cr-16Mo-Al	**B462** **B564** N06059	43/–	110/51 100/45	−196 ~ 450	s.g.: 8.61 PRE ≈ 47	(a) B462: forged or rolled B564: forging (b) Excellent resistance to pitting and crevice corrosion and freedom from Cl-SCC (c) Excellent resistance to mineral acids, such as HNO_3, H_3PO_4, H_2SO_4, and HCl acids and in particular to H_2SO_4 and HCl acid mixtures

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (10/13)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
<Bar, forging> Alloy 718 52Ni-19Cr-5Nb-3Mo-1Ti-Al-Ta	**B637** N07718	43/–	185/150	−254 ~ 700		(a) SAE ASS 5662/5663/5664/5832/5914/5962 (b) Age hardened – very high strength (c) Good environmental cracking resistance (high H_2S & CO_2) at high temperatures in deep, extremely hostile, oil and gas production environments (d) For oil & gas drilling and production facilities (e) ASME Code Case 1993, 2206, 2222 (f) ISO 9723, 9724, 9725 (g) DIN 17752, 17753, 17754 (h) See Note 18 in Plates & Strips
<Forging, bar & fittings> Alloy (Inconel) 600 72Ni-15Cr-8Fe	<Forging> **B564** N06600	43/–	80/35	−198~649	*Heat treatment* ; Anneal (983–1010 °C)	(a) Good corrosion resistance in oxidizing and reducing and high-temperature service (b) Oxidation resistance up to 1100 °C (2010 °F) in atmospheric (c) Good corrosion resistance in sulfur-free gas environments (d) The strength of B166 depends on the shape, work, and heat treatment
	<rod, bar & wire> **B166** N06600		95~120/ 70~90		; Cold work (as worked)	
			85~95/ 35~45		; Hot work (as worked)	
			80/35		; Cold or hot worked and anneal	
	<Fitting> **B366** CRNCI &WPNCI (N06600)		80/35		; Anneal (983–1010 °C)	
<Forgings> Alloy (Inconel) 625 60Ni-22Cr-9Mo-3.5Cb	<Forging> **B564** N06625	43/–	Up to 4” THK* 120/60 4″ and up to 10” THK* 110/50	−198~649	* Solution annealed s.g.: 8.44	(a) Developed high-temperature strength from Inconel 600 by Mo (b) Good corrosion resistance to Cl^-SCC (c) Good high-temperature oxidation resistance (d) Does not require PWHT for SCC resistance (e) Good weldability (f) Alloy 625 in the annealed condition is subject to severe loss of impact strength at room temperature after exposure in the range of 538–760 °C (1000–1400 °F) (g) Work-hardening rate is higher than ASS cold reduction ($\geq$15%) requires soft annealing
<Forging & wrought> Alloy (Hastelloy) B-2 69Ni-28Mo-1Cr-1Co-1Mo-2Fe	<Rod> **B335** N10665 <Fittings> **B366** WPHB-2 N10665 **B462** N10665	44/–	110/51	−198~427		(a) B462: Alloy pipe flanges, forged fittings, and valves and parts for corrosive high-temperature service (b) See Note 3 for B366
<Forging &Wrought> Alloy (Hastelloy) C-276 (N10276) 57Ni-16Mo -15Cr-2.5Co-5Fe-4W	<Rod> **B574** N10276 <Fittings> **B366** CRHC276 /WPHC276 **B462** N10276	44/–	100/41	−198~676		(a) B462: alloy pipe flanges, forged fittings, and valves and parts for corrosive high-temperature service (b) See Note 3 for B366
Alloy (Hastelloy) C-4 (N06455) 61Ni-16Mo -16Cr-2Co-3Fe	<Fittings> **B366** CR HC 4/WPHC4 **B462** N06455	44/–	100/41	−198~676		(a) B462: alloy pipe flanges, forged fittings, and valves and parts for corrosive high-temperature service (b) See Note 3 for B366

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Forgings & Wrought (Fittings) (11/13)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (See notes at the end of this table and those for Plates)
Alloy (Hastelloy) C-22 (N06022) 55Ni-21Cr −13.5Mo-2.5Co-3W-3Fe	<Fittings> **B366** CRHC 22/WPHC22 **B462** N06022	44/–	100/45	−198~427		(a) B462: Alloy pipe flanges, forged fittings, and valves and parts for corrosive high-temperature service (b) See Note 3 for B366
<Forging & Fitting> Aluminum alloys	<Forging> **B247** 3003 5083 6061	21/– 25/– 23/–	[Specimen axis parallel to direction of grain flow] 14/5 (at H112) 42/22 (at H111) 38/35 (at T6)	−196~204 −196~66 −196~204		(a) For cold boxes in gas plants and cryogenic service (b) Use at the lower temperature is available when the impact test is passed (c) See Sect. 2.1.7.3 for more details (d) See ALPEMA and Table 2.82 (max. design temperature per part and material) in this book for brazed aluminum plate-fin heat exchangers
<Forging & wrought> Titanium alloys	<Forging> **B381**, Gr F-1(R50250) F-2(R50400) F-3(R50550) F-4(R50700) F-5(R56400) F-6(R54520) F-7(R52400) F-9(R56320) F-11(R52250) F-12(R53400)	51/– 51/– 52/– 51/– 51/– 51/– 51/– 51/– 51/– 52/–	35/25 50/40 65/55 80/70 130/120 120/115 50/40 90/70 35/25 70/50	−59~36	s.g.: 4.40–4.51 Gr.F-9 and over: consult metallurgical engineer Gr.1–4: Unalloyed Gr.5: 6%Al, 4%V Gr.6: 5%Al, 2.5%V Gr.7: 0.12–0.25%V Gr.9: 3%Al, 2.5%V Gr.11: 0.12–0.25%Pd Gr.12: 0.3%Mo,0.8%Ni	(a) Remarkable corrosion resistance in oxidizing acid (HNO_3 except red fuming nitric) by virtue of a passive oxide film. Good corrosion resistance in seawater, wet chlorine, organic chlorides, but it is not immune and can be susceptible to pitting and crevice attack at elevated temperatures. Example, not immune to seawater corrosion if the temperature is greater than about 110 °C (230 °F) (b) Titanium can absorb hydrogen from environments containing hydrogen gas. At temperatures below 80 °C (176 °F) hydrogen pickup occurs so slowly that it has no practical significance, except in cases where severe tensile stresses are present. In the presence of pure hydrogen gas under anhydrous conditions, severe hydriding can be expected at elevated temperatures and pressures. Titanium is not recommended for use in pure hydrogen because of the possibility of hydriding should the oxide film be broken (c) Not recommended in aeration condition at 250 °C (482 °F) and over (d) See Sect. 2.1.7.4 for more details
	<Fittings> **B363** WP T1 (R50250) WP T2 (R50400) WP T3 (R50550) WP T7 (R52400) WP T9 (R56320) WP T11 (R52250) WP T12 (R53400)	51/– 51/– 52/– 51/– 51/– 51/– 52/–	Depends on the original materials in B363, Table 1	−59~316	s.g.: 4.40–4.51 Gr.WP-9 and over grades: consult metallurgical engineer Gr.1–4: Unalloyed Gr.7: 0.12–0.25%V Gr.9: 3%Al, 2.5%V Gr.11: 0.12–0.25%Pd Gr.12: 0.3%Mo,0.8%Ni	
Zirconium alloys	<Forging> **B493** R60702 R60704 R60705	61 - 62	55/30 60/35 70/55	−59~371* *Max. 316 °C (600 °F) is normally applied due to deterioration	s.g.: 6.48	(a) See the notes of zirconium alloys in Plates & Strips and Pipes & Tubes
Tantalum alloys	<Rod & wire> **B365** R05200 R05400 R05255 R05252 R05240		25/15 25/15 70/55 40/28 35/15	−196~204 −196~204 −196 ~ 66 −196 ~ 66 −196~204	*s.g.* R05200: 16.6 R05400: 16.6 R05255: 16.9 R05252: 16.7 R05240: 13.6	(a) Refractory metal – a high melting point (b) Good ductile, easily fabricated (c) Highly resistant to corrosion by acids, high resistance to localized (pitting, SCC and crevice), very good corrosion resistance in most organic acids, and exceptional corrosion resistance in mineral acids, good corrosion resistance in strong alkalis (d) High heat transfer efficiency & electricity (e) Very low thermal expansion (f) Characteristics of several types See 2.6.2.1 general notes and notes for plates (g) See Sect. 2.1.7.6 for more details

General Notes for Forgings & Wrought

a. Temperature Limits

(1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards

(2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. The impact test exemption temperature shall comply with the applicable codes/standards. Use the governing thickness for application of the impact test. See Appendix A

Forgings & Wrought (Fittings) (12/13)

(3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, low temperature toughness, etc.), and corrosion environment

b. Typical production process of ferrous steel forgings – Fig. 2.202

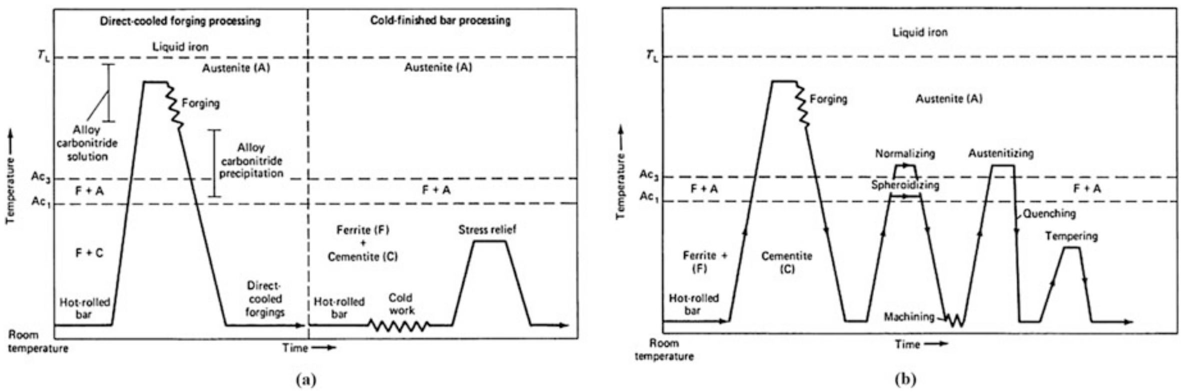


Figure 2.202 Typical production process of ferrous steel forgings. (**a**) For direct-cooled steel forgings. (**b**) For Q-T steel forgings. (Source: ASM Metal H/B. Vol.1)

c. Sizing limits of ASME standards
– ASME B16.5 : NPS ½ through NPS 24
– ASME B16.47: NPS 26 through NPS 60

d. Ferritic steel flanges conforming to ASME B16.5 and B16.47 and standard LWN are exempt from impact testing at temperatures not colder than −29 °C (−20 °F). Thick nozzle necks used for integral reinforcement must be evaluated in accordance with ASME Sec. VIII, Div.1, UCS-66 and Figure UCS-66.3, or ASME Sec. VIII, Div.2, Fig. 3.9 to 3.11 and Sect. 1.1.12 in this book indicate the applicable guideline for the governing thickness at a vessel shell attachment

e. When determining impact testing exemption or requirements, the governing thickness for welded nozzle type forgings is at the weld ends where butt welds are made. The governing thickness for flat heads or tube sheets is the larger of the flat component thickness divided by 4 or the thickness of the pressure part attachment at the welded joint. Refer to ASME Sec. VIII, Div. 1, UCS-66(a) and Figure UCS-66.3 and ASME Sec. VIII, Div. 2, Para. 3.11 through 3.19.

f. Typical grades of nickel alloy of stainless steel fittings
WPxxx: for ASME pressure fittings (wrought pipe)
CRxxx: for corrosion resistance

g. Forgings should be forged as close as practicable to finished shape and size to develop metal flow in a direction most favorable for resisting the stresses encountered in service. The strength and toughness properties of forgings can be highly directional and are dependent upon the direction of metal flow. The metal flow in forgings that are forged close to the finished shape of the component follows the surface contour, and are usually favorably oriented for the stresses encountered in service. However, some forging vendors do not always forge components close to the finished shape, as implied by the traditional definition of forging. They simply produce a forged billet and then machine the billet to the finished shape, which may not have metal flow that follows the surface contours. This requirement may be waived if the forging vendor can demonstrate by appropriate tensile and CVN impact tests that machined forgings do not have undesirable directionality. This requirement for heavy wall forgings is strongly recommended

h. When austenitic steels/alloys are to be used in services where they will be subject to stress corrosion, they should be supplied in the solution-heat-treated condition. The purchaser should indicate the additional requirements for thermally stabilized heat treatment for stabilized stainless steel/alloy when they are exposed to polythionic acid SCC environment. See Sect. 2.1.6.8 for more details

i. P.No.1 materials are not recommended above 427 °C (800 °F) for continuous operation because of graphitization after several hundred hours. See Sect. 2.3.1 for more details

j. See Table 2.68 for more details on the properties and development history of Ni-based alloys

k. Fitting Classes for WP Grades (See right table. – Table 2.194

l. If temper embrittlement in high temperature and hydrogen service is concerned for heavy wall forging of 1.25 to 3Cr steels, an application of ASTM A788, S24 is recommended

m. Roughness (Ra per ASME B46.1) Requirements for the Flange Faces seated by Gasket (ASME B16 series, API 660, etc.) – See Table 3.41 in this book

n. Several case studies for premature failure (crack) of RTJ (ring type joint) flanges of equipment and piping have been reported while there are no remarkable failure reports for RF (raised face) flanges used at similar pressures in high-pressure hydrocarbon processing. So, the API technical committees recommend RF (raised face)-type flange instead of RTJ flange in high-pressure environments if the design calculation is acceptable. The strong recommendation of RF-type flange instead of RTJ type will be specified in some API standards for high-pressure equipment and piping in the future

Table 2.194 Fitting Classes for WP Grades

Class	Construction	NDE
S	Seamless	None
W	Welded	RT or UT
WX	Welded	RT
WU	Welded	UT

Source: ASTM/ASME

o. See ASME B31.1, Table 112-1 for Piping Flange Bolting, Facing, and Gasket Requirements in Power Piping

Notes for Forgings & Wrought

1. 3.5% Ni forging materials have an intermittent history of having welding problems. If available fabricators do not have successful experience with this material, austenitic stainless steel is a better choice. For design or normal operating MDMTs or DMTs colder than −48 °C (−55 °F), consult with a responsible metallurgist
2. ASTM A350
   a) Impact test requirements (for Standard Size [10 by 10 mm] Specimens); See ASTM A350 for the requirements of sub-size specimen (Tables 2.195 and 2.196)

Table 2.195 CVN impact test requirements

Grade	Minimum impact Energy required for average of each set of three specimens, J [ft·lbf]	Minimum impact Energy permitted for one specimen only of a set J [ft·lbf]
LF1 & LF9	18 [13]	14 [10]
LF2-Cl.1 & LF3-Cl.1	20 [15]	16 [12]
LF5- Cl. 1 & 2	20 [15]	16 [12]
LF787, Cl. 2 & 3	20 [15]	16 [12]
LF6, Cl. 1	20 [15]	16 [12]
LF2-Cl.2 & LF3-Cl.2	27 [20]	20 [15]
LF6, Cl. 2 & 3	27 [20]	20 [15]

Table 2.196 Standard impact test temperature

Grade	Test temperature, °C [°F]	
	Standard	Supplementary[(2)]
LF1	−29 [−20]	−23 [−10]
LF2, Cl.1	−46 [−50][(1)]	−37 [−35]
LF2, Cl.2	−18 [0]	−12 [+10]
LF3, Cl.1 & 2	−101 [−150]	−87 [−125]
LF5, Cl.1 & 2	−59 [−75]	−51 [−60]
LF6, Cl.1 & 2	−51 [−60]	−40 [−40]
LF6, Cl.3	−18 [0]	−12 [+10]
LF9	−73 [−100]	−62 [−80]
LF787, Cl.2	−59 [−75]	−51 [−60]
LF787, Cl.3	−73 [−100]	−62 [−80]

Notes

(1) Currently MTI technical committee for impact test requirement of LTCS suggested to ASTM committees to change −46 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME requirements.

(2) Only applicable when the purchase requires. All test results including the test temperature shall be specified in the (C)MTR. In the case of −37 °F test of LF2, Cl.1, the material surface shall be marked as "LF2S 037." S = supplementary, 0 = negative, 37 = 37 °F.

b) When it is required to use impact-tested carbon or low-alloy steel forgings for tubesheets and flat covers, the appropriate specification that should be used is ASTM A-765

c) LF3: 3.5Ni steel requires a strong precaution related to weldability

3. ASTM B366
   a) Class WP (Wrought Pipe) Fittings are made by ASME B16.9, B16.11 and B16.28 per the standard
   b) Class CR (Corrosion Resistance) Fittings are made by MSS SP-43, MSS SP-95, or MSS SP-97, and do not require NDE
   c) Marking for purchasing: WP***S, WP***W, WP***WX as a suffix of WP
      S: Seamless (ASME B16.9, B16.11, B16.28)
      W: Welded (ASME B16.9, B16.28), welding and proofing test by manufacturer
      WX: Welded (ASME B16.9, B16.28), welding and proofing test are not limited only by manufacturer
      WU: Welded, Ultrasonic test
   d) The strengths depend on the properties of Raw Materials – Pipe or Tube/Plate Sheet, or Strip/Bar Forging and Forging. See B366, Table 1
4. ASTM A105 & A266: When the thickness is 38 mm (1.5 in.) and above, the impact test of these metals at −29 °C (−20 °F) and below may not be readily passed. LTCS (low temperature CS, e.g., ASTM A350-LF2-Cl.1, A333-6, or A420-WPL6) may be a better choice in this case if the supplier does not have successful experience
5. ASTM A765 CVN impact test requirements – Table 2.197

Table 2.197 CVN impact test requirements

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5 (Cl.1 & 2)
Minimum average value of a set of 3 specimens, J (ft-lbf)	18 [13]	20 [15]	20 [15]	35 [26][A]	20 [15]
Minimum value of one specimen, J (ft-lbf)	14 [10]	16 [12]	16 [20]	27 [20][A]	15 [12]
Test temperature [B] of, °C [°F]	−30 [−20]	−45 [−50] [C]	−101 [−150]	−30 [−20]	−60 [−75]

Notes

[A] Mandatory conformance to the values listed is a matter of agreement between the purchaser and the manufacturer. The energy values above are shown for information as to guarantees that are generally available.

[B] Actual test temperature should be established at time of order. If no temperature is specified, tests will be made at test temperatures shown in this table.

[C] Currently MTI technical committee for impact test requirement of LTCS suggested to ASTM committees to change −45 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME requirements.

6. ASTM A182: Flanges of any type, elbows, return bends, tees, and header tees shall not be machined directly from bar stock.
7. ASTM A403: Fitting Classes for WP Grades
   "S": Seamless without NDE, "W": Welded + RT or UT, "WX": Welded + RT, "WU": Welded + UT

2.6.2.5 Castings – See General Notes

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Castings (1/9)

Material/ brand	ASTM no.&Gr.	P no/Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Gray cast iron	**A126** A B C		 21/– 31/– 41/–	−29* ~ 204		(a) For cast valves and fittings (most economic) (b) Brittle (c) Recommended for low pressure/non-process parts (d) * For <0 °C, impact test is recommended
	A48 Multi classes		20–400/–			(e) A48: Castings are classified on the basis of the TS of the iron in separately cast test bars
Gray cast iron	**A278** No. 20 No. 25 No. 30 No. 35		 22/– 25/– 30/– 35/–	−29* ~ 204		(a) For cast valves and fittings (b) Brittle (c) For pressure-containing parts (d) No. 40/45/50/55/60: Stress relieved at 566–649 °C (1050–1200 °F) Use at >230 °C is preferable (e) Class of no. 150/175/200/225/250/275/ 300/325/350/380/415 may be used as SI unit (f) * For <0 °C, impact test is recommended
	No. 40 No. 45 No. 50 No. 55 No. 60		40/– 45/– 50/– 55/– 60/–	−29* ~ 343	Max. CE = % C + 0.3(%Si + % *P*) = 3.8%, $P \leq 0.25\%$, $S \leq 0.12\%$ For 232 °C and over	
Ductile iron cast	**A395** 60-42-18 65-45-15		 60/40 65/45	−29 ~ 343	Hardness & Elongation (%): 143~187 HBW/≥18 156~201 HBW/≥15	(a) For ferritic ductile iron pressure-retaining casings at elevated temperatures (b) For valves, flange, pipe fittings, pumps, other piping components (c) See API 619 for impact test (min.14/11 J) of rotary-type positive displacement compressors
	A536 60-42-10 70-50-05 80-60-03		 60/42 70/50 80/60	−29 ~ 343	Elongation: ≥10% ≥5% ≥3%	(a) Full spheroidal shape graphite (b) There are several other grades in A536. (c) See API 619 for impact test (min.14/11 J) of rotary-type positive displacement compressors
Dual (white & gray) cast iron	**A667** **A748** **A942**		N/S N/S *	−29** ~ 232	* TS for A942 Class 20: ≥ 20 ksi Class 25: ≥ 25 ksi Class 30: ≥ 30 ksi Class 35: ≥ 35 ksi ** For <0 °C, impact test is recommended.	(a) A667: for centrifugally cast dual metal cylinders. The white iron portion of the cylinder shall be made to a minimum hardness of 55 Scleroscope "C". The gray iron portion of the cylinder shall conform to Specification A278/A278M, Class 20 or Class 150 (b) A748: for statically cast chilled dual metal rolls for pressure vessel use (c) A942: for centrifugally cast dual metal abrasion-resistant roll shells. Hardness is as below: Type I — 450–500 HB Type II — 500–550 HB Type III — 550–600 HB Type IV — 600–650 HB
White cast iron	**A532** I-A I-B I-C I-D II-A II-B II-C II-D			−29* ~ 204 * For <0 °C, impact test is recommended.	*Designation* I-A: 4Ni-2.5Cr-Hc I-B: Ni-Cr-Lc I-C: Ni-Cr-GB I-D: Ni-HiCr II-A: 12%Cr II-B: 15%Cr-Mo II-C: 20%Cr-Mo II-D: 25%Cr	(a) For abrasion resistance (b) Min. hardness as cast I-A: 550 HB I-B: 550 HB I-C: 550 HB I-D: 500 HB II-A: 550 HB II-B: 450 HB II-C: 450 HB II-D: 450 HB
High Si Cast iron	**A518** Gr.1 Gr.2 Gr.3		Mechanical properties: only per the transverse bend test and hydrotest (at ≥40 psig)	−29*~ 900**	Gr.1: 0.65–1.10%C Cr ≤ 0.50% Gr.2: 0.75–1.15%C 3.25–5.0%Cr Gr.3: 0.70–1.10%C 3.25–5.0%Cr * For <0 °C, impact test is recommended. ** Normally applied at the boiling point of the service.	(a) 14.5%Si for all grades (b) For corrosion resistance in acidic environment; e.g., exploitation, centrifugal pumps, equipment (blades, mixer and other), reaction apparatus, compressors in sulphuric acid service Gr.2: particularly suited for application in strong chloride environments Gr.3: recommended for impressed current anodes (c) See ASTM A861 for pipe fittings-high Si cast (d) Reference: BS 1591

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Castings (2/9)

Material/brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Malleable cast iron	**A47** Gr. 32510 (Gr. 22010) ^ **A220**		50/32.5	−29*~ 400	* For <0 °C, impact test is recommended. ^ : for metric	(a) Ferritic malleable iron (b) Gr. *32,5*10: 32.5 ksi for SMYS *10%* for min. elongation in 2 in. Gr. *220*10: 220 MPa for SMYS *10%* for min. elongation in 50 mm (c) Hardness: max. 156 HB
Malleable cast iron	**A220** 40010(280M10)^ 45008(310M8)^ 45006(310M6)^ 50005(340M5)^ 60004(410M4)^ 70003(480M3)^ 80002(550M2)^ 90001(620M1)^		 60/40 65/45 65/45 70/50 80/60 85/70 95/80 105/90	−29*~ 400**	* For <0 °C, impact test is recommended. ** For continuous service at temperatures up to 650 °C design factors should be incorporated to compensate for possible property changes	(a) Pearlite malleable Iron (b) ^: for metric (c) Typical designation Gr. *400*10: 40.0 ksi for SMYS *10%* for min. elongation in 2 in. Gr. *280*M10: 280 MPa for SMYS *10%* for min. elongation in 50 mm
Cast steel	**A148** 80–40 (D50400)		80/40	−29*~ 343		(a) High-strength structure (b) There are several other grades (low-alloy steel and MSS) in A148 (c) *Impact-tested at −40 °C for Grade 165–150L, 210–190L, and 260–210L (d) All castings are heat treated either by full annealing, normalizing, normalizing and tempering, or quenching and tempering
Cast steel	**A216** WCA (J02502)	1/1	60/30		Elongation ≥24%	(a) For fusion welding and high temperature (b) This material is not recommended above 427 °C (800 °F) because of the graphitization after several hundred hours (c) Castings are furnished in the annealed, or normalized, or normalized and tempered condition
	WCB (J03002)	1/2	70/36	−29 ~ 538	≥22%	
	WCC (J02503)	1/2	70/40		≥22%	
0.35Cr-0.5Ni-0.5Cu-0.5Mo	**A217** WC 1	3/1	65/35	−29 ~ 538		(a) For pressure-containing parts in high temperature (b) Total Elements of Cu, Ni, Cr-W: <1.0%
1Cr-0.5Mo	**A356**-6	4/1	70/45	−29 ~ 538		(a) For pressure containing parts in high temperature (b) Same as characteristics and limitations of plates/pipes, Cr-Mo steels (c) A217: to be N-T (heat treated) T: min. 595 °C (1100 °F) for WC6 min. 675 °C (1250 °F) for WC9, C5, and C12
0.25Cr-0.5Mo	**A217** WC 6	4/1	70/40	−29 ~ 565		
2.25Cr-1Mo	**A217** WC 9	5A/1	70/40	−29 ~ 565		
5Cr-0.5Mo	**A217**-C5	5B/1	90/60	−29 ~ 649		
9Cr-1Mo	**A217**-C12	5B/1	90/60	−29 ~ 649		
9Cr-1Mo-V	**A217**-C12A	15E/1	85/60	−29 ~ 649		(a) For pressure-containing parts in high temperature (b) ASME B31.1: The hardness of the cast material after the final heat treatment (including PWHT) shall be 185–248 BHN or HRB 90 to HRC 25. Hardness testing shall be in accordance with supplementary requirement S13 of ASTM A217
Low temp	**A352**				*S23 Ceq.* LCA: Ceq. ≤ 0.5 LCB: Ceq. ≤ 0.5 LCC: Ceq. ≤ 0.55 * See UNS J91540, ASTM A743 (CA6NM), A487 (CA6NM), A757 (E3N) as well.	(a) Good low-temperature toughness (b) Good weldability (c) For low-temperature and cryogenic service (d) LC9: Q-T (heat treated) (e) CA6NM: heat treatment, min. 1010 °C (1850 °F), air cool [to 95 °C (203 °F)], final temper at 565–620 °C (1050–1150 °F), high strength, erosion resistance, *C* = corrosion resistance, *A* = 13Cr, 6 = 0.06%C, *N*=Ni (3.5–4.5%), *M* = Mo(0.4–1.0%) (f) Others: to be N-T or Q-T (heat treated) (g) See Tables 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.23, and 4.24 for preheat temperature requirements ** Currently MTI technical committee for impact test requirement of LTCS suggested to ASTM committees to change −46 °C [−50 °F] to −48 °C (−55 °F) which is to be consistent with ASME requirements
1/2Ni	LCA	1/1	60/30	−32 ~ 343		
1/2Ni	LCB	1/1	65/35	−46** ~ 343		
1/2Ni	LCC	1/2	70/40	−46** ~ 343		
0.55Mo	LC1	3/1	65/35	−59 ~ 343		
2 1/2Ni	LC2	9A/1	70/40	−73 ~ 343		
3 1/2Ni	LC3	9B/1	70/40	−101 ~ 343		
4 1/2Ni	LC4	9C/1	70/40	−115 ~ 343		
4Ni-12.5Cr	CA6NM*	6/4	110/80	−73 ~ 343		
9Ni	LC9	9B/1	85/75	−196 ~ 121		

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C — Castings (3/9)

Material/ brand	ASTM no. &Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
MSS 410	**A217/A743** CA15	6/3	90/65	−29 ~ 649 Max. 400 °C (750 °F) for long-term operation.		(a) A217: For pressure-containing parts in high temperature (b) A743: For general application (c) Casting surface cleaning (mechanical, physical) required (d) Min. preheating, 205 °C (400 °F) for welding (d) Valve trim: used at ≤400 °C (750 °F) (e) See above note for A217 (f) To be N-T (heat treated). T: min. 595 °C (1100 °F) (g) Use CA6NM (12.5Cr-4Ni: UNS J91540) for Erosion resistance
MSS 12Cr-4Ni	**A487/A743** CA6NM Cl.A Cl.B	6/4	110/80* 100/75	−73 ~ 343	Hardness: ≤23 HRC (255 HB) for Cl.B	(a) A487: For pressure parts (b) A743: For general application (c) * only for A743 (no classes) (d) UNS No. J91540 (e) High strength and erosion resistance (f) There are several other grades in A487 (g) Min. preheat temperature of 50 °C for welding
ASS 304 SS (J92600)	**A351** CF8(8A*)	8/–	70/30 (77/35)	−254 ~ 816*	Max. 316 °C (600 °F) is normally applied for valve trim materials due to high thermal expansion efficient. *Description of classes* CF *3M*; 3 = ≤0.03%C 8 = ≤0.08%C M = Molybdenum containing (316/317) CK *20*; 20 = ≤0.20%C	(a) A351 is for pressure containing parts (b) A743: For general application (c) A744 is for severe corrosion service (d) Solution heat treatment except thermally stabilizing heat treatment for 347 SS may be applied after (major repair) welding for high-temperature application (e) CF3A, CF3MA, CF8A: for service at ≤427 °C (800 °F) (f) CD4MCu (A743): for service at ≤316 °C (600 °F) (g) CF8 & CF8 M: When it is used at ≥538 °C (1000 °F), the solution heat treatment of casting material shall be quenched from 1038 °C (1900 °F) (h) CF8C should be stabilized at 870–900 °C (1600–1650 °F) for ≥1 h/in. (1 h/25 mm) and rapid cooling when purchaser requires the stabilization heat treatment. The grade designation symbol shall be followed by the symbol "S33" (i) For cryogenic services as well as high-temperature services *CF8A: used up to 427 °C (800 °F) due to thermal instability
	A743/744 CF8		70/30			
304L SS (J92500)	**A351** CF3(3A)		70/30 (77/35)	−254 ~ 454 Max.427 °C (800 °F) preferable.		
	A743/744 CF3		70/30			
316 SS (J92900)	**A351** CF8M		70/30	−254 ~ 816		
	A743/744 CF8M					
316L SS (J92800)	**A351** F3M		70/30	−254 ~ 454		
	A743/744 CF3M					
317 SS (J93000)	**A743** CG8M		75/35	−254 ~ 816		
317L SS (J92999)	**A743** CG3M		75/35	−254 ~ 454		
347 SS (J92710)	**A351** CF8C		70/30	−198 ~ 816		
	A743/744 CF8C					
310 SS (J94202)	**A351** CK20		65/28	−198 ~ 816		
PHSS 174 (J92180) 17Cr-4Ni-3Cu	**A747** CB7Cu-1		125/97 At H1150	−29 ~ 93		(a) PH (precipitation hardening) heat treatments have several different classes (e.g., H900, H925, H1025, H1075, H1100, H1150, H1150M, H1150 DBL) which have different YS, TS, hardness, and elongation. The number, xxxx (e.g., 1150), is the solution heat treatment temperature, °C (b) Use at lower temperature is available when the impact test is passed
15-5 (J92110) 15Cr-5Ni-3Cu	**A747** CB7Cu-2		125/97 At H1150	−29~93		

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Castings (4/9)

Material/brand	ASTM no. &Gr.	P no/ Gr no	SMTS/SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Duriron Corrosion resistant high-silicon iron 14.5 Si -4Cr	**A518** Gr.1 Gr.2 Gr.3	–	Transverse bend test: on supports 12″ apart: ● Load at center, min. 930 lbf ● Deflection at center, min. 0.026″ ● Hydrotest: min. 40psig	Per Service	[common] Max.1.5%Mn Max. 0.5%Cu, 14.20–14.75%Si Bal. Fe *Gr.1*: 0.65–1.10%C Max. 0.5%Cr Max. 0.5%Mo *Gr.2*: 0.75–1.15%C 3.25–5.0%Cr, 0.4-0-6%Mo *Gr.3*: 0.7–1.10%C,3.25-5.0%Cr, max. 0.2%Mo	(a) Hard machinability due to the high hardness, HRC 52 (b) Good corrosion resistance in all conc. H_2SO_4, HNO_3, and CH_3COOH (acetic acid). (c) Good corrosion resistance in HCl acid (d) Bad alkali corrosion resistance (e) Gr.2; mainly for strong chloride environments Gr.3: Mainly for impressed current anodes
DSS CD3MN 22Cr-5Ni-3Mo-Cu-N	**A890/A99**5 4A (J92205)	10H/1	90/60	−29 ~ 315	2205 DSS	(a) A890 for general application A995 for pressure containing part (b) Some users apply U factor [(>25) = 4.76Si + 2.65Cr + 3.44Mo–43.64; element = wt %] to obtain good castability (c) Heat treatment *1B*: Heat to 1040 °C (1900 °F) minimum, hold for sufficient time to heat casting uniformly, quench in water or rapid cool by other means *4A*: Heat to 1120 °C (2050 °F) minimum for sufficient time to heat casting uniformly to temperature and water quench, or the casting may be furnace-cooled to 1010 °C (1850 °F) minimum, hold for 15 min. minimum and then water quench. A rapid cool by other means may be employed in lieu of water quench *5A*: Heat to 1120 °C (2050 °F) minimum, hold for sufficient time to heat casting, furnace cool to 1045 °C (1910 °F) minimum, quench in water or rapid cool by other means *6A*: Heat to 1100 °C (2010 °F) minimum, hold for sufficient time to heat casting uniformly, quench in water or cool rapidly by other means (d) Brand material for *6A*: Zeron® 100 (e) J92205: U-factor = 2.65Cr + 3.44Mo + 4.76Si–43.64 > 25.0 because of min. 21%Cr and min. 2.5%Mo of Gr. 4A. [element: wt%]
DSS CE3MN 25Cr-7Ni-5Mo-N	**A890/A99**5 5A (J93404*)	10H/1	100/75	−29 ~ 315	2507 DSS	
DSS CD4MCuN 25Cr-5Ni-2Mo-3Cu-N	**A890/A995** 1B (J93372)	10H/1	100/70	−29 ~ 315	Modified 2205 DSS	
DSS CD3MWCuN 25Cr-7Ni-3.25Mo-0.25N	**A890/A995** 6A (J93380)	10H/1	100/65	−29*~316 *−40 °C (−40 °F) In ASTM A923	N = 0.24–0.3 wt% PRE ≥40	

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C — Castings (5/9)

Material/brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/ recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Ni-resist (F41000 ~F41007)	Austenitic gray iron **A436**				<BHN>	(a) Carbon content, 2.2–3.0% per order (b) Plane- or spheroidal-type graphites (c) Very good oxidation resistance at 700–800 °C (1290–1470 °F) – more than 10 times of grey cast iron) (d) Even though less general corrosion resistance than that of ASS, the pitting and crevice corrosion resistance is better than that of ASS in seawater (e) Graphite corrosion scarcely appears because of a small distant potential between austenitic structure and graphite structure (f) Ni-resist: Austenitic ductile iron castings for pressure containing parts suitable for low-temperature service (g) A439: Good elongation (h) A571: For service at −253 °C (−423 °F) or warmer (i) A439-grades: See Note 1 (j) A571: Pressure-containing parts suitable for low-temperature service (k) See Note 2 for several American standards (l) See NiDI Publication #11018 for more detail (m) DI = ductile iron (n) * See A571 for Cl.3 & 4. Use of Cl.3 & 4 is greatly limited
15Ni-6.5Cu-2Cr (3Cr)	Type 1(1b)		25(30)/–		131 ~ 183 (149 ~ 212)	
20Ni-2Cr(4.5Cr)	Type 2(2b)		25(30)/–	−29 ~ 816	118 ~ 174 (171 ~ 248)	
30Ni-3Cr	Type 3		25/–		118 ~ 159	
30Ni-5.5Si-5Cr	Type 4		25/–		149 ~ 212	
35Ni	Type 5		20/–		99 ~ 124	
20Ni-4.5Cu-1Cr	Type 6		25/–		124 ~ 174	
Ni-resist (F43000 ~F43007)	Austenitic DI cast **A439**				<BHN>	
20Ni-2Cr (3Cr)	D-2(2B)		58/30		139~202 (148~211)	
22Ni-2Mn-2Si	D-2C		58/28	−196 ~ 343	121 ~ 171	
30Ni-3Cr (1Cr)	D-3(3A)		55/30		139~202 (131~193)	
30Ni-5Cr-5Si	D-4		60/–		202 ~ 273	
35Ni-2Si-(2Cr)	D-5(5B)		55/30		131~185 (139~193)	
35Ni-5Si-2Cr	D-5S		65/30		139~193	
Ni-resist (F43010) Type D-2M 22Ni-4Mn-2Si	Austenitic DI cast **A571** * CL.1		65/30	−253~343	<BHN> 121–171	
	CL.2		60/25		111~171	
Alloy 20 29Ni-20Cr-2.5Mo-3.5Cu	**A351** **A743/744** CN7M	45/–	62/25	−46 ~ 149		(a) For pump in sulfuric acid (b) Good practical immunity to chloride SCC (c) Due to copper, susceptible to hot tearing during casting and weld cracking during repair Alternative material: CN-3Mn (AL-6XN), CK-3MCuN (254SMO) (d) A351 for pressure parts/A743 for general application, A744 for severe service
Alloy 254SMO (J93254) 20Cr-18Ni-6Mo-0.7Cu-0.2N	**A351** **A743/744** CK3MCuN	8/4	80/38	−196/399	s.g.: 8.00	(a) Strong Cl-SCC and pitting resistance [≤90 °C (194 °F)] (b) Super ASS (PRE > 40)
Abrasion resistant Cast iron	**A532** I-A I-B I-C I-D II-A II-B II-D III-A				Hardness-sand ≥550 HB ≥550 HB ≥550 HB ≥500 HB ≥550 HB ≥450 HB ≥450 HB ≥450 HB	(a) For abrasion-resistant cast iron (b) See Note 4 below for more details on compositions and requirements

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Castings (6/9)

Material/ brand	ASTM no. &Gr.	P no/Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Double pour, centrifugal cast, abrasion resistant roll shells	**A942** Type I Type 2 Type 3 Type 4		 20 25 30 35		Hardness (HB) 450–500 500–550 550–600 600–650	(a) For centrifugally cast white iron/gray iron dual metal abrasion-resistant roll shells (b) The outer layer is white iron and the inner layer is gray iron. There shall be no gradient of mottled iron between the white iron and the gray iron
Alloy 825 41Ni-21Cr-3Mo	**A494** CU5MCuC (N08826)	45/–	75/35	−198 ~ 538		More resistance for chloride SCC than 800/800H See alloy 825 in plates and strips
Alloy 59 55Ni-21Cr-13Mo-3W-3Fe	**A494** CX2MW (N06059)	43/–	80/45	−196 ~ 450	s.g.: 8.61 PRE ≈ 47	(a) A494: nickel alloy casting (b) Excellent resistance to pitting and crevice corrosion and freedom from Cl-SCC (c) Excellent resistance to mineral acids, such as HNO_3, H_3PO_4, H_2SO_4, and HCl acids and in particular to H_2SO_4 and HCl acid mixtures
Inconel 600 15Cr-<3Si-<11Fe-bal..Ni	**A494** CY40 CL.1/2	43/–	70/28	−198 ~ 649	CL1: As cast CL2: Quenched at ≥1040 °C.	(a) Resistance in high-temp. corrosion/oxidation and reducing environments
Inconel 625 21Cr-9Mo-4Cb-<5Fe-bal..Ni	**A494** CW6MC	43/–	70/40	−198 ~ 649		(a) High strength and erosion resistance (b) Resistance in high-temp. corrosion/oxidation and reducing environments (c) Good weldability
Alloy 400 (Monel 400) 67Ni-30Cu	**A494** 35-1	42/–	65/25	−198~482	Valve components: to be annealed.	(a) See for plates and strips of Monel 400 (b) Good weldability (c) Susceptible to mercury embrittlement
Hastelloy B 28Mo-5Fe-1Cr-bal.Ni	**A494** N12MV	44/–	76/40	−198 ~ 371		(a) Same as characteristics and caution to select plates/ pipes Hastelloy B (b) PWHT may be required after major weld repair
Hastelloy C-276 17Mo-16Cr-4.5W-6Fe-bal.Ni	**A494** CW12MW	44/–	72/40	−198 ~ 538		(a) Same as characteristics and caution to select plates/ pipes Hastelloy C-276 (b) PWHT may be required after major weld repair
Copper alloys Most brass and bronze	 **B763** (Note 3)	31–35	See B763		See ASTM B763.	(a) For sand castings in valves (b) C95200, C95300, C95400, C95410, C95500, C95600, and C95800 are generally weldable. Weld repair may be performed provided each excavation does not exceed 20% of the casting section or wall thickness or 4% of the casting surface area (c) See Sect. 2.1.7.2 for more details
Al bronze sand castings	**B148** C95200(Gr.A) C95300(Gr.B) C95400 (Gr.C) C95410 C95500 (Gr.D) C95520 C95600 (Gr.E) C95700 (Gr.F) C95800 C95820 C95900		As cast 65/25 65/25 75/30 75/30 90/40 – 60/28 90/40 85/35 94/39 –	 −254~ 316 −254~ 316 −198~ 316 −198~ 260 −269~ 260 −198~ 260 −198~ 37 −198~ 260 −198~ 204 −198~ 260 −198~ 260	*Composition* 88Cu-9Al-3Fe 89Cu-10Al-1Fe 85Cu-11Al-4Fe 84Cu-10Al-4Fe-2Ni 81Cu-11Al-4Fe-4Ni 78.5Cu-11Al-5Fe-5.5Ni 91Cu-7Al-2Si 75Cu-8Al-3Fe-2Ni-** 81.3Cu-9Al-4Fe-4.5Ni-* 79Cu-9.5Al-5.2Fe-*** 87.5Cu-13Al-4.5Fe	*S*olution treatment (not less than 1 h* followed by water quench) ^ 2 hr *A*nnealing treatment (not less than 2 h followed by air cool) C95300; S: 800–890 °C (1585–1635 °F) A: 620–660 °C (1150–1225 °F) C95400/C95410; S: 870–910 °C (1600–1675 °F) A: 620–660 °C (1150–1225 °F) C95500/C95520; S: 870–925 °C (1600–1700 °F)^ A: 495–540 °C (925–1000 °F) (b) NAB (Ni-Al bronze): excellent cavitation/erosion resistance. See Table 2.76 for some cautions (c) See BS EN1982 *12Mn, **1.2Mn, ***1.0Mn
Cu-Ni Alloys	**B369** C96200 (90:10) C96400 (70:30)	34/–	45/25 60/32	−198 ~ 93		(a) Excellent SCC/erosion resistance and high strength (b) See Sect. 2.1.7.2 for more details

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Castings (7/9)

Material/ brand	ASTM no.&Gr.	P no/ Gr no	SMTS/ SMYS, ksi	Temperature range, °C	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
Titanium alloys	**B367** C-2 (R52550) C-3 (R52550) C-5 (R56400) C-6 (R54520) C-7 (R52700) C-8 (R52700) C-9 (R56320) C-12(R53400) C-16(R52402) C-17(R52252) C-18(R58465) C-38(R54250)	51/–	50/40 65/55 130/120 115/105 50/40 65/55 90/70 70/50 50/40 35/25 90/70 130/115	−59~316	s.g.: 4.40–4.51	(a) For aircraft components (e.g., rotors of helicopter, etc.) (b) See Sect. 2.1.7.4 for more details
Aluminum alloy	**B26** *	*	*	*	* Per types and heat treated condition	(a) For aluminum alloy sand castings (b) There are various types in B26

General Notes for Castings

a. Temperature Limits
 (1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards
 (2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. The impact test exemption temperature shall comply with the applicable codes/standards. Normally the low temperature toughness of ferritic steels is lower than that of wrought steels. See Appendix A
 (3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, low temperature toughness, etc.), and corrosion environment

b. Castings normally have a slightly higher corrosion resistance than wrought materials whereas they have more defects such as shrinkage cracks, gas, and slag inclusions that may cause difficulty in service

c. See Sect. 2.6.2.3 for casting tubes for fired heaters and boilers

d. The materials which are not described the yield strength are not used for the welding unless approved by a responsible metallurgist

e. Classes of Corrosion-Resistant Alloy Castings: See Tables 2.68, 2.69, 2.70, 2.71, 2.72, and 2.73 for chemical compositions of nickel-based alloys
 Martensitic Alloys : CA15, CA40, CA6NM, CA 6 N
 Ferritic and Duplex Alloys : CB30, CC50, CD4MCu
 Austenitic Alloys : CE30, CF Types, CG8M, CH20, CK20, CN7M, CN7MS, IN 862
 Precipitation Hardenable Alloys: CB7Cu-1, CB7Cu-2
 Nickel Based Alloys : CZ100, M25S, M30C, M30H, M35-1, M35-2, N3M, N7M, N12MV, Cu5MCuC, CW2M, CW6M, CW6MC, CW12MW, CX2M, CX2MW, CT40, CY5SnBiM

f. See Tables 2.70 and 2.71 for heat-resistant nickel-based casting alloys and Sect. 2.6.2.3 for casting tubes of fired heaters and boilers

g. When austenitic steels/alloys are to be used in services where they will be subject to stress corrosion, they should be supplied in the solution-heat-treated condition. The purchaser should indicate the additional requirements for thermally stabilized heat treatment for stabilized stainless steel/alloy when they are exposed to polythionic acid SCC environment. See Sect. 2.1.6.8 for more details

h. *Repair by welding for casting* – Repair of injurious defects by welding should be permitted and major weld repairs should be permitted only subject to the approval of the purchaser. Unless otherwise specified by purchaser or material standard, weld repairs should be considered major if the depth of the cavity prepared for welding exceeds 20% of the required minimum wall thickness or if the total surface area exceeds 65 cm^2 (10 in^2). Defects shall be completely removed before welding. If defects are linear, complete removal should be checked by liquid penetrant inspection (Practice E 165). Only qualified operators and procedures (WPS & WPQ) in accordance with Practice ASTM A488 should be used. All weld repairs shall be subjected to the same inspection standard as the tubing

i. See ASME Sec. VIII, Div.1, UG-24 & Appendix 7 for quality factors, defects, identification, and marking

j. Cast Iron (normally no P numbers) and P.No.1 materials are not recommended above 427 °C (800 °F) for continuous operation because of the graphitization after several hundred hours. See Sect. 2.3.1 for more details

k. General Requirements for Castings: See below:
 ASTM A27 for Cast Steels
 ASTM A703 for Cast Steels – General Requirements for Pressure Containing Parts
 ASTM A297 for Fe-Cr, Fe-Cr-Ni Cast Alloys
 ASTM A781 for Common Requirements of Casting Steel/Alloy for General Industry Use

l. Casting Surface Acceptance Standards – Visual Examination: See ASTM A802

m. See EEMUA Publ.192 for "Guide for The Procurement of Valves for Low Temperature, 0 to −50°C"

n. Limitations of Cast Iron in ANSI/NACE MR0103/ISI 17945 (wet sour service)
 – Gray, austenitic, and white cast irons shall not be used as pressure-containing members. These materials may be used for internal components related to API and other appropriate standards, provided the purchaser has approved the use
 – Ferritic ductile iron in accordance with ASTM A395 is allowed for equipment when API, ANSI, and/or other industry standards approve its use
 – Typically, welding is not permitted on gray cast iron or ductile iron components except in minor repair welding

o. Types and the definition of cast iron classified in ANSI/NACE MR0175/ISO 15156 (wet sour service)
 – *Cast Iron*: iron-carbon alloy containing approximately 2–4% mass fraction carbon
 – *Grey Cast Iron*: cast iron that displays a grey fracture surface due to the presence of flake graphite
 – *White Cast Iron*: cast iron that displays a white fracture surface due to the presence of cementite

Castings (8/9)

– *Malleable Iron*: white cast iron that is thermally treated to convert most or all of the cementite to graphite (temper carbon)
– *Ductile Iron (or Nodular Cast Iron)*: cast iron that has been treated while molten with an element (usually magnesium or cerium) that spheroidizes the graphite

p. Limitations of Cast Iron in ANSI/NACE MR0175/ISI 15156 (wet sour service)
– Grey, austenitic, and white cast irons shall not be used for pressure-containing parts. These materials may be used for internal components if their use is permitted by the equipment standard and has been approved by the equipment user
– Ferritic ductile iron in accordance with ASTM A395 is acceptable for equipment unless otherwise specified by the equipment standard

Notes for Castings

1. Characteristics and Application of Ni-Resist Casting (from ASTM A439 Grades)
D-2: The most commonly used grade with primary ductile grade. Used for the service requiring corrosion resistance in alkaline services, erosion, and friction wear up to 760 °C (1400 °F). No copper contamination is required
D-2B: Provides higher erosion resistance and oxidation than type D-2 and is also recommended to use in neutral and reducing salts. Normally performs oil & gas well in metal-to-metal wear environment
D-2C: Used for parts that require erosion resistance and high ductility, such as pumps, valves, compressors, steam turbines, and turbocharger. Also, used for low-temperature application
D-2M: Normally for cryogenic service down to −170 °C (−275 °F)
D-2W: Has similar properties and applications as D-e, but has better weldability
D-3: Exhibits excellent elevated temperature properties and resistance to erosion in wet steam and salt slurries. Recommended for applications involving thermal shock and thermal expansion properties similar to FSS. Used pumps, valves, filter parts, exhaust gas manifolds, and turbocharger housings
D-3A: Provides good resistance to galling and wear, and intermediate thermal expansion
D-4: Provides better resistance to corrosion, erosion compared to D2 & D3 series
D-4A: Provides better resistance to corrosion, erosion compared to D-4 series, and superior oxidation resistance
D-5: Recommended for applications requiring low thermal expansion. Used for machining tool, scientific instruments, and glass molds
D-5B: Used in applications requiring minimum thermal stresses, and good mechanical properties and resistance to oxidation at high temperatures. Used in low-pressure gas turbine housings and glass molds at high temperatures
D-5S: Provides excellent resistance to oxidation when exposed to air at temperatures up to 980 °C (1800 °F) and is also recommended for applications involving thermal cycling at temperatures up to 870 °C (1600 °F). Used for gas turbines, turbocharger housings, exhaust manifolds, and hot pressing dies
D-6: Nonmagnetic with good mechanical properties. Used for switch insulator flanges, terminals, ducts, and turbine generator parts
2. UNS Numbers and correspondent American Standards for Ni-Resist Castings (✓: there is) – Table 2.198

Table 2.198 UNS Numbers and correspondent American Standards for Ni-Resist Castings

UNS No.	ASTM A395	ASTM A439	ASTM A476	ASTM A536	ASTM A571	ASTM A716	AMS	SAE J434	MIL-I-24137
F30000								DQ&T	
F32800	60-40-18			60-40-18				D4018	
F32900						✓			
F33100				65-45-12				D4512	
F33101							5315		✓
F33800				80-55-06				D5506	
F34100			80-60-03				5316		
F34800				100-70-03				D7003	
F36200				120-90-02					
F43000		D-2							
F43001		D-2B							
F43002		D-2C							
F43003		C-3							
F43004		C-3A							
F43005		D-4							
F43006		D-5							
F43007		D-5B							
F43010					D-2M				
F43020									✓
F43021									✓
F43030							5395		

3. ASTM B763 Copper Alloy Sand Castings for Valve Application: See Table 2.77 for more details
4. ASTM A532 Abrasion-Resistant Cast Iron – Hardness Requirements – Table 2.199

Table 2.199 ASTM A532 Abrasion Resistant Cast Iron-Hardness Requirements

			Sand cast, min. [A]														
						Hardened or hardened+SR											
			AC or AC + SR			Level 1			Level 2			Chill cast, min.[B]			Softened, max.		
Class	Type	Designation	HB	HRC	HV	HB	HRC	HV	HB	HRC	HV	HB	HRC	HV	HB	HRC	HV
I	A	Ni-Cr-HiC	550	53	600	600	56	660	650	59	715	600	56	660	–	–	–
I	B	Ni-Cr-LoC	550	53	600	600	56	660	650	59	715	600	56	660	–	–	–
I	C	Ni-Cr-GB	550	53	600	600	56	660	650	59	715	600	56	660	400	41	430
I	D	Ni-HiCr	500	50	540	600	56	660	650	59	715	550	53	600	–	–	–
II	A	12%Cr	550	53	600	600	56	660	650	59	715	550	53	600	400	41	430
II	B	15%Cr-Mo	450	46	485	600	56	660	650	59	715	–	–	–	400	41	430
II	D	20%Cr-Mo	450	46	485	600	56	660	650	59	715	–	–	–	400	41	430
III	A	25%Cr	450	46	485	600	56	660	650	59	715	–	–	–	400	41	430

Legend: *AC* as cast, *SR* stress relieved

Notes

[A] 90% of the minimum surface hardness level shall be maintained to a depth of 40% of the casting section, with any softer material being at the thermal center of the casting. A sampling procedure should be established by agreement between the supplier and the purchaser

[B] Non-chilled areas of casting shall meet minimum hardness or sand cast requirements

2.6.2.6 Bolts (Bolts and Studs) and Nuts – See General Notes

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Material	ASTM no. &Gr.	SMTS/SMYS, ksi (Note 1)	Temperature range, °C (Note 2)	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Bolts/studs> Carbon steel	**A307** Gr. A Gr. B	 60 min/– 60–100/–	−29 ~ 371	Hardness: 121*–241 BHN 121*–212 BHN *For length is less than 3dia.	(a) For CS structural steels with TS of 60 ksi (b) Production analysis limits for bolts $C \leq 0.33\%$, Mn $\leq 1.25\%$, $P \leq 0.041\%$, S (Gr. B) $\leq 0.051\%$ (c) Size: 0.25–4 in. (d) Preferable nuts: A563 Gr.A
<Bolts> Structural use medium carbon Steel	**A325** Type 1 ≤1 in.	120/92	−29 ~ 343	241–331 BHN	(a) Nut materials: A563 Gr. C or A194 Gr.2 & 2H (b) This bolt is similar to size 0.25–3 in., A449 bolt.
	1⅛~1½ in.	105/81		223–293 BHN	
<Bolts/studs> Q-T medium CS	**A449** Type 1 (N.D ¼~3 in.)	90/85	−29 ~ 343	183–235 BHN	
Low or medium carbon Martensitic steel	Type 2 (N.D ¼~1 in.)	120/92		255–321	
<Bolting> High strength, LAS	**A193** B7 <2.5 in. 2.5 ~ 4 in. 4 < 7 in.	 125/105 115/95 100/75	−48 ~ 538	Min. Tempering temperature : 595 °C (1100 °F)	(a) Temperature limitation for combination with nuts (a) ≤ 400 °C (750 °F): with A194 Gr. 2 or 2H (b) ≤ 427 °C (800 °F): with A194 Gr. 3 or 4 (b) To use A193-B7 M in sour service
<Nuts> CS	**194** 2H	150 for hex & 175 for heavy hex*	−48 ~ 538	248–327 BHN ($d \leq 1.5$ in.) 212–235 BHN ($d > 1.5$ in.)	(a) Typically combined with A193 Gr. B7 bolt (b) min. 0.4%C (c) To use A194-2HM (159-235BHN) in sour service. (d)*Min. proof stress using 120° hardened steel cone
<Bolting> High strength, LAS	**A193** B7 M	100/80	−48 ~ 538	Hardness: ≤235 BHN(22HRC)	(a) Be used to prevent SSC in wet H_2S service (b) Chemical tolerance: See A193, Table 1 (c) See Note 3

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Bolts and Nuts (2/9)

Material	ASTM no.&Gr.	SMTS/ SMYS, ksi (Note 1)	Temperature range, °C (Note 2)	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Nuts> LAS	**A194** 7 7M			Hardness: 7: 248–327 BHN 7M: 159–235 BHN	(a) 4140, 4142, 4145, 4140H, 42H, 4145H (b) To use A194-7M in sour service. (c) Min. tempering: @ 595 °C (1100 °F) for 7, @ 620 °C (1150 °F) for 7M
<Bolting> Low temperature LAS Chemical Tolerance: See A320, Table 3	**A320** L7	125/105	−101 ~ 371	Hardness: ≤321BHN(35HRC)	(a) Impact tested (b) Others: similar to A193 Gr. B7 (c) AISI 4140, 4142, or 4145
	L7M	100/80	−73 ~ 371	Hardness: ≤235BHN(99HRB)	(a) Impact tested (b) Others: similar to A193 Gr. B7M (c) See Note 3
	L43	125/105	−101 ~ 371	Hardness: ≤321BHN (35HRC)	(a) AISI 4340 (b) Impact tested (c) Others: similar to A193 Gr. B7
<Bolting> High strength	**A490** Type 1 & 3	150–170/130	−29 ~ 343	Hardness: L < 2D: 311–352BHN (33–38 HRC) L ≥ 2D: ≤352BHN (≤0.38 HRC)	(a) For structural bolts. 150 ksi min. (b) Type 3 is for weathering steel (c) Size range: 0.5–1.5 in.
<Bolts> High strength structure	**A325** Type 1 & 3	*1/2~1 in.*: 120/92 *1 1/8~1 1/2 in.*: 105/81	−29 ~ 343	Hardness: *0.5–1 in.*: L < 2D: 253–319BHN (25–34 HRC) L ≥ 2D: ≤319BHN (≤34 HRC) *1.125–1.5 in.*: L < 2D: 223–286BHN (19–30 HRC) L ≥ 2D: ≤286BHN (≤30 HRC)	(a) For structural bolts, heat treated, 120/105 ksi min. (b) Type 3 is for weathering steel (c) Size range: 0.5–1.5 in.
<Bolts/studs> Q-T steels	**A354** BC BD	115–150/ 99–130	−18 ~ 343 −7 ~ 343	Hardness: *0.25–2.5 in.*: BC: 255–331 BHN (26–36 HRC) BD: 311–363BHN (33–39 HRC) *>2.5 in.*: BC: 235–311 BHN (22–33 HRC) BD: 293–363 BHN (31–39 HRC)	(a) For structural bolts, studs, and externally threaded fasteners (b) Size range: 0.25–4 in. (c) Bolts/nuts combinations – BC, plain (or with coating of insufficient thickness to require over-tapped nuts) plus nut Gr. C (heavy hex) – BC, zinc-coated (or with coating of thickness requiring over-tapped nuts) plus nut Gr. DH (heavy hex) – BD, all finishes plus nut Gr. DH (heavy hex). This class is similar to SAE J429, Grade 8
<Bolts/studs> High strength Q-T CS/LAS	**A449** Type 1 & 3	*1/4–1 in.* 120/92 *>1–1 1/2 in.* 105/81 *>1 ½ to 3 in.* 90–58	−29 ~ 343	Hardness: *0.25–1 in.* 253–319 BHN (25–34 HRC) *>1–1.5 in.* 223–286 BHN (19–30 HRC) *>1.5–3 in.* 183–235 BHN	(a) Type 1: Plain CS, carbon-boron steel, alloy steel, or alloy boron steel Type 3: Weathering steel (b) Type 3 has several classes, A through F (c) Zinc coated (hit-dip or mechanical)
<Bolting> LAS/SS for high temperature	**A437** B4B B4C B4D	145/105 115/85 100–125/ 85–105 per size	−29 ~ 343	Hardness: *Bolt/studs*: B4B: ≤331 BHN B4C: ≤277 BHN B4D: ≤302 BHN *Nuts/washers*: B4B: 293–341 BHN B4C: 229–277 BHN B4D: 263–311 BHN	(a) Alloy-steel turbine-type bolting material specially heat treated. (b) Impact tested (min. 14 J for B4B and min. 34 J for B4C & B4D) (c) B4D: 11.5Cr-1Mo-0.25V-1.1W
<Nuts> CS/LAS	**A563** O, A, B, C, D, DH, C3, and DH3		−29 ~ 343	See A563, Table 3 for proof load and hardness	(a) For structural and mechanical. (b) Gr. C3 and DH3 nuts have atmospheric corrosion resistance and weathering characteristics

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Bolts and Nuts (3/9)

Material	ASTM no. &Gr.	SMTS/ SMYS, ksi (Note 1)	Temperature range, °C (Note 2)	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Nuts> Low temperature C-Mo	**A194** 4	150 for hex/175 for heavy hex*	−48 ~ 538	Hardness: 248–327 BHN (24–35 HRC)	(a) Impact tested (b) *Min. proof stress using 120° hardened steel cone
<Bolting> 5Cr −0.5Mo	**A193** B5	100/80	−29 ~ 649	Min. tempering temperature : 593 °C (1100 °F)	(a) For floating head cover of H/EX with Cr-Mo steel shell (b) Alternative materials: 410 SS or 405SS
<Nuts> 5Cr −0.5Mo	**A194** 3	150 for hex/175 for heavy hex*	−29 ~ 649	Hardness: 248–352 BHN (24–35 HRC)	(a) *Min. proof stress using 120° hardened steel cone
<Bolting> MSS 410	**A193** B6	100/85	−29 ~ 482		(a) Highly decreased toughness after several hundred hours at 400~550 °C [475 °C (885 °F) embrittlement]
<Nuts> MSS 410	**A194** 6	135 for hex/150 for heavy hex*	−29 ~ 482	Hardness: 228–271 BHN (20–28 HRC)	(a) *Min. proof stress using 120° hardened steel cone
<Bolting> ASS 304 SS 316 SS 321 SS 347 SS	**A193** B8 Cl.1/2 B8M Cl.1/2 B8T Cl.1/2 B8C Cl.1/2	*Cl.1* 75/30 *Cl.2* 100–125/ 50–95 Per size	−254 ~ 816	– Carbide solution treated in the finished condition – Cl.2 is to be used for the flange connection in pressure boundary (other than SSC/SCC environments).	(a) For ASS parts, internal trays, packing and its supports, jack bolts for flanges, air cooler header box plugs, etc. (b) 304L, 316L, 321: in low temperature [≤427 °C (800 °F)] and mild acidic service (pH > 5). (c) 0.04–0.1%C is required for high-temperature [>427 °C (800 °F)] strength. (d) All 300 series: Susceptible to Cl-SCC (e) See Note 4
<Bolts> ASS 304 SS 316 SS 321 SS 347 SS	**A320** B8/8A B8M Cl.1/2 B8T Cl.1/2 B8C Cl.1/2	75/30	−254 ~ 816	See Note 4.	(a) Classes; – Cl.1: carbide solution treated – Cl.1A: carbide solution treated in the finished condition – Cl.2: carbide solution treated and strain hardened
<Nuts> ASS 304 SS 316 SS 321 SS 347 SS	**A194** 8 8M 8T 8C		−254 ~ 816	Hardness: 126–300 BHN	(a) To use with 304 SS, 316 SS, 321 SS, 347 SS stud (b) The hardness for wet sour service to be 126–192 BHN or used with 8MA
<Bolting> Hardened SS S66286 S66286 S63198 S63198 S66220 S66220 S66545 S66545 S66285	**A453** 660-A/B/C 660-D* 651-A 651-B 662-A 662-B 665-A 665-B 668	130/85 130/105 100/70 95/60 130/85 125/80 170/120 155/120 130/85	−198 ~ 538**	Hardness: 24–37 HRC 24–35 HRC 95 HRB ~ 29 HRC 93 HRB ~ 28 HRC 24–35 HRC 24–35 HRC 32–41 HRC 32–41 HRC 24–37 HRC	(a) For high temperature with expansion coefficients comparable to ASS High tension/rupture strength at high temperature (b) Stress rupture test at 650 °C (1200 °F) see A453, Table 6 for stress rupture requirements (c) Solution heat treated (d) Chemical composition Gr. 660: 25.5Ni-14.5Cr-1.25Mo-2.1Ti (** max. 150 °C metal temperature in seawater) Gr. 651: 19.5Ni-19.5Cr-1.3Mo-1.3W-0.22Ti-0.4Nb Gr. 662: 26Ni-13.5Cr-2.8Mo-1.95Ti Gr. 665: 2.6Ni-13.5Cr-1.75Mo-3Ti (e) Chemical tolerance: See A453, Table 3 (f) * 120/95 ksi for >2.5 in.
<Anchor bolts> Steel	**F1554** 36^A 55 105	58–80/36 75–95/55 125–150/105	−29 ~ 371	*Size (diameter)* 0.25–4 in. (6.4–102 mm) 0.25–4 in. (6.4–102 mm) 0.25–3 in. (6.4–76 mm)	(a) Thread classes 1A: anchor bolts with class 1A threads 2A: anchor bolts with class 2A threads A when grade 36 is specified, a weldable grade 55 may be furnished at the supplier's option

1 ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 lb/in^3 (density) = 27.68 g/cm^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C Bolts and Nuts (4/9)

Material	ASTM no. &Gr.	SMTS/ SMYS , ksi (Note 1)	Temperature range, °C (Note 2)	General/recommended requirements	Characteristics and precautions (see notes at the end of this table and those for plates)
<Bolts/studs/nuts from bars/forgings> Hardened nickel alloy **Alloy 718** 52Ni-19Cr-5Nb-3Mo-1Ti-Al -Ta	**B637** N07718	180/150	−254 ~ 700* *650 is preferable.	See ASTM B637 for other PH-cold worked Ni alloys below; N07022, N07208, N07252, N07001, N07500, N07740, N07750, N07080, N07752, N09925, N07725	(a) Age hardened (precipitation hardened)-very high strength (b) Good environmental cracking resistance (high H_2S & CO_2) at high temperatures in deep, extremely hostile, oil and gas production environments (c) For oil & gas drilling and production facilities (d) ASME Code Case 1993 (Bolts/Nuts), N-62 (Valve components) (e) See Note 18 in Plates & Strips
<Bolts/studs/ screws> SS and nickel alloy bolts	**F2281**	See ASTM F2281	*	*Size (diameter)* ≥ 0.25 in. (≥6 mm) * See the temperature in plates and strips	(a) SS and nickel alloy bolts, hex cap screws, and studs, for heat resistance and high-temperature applications up to 982 °C (1800 °F) *Type I* heat resisting alloys for continuous service: Class A (ASS): 304/304L/316/316L SS Class B (MSS): 410/416/431 SS Class C (FSS): 430/430F SS *Type II* heat-resisting alloys for continuous and intermittent service: 309/310/321/347 SS *Type III* high-temperature alloys for continuous and intermittent service: Class A (Ni alloys): Alloy 600/601 Class B (PHSS): 660 SS Class C (PHSS): Other than 660 SS
<Bolts/studs/ screws/nuts-nonferrous alloys>	**F467** Nuts **F468** Bolts/studs /screws	See ASTM A468	*	*Size (diameter)* 0.25–1.5 in. (6–38 mm) * See the temperature in plates and strips	(a) F467 nonferrous nuts for general use – copper and its alloys (brass, bronze, cupro-nickel), nickel alloys, aluminum alloys, titanium alloys for 0.25–1.5 in. diameter bolts (b) F468 nonferrous bolts, hex cap screws, socket head cap screws, and studs for general use – copper and its alloys (brass, bronze, cupro-nickel), nickel alloys, aluminum alloys, titanium alloys for 0.25–1.5 in. diameter
<Bolts/studs/ screws> Stainless steels	**F593**		*	*Size (diameter)* 0.25–1.5 in. (6–38 mm) * See the temperature in plates and strips.	(a) Stainless steel bolts, hex cap screws, and studs for general use (corrosion resistance). (b) Group 1: 302HQ, 304, 304L, 305. 384,18-9LW Group 2: 316, 316L Group 3: 321, 347 Group 4: 430 Group 5: 410 Group 6: 431 Group 7: 630
<Bolting/nuts from rods/bars-Cu-Si alloy>	**B98** C65100 C65500	55/20 65/38	−196 ~ 100	≤0.5 in.: half-hard ≤1 in., hard	(a) C65100: 1.5Zn-1.3Si-bal.Cu C65500: 1.5Zn-3.2Si-bal.Cu (b) Various TS & YS per tempering type (c) For marine environment
<Bolting/nuts from rods/bars> Copper alloy (Al-bronze)	**B150** C61400 C62300	80/40 90/50	−196 ~ 150	≤0.5 in., HR50 ≤0.5 in., HR50	(a) C61400: 7Al-2.5Fe-Mn-bal.Cu C62300: 9Al-3Fe-Ni-bal.Cu (b) Various TS & YS per tempering type (c) For marine environment
<Bolting/nuts from rods/bars> Aluminum alloy	**B211** 3003 6061	24/– 30/–	−196 ~ 204	≤0.374 in., H16 ≤0,124 in., T4	(a) Various TS & YS per tempering type (b) For cryogenic service

General Notes for Bolts & Nuts

a. Type of Bolting Materials – Fig. 2.203 – The type below with bolt material standard number should be specified for purchasing.

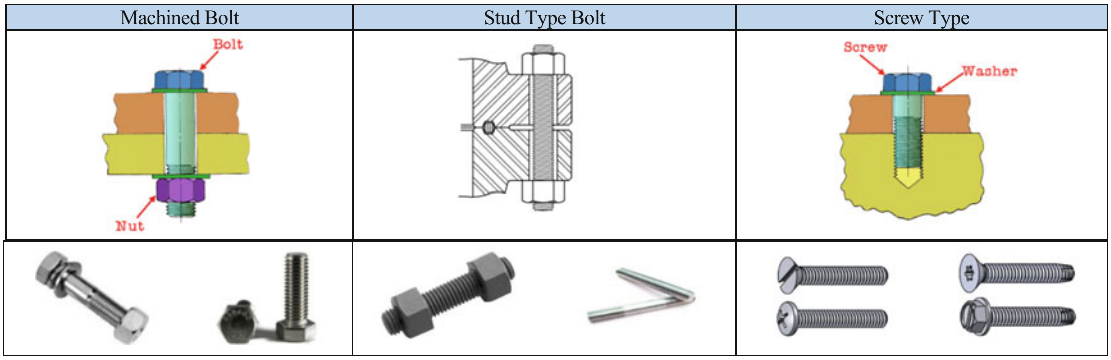


Figure 2.203 Type of bolting. (Source: ASME B1.xx)

b. Several Thread Types (Fig. 2.204) -Identification of 60-deg Inch Screw Threads Within the Scope of ASME B1.xx

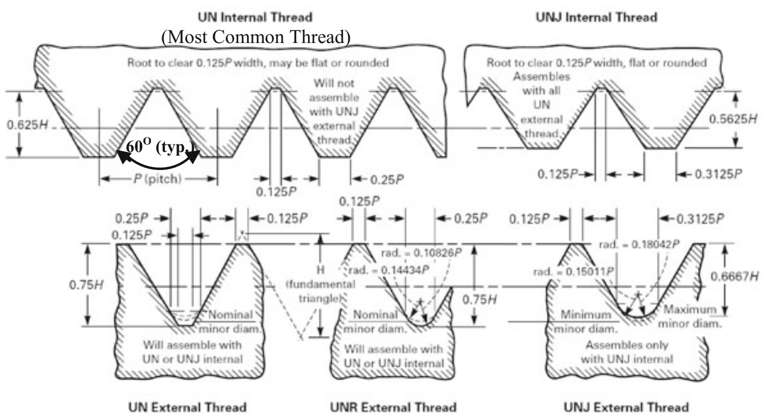


Figure 2.204 Several Thread Types. (Left) Compared to UNC (unified thread standard); *UNJ thread*: Its rounded external root ($r = 0.150$-0.180 pitch) not only greatly improves fatigue strength, but also reduces the rate of threading tool crest wear. *UNR thread*: The roots of the external threads are rounded with a radius of curvature ($r = 0.108$-0.144 pitch) improves fatigue strength. *UNF thread*: The fine threads have a slightly higher breaking load capacity due to the lesser thread depth and a larger tensile stress area for gages of the same identical material and diameter

c. Temperature Limits
 (1) Maximum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards
 (2) Minimum temperature: See ASME Sec. II, Part D, B31.3, B31.1, and other applicable codes/standards. See Note 2 below
 (3) The actual temperature range for use can be narrowed due to the allowable stress (e.g., too low a value or no data at a certain temperature and above in the applicable code), creep-rupture, fatigue, metallurgical degradation (graphitization, stress relaxation, reheat, temper embrittlement, low temperature toughness, etc.), and corrosion environment

d. Strength of Nuts: To be identified/evaluated with proof load unless otherwise specified

e. Applied forces and seating: See Fig. 2.205

f. Stress relaxation is a decreased tendency for the bolt to return to its original shape when unloaded. After several tightening, the loss of preload and leakage may occur. So, the TS of bolting material should be higher than that of the flange. 15 psi higher at least is preferable

g. See Sect. 3.3.4 for more detail of bolt tensioning/torqueing

h. Care, such as sufficient hydrogen baking out, for hydrogen embrittlement during galvanizing treatment is required for high-strength bolting materials

i. Proof load is defined as the maximum tensile force that can be applied to a bolt that will not result in plastic deformationIn other words, the material must remain in its elastic region when loaded up to its proof load. Proof load is typically between 85 and 95% of the yield strength

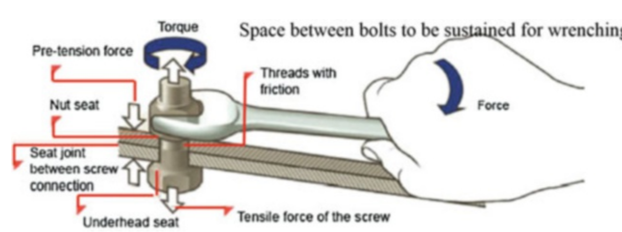


Figure 2.205 Forces and seating during bolting. (Source: ASME PCC-1 modified)

Bolts and Nuts (6/9)

j. Q-T-treated bolting materials should not be hot dip galvanized unless otherwise approved by the purchaser. Once galvanizing is required, the fasteners, threaded components, and miscellaneous items should be hot dip galvanized in accordance with ASTM A153. As an alternative to ASTM A153, threaded components may be mechanically galvanized per ASTM B695, Class 50 or higher. Hot-dip-galvanized nuts should be tapped oversize in accordance with ASTM A563 except that the maximum overtapping shall not exceed 25% of the minimum overtapping. Mechanically galvanized nuts may be tapped oversize before galvanizing. Overtapping before mechanical galvanizing should result in a diametrical increase by a minimum of 8 t and a maximum of 10 t where it is the minimum zinc layer thickness specified (t = thickness)Hot dip or mechanically galvanized nuts should be lubricated in accordance with ASTM A563. The galvanized bolting should be used up to 65 °C of service temperature in continuous operation
k. High-strength galvanized bolting materials, typically over 150 ksi of TS, can be subject to hydrogen embrittlement. In this case, practices to safeguard against hydrogen embrittlement in ASTM A145 should be applied
ASTM F2329 (Zinc coated or Hot Dip Galvanized CS/LAS Fastener) states that there is a risk of internal hydrogen embrittlement for high-strength fastener (hardness ≥33 HRC), so that these fasteners over 25 mm (1 in.) diameter shall not be hot dip zinc coated at high temperatures in order to avoid microcracks
ASTM F3125 (High Strength Structural Bolts, CS & LAS Heat Treated, 120–150 ksi of SMTS) states that hydrogen embrittlement testing required by IFI 144 shall be performed in accordance with Test Method F1940 for internal hydrogen embrittlement and F2660 for environmental hydrogen embrittlement
ASTM A354 and A490 state some cautions for prevention of hydrogen embrittlement
API Spec 20E states that for internal hydrogen embrittlement prevention, All electroplated parts (regardless of strength level) shall be baked within 2 hours after plating at 191 °C–218 °C (375 °F–425 °F) for 8 hours minimum (refer ASTM B850-98(15) Class ER9), and control of the electroplating bath shall be in conformance with ASTM F519 on sample strengths referenced in ASTM F519, verified at a frequency of not more than 60 days. Acceptance criteria shall be a tensile sample (type 1a.1) with no failure after 200 hours at 75% TS
l. See Sect. 3.5.5 for more details on corrosion prevention for bolting materials
m. Welding: Basically the Bolts & Nuts materials do not have the *P*-Numbers. The material with similar chemical composition of the wrought materials may be applied for tack welding
n. All CA and LAS bolting materials that are exposed to corrosive atmosphere should be coated accordingly unless otherwise specified in the above table and/or project specification indicated
o. See ASTM A962 for Common Requirements for bolting intended for use at any temperature from cryogenic to the creep range
p. 17Cr-4Ni (S17400) and 15Cr-5Ni (S15500) bolting: shall not be used for pressure-containing bolting applications in double H-1150 condition in Wet Sour Service (ANSI/NACE MR0175/ISO 17945)
q. Recommendable combination of bolts and nuts unless otherwise noted in the above tables and other notes (affects test requirements or others) – Table 2.200

Table 2.200 Recommendable combination of bolts and nuts

Bolt	Nut	Bolt	Nut	Bolt	Nut
A193 Gr. B5	A194 Gr.3	A193-Gr B8T Cl.1 with 0.04% C min.	A194 Gr.8MA/8TA	A320 Gr. L7M	A194 Gr.7ML
A193 Gr B6	A194 Gr.6	A193 Gr. B8T Cl.2	A194 Gr.8MA/8TA	A320 Gr. B8, Cl. 2	A194 Gr.8MA/8TA
A193 Gr. B7	A194 Gr.2H A194 Gr.4*	A193 Gr B8M Cl.1 with 0.04% C min.	A194 Gr.8MA	A325 Type 1	A563-Gr. DH
A193 Gr. B7M	A194 2HM	A193 Gr. B8M, Cl.2	A194 Gr.8MA	A325 Type 1, Galv.	A563 Gr. DH Galv.
A193 Gr. B8, Cl.1	A194 Gr.8A/8CA	A193 Gr. B16	A194 Gr.4 except A194 Gr.7 for B31.1	A276 Type 310	A276 Type 310
A193 Gr. B8,Cl.2	A194 Gr.8MA/8TA	A913 Gr.L7/L43	A194 Gr.4L/7L	B166 Gr. 600 (N06600) hot fin	B166 Gr.600 (N06600)
A193-Gr B8C Cl.1 with 0.04% C min.	A194 Gr.8MA/8TA	A307 Gr. B	A563 Gr.A	SB 572 -X ANN (N06002)	SB 572 -X ANN (N06002)
A193 Gr. B8C Cl.1	A194 Gr.8MA/8TA	A307 Gr. B Galv.	A563 Gr.A Galv.	B166 Gr. 600 (N06600) hot fin	B166 Gr.600 (N06600)
A193 Gr. B8C Cl.2	A194 Gr.8MA/8TA	A320 Gr. L7	A194 Gr.4	B408-Gr 800H (N08810)	B408-Gr.800H (N08810)

*By the responsible metallurgist approval/request

r. Even though Cadmium (Cd) plating has thin film thickness and excellent corrosion resistance in marine environment, the Cd plating process or airborne Cd is highly toxic, and can be source of hydrogem embrittlement and liquid metal embrittlement under a certain condition. Therefore, Cd plated bolts (fasteners) should be restricted from use in the following applications:
– All pressure-retaining applications regardless of operating temperature
– All applications where the operating temperature exceeds 204 °C (399 °F)
– Where there is any likelihood of welding or hot work
s. zinc (Zn)- or Cadmium (Cd)-plated/coated bolts (fasteners) should not be used in wet sour service (SSC application zones in NACE)
t. Hot and Half Bolting for Plant MaintenanceBolts in flange connection that have been in service may be difficult to remove during shutdown because all bolting materials are still on expanded condition (under tension load). It is also applicable in cryogenic service. Hot bolting is the sequential removal and replacement of bolts on flange connection while under reduced operating pressure (normally ≤50% of maximum operating pressure). It is carried out one bolt at a time in a predetermined cross pattern sequence. Each replaced bolt is fully tensioned before the next one is removed. Hot bolting is also used to check the residual stress of the bolt during operation or to retighten loose bolting. Currently bigger size extra flanges (e.g., hydratight) may be also used for hot bolting. Meanwhile, half bolting is to remove every other bolting during plant depressurization (close to ATM). Typically half the numbers of bolts are left. Half Bolting may be also referred to as skip bolting or odd bolting. See ASME PCC-2, Article 3.11 for more details

Bolts and Nuts (7/9)

u. Bolt Thread Standards
- ASME B1.1 United Inch Screw Threads (UN & UNR Thread Form)
- ASME B1.2 Gases and Gaging for United Inch Screw Threads
- ASME B1.3 Screw Thread Gaging Systems for Acceptability – Inch and Metric Screw Threads (UN, UNR, UNJ, M, and MJ)
- ASME B1.5 ACME Screw Threads
- ASME B1.7 Screw Threads – Nomenclature, Definition, and Letter Symbols
- ASME B1.8 Stub ACME Screw Threads
- ASME B1.9 Buttress Inch Screw Threads
- ASME B1.10M United Miniature Screw Threads
- ASME B1.11 Microscope Objective Threads
- ASME B1.12 Class 5 Interference-Fit Threads
- ASME B1.15 United Inch Screw Threads (UNJ Thread Form)
- ASME B1.16M Gases and Gaging for Metric M Screw Threads
- ASME B1.20.1 Pipe Threads, General Purpose (Inch)
- ASME B1.20.3 Pipe Threads, Inch, Dryseal
- ASME B1.20.5 Gaging for Dryseal Pipe Threads (Inch)
- ASME B1.20.7 Hose Coupling Screw Threads (Inch)
- ASME B1.21M Metric Screw Threads: MJ Profile
- ASME B1.22M Gages and Gaging for MJ Series Metric Screw Threads

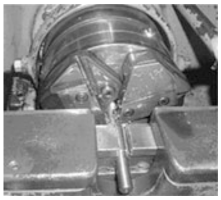
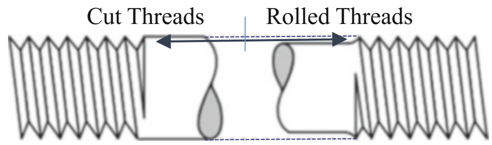
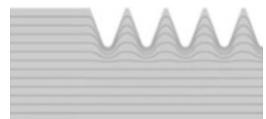
v. Washers: ASTM A436/F436 M Hardened Steel Washers

w. Other Bolting Standards, including plating, coating, hydrogen embrittlement, decarburization, etc.
- ASME PCC-1, Guidelines for Pressure Boundary Bolted Flange Joint Assembly
- ASTM A145 Safeguarding Against Embrittlement of Hot-Dip Galvanized Steel Products and Procedure for Detecting Embrittlement
- ASTM A354 Q-T LAS Bolts Studs and Other Externally Threaded Fasteners
- ASTM A394 Steel Transmission Tower Bolts, Zinc-Coated and Bare
- ASTM A449 Hex Cap Screws, Bolts and Studs, Steel, Heat Treated, 120/105/90 ksi Minimum Tensile Strength, General Use
- ASTM A490 Structural Bolts, Alloy Steel, Heat Treated, 150 ksi Minimum Tensile Strength
- ASTM B849 Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement
- ASTM B850 Post-Coating Treatments of Steel for Reducing Risk of Hydrogen Embrittlement
- ASTM E1077 Estimating the Depth of Decarburization of Steel Specimens
- ASTM F326 Electronic Measurement for Hydrogen Embrittlement From Cadmium-Electroplating Processes
- ASTM F519 Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments
- ASTM F1554 Anchor Bolts, Steel, 36, 55, and 205-ksi Yield Strength
- ASTM F1624 Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique
- ASTM F1940 Process Control Verification to Prevent Hydrogen Embrittlement in Plated or Coated Fasteners
- ASTM F1941 Standard Specification for Electrodeposited Coatings on Threaded Fasteners [Unified Inch Screw Threads (UN/UNR)]
- ASTM F2328 Determining Decarburization Carburization in Hardened Tempered Threaded Steel Bolts, Screws, Studs, and Nuts
- ASTM F2329 Zinc Coating, Hot Dip, Requirements for Application to CS & LAS Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners
- ASTM F2660 Qualifying Coatings for Use on A490 Bolts Relative to Environmental Hydrogen Embrittlement
- ASTM F3125 High-Strength Structural Bolts, CS & LAS Heat Treated, 120–150 ksi of SMTS
- API Spec 20E Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries
- API Spec 20F Corrosion-Resistant Bolting for Use in the Petroleum and Natural Gas Industries
- ANSI/API RP17 Design and Operation of Subsea Production Systems – General Requirements and Recommendations
- API TR 21TR1 Materials Selection for Bolting (LAS per API Spec 20E and Ni-based and stainless alloys per API spec 20F)
- FHWA-SA-91-031 Federal Highway Administration Memo
- IFI-144 Test Evaluation Procedures for Coating Qualification Intended for Use on High-Strength Structural Bolts
- ISO 898, Part 1 to 7 Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs
- ISO 13628-1 Petroleum and natural gas industries – Design and operation of subsea production systems – Part 1: General requirements and recommendations
- NASA Reference Publication 1228, Fastener Design Manual, 1990

x. See Table 2.201 for comparison between cut threads and rolled threads

Bolts and Nuts (8/9)

Table 2.201 Comparison between cut threads and rolled threads

Item	Cut threads (conventional method)	Rolled threads (advanced)
Applicable	Internal and external threads	External threads, mainly for nonstandard threaded fasteners or fatigue environments, normally cold working, normally limited thread length and/or diameter
Production	Conventional machining	Rolling the reduced diameter, about pitch diameter. Extruded by shank (forming) between two reciprocating serrated dies to compress thread roots
Threading		 
Grain flow		
Advantage	Various diameters and full length threads available All specifications (internal & external threads) can be manufactured with cut threads	More accurate, uniform thread dimension, smoother thread surface (so, there are no high spots to prevent proper torqueing or allow loosening), higher fatigue (about +40%) and shear strength because their grain flows in more than one direction in cut threads. No machined chips (no weight loss), high productivity (lower coat) for a large quantity of bolts
Disadvantage	Expensive, produced machined chips (weight loss)	High risk of hydrogen induced SCC (hydrogen embrittlement) at thread root Max. diameter of 1″ and a max. thread length of 8″ in Portland Bolt. May be uneconomic to roll a limited number of pieces For deep thread (over 15% of the diameter), the rolling may be very difficult because after rolling the pieces can be distorted A325 and A490 structural bolts cannot be produced with a reduced body diameter Not practical for internal threads
Remark	ASTM A193 and ASTM A320 address heat treatment after thread rolling or thread cutting only for Gr. B7M and L7M bolting respectively, with the implication that all other grades of bolting can be thread rolled after heat treatment. There are no requirements for hardness measurement or control for rolled threads after heat treatment.	

Notes for Bolts and Nuts

1. The tensile strength of bolts in pressure boundary should be higher than that of the flange (preferable 20–50 ksi higher in noncracking environments)
2. The temperature limitations in Table 2.202 may be used [source: ASME B31.3, Appendix A-2M Table, Note (42)]However, the maximum permissible temperature may be reduced due to the allowable stress issue

Table 2.202 For Note 2

Grades of nuts A194-xx	Metal temperature		Grades of nuts A194-xx	Metal temperature	
	°C	°F		°C	°F
1	−29 to 482	−20 to 900	7L	−101 to 593	−150 to 1100
2, 2H, 2HM, 4, 7, 7M	−48 to 593	−55 to 1100	8FA	−29 to 427	−20 to 800
3	−29 to 593	−20 to 1100	8MA, 8TA	−198 to 816	−325 to 1500
4L	−101 to 593	−150 to 1100	8, 8A, 8CA	−254 to 816	−425 to 1500
6	−29 to 427	−20 to 800			

Bolts and Nuts (9/9)

ASME Sec. VIII, Div.1-figure UCS-66 General Note (e); carbon and low alloy steel	ASME B31.3, K304.5 indicates to use ASME Sec. VIII, Div.2 Part 4, para. 4.16, or Part 5, or ASME Sec. VIII, Div. 3, Article KD-6, and ASME Sec. II, Part D; carbon, low- and high-alloy steel [the summary of ASME Sec. VIII, Div.2 is below.]
IT exemption for the following temperature, °C (°F) and above; SA-193 B5 : −29 (−20) SA-193 B7 (≤2 ½ in. dia) : −48 (−55) SA-193 B7 (2 ½ in. < dia ≤7 in): −40 (−40) SA-193 B7M : −48 (−55) SA-193 B16 : −29 (−20) SA-307 B : −29 (−20) SA-320 L1, L7M, L79, L70~73 : −73 (−100) SA-320 L7, L7A, L7B, L7C : −101 (−150) SA-325 1 & 2 : −29 (−20) SA-354 BC : −18 (0) SA-354 BD : −7 (+20) SA-449 : −29 (−20) SA-540 B23 & B24 : −12 (+10) SA-194 2, 2H,2HM, 3, 4, 7, 7 M & 16: −48 (−55) SA-540 B23 & B24 : −48 (−55)	IT exemption for the following temperature, °C (°F) and above; SA-193 B5 (≤4 ½ in. dia) : −29 (−20) SA-193 B7 (≤2 ½ in. dia) : −48 (−55) SA-193 B7 (2 ½ in. < dia ≤4 in) : −40 (−40) SA-193 B7 (4 in. < dia ≤7 in.) : −40 (−40) SA-193 B7M (≤2 ½ in. dia) : −48 (−55) SA-193 B16 (≤2 ½ in. dia) : −29 (−20) SA-193 B16 (2 ½ in. < dia ≤4 in) : −29 (−20) SA-193 B16 (4 in. < dia ≤7 in.) : −29 (−20) SA-320 L7 (≤2 ½ in.dia): General Note (3) of Figure 3.4/3.4M in Div.2 SA-320 L7M (≤2 ½ in.dia): General Note (3) of Figure 3.4/3.4M in Div.2 SA-320 L43 (≤1 in. dia): General Note (3) of Figure 3.4/3.4M in Div.2 SA-508 5-2: General Note (3) of Figure 3.4/3.4M in Div.2 SA-540 B24-1 (bolts) : −12 (+10) SA-540 B23, B24 (nuts) : −48 (−55) SA-194 2, 2H, 2HM, 3, 4, 7, 7 M, 16 : −48 (−55) SA-193 B6 (≤4 ½ in. dia) : −29 (−20) SA-193 B8-1 : −254 (−425) SA-193 B8C-1 : −254 (−425) SA-193 B8M-1 : −254 (−425) SA-193 B8MNA –1A : −196 (−320) SA-193 B8NA-1A : −196 (−320) SA-193 B8T-1 : −254 (−425) *Table 3.6 in ASME Sec. VIII, Div.2*; copper and aluminum alloys SB-98 C65100, C65500, C66100: −196 (−320) SB-150 C61400, C62300, C66300, C64200: −196 (−320) SB-187 C10200, C11000: −196 (−320) SB-211 A92104, A92204, A96061: −196 (−320) *Table 3.7 in ASME Sec. VIII, Div.2*; nickel alloys SB-160 N02200, N02201 : −196 (−320) SB-164 N04400, N04405 : −196 (−320) SB-166 N06600 : −196 (−320) SB-335 N10001, N10665 : −196 (−320) SB-408 N08800, N08810 : −196 (−320) SB-425 N08825 : −196 (−320) SB-446 N06625 : −196 (−320) SB-572 N06002, R30556 : −196 (−320) SB-573 N10003 : −196 (−320) SB-574 N06022, N06455, N10276 : −196 (−320) SB-581 N06007, N06039, N06975 : −196 (−320) SB-621 N08320 : −196 (−320) SB-637 N07718, N07750 : −196 (−320)

3. The following materials are recommended in Wet H_2S Service (AISI/NACE MR0103/ISO 17945 and ANSI/NACE MR0175/ISO 15156) and HF services. However, for large size bolts, material upgrading may have to be considered
   – SA193-B7M/SA194-2HM (SMTS/SMYS: 100 ksi/80 ksi)
   – SA193-B8M/SA194-8M (SMTS/SMYS: 75 ksi/30 ksi) – for Wet H_2S Service
   – SA320-L7M/SA194-7M (SMTS/SMYS: 100 ksi/80 ksi)
4. Cl. 2 should be used for pressure-containing joints to compensate the stress relaxation. If the flange is A182-F304/F316 [SMTS: 75 ksi], the bolt shall be B8 (304 SS)/B8M (316 SS), Cl.2 which have SMTS of 125/110 ksi respectively because B8 (304 SS)/B8M (316 SS), Cl.1 has SMTS of 75 ksi for both – high risk of leakage

2.6.2.7 Insulation/Refractory Materials (Nonmetallic) – See General Notes

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (1/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F) Note 5	Advantages/application	Disadvantages	Remark
Insulation-granular	Calcium Silicate Block & Pipe-Thermal Insulation [HC] [PP] [FP]	C533	27–927* (80–1700) *650 (1200) for type I and IA	– Low thermal conductivity when dry, – Available in a variety of shapes/sizes, – Available with low chloride levels. – Protection against freezing on piping operating at temperatures between 16 °C (60 °F) and 316 °C (600 °F)	– Will readily absorb moisture (very high hygroscopic), not good for cyclic service with up/down 150 °C (300 °F) – Fragile (i.e., brittle) and requires care to avoid breakage during installation – Chlorides can accumulate in service because of absorption and evaporation of water from the local atmosphere – It may be detrimental to some coatings, such as alkyds and inorganic zinc, when it is exposed to pH 9-10 environment	Nominal density, kg/m^3 (water absorption, max.%) *Type I (block)*: 240 (20) *Type I (pipe)*: 240 (20) *Type IA (block)*: 352 (20) *Type II (block)*: 352 (20) In general, calcium silicate material can absorb up to 400% of its weight when immersed in water. Therefore, it is recommended to use at 150 °C (300 °F) and above
	Molded Expanded Perlite Block & Pipe-Thermal Insulation [HC] [PP] [FP] [AI]	C610	27–650 (80–1200)	– Water-resistant up to 205 °C (400 °F), – Good resistance to mechanical damage, – Available in a variety of shapes/sizes – ASTM C610 includes a test method for determining the effect of temperature on water resistance	– More fragile than calcium silicate during installation – Higher thermal conductivity than calcium silicate	Nominal density, kg/m^3 (water absorption, max.%) *Block & Pipe*: 240 (10) At lower temperatures, the additives for water resistance provide protection from absorption of water. At approximately 315 °C (600 °F) and above, some additives burn out, and water resistance is reduced
	Expanded perlite loose fill insulation [CC] [HC]	C549	−273 to 760 (−459 to 1400)	– Cryogenic to high temperature	Pour the insulating material into the spaces and cavities to be insulated in a manner that minimizes free-fall and impact. This will minimize crushing and breakdown of insulation Particles and unnecessary formation of dust	Nominal density, kg/m^3 (water absorption-14 days, max.%) ; 32–176 (1) The thermal resistance depends on the density
	Flexible aerogel insulation [CC] [HC]	C1728	−197 to 650 (−321 to 1200)	– Highest thermal performance of any insulating material known – Significantly reduced thickness for equivalent performance to other insulating systems, – Wide range of temperature applications (note: may require a change in specific product to cover hot or cold insulation) – Properly installed protective vapor retarders or barriers shall be used on below ambient temperature applications to reduce movement of moisture through or around the insulation to the colder surface	– Aerogels may be hygroscopic, – Need chemical treatment to be hydrophobic, – Typically higher cost of materials (note: installed cost and performance may provide economic justification) – Failure to use a vapor retarder or barrier could lead to insulation and system nonperformance	Type I, grade 1B: Aspen aerogels Type III, grade 1A: Aspen aerogels Type III, grade 2

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (2/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F) Note 5	Advantages/application	Disadvantages	Remark
Insulation fibrous Note 1 & 4	Mineral fiber for pipe insulation (wool) (fiberglass) [HC] [PP] [AH]	C547	−18 to 760 (0–1400) *Type I*—Molded, to 454 °C (850 °F). *Type II*—Molded, to 650 °C (1200 °F). *Type III*—Precision v-groove, to 650 °C (1200 °F) *Type IV*-molded, to 538 °C (1000 °F) *Type V*- molded, to 760 °C (1400 °F)	– Noncombustible. – To form hollow cylinders for standard pipe and tubing sizes	– Compressing the material reduces its effectiveness – Absorbs water – Can cause skin allergies	Nominal density, kg/m^3 (water vapor absorption, max.%) *Type I*: 48 (5) *Type II*: 96 (5) *Type III*: 96 (5)
Insulation fibrous Note 1 & 4	Mineral fiber blanket (wool) [HC] [PP] [AH]	C592	−18 to 650* (0–1200*) * 454(800) for Type I	– Has lower thermal conductivity than calcium silicate and perlite – Low leachable chloride content (<5 ppm). The maximum use temperature of the facings and adhesives may be lower than the maximum use temperature of the insulation. For example, usually galvanized hexagonal wire-woven netting and tie wires or stitching performs well under continuous exposure to temperatures up to 200 °C (392 °F). Exposure to temperatures above this limit can cause the outer free zinc layer to peel. Though there are potential or occasional concerns for corrosion conditions at various temperatures, galvanized wire, stitching, or facings generally are not recommended for temperatures above 260 °C (500 °F). In addition, the user of this specification shall ensure that sufficient insulation thickness is installed so that none of the accessory items (facings, adhesive, coatings, and lagging) are exposed to temperatures above their maximum use temperature. Practice ASTM C680 can be used to determine surface temperatures	– Fibrous insulations are readily permeable to vapors and liquids – Most fibers can readily wick hydrocarbons and water; – Mineral fiber is subject to mechanical damage because of its low compressive strength and lack of resiliency – Chlorides can accumulate in service because of absorption and evaporation of water from the local atmosphere	Nominal density, kg/m^3 (water vapor absorption, max.%) *Type I*: 160 (5) *Type II*: 192 (5) *Type III*: 128 (1.25) *Type IV*: 128 (1.25) Use of type II for [AH] is recommended
	Mineral Fiber blanket for commercial & industrial Note 1 [HC] [PP]	C553	−18 to 650* (0–1200*) *Type I*: 232 (450) *Type II*: 232 (450) *Type III*: 232 (450) *Type IV*: 454 (850) *Type V*: 538 (1000) *Type VI*: 538 (1000) *Type VII*: 650 (1200)			Nominal density, kg/m^3 (water vapor absorption, max.%) *Type I*: 96 (5) *Type II*: 96 (5) *Type III*: 96 (5) *Type IV*: 128 (5) *Type V*: 160 (5) *Type VI*: 160 (5) *Type VII*: 192 (5)

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (3/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F) Note 5	Advantages/ application	Disadvantages	Remark
	Mineral fiber-block and board thermal insulation [HC] [PP] [AH]	C612	−18 to 982* (0–1800*) * Max. Temperature *Type IA & IB*: 232 °C (450 °F) *Type II*: 454 °C (850 °F) *Type III*: 538 °C (1000 °F) *Type IVA & IVB*: 649 °C (1200 °F) *Type V*: 982 °C (1800 °F)	While it is recommended that the specification data be presented as conductivity versus temperature, several existing specifications may contain mean temperature data from tests conducted at specific hot and cold surface temperatures In these cases, the conductivity as a function of temperature from the practice ASTM C1045 analysis may provide different results. To ensure that the data is compatible, a practice ASTM C680 analysis, using the conductivity versus temperature relationship from practice ASTM C1045 and the specific hot and cold surface temperatures, is required to determine the effective thermal conductivity for comparison to the specification requirements	– Susceptible to CLSCC on ASS.	Nominal density, kg/m^3 (water vapor absorption, max.%) *Type IA*: 128 (5) *Type IB*: 128 (5) *Type II*: 128 (5) *Type III*: 160 (5) *Type IVA*: 192 (5) *Type IVB*: 192 (5) *Type V*: 320 (5)
	Perpendicularly oriented mineral fiber [HC] [PP]	C1393	atm to 538* (atm to 1000*) * See right	*Max. Use temperature *Type I*: 232 °C (450 °F) *Type II*: 343 °C (650 °F) *Type IIIA*: 454 °C (850 °F) *Type IIIB*: 454 °C (850 °F)		*Category 1* – Greater minimum compressive resistance properties are required. *Category 2* – Lesser minimum compressive resistance properties are required Nominal density, kg/m^3 (water absorption, max.%) *Type I*: 96 (5) *Type II*: 96 (5) *Type IIIA*: 96 (5) *Type IIIB*: 96 (5) *Type IVA*: 96 (5) *Type IVB*: 128 (5)
Insulation fibrous Note 1 & 4	High temperature Fiber blanket (ceramic wool) [HC] [FP]	C892	732 °C (1350 °F) to * °C(°F) Type I: 732 (1350) Type II: 871 (1600) Type III:1316 (2400) Type IV:1427 (2600) Type V: 1649 (3000)	– Used for cracking furnaces [≈1315 °C (2400 °F)] and reformer furnaces [≈1204 °C (2200 °F)] – The density may be increased by monolithic modules include minimum 15% zirconia content Maximum shrinkage should be less than 2% as installed at service temperature		*Nominal density, kg/m^3* Grade 3:48 Grade 4: 64 Grade 6: 96 Grade 8: 128 Grade 12: 192
	Glass fiber mechanically bonded Flet [HC] [FP]	C1086	Up to 650 °C (1200 °F)	– For use on machinery and equipment, such as steam turbines, boilers, boiler feed pumps, and piping		*For fire resistance* – To meet the test method USCG 164.009 (per MIL-STD-1623)

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (4/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F) Note 5	Advantages/application	Disadvantages	Remark
Insulation-cellular	Cellular glass [CC] [AC] [AH]	C552	−267 to 427 (−450 to 800) NACE SP0198 CUI notes that it is commonly used in the below-ambient to moderate temperature range of −25 to 200 °C (−13 to 392 °F).	– Almost does not absorb water – High resistance to mechanical damage when jacketed – Thermal conductivity does not deteriorate with aging – Used where spillage or leakage of a product onto the insulation is probable and the saturated insulation either creates a potential fire hazard, such as, but not limited to, auto ignition – Used on all direct burial or underground piping, extending to a height of 150 mm (6 in.) above grade precluding the use of wicking-type insulation, provided that the max. operating temperature of the line is below 204 °C (400 °F)	– Susceptible to thermal shock if temperature gradient >150 °C (300 °F) – Easily abrades in vibrating service and fragile before application – Higher price when compared to other insulation types	*Type I*: Flat block, generally manufactured in Gr. 1 & 2 *Type II*: Pipe and tubing insulation, generally fabricated in Gr. 1 & 2 *Type III*: Special shapes, generally fabricated in Gr. 1 & 2 *Type IV*: Board, generally fabricated in grade 2 Nominal density, kg/m^3 (water absorption, max.%) *Grade I*: 98–138 (0.5) *Grade II*: 109–156 (0.5) – It is anticipated that single-layer pipe insulation in half sections or the inner layer of a multilayer system may exhibit SCC above 250 °F (122 °C)
	Polyurethane [HC] or [CC]	Common for all urethane types	Note 2	– Low permeability and absorption characteristics (closed cell) – Multiple product forms and easy to apply in the field – Provides a seamless seal	– Can be ignited and release toxic gases if exposed to an open flame – Sensitive to ultraviolet (UV) radiation (sunlight) – Can be vulnerable to some acids, caustics, solvents, hydrocarbons, and other chemicals – Susceptible to long freeze-thaw cycles; cells can break open and become filled with water	
	Spray-applied rigid cellular polyurethane [HC]	C1029	−30 °C to 107 °C (−22 to 225 °F)	A rigid, closed-cell foam that is formed by a chemical reaction at the time of application		
	Aerosol polyurethane and aerosol latex foam sealants	C1620		Type I *aerosol polyurethane foam sealants* in containers 1 l or less Type II *aerosol latex foam sealants* in containers 1 l or less Type 1 & II, grade 1 *aerosol foam sealants* contain flammable gas blowing agent or propellant, or both, and are classified as a flammable aerosol by DOT Type I, grade 2 *aerosol foam sealants* contain nonflammable blowing agent or propellants, or both, and are not classified flammable		

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (5/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F)	Advantages/ application	Disadvantages	Remark
Insulation-cellular	Polyiso-cyanurate foam Unfaced preformed rigid cellular [CC] [AC]	C591	−183* to 150 (−297* to 300) * At temperatures below −70 °F (−51 °C) the physical properties of the polyisocyanurate insulation at the service temperature are of particular importance.	– Low permeability and absorption characteristics – Multiple product forms and easy to apply in the field – A rigid, closed-cell foam that is formed by a controlled chemical reaction	– Like other organic compounds, polyisocyanurate is flammable – Primarily a cold system insulation material – When burned without enough oxygen or at lower temperatures, a number of chemicals are produced that can irritate eyes, nose, and the respiratory system – Repeated freeze-thaw cycles can cause cells to break open and become filled with water	Nominal density, kg/m^3 (water absorption, max.%), *Type I*: 29 (2) *Type II*: 40 (1) *Type III*: 48 (1) *Type IV*: 32 (2) *Type V*: 60 (1) *Type VI*: 96 (0.8)
	Polyiso-cyanurate foam Faced rigid cellular [CC] [AC]	C1289	−40 to 93 (−40 to 200)	*Type I* – Faced with aluminum foil on both major surfaces of the core foam – *Class 1* – Nonreinforced core foam – *Class 2* – Glass-fiber-reinforced core foam *Type II* – Faced with organic/inorganic/asphalt saturated/ polymer –bonded/fibrous felt or uncoated/asphalt coated/ polymer-bonded/glass fiber mat membrane facers on both major surfaces of the core foam. *Type III* – Faced with a perlite insulation board on one major surface of the core foam and an organic/inorganic/ asphalt-saturated/polymer-bonded/fibrous felt or uncoated/ asphalt-coated/polymer-bonded/glass fiber mat membrane facer on the other major surface of the core foam *Type IV* – Faced with a cellulosic fiber insulating board on one major surface of the core foam and an organic/ inorganic/asphalt-saturated/polymer-bonded/fibrous felt or uncoated/asphalt-coated/polymer-bonded/glass fiber mat membrane facer on the other major surface of the core foam *Type V* – Faced with oriented strand board or waferboard on one major surface of the foam and an organic/inorganic/ asphalt-saturated/polymer-bonded/fibrous felt or uncoated/ asphalt-coated/polymer-bonded/glass fiber mat membrane facer on the other major surface of the core foam *Type VI* – Faced with a perlite insulation board on both major surfaces of the core foam		(water absorption 2 hrs, max.%), *Type I-Cl.1*: (1) *Type I-Cl.2*: (1) *Type II*: (1.5) *Type III*: (1) *Type IV*: (2) *Type V*: (1) *Type VI*: (1.5)
	Elastomeric cellular foam [CC] [AC]	C534	[tubular – type I] *Grade 1*: −183 to 104 (−297 to 220) *Grade 2*: −183 to 175 (−297 to 350) *Grade 3*: −183 to 120 (−297 to 250) [sheet – type II] *Grade 1 & 3*: −183 to 104 (−297 to 220) *Grade 2*: −183 to 175 (−297 to 350)	– A flexible, closed-cell foam that is formed by an extrusion process – Very low *water absorption: max. 0.2% for all grades*		*Gr.1*: For commercial or industry *Gr.2*: For industry *Gr.3*: For industry where halogens are not permitted

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (6/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F)	Advantages/application	Disadvantages	Remark
	Polystyrene foam [CC] [AC]	C578	−183 to 74 (−297 to 165) −54 to 74 (−65 to 165)	– Low thermal conductivity – Excellent resistance to water and water absorption from freeze-thaw cycling – Very stable and does not biodegrade – Resistant to photolysis – A rigid, closed-cell foam that is formed by either an extrusion or a molding process	– Like other organic compounds, polystyrene is flammable – When burned without enough oxygen or at lower temperatures, polystyrene can produce a number of chemicals including polycyclic aromatic hydrocarbons, carbon black, and carbon monoxide, as well as styrene monomers, which can irritate eyes, nose, and the respiratory system – Primarily a cold system insulation material	Two types: 1. Expanded polystyrene (EPS) foam and 2. Extruded polystyrene (XPS) foam Nominal density, kg/m^3 (water absorption, max.%) *Type I*: 15 (4) *Type II*: 22 (3) *Type IV*: 26 (0.3) *Type V*: 48 (0.3) *Type VI*:29 (0.3) *Type VII*:35 (0.3) *Type VIII*: 18 (3) *Type IX*: 29 (2) *Type X*: 21 (0.3) *Type XI*: 12 (4) *Type XII*:19 (0.3)
Refractory coating Note 3	Light weight proprietary fireproofing coatings		See right	Commercial materials (only for reference): – Polyamide cured epoxy based: Thermo-Lag 440®, Hempadur 4515–1148 A®, Jotachar 1709®/ JF750® or Eq. – Inorganic zinc based: Thermaline 4700® [≤538 °C (1000 °F)], or Eq. – Silicon ceramic based: Dampney Thurmalox 240® [(≤760 °C (1400 °F)), Thurmalox 242® [≤871 °C (1600 °F)] or Eq. – Combination: Pyroclad X1® or Eq.		The maximum temperature, resistant period, and required thickness should be confirmed by the supplier Mesh reinforcement may or may not be used under the coating
Refractory Note 3	Concrete – Type 1 Portland cement	C150		e.g., FENDOLITE®M-II or Eq.		– Water shall be free of oils, acids, alkalis, salts or other substances injurious to concrete. Use of potable water is desirable – Gunite cement lining is the most common practice
	Sand – High silica	C33		– High silica sand with clean, sharp, hard, durable particles conforming to ASTM C33 – the sand shall be neither excessively dry nor wet; approx. 4 wt% moisture is desirable		
	Calcium silicate	C533	27–927* (80–1700) *650 (1200) for type I and IA	The insulation at least 4-1/2″ thick may be used for fireproofing of piping and conduit		See ASTM C533 calcium silicate for insulation

1ksi = 1000 psi = 6.895 MPa = 6895 kPa, 1 kg/m^3 (density) = 0.001 g/cm^3 = 0.0624 lb/ft^3 (s.g.), °F = 1.8 °C + 32, Δ°F = Δ1.8 °C

Nonmetallic (7/12)

Category	Material [application group]	ASTM no	Temperature range for use, °C (°F)	Advantages/application	Disadvantages	Remark
Refractory-vibracast Note 3	Lightweight insulating refractory Density: 1120–1440 kg/m^3		Up to 1315 °C (2400 °F)	Commercial materials (only for reference) *Manufacturer* — *Product name* Harbison-Walker Refractories — GREENLITE 45L® Plibrico Japan Co., Ltd. — PLICAST LW 3-22A® Resco Products, Inc. — RESCOCAST 9®		It is for internally insulating vessels, equipment, piping, and duct work vibracast monolithic refractory lining, but not for fired heaters Density: per ASTM C134
	Mid-weight insulating refractory Density: 1600–2320 kg/m^3		Up to 1315 °C (2400 °F)	Commercial materials (only for reference) *Manufacturer* — *Product name* Harbison-Walker Refractories — Green Kleen 60 plus® Plibrico Japan Co., Ltd. — PLICAST 3-24® Resco Products, Inc. — RESCOCAST 17EC® Vesuvius Refractories International, Inc. — AR 153 VC® Thermal Ceramics — KAO-TUFF CV®		The maximum temperature and resistant period should be confirmed by the supplier
	Low Iron insulating refractory Density: 1040–1600 kg/m^3		Up to 1370 °C (2500 °F)	Commercial materials (only for reference) *Manufacturer* — *Product name* Harbison-Walker Refractories — KAST-O-LITE 30 LI® Plibrico Japan Co., Ltd. — PLICAST LW 3-23® Resco Products, Inc. — RESCOCAST 4 LI® (Fe < 1.0 wt%)		

General Notes: *N/A* = not applicable

a. References: API RP583 (Corrosion Under Insulation and Fireproofing), API STD521 (Pressure-relieving and Depressuring Systems), and NACE SP0198 (Control of Corrosion Under Thermal Insulation and Fireproofing Materials)

b. Water absorption, max.% is based on volume. Water vapor absorption (sorption), max.% is based on weight

c. See ASTM C168 for Terminology Relating to Thermal Insulating Materials

d. Types and Application of Insulation: [ ] initial of application group
- Heat Conservation, above Ambient – Heat Conservation [HC]
- Heat Conservation, below Ambient – Cold Conservation [CC]
- Personnel Protection, over 60 or 65 °C (140 or 150 °F) [PP]
- Process Control, Ambient and Higher [HC]
- Heat Conservation (Steam Traced), Ambient and Higher [HC]
- Heat Conservation (Electric Traced), Ambient and Higher [HC]
- Heat Conservation (Hot Liquid Traced), Ambient and Higher [HC]
- Heat Conservation (Jacketed Construction), Ambient and Higher [HC]
- Sound (Acoustic) Control, Ambient and Higher [AH]
- Sound (Acoustic) control, below ambient through −196 °C (−320 °F) [AC]
- Fire Protection, Ambient and Higher [FP] – See API STD521 (Pressure-relieving and depressuring systems)
- Reduction of heat gain and condensation control, below ambient through −196 °C (−320 °F) [CC]
- Autoignition resistant hot Insulation [AI]

e. The maximum thickness of each layer in block type insulation should be 50 mm or 75 mm (2 in. or 3 in.)

f. Non-asbestos-containing insulation should be used

g. For ASS,
- See ASTM C795 Standard Specification for Thermal Insulation for Use in Contact with ASS
- See ASTM C692 Standard Test Method for Evaluating the Influence of Thermal Insulations on External SCC Tendency of ASS (Fig. 2.206)
- See ASTM C929 Standard Practice for Handling, Transporting, Shipping, Storage, Receiving, and Application of Thermal Insulation Materials for Use in Contact with ASS

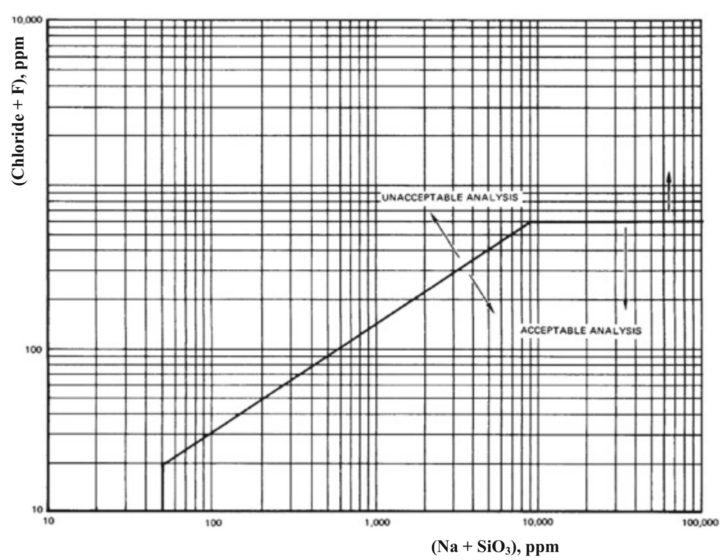


Figure 2.206 Acceptability of Insulation Materials (ASTM C692). This figure in ASTM C692 indicates that the acceptability of insulation materials on the basis of the plot of the chloride (ppm) and (Na + SiO_3) analysis to avoid external SCC on ASS. Sodium (Na), silicate (SiO_3), and chloride in Thermal Insulation: The minimum allowable value of Na + SiO_3 shall be 50 ppm for thermal insulation on ASS. Also, some users specify the ratio of (Na + SiO_3) to chlorides as 20 to 1 for calcium silicate and mineral fiber or 200 to 1 for perlite

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h. *Standard Spec*. and Test Methods for Property Determination (Fig. 2.206)
- ASTM E96 water vapor permeability at 23 °C ± 1 °C (73 °F ± 2 °F)
- ASTM C165 Procedure A, Compressive strength
- ASTM C167 Thickness and Density of Blanket or Batt Thermal Insulations
- ASTM C168 Standard Terminology Relating to Thermal Insulations
- ASTM C177 C236, or C518, Thermal resistance
- ASTM C195 Mineral Fiber Thermal Insulating Cement
- ASTM C203 Breaking Load and Flexural Properties of Block-Type Thermal Insulation
- ASTM C209 Cellulosic Fiber Insulating Board
- ASTM C302 Density of Preformed Pipe Covering-Type
- ASTM C303 Block and Board Type Thermal Insulation
- ASTM C335 Steady-State Heat Transfer Properties of Pipe Insulation
- ASTM C355 *Thermal Conductivity*
- ASTM C356 *Linear Shrinkage* of Preformed High-Temperature Thermal Insulation Subjected to Soaking Heat
- ASTM C411 Hot-Surface Performance of High-Temperature Thermal Insulation
- ASTM C421 Tumbling Friability of Preformed Block-Type and Preformed Pipe-Covering-Type Thermal Insulation
- ASTM C449 Mineral Fiber Hydraulic-Setting Thermal Insulating and Finishing Cement
- ASTM C450 Prefabrication Field Fabrication of Thermal Insulating Fitting Covers for NPS Piping, Vessel Lagging, Dished Head Segments
- ASTM C466 Breaking Load and Calculated Modulus of Rupture of Preformed Insulation for Pipes
- ASTM C518 Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
- ASTM C533 Calcium Silicate Block and Pipe Thermal Insulation
- ASTM C547 Mineral Fiber Pipe Insulation
- ASTM C550 Measuring Trueness and Squareness of Rigid Block and Board Thermal Insulation
- ASTM C552 Cellular Glass Thermal Insulation
- ASTM C553 Mineral Fiber Blanket Thermal Insulation for Commercial and Industrial Applications
- ASTM C585 Inner and Outer Diameters of Thermal Insulation for Nominal Sizes of Pipe and Tubing
- ASTM C592 Mineral Fiber Blanket Insulation and Blanket-Type Pipe Insulation (Metal-Mesh Covered) (Industrial Type)
- ASTM C610 Molded Expanded Perlite Block and Pipe Thermal Insulation
- ASTM C612 Mineral Fiber Block and Board Thermal Insulation
- ASTM C647 Properties and Tests of Mastics and Coating Finishes for Thermal Insulation
- ASTM C692 Evaluating the Influence of Thermal Insulations on External SCC Tendency of ASS
- ASTM C795 Thermal Insulation for Use in Contact with ASS
- ASTM C871 Chemical Analysis of Thermal Insulation Materials for Leachable Chloride, Fluoride, Silicate, and Sodium Ions
- ASTM C892 High-Temperature Fiber Blanket Thermal Insulation
- ASTM C921 Properties of Jacketing Materials for Thermal Insulation
- ASTM C929 Handling, Transporting, Shipping, Storage, Receiving of Thermal Insulation Materials for Use in Contact with ASS
- ASTM C930 Potential Health and Safety Concerns Associated with Thermal Insulation Materials and Accessories
- ASTM C1104 Water Vapor Sorption of Unfaced Mineral Fiber Insulation
- ASTM C1029 Spray-Applied Rigid Cellular Polyurethane Thermal Insulation
- ASTM C1094 Flexible Removable Insulation Covers
- ASTM C1114 Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus
- ASTM C1616 Moisture Content of Inorganic Insulation Materials by Weight
- ASTM D1621 Compressive Properties of Rigid Cellular Plastics
- ASTM D1622 Apparent Density of Rigid Cellular Plastics
- ASTM D1623 Tensile and Tensile Adhesion Properties of Rigid Cellular Plastics
- ASTM D2126 Response of Rigid Cellular Plastics to Thermal and Humid Aging
- ASTM D2842 Water Absorption of Rigid Cellular Plastics
- ASTM D2856 Open Cell Content of Rigid Cellular Plastics by the Air Pycnometer
- ASTM E84 Surface Burning Characteristics of Building Materials
- ASTM E136 Behavior of Materials in a Vertical Tube Furnace at 750 °C (1382 °F)

i. Storage of Insulation Materials
The insulation should be stored in a dry atmosphere under cover and inspected at intervals not exceeding 3 months according by manufacturers/installers. Cartons should be stored end up and be stacked no more than three high

j. Determining Thermal Conductivity (k) of Insulation Materials (Btu/hr. ft^2) – Table 2.203 (conventional data)
$k = \alpha + \beta\, T + \rho\, T^2 + \gamma\, T^3$ where the service temperature, T is °F

Table 2.203 Determining Thermal Conductivity (k) of Insulation Materials

Insulation materials as 1980 edition	α	β	ρ	γ	Temperature range for this formula, °C (°F)
Calcium silicate, ASTM C533-class 1	0.3504	5.196×10^{-4}	0	0	38–371 (100–700)
White fiberglass blanket with binder					
Density = 3 lb/ft^3 (48 kg/m^3)	0.2037	0.0616×10^{-4}	1.403×10^{-6}	-5.0×10^{-10}	10–427 (50–800)
Density = 6 lb/ft^3 (96 kg/m^3)	0.2125	-2.325×10^{-4}	1.797×10^{-6}	-7.97×10^{-10}	10–482 (50–900)
Rigid fiberglass sheet					
ASTM C547-class 1	0.2391	9.192×10^{-4}	6.942×10^{-10}	0	−11 to 49 (11–121)

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ASTM C547-class 2	0.2782	12.260×10^{-4}	0	0	3–96 (37–204)
ASTM C612-class 1	0.2537	3.051×10^{-4}	1.950×10^{-6}	0	−18 to 121 (0–250)
ASTM C612-class 3	0.2631	2.301×10^{-4}	1.614×10^{-6}	0	−18 to 135 (0–275)
Density = 4 lb/ft^3 (64 kg/m^3)	0.2113	3.857×10^{-4}	1.200×10^{-6}	0	−18 to 149 (0–300)
Density = 6 lb/ft^3 (96 kg/m^3)	0.1997	2.557×10^{-4}	9.048×10^{-7}	0	−18 to 149 (0–300)
Cellular glass from, ASTM A522-class 1	0.3488	5.038×10^{-4}	1.144×10^{-7}	7.172×10^{-10}	−184 to 260 (−300 to 500)
Mineral wool					
Basaltic rock blanket, density = 9 lb/ft^3 (144 kg/m^3)	0.2109	3.382×10^{-4}	5.495×10^{-7}	0	−18 to 427 (0–800)
Basaltic rock blanket, density = 12 lb/ft^3 (192 kg/m^3)	0.2798	0.951×10^{-4}	6.478×10^{-7}	0	−18 to 427 (0–800)
Metallic slag block, density = 6 lb/ft^3 (96 kg/m^3)	0.1076	5.714×10^{-4}	3.124×10^{-7}	0	−18 to 316 (0–600)
Metallic slag block, density = 18 lb/ft^3 (288 kg/m^3)	0.3190	0.887×10^{-4}	2.174×10^{-7}	0	−18 to 649 (0–1200)
Mineral wool-based cement	0.4245	6.293×10^{-4}	-1.638×10^{-7}	3.533×10^{-10}	−18 to 510 (0–950)
Performed expanded perlite, ASTM C610	0.3843	3.000×10^{-4}	2.2381×10^{-7}	0	10–399 (50–750)
Expanded perlite-based cement	0.6912	5.435×10^{-4}	0	0	10–343 (50–650)
Expanded polystyrene block, ASTM C578-grade 2	0.1711	2.760×10^{-4}	1.796×10^{-6}	-3.997×10^{-10}	−50 to 43 (−58 to 110)
Polyurethane, density = 2.2 lb/ft^3 (35 kg/m^3)					
Aged 720 days at 25 °C (77 °F), 50% relative humidity	0.1662	-4.094×10^{-4}	-5.273×10^{-6}	2.534×10^{-10}	−50 to 0 (−58 to 32)
85% closed cell	0.1516	-3.370×10^{-4}	7.153×10^{-6}	-2.858×10^{-10}	0–50 (32–122)
New polyurethane	0.1271	-2.490×10^{-4}	-7.962×10^{-7}	4.717×10^{-10}	−50 to 0 (−58 to 32)
95% closed cell	0.0972	7.813×10^{-4}	-7.152×10^{-6}	2.858×10^{-10}	0–50 (32–122)
Exfoliated vermiculite (insulating cement)					
Aislagreen® (A.P. Green S.A. in Mexico)	0.4800	6.000×10^{-4}	0	0	−18 to 649 (0–1200)
ASTM C196	0.8474	5.071×10^{-4}	0	0	−18 to 649 (0–1200)

k. Variation of Effective Thermal Conductivity (ke) with Cold Vacuum Pressure (See Fig. 2.207)

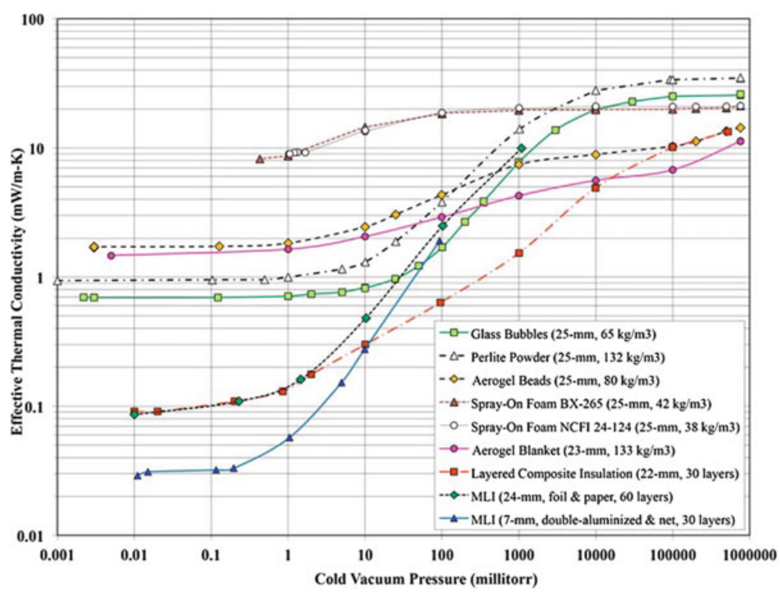

Figure 2.207 Examples of the variation of effective thermal conductivity (ke) with cold vacuum pressure are shown for different cryogenic insulation systems. (Source: ASTM C1774). The boundary temperatures are approximately 78°K and 293°K, the residual gas is nitrogen, and the total thicknesses are typically 25-mm (3 in.)

l. Purpose of Fire Proofing and Refractory: The fire proofing materials which are coated on the equipment supports (skirts, saddle, lugs), structures, and building should tolerate for the initial 2–4 hours of a fire emergency. The time is targeted on the minimum period until the firefighting system is effectively performed. Hence, typically the fire protection performance is tested for up to 2–4 hours under turbulent conditions, where the fire temperature is over 800–1000 °C (1472–1832 °F) per the regulation or specification. Meanwhile, the refractory materials have the duty for fire proofing and/or reducing the skin metal temperature under the refractory. As a result, for the second duty, the base metal may be designed below the creep-rupture temperature (below the Ac1, lower critical phase transformation temperature)

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m. References for Fire Proofing & Refractory
- – API RP2218 Fireproofing Practices in Petroleum and Petrochemical Processing Plants
- – API STD936 Refractory Installation QC-Inspection and Testing Monolithic Refractory Linings and Materials
- – ANSI A2.1 Methods for Fire Tests of Building Construction and Materials
- – ASTM C16 Test Method for Load Testing Refractory Shapes at High Temperatures
- – ASTM C20 Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water
- – ASTM C71 Terminology Relating to Refractories
- – ASTM C113 Test Method for Reheat Change of Refractory Brick
- – ASTM C133 Test Method for Cold Crushing Strength and Modulus of Rupture of Refractories
- – ASTM C134 Size, Dimensional Measurements, and Bulk Density of Refractory Brick and Insulating Firebrick
- – ASTM C150 Specification for Portland Cement
- – ASTM C181 Test Method for Workability Index of Fireclay and High-Alumina Plastic Refractories
- – ASTM C201 Thermal Conductivity of Refractories
- – ASTM C210 Test Method for Reheat Change of Insulating Firebrick
- – ASTM C309 Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
- – ASTM C580 Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacings
- – ASTM C704 Abrasion Resistance of Refractory Materials at Room Temperature
- – ASTM C860 Determining the Consistency of Refractory Castable Using the Ball-In-Hand Test
- – ASTM C862 Preparing Refractory Concrete Specimens by Casting
- – ASTM C865 Standard Practice for Firing Refractory Concrete Specimens
- – ASTM D2240 Rubber Property – Durometer Test for Indentation Hardness of Homogeneous Materials
- – ASTM E 84 Test for Surface Burning Characteristics of Building Materials
- – ASTM E119 Fire Tests of Building Construction and Materials (applicable unless the project has a fire proofing specification
- – ASTM E605 Thickness and Density of Sprayed Fire-Resistive Material Applied to Structural Members
- – ASTM E736 Cohesive/Adhesion of Sprayed Fire-Resistive Materials Applied to Structural Members
- – ASTM E761 Compressive Strength of Sprayed Fire-Resistive Material Applied to Structural Members
- – ASTM E1529 Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies
- – ASTM E1725 Fire Tests of Fire-Resistive Barrier Systems for Electrical System Components
- – EN ISO 1927-1 Monolithic (unshaped) refractory products – Part 1: introduction and classification
- – EN ISO 1927-2 Monolithic (unshaped) refractory products – Part 2: sampling for testing
- – EN ISO 1927-3 Monolithic (unshaped) refractory products – Part 3: characterization as received
- – EN ISO 1927-4 Monolithic (unshaped) refractory products – Part 4: determination of consistency of castables
- – EN ISO 1927-5 Monolithic (unshaped) refractory products – Part 5: preparation and treatment of test pieces
- – EN ISO 1927-6 Monolithic (unshaped) refractory products – Part 6: measurement of physical properties
- – EN ISO 1927-7 Monolithic (unshaped) refractory products – Part 7: tests on pre-formed shapes
- – EN ISO 1927-8 Monolithic (unshaped) refractory products – Part 8: determination of complementary properties
- – NFPA 15 Water Spray Fixed Systems for Fire Protection
- – NFPA 30 Flammable and Combustible Liquids Code
- – NFPA 58 Storage and Handling of Liquefied Petroleum Gases
- – NFPA 101 Life Safety Code
- – NFPA 231 Fire Tests for Building Construction and Materials
- – NFPA 231C Rack Storage of Materials
- – NFPA 255 Methods of Test of Surface Burning Characteristics of Building Materials
- – NFPA 321, Basic Classification of Flammable and Combustible Liquids
- – CFR 29 U.S. Code of Federal Regulations, Title 29
- – FM Global Datasheet 7-14 Protection for Flammable Liquid/Flammable Gas Process Equipment
- – FM Global Datasheet 4-1N Water Spray Fixed Systems
- – IRI IM.2.5.1 Fireproofing for Oil and Chemical Properties
- – UL 263 Fire Tests of Building Construction and Materials
- – UL1709 Rapid Rise Fire Tests pf Protection Materials for Structural Steel
- – UL 2196 Tests of Fire Resistive Cables
- – BS 476 Fire Tests for Building Materials and Structures
- – ISO/TR 22899 Determination of the Resistance to Jet Fires of Passive Fire Protection
- – ISO 834-1 AMD 1 Fire Resistance Tests
- – Norsok M-501 Surface Preparation and Protective Coating
- – DOE/ID/12903-4 Lightweight Alumina Refractory Aggregate, 1996
- – NASA TT F516 Thermal Conductivity of Refractory materials, 1966
- – Handbook of Refractory Practice, Harbison-Walker, 2005

n. Anchor support metals for refractory lining or hot insulation: See Sect. 2.6.2.3

o. See Table 3.17 for the purpose and the commercially/economically applicable insulation materials

p. UL1709 for fire proofing materials/coatings indicates that:To evaluate the performance of protective material through a test in a furnace capable of reaching 1103 °C (2000 °F) within 5 minutes of operation, the materials must provide sufficient fire protection so that equipment maintains structural integrity for 30 minutes in 1103 °C (2000 °F) fire

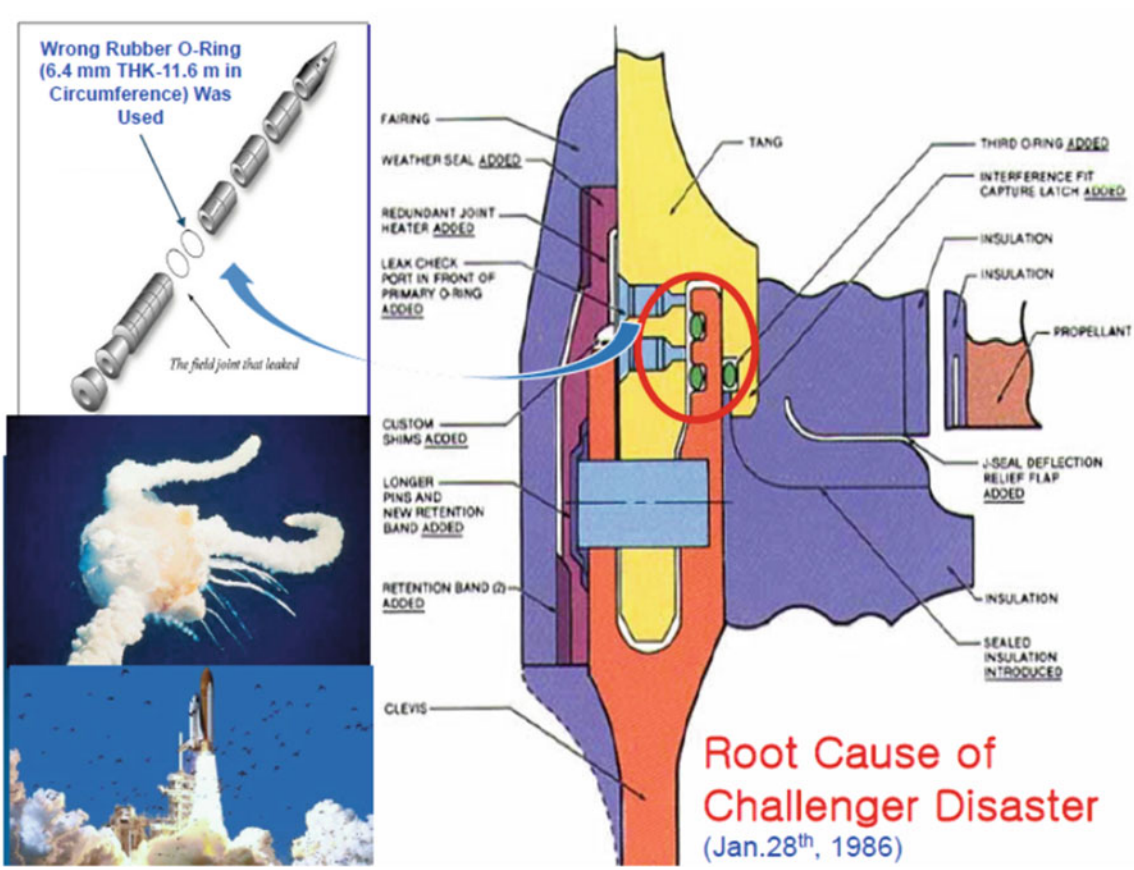
q. See the following websites for the comparison of several insulation materials
https://insulation.org/wp-content/uploads/2016/10/Insulation-Materials-Spec-Chart-Updated-JULY-2016.pdf
https://insulation.org/wp-content/uploads/2016/10/Guide-to-Insulation-Product-Specifications-November-2016.pdf

Nonmetallic (11/12)

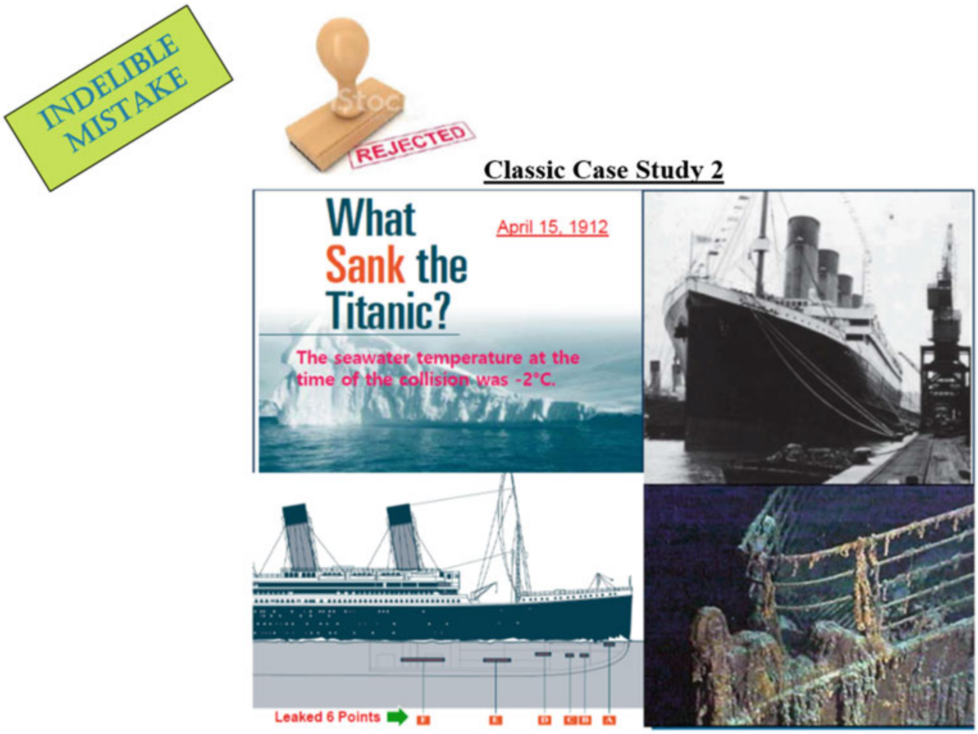
Notes

1. Chemical composition (wt%) of Mineral Fiber (typical)
   SiO_2: 30–45, Al_2O_3: −15, TiO_2: 2–4, Fe_2O_3: ≤2.5, CaO: 3–35, MgO: 6–12, Na_2O: ≤1.0, K_2O: ≤1.0, P_2O_5: ≤1.0
2. The high and low temperature limits per rigid (PUR-polyurethane rigid or PIR-polyisocyanurate rigid) or sprayed materials should be confirmed by the insulation supplier
3. There are many different types of refractory materials and its blending. The only most popular applications for equipment and structures in oil and gas industry are introduced in this table. See the references in general note "m" above for more details on refractory
4. ASTM C764 Mineral Fiber Loose-Fill Thermal Insulation (Type I: Pneumatic application, Type II: Pouring application) may be used together
5. See API RP583 (CUI), Table 6 for commonly applied temperature limits of several insulation materials

Classic Case Study 1

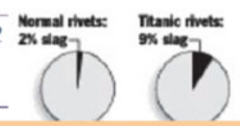


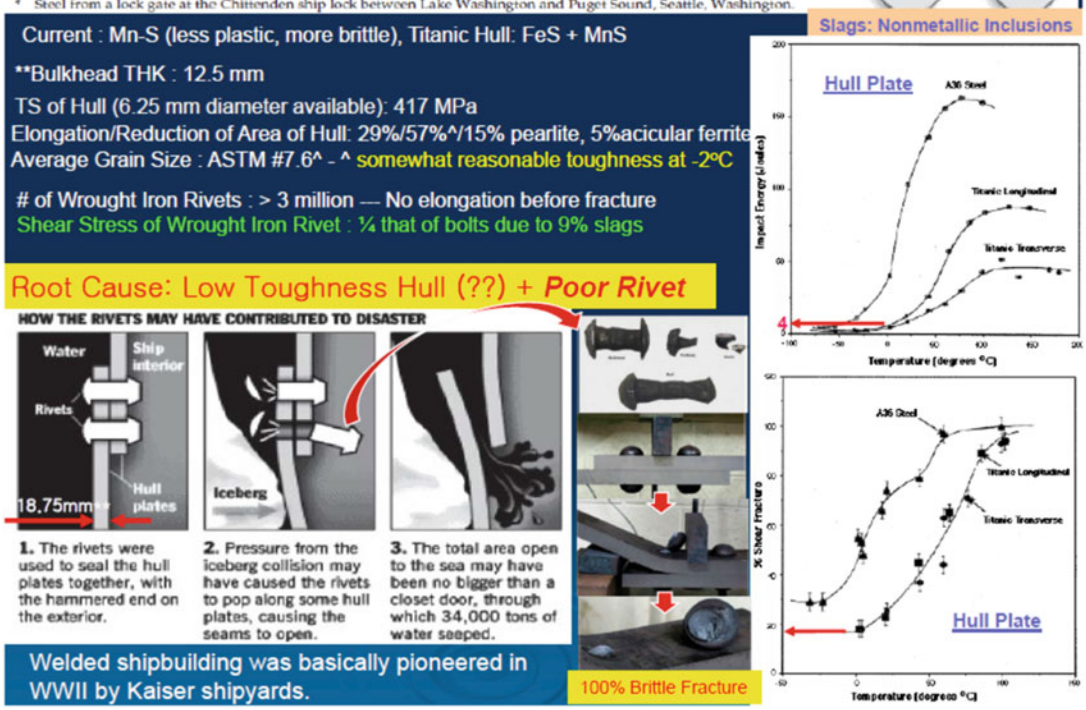
In many cases, tremendous failure comes from disqualification of a minor part.



	C	Mn	P	S	Si	Cu	O	N	Mn:S Ratio
Titanic Hull Plate	0.21	0.47	0.045	0.069	0.017	0.024	0.013	0.0035	6.8:1
Lock Gate*	0.25	0.52	0.01	0.03	0.02	—	0.018	0.0035	17.3:1
ASTM A36 (Current)	0.20	0.55	0.012	0.037	0.007	0.01	0.079	0.0032	14.9:1

* Steel from a lock gate at the Chittenden ship lock between Lake Washington and Puget Sound, Seattle, Washington.





In many cases, tremendous failure comes from disqualification of a minor part.

Chapter 3
Fabrication and Construction of Equipment and Piping

3.1 Pressure Vessels and Heat Exchangers

3.1.1 General Consideration of Fabrication and Construction

3.1.1.1 Applicable Codes, Standards, and Regulations

Table 3.1 shows the country standards for procedure vessel code. It may be bottom-line requirements for fabrication. Traditionally the local regulations (state, province, and city) and project specifications are more conservative than the country codes.

3.1.1.2 Check Points for Fabrication, Construction, and Operation

The activities in Table 3.2 should be considered for fabrication or construction other than pressure design.

In addition, the following checkpoints for fabrication and materials should be also confirmed before fabrication or construction:

(a) Applicable codes and standards for design and fabrication
(b) Permitted materials codes and standards
(c) Limitations of project specifications for the exemption and mitigation conditions in codes/standards
(d) Scope of work/supply – internals, ladder/platforms, insulation, fireproofing, spare parts, CP (cathodic protection), coating (finish coat), etc.
(e) Service temperature – MDMT (minimum design metal temperature), design temperature, maximum operating, depressurizing condition, and upset condition
(f) Service type – environment cracking, lethal, cyclic, etc.
(g) Chemical compositions, PMI and traceability for base materials and welding electrodes
(h) Heat treatment requirements – temperature, procedure, PWHT times, PWHT holding, tempering temperature control for tempered steels, etc.
(i) Test and inspection – ITP (test and inspection plan), base metals, WPS/PQR, productions, NDE, pressure test, NCR, etc.
(j) Welding – permitted welding processes and consumable vendors
(k) Coating – internal and external of equipment, pre-coat of base metal, etc.
(l) Packing and transportation – skids, protection, sealing, temporary coating, etc.
(m) Approved vendors' and subcontractors' list
(n) Change order request procedure
(o) Specification deviation request procedure

3.1.2 Fabrications of Parts

Figure 3.1 shows major steps of pressure vessel fabrication. All steps should be based on the safety, economy, minimizing deformation, mechanical/metallurgical degradation, environmental damage, and fabrication schedule.

3.1.3 Fabrication Sequence and Weld Seam Location

The fabrication sequence and weld seam location should be carefully selected in accordance with the following:

(a) Deformation and residual stresses (to minimize)
(b) Safety when the weld joint bursts
(c) Falling health of welders due to fumes (to minimize)

J. -C. Eun, *Handbook of Engineering Practice of Materials and Corrosion*,
https://doi.org/10.1007/978-3-030-36430-4_3

Table 3.1 Country standards for pressure vessel code

Code	Country	Code	Country
AD 2000	German	JIS B8265 (general) & 8266 (alternative)	Japan
AS 1210	Australia	KS B6750	S. Korea
ASME Section VIII, Div.1, 2, and 3	USA	PD5500	UK
BS EN 13445-1, 4	UK	PED (Pressure Equipment Directive)	Europe
GB 150	China		
IS 2825	India		

Table 3.2 (1/2) Major checkpoints for fabrication/construction/operation of equipment

Step	Critical Checkpoints	Considerable Codes, Standards, and Regulations[1]	Expected Damage and Preparation
Fabrication	1. Organization 2. Scope of work at shop and field 3. ITP 4. Fabrication sequence and schedule 5. Dead weight 6. Language, tolerance	– Applicable BPVC and standards – Local regulations – WPS/PQR applied at the field as well as main and subcontractor shops – Certified and/or approved labors and approved QA-QC system per code & standards	– Safety-PPE – Plastic deformation or crack
Transportation	1. Dead weight 2. Road survey 3. Weather and tide 4. Local regulations 5. Packages (scope, tags, and sealing) 6. Loading/unloading port capacity	– International and local regulations – Center of gravity and strength calculation for shaking load	– Safety-PPE – Plastic deformation – Corrosion
Erection and Assembly	1. Erection sequence 2. Dead load of vessel less: fireproofing, refractory lining, piping, all loose internals, catalyst, packing, and insulation 3. Temporary loads/forces caused by erection 4. Full wind and/or earthquake 5. Assembly at shop and field	– Crane and lifting design & calculation – Center of gravity and strength calculation for shaking/impact factors	– Safety-PPE – Failure due to ineffective use of cranes and lifts
Hydrostatic/ Pneumatic Test or Flushing of Equipment	1. Hydrotest water quality and contamination 2. Dead load of vessel plus fireproofing, all installed internals, insulation, and platforms and other equipment supported from the equipment 3. Applicable live loads excluding vibration and maintenance live loads[3] 4. Piping loads including pressure thrust[4] 5. Pressure and fluid load (water) for testing or flushing equipment and piping unless pneumatic test is specified 6. Wind load for a max. wind speed, such as 35–55 mph 7. Ground subsidence during hydrotest	1. Requirements of Sect. 5.5 in this book should be carefully considered 2. Procedure including safe distance per code and standard 3. Maximum temperature and pressure as well as thermal shock during flushing	– Safety – Plastic deformation or crack due to over pressure, rapid pressurization, and brittle materials used
Painting & Coating	1. Scope at shop and field 2. Interval of each layer 3. Isolated work place for surface preparation and spray coating/painting	1. Approved specifications including VOC 2. Inspection per specification/ procedure 3. See Sects. 3.4.3 and 3.4.4 for more details	– Safety-PPE – Contamination
Normal Operation	1. Dead load of vessel plus fireproofing, all internals, catalyst, packing, refractory, insulation, and platforms and other equipment supported from the equipment 2. Applicable live loads excluding vibration and maintenance live loads[3] 3. Piping Loads including pressure thrust[4] 4. Pressure and fluid load during normal operation, excluding fluid transient loads 5. Thermal loads[5]	– All loads conditions to be considered – e.g., ASME Sec.VIII, Div.1, UG–22 – PRD (pressure relief devices) – e.g., ASME Sec.VIII, Div.1, UG–126/127/128	– Safety-PRD – Plastic deformation or crack – Fire and explosion

Table 3.2 (2/2) Major checkpoints for fabrication/construction/operation of equipment

Step	Critical Checkpoints	Considerable Codes, Standards, and Regulations[(1)]	Expected Damage and Preparation
Abnormal or Startup Operation plus Occasional[(2)]	1. Dead load of vessel plus fireproofing, all internals, catalyst, packing, insulation, and platforms and other equipment supported from the equipment 2. Applicable live loads excluding vibration, and maintenance live loads[(3)] 3. Piping Loads including pressure thrust[(4)] 4. Pressure and fluid load during abnormal operation, including startup or abnormal fluid transients 5. Thermal loads[(5)] 6. Wind load for a max. wind speed, such as 35–55 mph.	– PRD (pressure relief devices) – e.g., ASME Sec.VIII, Div.1, UG–126/127/128	– Safety-PRD – Plastic deformation or crack – Fire and explosion

Notes:
[(1)]The loads listed in ASME Sec. VIII, Div.1, UG–22 should be considered if applicable.
[(2)]Abnormal or startup operating conditions need to be analyzed if the conditions are not specified by the owner
[(3)]Live loads should not be included in this load case when their exclusion results in a more conservative design
[(4)]Piping loads and loads due to other equipment (such as agitators) acting on all vessel nozzles should be included as a design load. Nozzles subjected to piping forces and moments should be analyzed for additional shell reinforcement requirements. Forces and moments, and their orientations, to be used in the calculations should be those given on the vessel drawing
[(5)]Thermal loads resulting from using materials with different coefficients of thermal expansion and/or from temperature gradients introduced during normal operation and/or startup, shutdown, or other transient modes of operation should be included as a design load

Figure 3.1 Major Steps of Pressure Vessel Fabrication

(d) Welding consumables and time (to minimize)
(e) To consider the accessibility and sequence/closing seam
(f) To consider the commercial size of the base metal
(g) Transportation when they are shipping as segments
(h) Assembly of modules or sections

Table 3.3 and Fig. 3.2 show typical fabrication sequence of pressure vessel.

Figure 3.3 shows the sequence for welding, NDE/inspection, and heat treatment of heavy wall reactors.

Table 3.3 Fabrication sequence of pressure vessels

1	2	3	4	5	6	7	8	9
Raw Materials Inspection	Cutting	Forming Bending Machining	Long Seam Welding	Assembly & Girth Seam Welding	Final Assembly All Attachments	PWHT	Hydrotest	Coating and Packing/Shipping Transportation
Materials Inspection	Marking Inspection	Dimension Measuring	NDE & Production Test Coupon	NDE	NDE	Heat Recording NDE	Witness & Inspection	Inspection

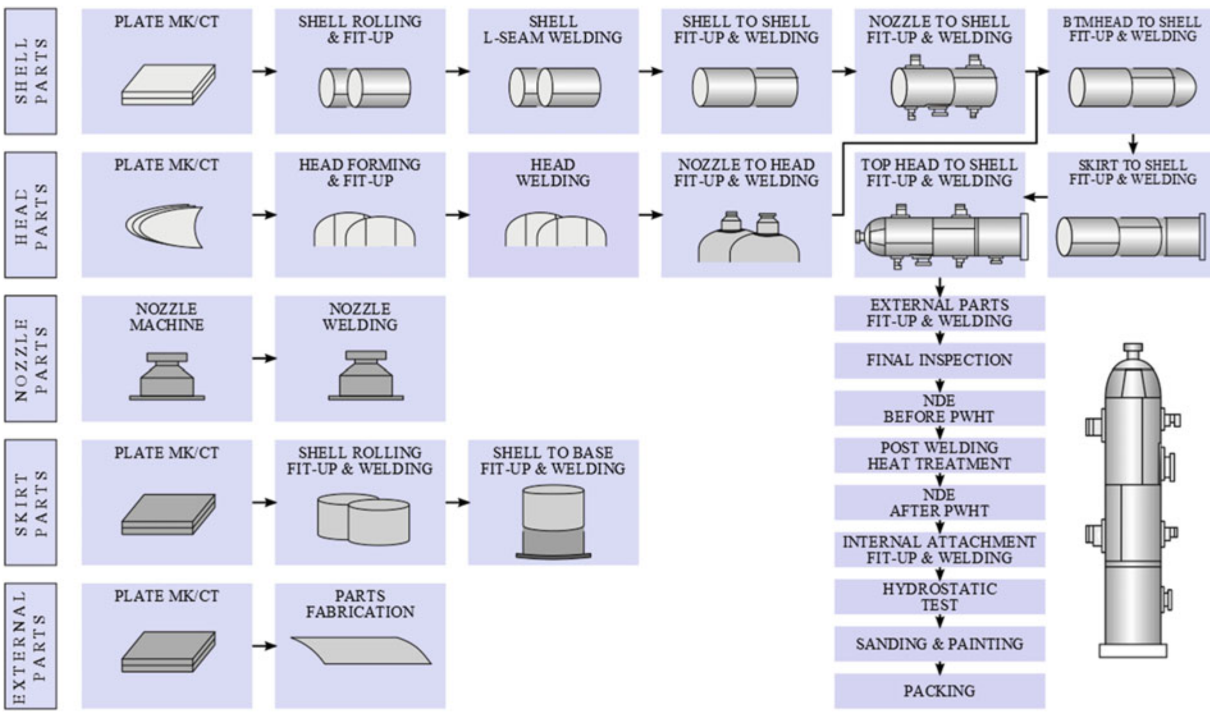


Figure 3.2 Fabrication sequence of pressure vessels (overview)

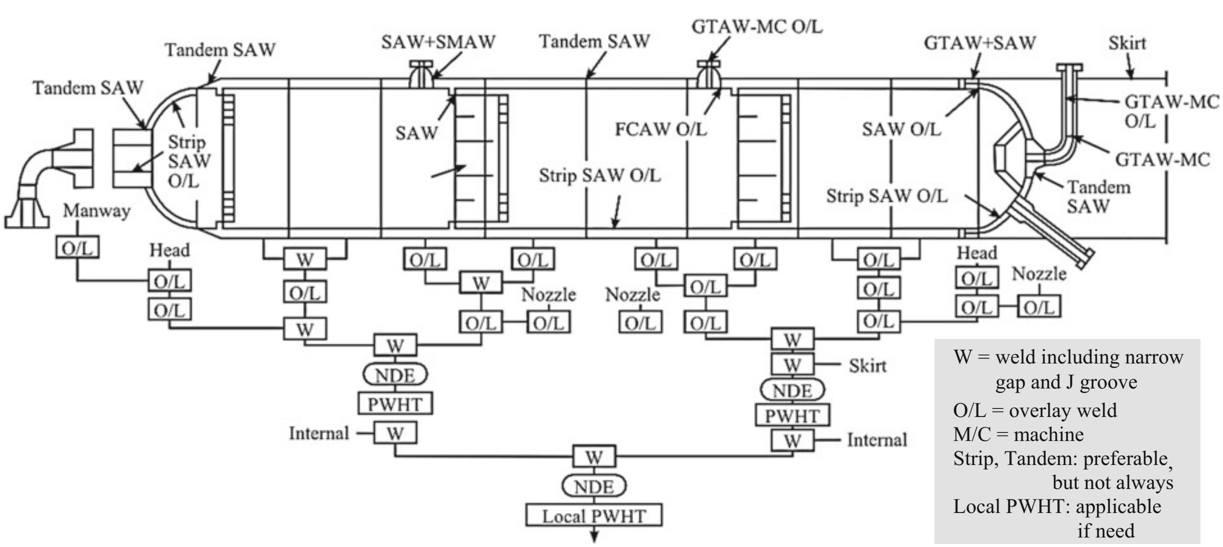


Figure 3.3 Fabrication sequence for welding, NDE/inspection, and heat treatment of heavy wall reactors

3.1.4 Specific Requirements for Fabrication

3.1.4.1 Cold Work (Cold Forming and Cold Bending)

(a) Metallic Characteristics, Definition, and Application of Cold Work

1. Metallic Characteristics of Cold Work

Plastic deformation, which is carried out in a temperature region and over a time interval such that the strain hardening is not relieved, is called *cold work*. Cold working produces additional dislocations within the metal structure. In the early stages of plastic deformation, slip is essentially on primary glide planes and the dislocations form coplanar arrays. As deformation proceeds, cross slip takes place. The cold-worked structure forms high dislocation density regions that soon develop into networks. The metal becomes less malleable and ductile. The following properties affect cold work significantly:

– Tensile strength (increase)
– Hardness (increase)
– Yield strength (increase)
– Ductility (decrease)

2. Definition and Application of Cold Work

ASME Section II, Part D, A-205.1

Cold working is any process of plastic deformation of a metal that occurs at temperatures below the material's transformation or recrystallization temperature (LCPTT; see Tables 1.70, 3.4, 4.113 in this book) and in which the material is hardened by the strain. As the hardness of a cold-worked material is increased, the ductility of the material decreases. The amount of hardening that occurs with a given amount of cold work varies with the alloy system, and cold work effects are particularly pronounced in alloy steels like ASS (300 series SS). When ASS that have been moderately to heavily cold-worked are operated in the creep range (generally above about 540 °C (1000 °F)), recrystallization may occur, and the grain size can be substantially reduced, particularly if the temperature is limited to a level only slightly above the recrystallization temperature. This can result in an increase in the creep rate, with a corresponding decrease in creep rupture strength. In addition, cold work contributes to certain types of microstructural instability. In addition, the residual stresses induced by cold work can substantially increase the risk of cracking in ASS and other austenitic alloys when these materials expose to certain types of aggressive environment (e.g., SCC and various embrittlement).

Concern over the effects of cold work has led to the implementation of various requirements in the construction codes for heat treatment of certain cold-worked materials once a critical level of strain is exceeded.

It is understood that because of the complexity of the relationship between cold work and material degradation, implementation of the heat treatment rules is not a guarantee that premature failures will be avoid in all situations. Likewise, violation of the limits defined in the rules will inevitably result in premature failures. Factors such as melting practice, consolidation (forming) and heat treatment practices of the material producer, and the initial grain size all can play a role in determining whether a cold-worked material operates reliably in service. However, the rules represent a consensus of what can be considered good practice by parties representing disparate interests and, in general, serve to benefit the end-user.

[Commentary Notes] However, the rules represent a consensus of what can be considered good practice by parties representing disparate interests and, in general, serve to benefit the end-user.

BS EN 13445-4

Cold forming of material group 1.1, 1.2, 1.3, 2.1, 3.1, 4, 5, 6, and 9 specified in Table 2.101 in this book should be carried out *at temperatures at least 30 °C (54 °F) below the maximum permissible holding temperature for the PWH*T in Table 4.134. Cold forming of material group 8.1, 8.2, and 10 in Table 2.101 should be carried out at temperatures below 300 °C (572 °F).

ASME B31.1

Cold bending or forming is performed at a temperature below the LCPTT minus 56 °C (100 °F) except at a temperature below 705 °C (1300 °F) P. No 15E, while hot bending or forming is performed at a temperature equal to or above the LCPTT minus 56 °C (100 °F) except at a temperature equal to or above 705 °C (1300 °F) for P. No 15E. (See Table 4.113 for lower critical temperatures.)

Mill Supplier (for reference)

Cold forming considering high hardening and/or residual stresses by strains is when it is done at 500 °C (930 °F) and below.

(b) Advantage

– Cheaper compared to hot work
– Good dimensional control
– Good surface finish of the component
– Strength and hardness of the metal are increased
– An ideal method for increasing hardness of those metals that do not respond to the heat treatment

(c) Disadvantage

– Decreased ductility – subsequent heat treatment is mostly needed to remove the residual stresses set up during cold working
– Only ductile metals can be shaped through cold working
– Susceptible to cracking environment (SCC, SSC, hydrogen embrittlement, etc.)

(d) Calculation of Fiber Elongation

A basic measurement of degree of plastic deformation **(%CW) = (Ao – Ad)/Ao × 100**
where, Ao = the original area, Ad = the area after deformation
However, most industrial codes/standards address the fiber elongation calculation formulas after cold work and the heat treatment requirements in accordance with the material, component's shape, and other type. See papa. 4.12.3 (1) and (2) in this book for stress relieving requirements per the fiber elongation by cold work in ASME and BS EN.

(e) Cold Work Effects of Stainless Steels
Cold forming operations performed during the manufacture of austenitic stainless steel (ASS) pressure parts may cause impaired service performance when the component operates in the creep range [above 540 °C (1004 °F)]. This impairment may entail some of the following:

1. Recrystallization to a finer-grain size, leading to an increase in creep rate and a decrease in rupture strength; the major variables governing recrystallization kinetics are extent (as fiber elongation) of cold work, temperature, time, and alloy composition. For a given amount of cold work, the recrystallization kinetics is broadly described by an Arrhenius type of relationship in which recrystallization occurs in a short time (minutes to hours) at a high temperature [but, in a long time (hundreds to thousands of hours) at a lower temperature]. At forming strains below about 20%, recrystallization is not likely to occur during the service life of an ASS component if the temperature is sufficiently low [about 565 °C (1049 °F) or lower for simple alloys like 304H SS or 316H SS or about 620 °C (1148 °F) or lower for a more complex material like Alloy 800H]. At a sufficiently high level of cold forming strain and service temperature, recrystallization during operation becomes a threat to the long-term serviceability of an alloy. Because of the relationship between grain size and creep rupture strength, the fine-grained and recrystallized material has lower stress-rupture strength, higher creep rate, and higher rupture ductility. The consequence is premature failure relative to an equivalent unstrained material that does not recrystallize during service. Heat treatment after cold forming at temperatures given in the material specification will restore the intended properties of the material and will minimize the threat of premature failure due to recrystallization during the time of operation.
2. A decrease in ductility that renders the component vulnerable to premature failure from the formation of cracks, particularly at attachments and stress concentrations; as austenitic alloys are cold-worked, the hardness and strength are enhanced, but the ductility is reduced. At temperatures below the creep range, this tradeoff between strength and ductility can be exploited without significant risk of service problems related to low ductility (reheat cracking or stress relaxation cracking – see Sect. 2.1.6.9). However, as operation intrudes into the creep range, another problem besides recrystallization emerges, which involves failure due to impaired stress-rupture ductility. This phenomenon is operative below the recrystallization threshold. It is characterized by premature creep crack growth in the cold-worked material and is exacerbated by the presence of stress concentrators (e.g., notches, welded attachments, etc.).

   The alloys that are most susceptible to premature failure from ductility impairment are those which have been strengthened by the addition of a potent carbide former such as Cb (347H SS) or by the addition of gamma prime (γ‘) formers such as Ti and Al (Alloy 800H). Ti is a carbide former in 321H SS, but it has less effect on the ductility impairment mechanism than columbium in 347H SS. Even when solution treated, these particle-strengthened alloys are typically stronger but have less stress-rupture ductility than the simpler substitutional-strengthened alloys, such as 304H SS and 316H SS. Failures by ductility impairment are always intergranular and occur with little or no macro-distortion of the component; i.e., there is no obvious necking down or swelling of the failed component.

   The ductility impairment damage mechanism is not fully understood, but it is generally thought to involve deformation of the grains by cold work, followed by precipitation at intergranular dislocation sites created by the cold work during service exposure. This produces a matrix with very high creep strength, so that most creep deformation must be accommodated at the "weaker" grain boundaries.

   Such strain concentration at the grain boundaries greatly increases the risk of low ductility creep crack growth type fractures. In the extreme case, the rupture ductility cannot accommodate the inelastic strains associated with redistribution of the cold-forming residual stresses; fracture initiates soon after service begins; and failure occurs within months or even weeks. The same phenomena have been observed in heavily constrained thick section weldments in materials such as 347H SS and Alloy 800H and have been referred to as relaxation cracking or strain-induced precipitation hardening (SIPH). As was the case with recrystallization, heat treatment after cold forming at the temperatures indicated in the material specification restores the intended properties of the material and minimizes the threat of premature failure by ductility impairment.
3. Strain (deformation)-induced martensite and magnetization can be created per the strain. See Sect. 2.1.6.12(a) and (b) for more details.

(f) Cold Working of Aluminum Alloys
It is permissible to soften aluminum that has been cold-worked when the manufacturer, purchaser, and inspecting authority agree that the extent of the cold working is sufficient to necessitate treatment.

The requirements for any softening treatments should be subject to agreement between the manufacturer, purchaser, and inspecting authority [PD5500, Al.4.2.2.4.2].

(g) Other Requirements
Cleanliness of tooling and selection of correct lubrication are of particular importance. Suitable interface material should be used between cold forming equipment and workpiece. Especially the cleanliness for corrosion resistance alloys (SS, nickel alloys, copper alloys, titanium alloys, zirconium alloys, etc.) should be thoroughly controlled.

3.1.4.2 Hot Work (Hot Forming and Hot Bending)

(a) Definition, Application, and Metallic Characteristics of Hot Work

Hot working is usually performed at elevated temperatures that exceed the limits of cold work above. *Hot working* refers to the process where metals are plastically deformed above their recrystallization temperature and strain hardening does not occur. As a general guideline, the lower limit of the hot working temperature of a material is about 0.6 times its melting temperature (see Appendix A.8 in this book for melting temperatures of several metals). Lead, however, is hot-worked at room temperature because of its low melting temperature. At the other extreme, molybdenum is cold-worked when deformed even at red heat because of its high recrystallization temperature. The resistance of metals to plastic deformation generally falls with temperature. For this reason, larger massive sections are always worked hot by forging, rolling, hot drawing, or extrusion. Metals display distinctly viscous characteristics at sufficiently high temperatures, and their resistance to flow increases at high forming rates. This occurs not only because it is a characteristic of viscous substances, but also because the rate of recrystallization may not be fast enough.

ASME B31.1

Hot bending or forming is performed at a temperature above *LCPTT* minus 56 °C (100 °F), where *LCPTT* is the lower critical phase transformation temperature of the material. (See Table 4.113 for lower critical temperatures.)

The following characteristics are normally shown by hot work:

– No strain hardening
– Usually performed at elevated temperatures
– Lead and tin are exceptions (low melting point)
– Lower limit of the hot working temperature: 60% of the melting temperature

1. Hot Spinning and Forming

The process consists of heating the metal to forging temperature and then forming it into the desired shape on a spinning lathe which is similar to an engine lathe.

Usually shapes of circular cross-section, which are symmetrical about the axis of rotation, are formed by this process. The workpiece is shaped over a formed revolving metal holding device, called chuck, with the help of spinning tools. It very well compares with drawing of stamping in so far as the production in small quantities is concerned, since the cost of dies for such small quantities will lead to uneconomical production through the latter methods. Hot spinning is generally used for thicker plates and sheets that cannot be shaped through cold spinning.

2. Hot Forging

These process basic alloys consist of heating the metal to plastic state and then applying pressure to form it into different shapes and sizes. Unlike rolling, the pressure in this case is not continuous but intermittent. The hot metal piece may be compressed along its length to increase its cross-section, along its cross-section to increase its length, within a closed cavity to acquire the shape of that cavity or in different directions to bend it into different shapes. The pressure may be applied by hand hammer called hand or smith forging, by power hammers, called hammer forging, by presses (press forging) or upset forging machines.

3. Hot Drawing

This process is widely used for the production of thicker walled seamless tubes and cylinders. It is usually performed in two stages. The first stage consists of drawing a cup shape out of a hot circular plate with the help of a die and a punch. The second stage consists of reheating the drawn cup, and drawing is further to the desired length having the required wall thickness. The second drawing operation is performed through a number of dies, which are arranged in a descending order of their diameters, so that the reduction in wall thickness is gradual in various stages. The farther end of the drawn object is always blind, which may be cut off to produce a through hole, if required.

(b) Recrystallization Temperatures (Phase Transformation) of Several Metals

Table 3.4 shows the recrystallization temperatures of several metals. See Table 4.113 for lower critical phase transformation temperature (LCPTT) of several commercial carbon and low alloy steels as well.

(c) Advantage

1. Plastic-deformed readily. Large shape changes are possible without ruptures. Smaller, faster-acting machines.
2. No strengthening occurs during hot working.

Table 3.4 Recrystallization temperatures of several metals

Metal	Recrystallization Temperatures, °C (°F)	Remark
Lead & Tin	≤ 10 (50)	
Zinc	25 (77)	
Magnesium & Aluminum	150 (302)	
Gold, Copper, and Silver	200 (392)	
Iron, CS, and Low Alloy Steel[(a)]	Approx. 725–820 (1340–1505)	See Table 4.113
Tungsten	1400 (2552)	

Notes: (source: API 530, ASME VIII-D1, B31.1, Handbook of SS, and NiDI Publ. 1232, and Anil Sinha, Physical Metallurgy Handbook, McGraw Hill, 2002)

[(a)]For 0.3–0.6%C low alloy steel, recrystallization temperatures (°C) = 854-179C-13.9Mn-17.8Cu-1.7Ni + 44.4Si [wt % in element]

3. Elimination of imperfections.
   – Impurities are broken up and distributed throughout material.
   – Gas pores can be closed. Porosity is eliminated readily.
   – Composition differences can be reduced.
   – Concentrated impurities, if any in the metal are disintegrated and distributed throughout the metal.
4. Anisotropic behavior is gained.
5. A uniformity is established either by squeezing other impurities into fiber slags or distributing them throughout the mass.
6. Surface has a finer-grain size than the center.
7. Metal remains soft and ductile during process.
8. Hardness and ductility of metal are not changed.
9. Grain structure of the metal is refined and physical properties improved (Fig. 3.4).
10. Surfaces need not be clean and scale free.

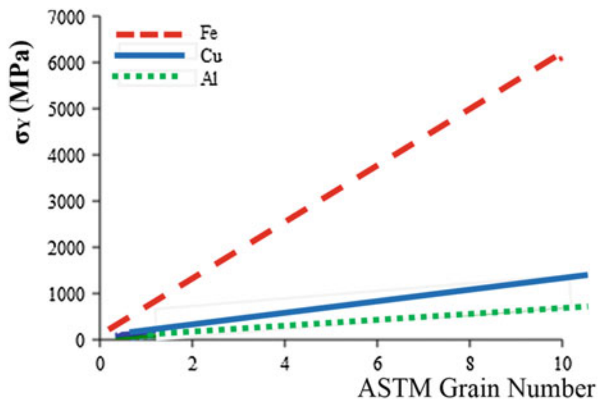


Figure 3.4 Strength by grain refinement in CS. (Source: ASM Metal H/D Vol. 1 – modified)

(d) Disadvantage
1. It involves excessive expenditure because of high cost of tooling. This, however, is compensated by the high production rate and better quality of products (high-temperature and high-energy consumption).
2. Metal loss due to high temperature a rapid oxidation or scale formation takes place during process, leading to poor surface finish and loss of metal.
3. On account of the loss of carbon from the surface of the steel piece being worked, the surface layer loses its strength, which is a disadvantage when the part is put to service.
4. This weakening of the surface layer may give rise to a fatigue crack that may ultimately result in fatigue failure of the part.
5. Close tolerances cannot be maintained.

(e) Hot Forming of CS and LAS

BS EN 13445-4 addresses that:

Hot forming of material group 1.1, 1.2, 1.3, 3.1, 4, 5, 6, and 9 specified in Table 2.101 should be carried out at temperatures above the maximum permissible holding temperature for stress relieving/PWHT in Table 4.134 in this book, usually in the temperature range of normalizing, in accordance with the material specifications.

Hot forming of thermo-mechanically treated steel grades is not permitted.

The forming procedure should define the rate of heating, the holding temperature and the holding time given to the formed part.

Hot forming is a process that is performed at temperatures above the stress relief temperature and will usually be carried out in the austenite region.

In view of danger of excessive grain growth, the product should be austenitized above Ac3, but not higher than 1050 °C (1922 °F). After reaching the temperature in the product, it should be kept at temperature not longer than 10 min. For the same reason, the heating rate should be defined.

After hot forming, the product should be cooled in still air, unless otherwise specified.

As every heat treatment above the normalizing temperature leads to a grain growth that adversely affects the impact values, the hot forming for normalized steels should be divided into two groups below.

1. Normalized steels with specified impact values at temperatures of ≥ -20 °C (-4 °F).

   For normalized steels that are hot formed only in a single operation the maximum temperature of the product should not be above 980 °C (1796 °F).

   For hot forming operations in more than a single operation the maximum temperature of the product should not be above 1050 °C (1922 °F). Before the last operation, the product should be cooled down below 500 °C (932 °F). For the last operation, the maximum temperature of the product should be below 980 °C (1796 °F) for steels with a minimum yield strength 360 N/mm2 (52 ksi) or 940 °C (1724 °F) for steels with a minimum yield strength >360 N/mm2 (52 ksi).

   A subsequent heat treatment may be waived, if the forming process of the last operation has been completed at a temperature above 750 °C (1392 °F) or above 700 °C (1292 °F) where the degree of deformation does not exceed 5%. If the conditions, especially regarding the maximum and minimum temperatures in the last operation cannot be achieved, normalizing as specified by the steel manufacturer should be carried out after the forming process.

   For steels that have to be tempered after normalizing, the prescribed tempering treatment may be performed when the hot forming has been carried out according to above.

2. Normalized steels with specified impact values at temperatures of < -20 °C (-4 °F)

   For normalized steels which are hot formed only in a single operation, the maximum temperature of the product should not be above 940 °C (1724 °F) when the steels with minimum yield strength $\leq$360 N/mm^2 (52 ksi) or 925 °C (1697 °F) for steels with a minimum yield strength >360 N/mm^2 (52 ksi).

For hot forming operations in more than a single operation, the maximum temperature of the product should not be above 1050 °C (1922 °F). Between the different operations, the product should be cooled down below 500 °C (932 °F). For the last operation, the maximum temperature of the product should be below 940 °C (1724 °F) for steels with a minimum yield strength ≤360 N/mm2 (52 ksi) or 925 °C (1697 °F) for steels with a minimum yield strength >360 N/mm2 (52 ksi).

A subsequent heat treatment may be waived, if the forming process of the last operation has been completed at a temperature above 750 °C (1382 °F) or above 700 °C (1292 °F) if the degree of deformation does not exceed 2%. If the conditions, especially regarding the maximum and minimum temperatures in the last operation cannot be achieved, normalizing as specified by the steel manufacturer should be carried out after the hot forming process.

For steels that have to be tempered after the normalizing, the prescribed tempering treatment may be performed when the hot forming has been carried out according to above.

3. Quenched and tempered steels
For quenched and tempered steels, it is necessary to perform a total new quenching plus tempering operation after hot forming. For the hot forming process itself, the conditions specified in (1) and (2) above should apply.

(f) Hot Forming of Stainless Steels

BS EN 13445-4, Sect. 9.3.2 addresses that:

Hot forming of material group 8.1, 8.2 (ASS), and 10 (DSS) in Table 2.101 in this book should be carried out in accordance with Table 3.5.

(g) Hot Forming of Nickel Alloys

BS PD 5500, Ni.4.2.1 addresses that:

Nickel and nickel alloys to be hot-worked should be heated uniformly, without flame impingement, to a temperature not exceeding the maximum given for the particular material in Table 3.6. The hot forming temperature should not exceed the final annealing temperature.

Nickel and nickel alloys should be cleaned before heating as they can be embrittled by sulfur, phosphorus, lead, zinc, and other low melting point metals and alloys which can be present in marking materials, die lubricants, pickling liquids, dirt accumulated in storage, furnace slag, and cinder. Any foreign substance, even those that are not being embrittle, can burn into the surface of the metal at high temperatures.

Most fuels may be used if detrimental impurities, such as sulfur, are kept at low levels. In view of the above, however, it is preferable that nickel and nickel alloys are cold-worked whenever possible.

(h) Hot Forming of Copper Alloys

BS PD 5500, Cu.4.2.2.4 addresses that:

Copper and copper alloy plates to be hot-worked should be uniformly heated in a neutral or oxidizing atmosphere, without direct flame impingement, to a temperature within the range specified in Table 3.7. Where hot forming is to be used, tests should be carried out to demonstrate that the proposed heat treatment gives acceptable properties on a representative test piece.

(i) Hot Forming of Titanium Alloys

BS PD 5500, Ti.4.2.2.4 addresses that:

Hot forming should be carried out in accordance with written manufacturing procedures. These

Table 3.5 Forming conditions for material group 8.1, 8.2, and 10[(3)] (BS EN 13445-4, Table 9.3-1)

Materials	Max. Temperature, °C (°F)	Min. Temperature, °C (°F)	Cooling Conditions from The Highest Forming Temperature[(2)]
Low-Carbon SS[(2)] Stabilized SS[(4)]	1150 (2102)	850 (1562)	Air cooling for $t \leq 25$ mm (1″) Water cooling for $t > 25$ mm (1″)
Non-stabilized SS			Air cooling for $t \leq 6$ mm (1/4″) Water cooling for $t > 6$ mm (1/4″)

Notes:
[(1)]C ≤ 0.03%
[(2)]Cooling conditions defined in the material specifications should be governed
[(3)]Material group 8.1 and 8.2: ASS
Material group 10: DSS
[(4)]See Table 2.47, Note 1, in this book

Table 3.6 Maximum hot forming temperatures of nickel alloys (PD5500, Table Ni.4.2-1)

Materials	Temperature, °C (°F)
NA 11 (UNS N02200-Alloy 200)	930 (1706)
NA 12 (UNS N02201-Alloy 201)	930 (1706)
NA 13 (UNS N04400-Alloy 400)	980 (1796)
NA 14 (UNS N06600-Alloy 600)	1040 (1904)
NA 15 (UNS N08800-Alloy 800)	980 (1796)
NA 16 (UNS N08825-Alloy 825)	980 (1796)
NA 21 (UNS N06625-Alloy 625)	1040 (1904)

Note
1. All classes should comply with BS 3072, 3074, and 3076

Table 3.7 Hot forming temperatures of copper alloys (PD5500, Table Cu.4.2-1)

Materials	Temperature, °C (°F)
Copper	750 to 950 (1382 to 1742)
70Cu-30 Zn Brass	750 to 870 (1382 to 1544)
Aluminum Brass	575 to 725 (1067 to 1337)
Admiralty Brass	680 to 780 (1256 to 1436)
60Cu-40Zn Brass (Low Lead)	650 to 750 (1202 to 1382)
Naval Brass	650 to 750 (1202 to 1382)
90–10 Copper-Nickel	850 to 950[a] (1562 to 1742[a])
70–30 Copper-Nickel	925 to 1025[a] (1697 to 1877[a])
66Cu-30Ni-2Fe-2Mn	925 to 1025[a] (1697to 1877[a])
Aluminum Bronze	800 to 975[a] (1472 to 1787[a])

Note
[a]These materials should not be hot formed below this temperature range due to hot shortness

procedures should include information such as material preparation for heating, heating times and temperatures, inspection and quality controls, and any subsequent heat treatment and cleaning procedures. Suitable interface material should be used between forming equipment and workpiece.

The material should be heated uniformly in a furnace to a maximum temperature of 600 °C (1112 °F), using a slightly oxidizing or inert atmosphere. Soaking times should not exceed 1 hour per 50 mm (2 in.) of section thickness and should be to a minimum.

Following any hot forming operation, or when specified after cold forming, the material should be given an annealing treatment in accordance with Table 4.140, precautions should be taken to avoid contamination and embrittlement. After annealing the surfaces might require a descaling treatment.

(j) Hot Forming of Aluminum Alloys

BS PD 5500, Al.4.2.2.4.1 addresses that:
Aluminum plates to be treated or hot-worked should be heated uniformly in a neutral or oxidizing atmosphere, without flame impingement, to a temperature not exceeding 450 °C (842 °F). Deformation should not be carried out after the temperature of the material has fallen below 300 °C (572 °F). Local heating should not be used.

(k) Requirements due to Hot Work of Clad Steels
See Table 4.115.

(l) Requirements due to Hot Work of Tubular Products
See Table 4.124.

(m) Treatments after Hot Forming [sources]

1. Scale removal
Heavy scale remaining after any hot forming operation should be removed by a suitable descaling process which will not impair the quality of the material or have an adverse effect on the corrosion resistance of the exposed surfaces [PD 5500, 4.4.2.1].

2. Normalizing of ferritic steels [PD 5500, 4.4.2.1 and 4.4.2.2]
Hot-formed parts of vessels should receive a normalizing or grain refining heat treatment, either before or after welding, unless the process of hot forming was performed within such a temperature range and followed by cooling in such a manner as would provide this treatment for the material concerned.

Where normalizing is undertaken, the parts should be brought to normalizing temperature at a suitably controlled rate and should be maintained at the temperature long enough for thorough soaking.

Actual heating rates are not critical but should be controlled to the extent necessary to avoid any possibility of mechanical damage to the parts in question during the heating process. They should then be uniformly cooled at the appropriate rate. This is generally achieved by cooling freely in still air.

Where the geometry of the parts is such that the cooling rate will not be the same throughout, the necessity for a further stress relieving treatment should be considered with particular attention being paid to a slow rate of cooling. In the case of alloy steels, the range of cooling rates experienced should not result in mechanical properties different from those specified.

3.1.4.3 Fabrication Requirements in ASME Codes (Pressure Vessels and Piping) – Table 3.8

Table 3.8 (1/3) Fabrication requirements in ASME (all paragraphs and tables are from each code)

Limitation and Requirements	ASME Sec. VIII, Div.1	ASME Sec. VIII, Div.2	ASME Sec. VIII, B31.3
Materials identification See Sect. 2.5.1 in this book for more details	**UG-77, 85, 94** To maintain traceability by QC system	**Annex 6-A** PMI Practice	**(A/M/MA)323.1** (1) Listed materials (2) Unlisted materials (3) Unknown materials (4) Reclaimed materials
Nominal thickness as Governing thickness See Sect. 1.1.12 and 2.2.2.2, Figs. 2.135, 2.138, and 2.139 in this book for more details	**UW-40(f): For PWHT requirements** (1) Butt joints with full penetration (2) Groove welds (3) Fillet welds (with groove) (4) Stud welds (5) Unequal thicknesses **UCS-66(a): For impact test requirements** Guideline for plates and pipes, casting, flat non-welded parts, non-welded parts > 6″, non-welded parts-flange, dished portion **UHT-56(a)** For PWHT of Q-T steels in Table, UHT-56; for clad or weld overplayed vessels or parts of vessels, the total thickness of the base materials should be employed	**3.11.2.3** Exemption from impact testing based on the MDMT, thickness, and material specification **Figs. 3.7 and 3.8** Impact test exemption curves **6.6.6.1** For clad or weld overlayed vessels or parts of vessels, the total thickness of the base materials should be employed to determine PWHT requirements	**(M)331.1.3** for PWHT See Table 4.127 in this book for more details **Fig. 323.2.2A** for impact test
Ligaments for tube holes	**UG-53** Ligament	**4.10.2** Ligament efficiency	–

Table 3.8 (2/3) Fabrication requirements in ASME (all paragraphs and tables are from each code)

Limitation and Requirements	ASME Sec. VIII, Div.1	ASME Sec. VIII, Div.2	ASME Sec. VIII, B31.3
Repair of defects in materials/welds	**UG-78** Repair of defects in materials **UW-38** Repair of defects in welds **UW-51(b)** Repair welding **UW-52(d)(2)** RT requirements after repair welding **UCS-56(f)** PWHT requirements after weld repairs to P No. 1 Gr. 1, 2, and 3 and to P No. 3 Gr. 1, 2, and 3 **UNF-56(d)(3)** PWHT requirements after weld repairs of nonferrous metals Appendix 7-4 RT requirements for repair of castings	**3.8.2.4** PWHT requirements after weld repairs of ferrous castings **3.8.3.2** PWHT requirements after weld repairs of nonferrous castings **6.4.5.** PWHT after repairs **6.6.5.6** Repair welding of temporary attachments **6.7.8** Repair of defects in materials and welding **6.7.10.2** Repair welding for forged parts **7.4.10.2 & 7.4.11.10** Examination of weld repairs	**328.6** Weld repair **323.4.2(a)** Repair welding of ductile iron **345.2.6** Repairs after leak testing **A328.6** Bonding repair **A334.2** Repair of defects on nonplastic piping **K323.1.6** Repair of materials by welding
Local thin areas in cylindrical shells and spherical segments of shells	**Appendix 32**; when designed under internal pressure	**4.14.2** to apply Sec. VIII, div.2, Part 5 Design by analysis Requirements or API 579-1/ASME FFS-1	–
High Elongation on Forming Shell Sections and Heads for Div.1 & 2 Bending and Forming for B31.3	**UCS-79**; *P-No. 1-1, 1-2, and 15E*: Required Heat Treatment per Table 4.123 in this book for the extreme fiber elongation (EFE) >5% after cold formed and any of the conditions in Table 4.124, Note (2)(d) in this book.; all vessel shell sections, heads, and other pressure parts fabricated by cold forming shall be heat treated per Table 4.123 in this book *P-No. 1-1, 1-2 with EFE $\geq$ 40% and other than P-No. 1-1, 1-2, 15E*: All vessel shell sections, heads, and other pressure parts fabricated by cold forming shall be heat treated per Table 4.123 in this book **UHA-44**; Heat Treatment Required for EFE > Limitation in Table UHA-44; **UNF-79**; Heat Treatment Required for EFE > Limitation in Table UNF-79 **UHT-79**; Heat Treatment Required for EFE >5%	**6.1.2.3** Forming of Carbon and Low Alloy Material Parts The application guideline is almost same as those in Div.1 See Table 4.124, Note (4) in this book The required stress relieving shall be in accordance with Table 4.124 in this book	**(MA)332.2** Bending (2) Bending/forming temperature a. Cold bend: < transformation range of ferritic metals **332.4** Required heat treatment (H.T) (1) After hot work: H.T is required for P. 3,4,5,6, and 10A metals in all thickness (2) After cold work: H.T is required in all thickness per Table 331.1.1 for any of following conditions (a) P 1 to 6 metals: EFE > 50% of specified basic min. elongation (b) Impact test required metals: EFE >5% (c) When specified
Opening in Pressure Vessels Dimensions and Shape of Opening	**UG-36** Shape of Opening, Size of Openings, Strength and Design of Finished Openings, Openings Through Welded Joints, Reducer Sections Under External/Internal Pressure, Oblique Conical Shell Sections Under Internal Pressure	**4.5** Design Rules for Openings in Shells and Heads	–
Permissible Out-of-Roundness	**UG-80**; For Cylindrical Conical, and Spherical Shells. (a) Internal pressure; $\leq \pm 1\%$ of OD or ID (b) External pressure; see Fig. UG-80.1	**4.3.2.1** Tolerance of Spherical Shells **4.4.4** Tolerances of Cylindrical and Conical Shells **6.7.4** Tolerances on Cylindrical Forgings	**(A/MA)332.2** Bending (1) Bend flattening: the different diameter (max–min) $\leq$ 8% of OD for internal pressure and 3% of OD for external pressure
Tolerance for Formed Heads	**UW-81**; Tolerance of Formed Heads When D = nominal I.D. (1) Inner surface should not deviate outside of specified shape >1.25% of D nor inside of specified shape >0.625% of D * The knuckle radius should not be less than that specified (2) When designed for external pressure, in addition to satisfying (1) above, meet the tolerances specified for spheres in UG-80(b) using 0.5 for L/Do [Do = O.D, L = span without stiffener ring]	**4.3.2.2** Tolerances for Formed Heads Inner surface should not deviate outside of specified shape >1.25% of D nor inside of specified shape >0.625% of D	–
Alignment Tolerance for Weld Joints See Sect. 4.1.4 for more details	**UW-33**; See Table 4.7	**6.1.4** Fitting and Alignment of Weld Parts – Means for Maintaining Alignment During Welding **6.1.6** Alignment Tolerance for Edges to be Butt Welded **6.6.5.4** Joint Alignment	**328.4.3** Alignment **Fig. 328.4.3** Trimmed and Permitted Misalignment
Alignment Tolerance for Peaking Height	–	**6.1** Peaking Height at a Category a Joint	–

Table 3.8 (3/3) Fabrication Requirements in ASME (all paragraphs and tables are from each code)

Limitation and Requirements	ASME Sec. VIII, Div.1	ASME Sec. VIII, Div.2	ASME Sec. VIII, B31.3
Reinforcement on Welds	**UW-35**; For Butt Joints See Table 4.8	**6.6** Maximum Reinforcement for Welded Joints	**Table (A/MA) 341.3.2**, Symbol L
Reinforcement of Opening	**UG-42**; On Shell and Head **UG-39**; On Flat Head	**4.5.7** Reinforcement of Openings Subject to Compressive Stress **4.11.4.1** Reinforcement of the Opening in the Jacket	–
Minimum Numbers of Pipe Threads for Connections	**Table UG-43** Minimum Number of Pipe Threads for Connections	**Table 4.5.1** Minimum Number of Pipe Threads for Connections	**(A/MA)335.3** General requirements only
NDE Requirements per Weld Joints	–	**4.2.5.2 through 4.2.5.6** NDE Requirements for Each Weld Joint Category	–
Proof Pressure Tests	**UG-101** Proof Tests to Establish MAWP **UCI-101** Hydrotest to Destruction of CI **UCD-101** Hydrotest to Destruction of DI	–	**(A/MA)345** General testing only
Nameplates	**UG-119 Nameplates** **MA-18** Adhesive Attachment of Nameplates	**2-F.5(a)** Markings on Nameplate **2-F.6** Duplicate Nameplate	–
Marking	**UG-116** Required Marking **UG-117** Certification Marks **UG-118** Marking Methods **UG-129** Marking for Safety Devices **UG-130** Certification Mark	**2-F.4** Part Marking **2-F.5 through 2-F.9** Nameplate and Vessel Shell **6.6.10** Stamping and Reports **Annex 2-G** Obtaining and Using Certification Mark Stamps **Annex 2-F** Contents and Methods of Stamping **6-A.8** Marking	–
Data Reports	**UG-120** Data Reports	**6.6.10** Stamping and Reports **Annex 2-B** Certifying a Manufacturer's Design Report **Annex 2-D** Manufacturer's Data Reports **Annex 2-C** Report Forms and Maintenance of Records **6-A.8** Documentation	**(A/MA)346**
Fabrication by Forging	**UF-26 through 43**	**6.7** Special Requirements for Forged Fabrication	–
QC System	**MA 10** QC System	**Annex 2-E** QC System	**Appendix Q** **341** Qualification for Inspector and Personnel

3.1.5 Packing, Shipping, and Transportation

Transportation for offshore facilities is not covered in this book because they are too much complicated. The following should be confirmed as a minimum for packing, shipping, and transportation of onshore facilities.

- Scope of work (module, installation of insulation, assembly of internals, field welding, etc.)
- Module/facility size, skid type, and center of gravity – strength calculation
- Full-/pre-/loose-assembly before shipping
- Blind type and sealing requirements for all opening
- Corrosion prevention
- Transporter type-shaking/impact load factors
- Weather (typhoon, rainy season, etc.) in the shipping route
- Road route survey until completion of transportation (probably next 1–2 years)
- Local regulations and security in all states or provinces to pass through

Figure 3.5 shows the equipment which are packed and ready for shipping.

3.1.6 Erection of Equipment and Piping

The following should be considered as a minimum:

- To confirm the center of gravity as well as lifting weight of equipment. To be added the weight of the insulation, fireproofing, internal assembly, and external piping if assembled before erection.

Figure 3.5 Equipment packed and ready for shipping

- To confirm the load distribution on each lug per the erection angle. The erection load calculations per lifting angle should be described in the strength calculation sheets.
- Construction sequence.
- Selection of lifting crane and tailing crane
- Crane selection with accessibility and maximum boom angle – sometimes the designed boom angle is not applied due to changed construction schedule or sequence.
- To confirm the shackle diameter and hole diameter of lifting lugs. The holes for shackle on lifting lugs should be located outside of the insulation if the insulation is assembled before lifting and erection.
- Load distribution at lifting and tailing lugs
- Damage during lifting due to dead weight or local stress at the body with lug (mostly in thin wall) or insufficient shaking impact factor.
- No interruption of external attachments (nozzles, lugs, rings, etc.) is required during lifting and erection.
- If the skirt thickness is not heavy, the local stress at the tailing lug area should be analyzed to avoid buckling.
- Equipment including template and piping spools to be marked the direction (north, south, west, and east) before installation.
- Template and gauge plate for skirt type vessels to be designed and placed before erection.
- To have the accessibility for H/EX bundle replacement/cleaning and the pigs in launcher and receivers.
- To confirm the parts to be pre-assembled before erection and finally assembled after erection.
- Local regulations in the field.

Figure 3.6 shows the loads on lifting and tailing lugs. Figure 3.7 shows erection sequence of coke drums in delayed coker unit of refinery plants.

Figure 3.6 Erection of Tall Pressure Vessel-Posted by Richard L. Krabbendam. (Source: http://www.heavyliftspecialist.com)

3.1.7 *Heat Exchangers (H/EX)*

3.1.7.1 Work Hardening and Non-work Hardening Metals Described in TEMA and API

- Work hardening materials: austenitic stainless steel, duplex stainless steel, titanium, copper-nickel or high-nickel alloy tubes, etc.
- Non-work-hardening materials: ferrous steels, etc.

Figure 3.7 Erection sequence and replacement of coke drums in delayed coker unit of refinery plants

Table 3.9 Maximum allowable tube wall thickness reduction for roller-expanded tube-to-tubesheet joints

Materials	Maximum Allowable Tube Wall Thickness Reduction (%) for Roller-Expanded Tube-to-Tubesheet Joints[c,d]
CS and LAS (up to 9% Cr) steel	8[a]
SS (high alloy steel)	6[a]
DSS	b
Titanium and work hardening nonferrous	5[a]
Nonferrous non-work hardening (e.g., admiralty brass)	8[a]

Source: API 660, Table 6

Notes

[a]These can be increased by a further 2%, if approved by the purchaser

[b]To be agreed between purchaser and vendor. Tube expansion may increase hardness significantly. For more information, see API TR 938-C

[c]If welded-and-expanded joints are specified, tube wall thickness reduction should begin at least 6 mm (1/4 in.) away from welds

[d]The minimum length of expansion should be in accordance with TEMA Section 5, Paragraph RCB-7.1. However, in no case should the expansion extend within 3 mm (1/8 in.) of the shell side face of the tubesheet

3.1.7.2 Requirements for Tubes

(a) Minimum Tube Wall Thicknesses
See Tables 1.11, 1.12, 1.13, and 1.14 for the requirements in codes, standards, and some company standards.

(b) Thickness Reduction of Rolled Tubes (Tube Expansion)
The required tube wall reduction should be calculated by the following equation:

$$\%\text{Wall Reduction} = \frac{(T - t) - (D - d)}{(d - t)} \times 100$$

where: T – Inside diameter of tube after expansion
t – Inside diameter of tube before expansion
D – Average diameter of tube holes, based on tube hole inspection per Paragraph 8.1
d – Average outside diameter of tube

API 660 requires the minimum allowable tube wall thickness reduction for roller-expanded tube-to-tubesheet joint as seen in Table 3.9.

(c) Thickness Reduction of U-Bends – TEMA RCB-2.3
When U-bends are formed, it is normal for the tube wall at the outer radius to thin. The minimum tube wall thickness in the bend portion before bending should be:

$$t = t_1 \times (1 + \text{do}/4R)$$

where: t = Required tube wall thickness prior to bending
t_1 = Minimum thickness calculated by code rules for a straight tube
do = Tube outside diameter
R = Mean radius of bend

The thickness of U-tubes after forming should not be less than the design thickness. More than one tube gauge, or dual gauge tubes, may be used in a tube bundle to meet the minimum required thickness. Some companies state that if required to maintain minimum tube wall thickness, the inner two rows of U tubes should have a wall thickness one gauge thicker than the remaining tubes.

TEMA states that:

– Non-work-hardening material and tempered: Tube wall thinning in the bends should not exceed a nominal 17% of original tube wall thickness regardless of bending temperature (cold or hot)
– Work hardening materials: Stress Relieving may be required for cold bends

(d) Heat Treatment Requirements for U-Bends: See Sect. 4.12.3.16.

3.1.7.3 Requirements of Tube-to-Tubesheet Joints Design and Fabrication

(a) ASME Section VIII, Div.1 states that:
– Basis for Establishing Allowable Loads for Tube-To-Tubesheet Joints in Nonmandatory Appendix A.
– Some Acceptable Types of Tube-to-Tubesheet Welds in Table A-2.
– Typical Test Fixtures for Expanded or Welded Tube-to-Tubesheet Joints in Fig. A-3.
– Tube Expansion Procedure and Qualification in Nonmandatory Appendix HH.

(b) ASME Section VIII, Div.2 states that:

1. Material Requirements
   Tubes may be attached to tubesheets by welding, provided the tubes and tubesheets or tubesheet facings are of weldable materials covered by ASME Sec. VIII, Div.2.
2. Holes in Tubesheets
   (a) Preparing Holes in Tubesheets. Tube holes in tubesheets should be produced by any process that does not impair the properties of the material and produces a tube hole with a finish meeting the requirements of ASME Sec. VIII, Div.2, 6.3.2.3.
   (b) Clearance Between Tubes and Tube Holes. The clearance between the outside surface of the tubes and the inside surfaces of the tube holes should not exceed the clearance specified by the welding procedure qualification tests.
   (c) Finish of Holes. The edges of the tubesheet at the tube holes on the side to be welded should be free of burrs, and the edges of the tubesheet at the tube hole on the side opposite the weld should have sharp corners removed. The surfaces of tube holes in tubesheets should have a workmanship-like finish.
3. Weld Design and Joint Preparation
   The weld dimensions and weld detail, and joint preparation, if used, should comply with the details included in the WPS.
4. Qualification of Welding Procedure
   Tube-to-tubesheet welding procedure specifications should be qualified in accordance with the requirements of ASME Sec. IX, QW-193.
5. Others
   – Efficiencies for Welded and/or Expanded Tube-to-Tubesheet Joints in ASME Sec. VIII, Div.2, Table 4-C.1.
   – Some Acceptable Types of Tube-to-Tubesheet Joints in ASME Sec. VIII, Div.2, Fig. 4-C.1.
   – Typical Test Fixtures for Expanded or Welded Tube-to-Tubesheet Joints in ASME Sec. VIII, Div.2, Fig. 4-C.2.

(c) TEMA states that:
When the Tube-to-Tubesheet Joints are expanded:
– Class R & B: tubes should be expanded into the tubesheet for a length no less than 50.8 mm (2 in.) or the tubesheet thickness minus 3.2 mm (1/8 in.), whichever is smaller. In no case should the expanded portion extend beyond the shell side face of the tubesheet. When specified by the purchaser, tubes may be expanded for the full thickness of the tubesheet.
– Class C: Tubes should be expanded into the tubesheet for a length no less than two tube diameters, 50.8 mm (2 in.) or the tubesheet thickness minus 3.2 mm (1/8 in.), whichever is smaller. In no case should the expanded portion extend beyond the shell side face of the tubesheet. When specified by the purchaser, tubes may be expanded for the full thickness of the tubesheet.

(d) API 660 (Shell and Tube Type H/EXs) states that:
– For shell-side-clad (or weld overlay) tubesheets, the tube should be expanded to seal against the cladding material for a minimum distance of 6 mm (1/4 in.). The purchaser should specify if a groove is required within the shell side cladding.
– For tube side clad (or weld overlay) tubesheets with either strength-welded or seal-welded and expanded tube-to-tubesheet joints, tube hole grooves, when provided, should be located in the base material and not in the applied cladding or weld overlay.
– For welded-and-expanded tube-to-tubesheet joints requiring PWHT, the tubes should be expanded after PWHT.
  See ASME Section VIII, Div.1, UCS-56 for the PWHT requirements of the welds on tube-to-tubesheet joints.
– Tubes should be flush with or extended by no more than 5 mm (3/16 in.) beyond the face of the tubesheet, except in vertical exchangers when tubes should be flush with the top tubesheet, unless otherwise specified by the purchaser.

(e) API RP 661 (Air Coolers) states that:
– All carbon steel and low alloy chromium steel headers should be subjected to PWHT. Welded tube-to-tubesheet joints should exclude the PWHT unless required by the pressure design code or specified by the purchaser.
– If work hardening materials such as ASS, DSS, titanium, Cu-Ni, or high-Ni alloy tubes are specified, the tube holes should be machined in accordance with API 661, Table 11, special close fit.
– Tubes should be expanded into the tubesheet for a length at least the smaller of 50 mm (2 in.) or tubesheet thickness less 3 mm (1/8 in.).
– Recessed-type tube-to-tubesheet welds (in the tube holes) should not be used.

6. Some company standards state the welding requirements for tube-to-tubesheet joints as seen Table 3.10.

Table 3.10 (1/2) Requirements for tube-to-tubesheet joints of H/EXs (only for recommendation)

Service/Design(1)	Tube-to-Tubesheet Joints Design(2)
Hydrogen service, hydrogen-rich service, or HF acid service	Seal welded
Services where stream mixing cannot be tolerated as specified by the end-user's engineer	Seal welded
Tube outside diameter of 2 inch	Strength welded
Dissimilar materials [ferritic, austenitic, nickel-based(3)] for tube and tubesheet	Seal welded
Clad or overlayed tubesheet(3)	Seal welded
Flexible tubesheet design	Strength welded

Table 3.10 (2/2) Requirements for tube-to-tubesheet joints of H/EXs (only for recommendation)

Service/Design(1)	Tube-to-Tubesheet Joints Design(2)
Shell side or tube side design pressure 1000 psig or greater	Strength welded
All other services and designs	(*) Grooved and rolled, unless otherwise specified by the end-user's engineer(4)
Steam Reboilers in 600 psi service and above	Strength welded
Cooling water with brine or seawater	Seal welded, full expansion

Notes
(1)If conflicts arise between different service or design requirements, the more stringent requirements should apply
(2)Grooving and rolling requirements should be in accordance with the design specifications
(3)(*) Titanium- and copper-based alloys such as admiralty brass are not seal welded, unless specified by the end-user's engineer
(4)(*) When approved by the end-user's engineer, the manufacturer may utilize an alternate tube-to-tubesheet joint to increase the maximum allowable axial load as calculated in the nonmandatory Appendix A, Section VIII, Division I of the ASME Code

3.2 Piping and Valves

3.2.1 Fabrications of Parts

If available, all piping and the components should be designed by 3D modeling, so that any interference for layout, physical access and inspection, and maintenance should be avoided.

3.2.1.1 Piping Spool Fabrication

The following should be considered as a minimum:

- Closing seam
- Pressure test
- Fabrication sequence
- Local regulations in the shop and field
- Spool ends for connection
- WPS/PQR – welding position 1G or 2G is preferable at shop
- Isolation shop for stainless steels and nonferrous metals
- To avoid the sources of liquid metal embrittlement (LME) in stainless steel piping work

Figure 3.8 shows fabrication and packing of piping spools at shop.

Figure 3.8 Fabrications of piping spools

3.2.1.2 Miter Welding

Proposals for the use of miter bends should be subject to approval by the end-user. Miter bends should not be used where the design pressure exceeds 75 psig or where the stress-range reduction factor, f, in the case of thermal or pressure cycling, would be less than 1.0.

3.2.2 Cold Bending of Pipe

Cold bending of ferritic materials should be done at a temperature below the lower critical phase transformation temperature (Table 4.113). Unless otherwise specified in the applicable codes, standards, and specifications, the following may be applied.

The results after bending may be inspected randomly with a certain percentage. Once some of them are failed to meet the requirements, the inspection should be extended to 100%.

3.2.2.1 Dimensions

The bends should be within the tolerances of several dimensions, such as angle, radius, ovality, tangent points, plane, center to center distance (180° bends), etc.

(a) Ovality Measurements – Recommendation
Flattening of a bend, the difference between maximum and minimum diameters at any cross-section, should not exceed 8% of nominal OD for internal pressure and 3% for external pressure. Removal of metal should not be used to achieve these requirements. At least 10% of bends should be inspected the ovality at the 45° point on the bend.

(b) Thinned Thickness Measurements – Recommendation
If the wall thickness after bending could be within 5–10% of t_{min} (i.e., 0.875 mill under tolerance × 0.875 bend thinning × tn – CA), the responsible inspector should check the wall thicknesses of 100% of the bends at 150 mm (6 in.) from each tangent point and at the 1/4, 1/2, and 3/4 points of the bend [t_{min} = the calculated minimum wall thickness, tn = nominal pipe wall thickness, CA = corrosion allowance].

3.2.2.2 Heat Treatment Requirements

Cold bends should be heat treated in accordance with ASME B31.3, 332.4 (heat treatment requirements after hot/cold bending and forming) or equivalent code except below.

(a) All cold bends in CS process piping that require PWHT of the welds for process reasons should be heat treated after bending.
(b) All cold bends in CS process piping that are designed for colder than −29 °C (−20 °F) service (including depressing cases) should be heat treated after bending.
(c) Heat treatment of CS piping should be at 621 ± 14 °C (1150 ± 25 °F), for 1 hour per inch of wall thickness with a one hour minimum soak time. Lower temperatures for longer times may not be acceptable.
(d) All CS cold bends that do not meet the hardness limits per codes and specifications should be heat treated.

3.2.2.3 NDE: Recommendation

For welded pipe, the weld seam of the first bend for each nominal size and wall thickness should be 100% PT examined after bending. Thereafter the welds of 5% of all bends made from welded pipe should be PT examined after bending.

3.2.2.4 Other Tests: Recommendation

The metal hardness after cold bending can be increased, so that 5–10% bends should be checked the hardness values at the outside arc for the required hardness value. All heat treated bends should be hardness tested after heat treating.

3.2.3 Induction Bending of Pipe

Unless otherwise specified in the applicable codes, standards, and specifications, the followings may be applied.

The results after induction bending may be inspected randomly with a certain percentage. Once some of them are failed to meet the requirements, the inspection should be extended to 100%.

3.2.3.1 Application of Induction Bending

The induction bending equipment is composed of three basic components consisting of a bed, a radial arm, which is set at the required radius, and an induction heating system. The pipe is placed in the bed and the front tangent is clamped to the radial arm. The induction heating system heats a narrow circumferential band around the pipe to the appropriate bending temperature. When this temperature is reached, the pipe is continuously moved through the heating coil, while a bending moment is applied to the heated area. After passing through the coil, the pipe may be either forced or naturally cooled as required by the appropriate qualified bending procedure. Figure 3.9 shows the views of induction bending.

Figure 3.9 Hot Induction Bending if NPS 48 Pipe. (Source: Mannemann Paper for Oil and Gas Industry International Symposium, 2006Mannemann brochure, 2013)

Figure 3.10 View on Induction Coil and Heated Zone During Bending. (Source: Mannemann Paper for Oil and Gas Industry International Symposium, 2006Mannemann brochure, 2013)

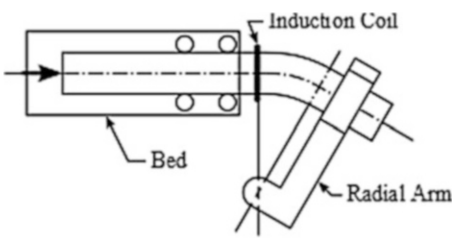


Figure 3.11 Induction Bending of Pipe. (See ASME B16.49 for butt-welding induction bends for transportation and distribution systems)

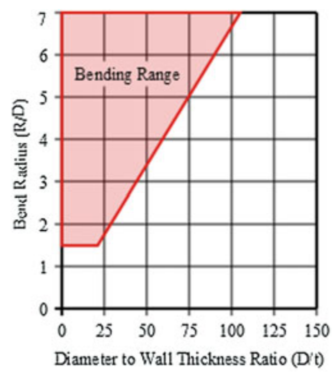


Figure 3.12 Induction and Increment Bending Range of CS Pipe

Figure 3.11 shows a typical bending tools of pipe induction bending, and Fig. 3.12 shows a typically applicable range of CS pipe induction bending.

3.2.3.2 General Requirements of Induction Bending (Recommendation Unless Otherwise Specified in the Purchaser's Specifications)

(a) Induction bending of pipe should be in accordance with the fabricator's written procedures as modified by this specification. Fabricator should submit his written procedures to client for approval prior to start of fabrication.
(b) Fabricator should review wall thinning after bending against the requirements of the individual line class guide to ensure that wall thickness after bending is not below calculated minimum wall plus corrosion allowance.
(c) In calculating the required wall thickness of welded pipe after bending, the weld joint factor per ASME B31.3, Table 302.3.4, should be considered.
(d) No circumferential welds should be located in the bend.
(e) On single plane bends, the pipe should be loaded into the machine so that the thickest quadrant will lie in the outside arc of the bend. If the pipe is of welded construction, the weld seam should be located preferably along the upper neutral axis and may be tilted towards the inside arc of the bend no more than 30 degrees. If the thickest quadrant and the location of the weld seam are at variance, the weld seam location should govern. These requirements do not apply to multiplane bends.
(f) Shop butt-welds should be located no closer than the smaller of 75 mm (3 in.) or 1/2 nominal pipe diameter to the tangent line. Shop butt-welds located the smaller of 150 mm (6 in.) or one nominal pipe diameter to the tangent line should require 100% RT unless the inside diameter is accessible for visual inspection. The internal access should allow for weld joint mismatch and should provide for back-grinding and back-welding, if necessary, for removal of any weld joint mismatch.

(g) Shop socket welds should be located no closer than two nominal pipe diameters to the tangent line when operating temperature is greater than 204 °C (400 °F). Shop socket welds should be located no closer than one nominal pipe diameter to the tangent line when the operating temperature is below 204 °C (400 °F).
(h) Bevels for field butt-welds should be located no closer than the larger of 6 inch or one nominal pipe diameter from the bend tangent line.
(i) Induction bends should be heat treated in accordance with ASME B31.3, 332.4 (after hot/cold bending) of and/or the approved pre-production bend qualification tests except as modified by this specification.
(j) All induction bends in CS process piping that require PWHT of the welds for process reasons should be designated by a suffix mark after heat treated.
(k) All induction bends in CS process piping that are designed for colder than −29 °C (−20 °F) service (including depressurizing cases) should be heat treated.
(l) Heat treatment of CS piping should be at 621 °C (1150 °F) ±14 °C (25 °F), for 1 hour per inch of wall thickness with a 1 hour minimum soak time. Lower temperatures for longer times are not acceptable.
(m) All CS bends that do not meet the hardness limits per codes and project specifications should be heat treated.
(n) No stoppage should be permitted once the bending operation has started.
(o) For induction bending, the maximum bending temperature should be measured at two positions (180 degrees apart). The accuracy for temperature measurement should be in ±5 °C (9 °F). The temperature cycle during bending should be documented by thermocouple readings from an actual bending cycle. Temperature measurements by optical or emission pyrometers are acceptable.
(p) The longitudinal weld in pipe should be located at the neutral axis of the finished bend.
(q) There should be no circumferential welds located in the bend area.
(r) A minimum of 300 mm (12 in.) of straight pipe should be left on either end of the bend.
(s) CRA material and its clad pipe may also be bent by induction bending.
(t) ISO 15590-1 (petroleum and natural gas industries – induction bends, fittings, and flanges for pipeline transportation systems, Part 1: Induction Bends) may be applicable.

3.2.3.3 Mechanical Tests (Recommendation Unless Otherwise Specified in the Purchaser's Specifications)

For bends without tangents, mechanical testing, as outlined below, should be performed at the intrados and extrados at the point of maximum bending.

(a) The mechanical testing requirements, acceptance criteria, and test temperature should be the same as required for the adjoining pipe or as stipulated by contractor in the mother pipe specification or purchase order.
(b) For welded pipe, testing should be performed in the weld metal in bend, weld metal in start transition, and weld metal in stop transition.
(c) For bends where the transition zones and tangent lengths are not retained in the delivered bend, or where the entire bend pipe has been processed and heat treated the same as the bent portion, mechanical testing in these areas is not required.
(d) If thermal cutting has been used to remove test samples, the full extent of the HAZ should be removed during preparation of the test samples.
(e) If the result from any location fails to conform to the applicable mother pipe specification, a retest may be taken. The retest should comprise of two additional specimens taken immediately adjacent to the failed specimen. Both retest specimens must pass.

3.2.3.4 Dimensions (Recommendation Unless Otherwise Specified in the Purchaser's Specifications)

(a) Bend Angle
  1. The maximum deviation from the specified bend angle should be no more than 1 degree.
  2. The bend angle should be measured with the bend in the horizontal plane and free of frictional restraint.
(b) Bend Radius
  1. The bend radius should not be less than that specified by contractor, and the tolerance should be smaller than 1.0% or 10 mm (0.4 in.).
  2. The bend radius should be measured with the bend in the horizontal plane and free of frictional restraint.
(c) Ovality Measurements and Out-of-Roundness
  1. Ten percent of bends should be checked by the fabricator at the front tangent end, bend start, 1/4 point, 1/2 point, 3/4 point, bend finish, and rear tangent end. The fabricator should make a notation on the shop copy as to which bend was checked. The fabricator should keep a log as to the quantity of bends on the job by size, the quantity of bends checked, and the ISO's on which bends were checked.
  2. The out-of-roundness and any other specified relevant dimensional requirements should be checked after bending. Measurement should be by calipers, rod gauge, or equivalent. Diameter tape measurement is not acceptable.
  3. The out-of-roundness should be 1% at ends.
  4. The out-of-roundness should be 2.5% in bend radius.
  5. As a minimum, measurements should be taken at midsection of the bend and the two tangent locations.
(d) Thinned Thickness Measurements

This test is performed to evaluate the overall thinning that will occur at the extrados by the induction process. The minimum wall thickness at any point on the pipe bend should not be less than the greater of the minimum wall thickness required by the system design code incorporating the bend or the minimum wall thickness of the installed adjoining pipe.

If the wall thickness after bending could be within 5–10% of t_{min} (i.e., 0.875 mill under tolerance × 0.875 bend thinning × tn – CA), the responsible inspector should check the wall thicknesses of 100% of the bends at 150 mm (6 in.) from each tangent point and at the 1/4, 1/2, and 3/4 points of the bend [t_{min} = the calculated minimum wall thickness, tn = nominal pipe wall thickness, CA = corrosion allowance].

3.2.3.5 Bends Intended for Pigging Application

The permissible dimensions should be advised by the purchaser.

3.2.3.6 Post Bending Heat Treatment Requirements (Recommendation Unless Otherwise Specified in the Purchaser's Specifications)

Induction bends should be heat treated per ASME B31.3, 332.4 (after hot/cold bending) except below.

(a) All induction bends in CS process piping that require PWHT of the welds for process reasons should be heat treated after bending.
(b) All induction bends in CS process piping that are designed for colder than −29 °C (−20 °F) service (including depressing cases) should be heat treated after bending.
(c) Heat treatment of CS piping should be at 621 ± 14 °C (1150 ± 25 °F), for 1 hour per inch of wall thickness with a 1 hour minimum soak time. Lower temperatures for longer times are not acceptable.
(d) All CS induction bends that do not meet the hardness limits per codes and specifications should be heat treated.
(e) All ASS, DSS, and super DSS bends should be subjected to a separate solution annealing treatment followed by water quenching.

3.2.3.7 NDE (Recommendation Unless Otherwise Specified in the Purchaser's Specifications)

(a) For welded pipe, the weld seam of the first bend for each nominal size and wall thickness should be 100% liquid penetrant examined after bending. Thereafter the welds of 5% of all bends made from welded pipe should be liquid penetrant examined after bending.
(b) The wall thickness of the qualification pipe should be measured ultrasonically before and after bending at a minimum of five locations along both the inner and outer radii of the bend (between and including the start and stop points of the bend arc angle).

3.2.3.8 Essential Variables of Pipe Bending (Recommendation Unless Otherwise Specified in the Purchaser's Specifications)

Any significant changes outside the essential variables for each material type and grade should require requalification. The essential variables in Table 3.11 should be applied for bending procedure qualification and are applicable to the "Post Bend" condition. MTR for bent pipe should be supplied by bending contractor. If changes outside the variables listed in Table 3.11 occurred, a new bending procedure should be provided by bending contractor and approved by the purchaser.

Table 3.11 Maximum permissible variation for essential variables of pipe bending

Essential Variable	Maximum Permissible Variation
Bending Machine and Machine Number	Any Change
Material	P No. or UNS number
Heat Number of Metal	Any Change
Heat Treatment Condition of Base Metal	Any Change
Diameter	Any Change
Wall Thickness	± 3 mm (0.118 in.)
Bend Radius	One radius qualifies all larger radii
Bend Angle	± 1 degree
Differential Temperature at the Same Location Between OD and ID During Bending	± 20 °C (36 °F)
Bending Speed	± 2.5 mm (0.1 in.) per minute
Induction Heating Frequency	± 20%
Induction Coil Design	Any Change
Cooling Technique	Any Change
Coolant Flow Rate or Pressure	± 10%
Coolant Temperature	± 15%
Weld Seam Location	± 15 degrees from the location in the qualification bend
Post Bend Heat Treatment	Any Change (beyond the tolerance) Soaking time: −0/ + 15 minutes Soaking temperature: ± 15 °C (27 °F)
Carbon Equivalent (per IIW formula)(1)	0.03 higher than the maximum requirement(1)

(1)For offshore piping, the carbon equivalent (Pcm; see Sect. 4.4.1): 0.02 higher than the maximum requirement

References

– Basic requirements : ASME B31.xx series
– All Materials: PFI ES-24 Pipe Bending Methods, Tolerances, Process and Material
– CS, LAS, and SS: TPA-IBS Recommended Standards for Induction Bending of Pipe and Tube Requirements
– CS and LAS: ISO 15590-1 Petroleum and natural gas industries — Induction bends, fittings and flanges for pipeline transportation systems — Part 1: Induction bends
– CS: ASME B16.49 Factory-Made Wrought Steel, Buttwelding Induction Bends for Transportation and Distribution Systems

3.2.4 Cryogenic Valves

The valves are making at atmospheric condition, but they are using at the extremely low temperature (cryogenic service). The valve performance without leakage is very important because all metallic components will be contracted at the cryogenic service. Therefore, the followings should be considered at design, fabrication, and maintenance.

– Materials selection (metals and nonmetals) including galling resistance and impact test.
– Sealing design.
– Heat treatment including sub-zero treatment (see Sect. 4.12.8).
– Test and inspection (full RT, pressure/leak tests including permitted leakage rate, e.g., $\leq$ xx $mm^3/s \times$ DN (nominal size, mm), test temperature/pressure, sub-zero treatment, etc.) – see Sect. 5.5.6 for cryogenic leakage test.
– Safety design to avoid frostbitten damage.

References

- MSS SP 134 Valves for Cryogenic Service Including Requirements for Body/Bonnet Extensions
- BS 6364 Specification for Valves for Cryogenic Service
- API 598 Valve Inspection and Testing

3.2.5 Marking and Color Coding of Piping Materials

Color coding of piping materials is intended as an aid to construction in preliminary recognition of material types. Stock code numbers and other permanent markings should be checked before fabrication and/or erection starts. The presence of a color code does not diminish the need for permanent markings to be transferred whenever material is cut during fabrication and construction. It can be used for maintenance as well.

Here are some reference specifications for color coding of piping materials.

3.2.5.1 Applicable Components

Pipe, fittings, flanges, line blinds, gaskets, bolts, nuts, cap screws, and steel plates supplied as bulk material.

3.2.5.2 Codes and Standards

- BS EN 1226 or 593
- PFI ES22
- ASME A13.1

3.2.5.3 Marking Materials and Techniques

(a) Color coding materials should be durable and have distinctive colors such as OSHA Safety Colors.
(b) For items to be marked after application of the first or prime coat, color coding and erection marking should be an inorganic coating as top coat. Color coding and marking with coatings or ink should be on the end of the pipe. When a bare cutback has been left for subsequent welding, color coding and marking should be applied to the exterior of the pipe on the cutback, otherwise it should be applied to the bare pipe ID. Color coding should not be placed on the flange faces, weld bevels, or any surface intended for welding. Coating and/or ink used for coding or marking should not be applied directly over any primed surface without prior written acceptance by the buyer.
(c) The coating material manufacturer's latest published instructions for surface preparation, mixing, thinning, application, environmental restrictions, and cure should be strictly observed.
(d) Alternate methods and materials for marking primed items (such as colored adhesive tape, labels, tags, etc.) are subject to buyer review and written acceptance prior to use. When proposing an alternative, a detailed description of the proposed materials, methods, techniques, processes, etc. should be submitted.

3.2.5.4 Items Excluded from Marking

(a) In-line piping components, such as valves, strainers, sight flow indicators, SP items, etc., should not be color coded.
(b) Piping components supplied as fabricated spools or in package units or other subassemblies should not be color coated.
(c) Galvanized piping components and flanged lined fittings should not be color coded.
(d) Items shipped to the buyer fully coated (in accordance with the Project Coatings Specification) should not be marked on the exterior with paint. The seller's system for marking should be submitted to the buyer for approval. The proposed system must include the intended details and products.

3.2.5.5 Typical Marking Procedure with Color Coding

On fittings and flanges, the location of the markings should be in accordance with the materials standards and company standards, and the marks shall not be removed in storage as well as operation stage.

On spiral wound gaskets, the location of the markings should be in accordance with ASME B16.20 unless specified otherwise here in.

(a) Typical Marking Width of Stripe for pipes and fittings
NPS 1–1/2 and smaller ¼ inch
NPS 2 thru 4 ½ inch
NPS 6 and larger 1 inch
(b) Color Coding of Pipes/Flanges/Fittings Materials
The inventory/consumable materials in the maintenance and fabrication shops shall be correctly selected per the spec and drawing (bill of materials) requirements. All material recognition systems should be classified by color coding, stamping, or tagging to avoid using wrong material. Tables 3.12, 3.13, and 3.14 shows sample standards for piping, bolting, and gasket materials, respectively.
(c) Color Coding of Bolting and Screw Materials
(d) Color Coding of Gasket Materials

3.2.6 Gasket Selection

3.2.6.1 General Requirements (Recommendation)

(a) The guaranteed compressed thickness should be confirmed before purchasing.
(b) Gaskets should be certified asbestos-free.

Table 3.12 Color table of piping (only for reference)(1)

Material Group	Material (ASTM, API, and Nonmetals)(2)	Color on End(2)
CS without	EFW, ERW, Cast Iron, Forgings, Fittings (common)	None (by Tag or Stamp)
impact test (IT)	EFW, ERW + Galvanized	None (by Tag or Stamp on No-Galvanized art)
	Seamless, Normalized, Q-T	1 Line with Solid W
	Resistance for Sour or HF service	1 Line with Solid G
	Ductile (or other special) Iron	1 Line with Solid W
Low Temperature	Impact- Tested CS @-29 °C (−20 °F) and above	1 Line with Solid Y
CS (LTCS) with	Impact- Tested CS below −29 °C (−20 °F)	2 Lines with Solid Y
impact test (IT)	API 5 L Gr. B PSL2 DSAW, IT@-29C	2 Lines with Solid W
	API 5 L Gr. B PSL2 DSAW, IT@-29C, Normalized	2 Lines with Solid G
Low Alloy Steels	4140	1 Line with Solid A
(LAS)	4340	1 Line with Solid G
	0.15%C-0.5%Mo	1 Line with Solid B
	1¼ %C-0.5%Mo	2 Lines with Solid A
	2¼ %Cr-1%Mo	2 Lines with Solid G
	5% Cr-0.5%Mo	2 Lines with Solid G
	9%Cr-1%Mo	2 Lines with Solid B
	9% Cr-1%Mo-V, modified	3 Lines with Solid B
(super) SS* * Color code painting for ASS which is welded at shop and/or field is not recommended due to high risk of liquid metal embrittlement (LME) – -See Sect. 2.1.6.6	405 SS	1 Line with Solid
	410 SS	1 Line with Intermittent B
	416 SS	1 Line with Solid B
	17-4 PHSS	1 Line with Intermittent
	304 SS	1 Line with Solid P
	310 SS	1 Line with Solid R
	316 SS	1 Line with Intermittent R
	317 SS	1 Line with Solid T
	321 SS	1 Line with Intermittent T
	347 SS	2 Lines with Solid T
	Alloy 20	2 Lines with Solid B
	A790-S31803/S32205 (DSS)	2 Lines with Solid B
	A312-N08367 (AL6XN)	2 Lines with Solid P
Ni Alloy	Nickel	1 Line with Intermittent W
	Monel	1 Line with Intermittent G
	Hastelloy “B”	1 Line with Intermittent W
	Hastelloy “C”	1 Line with Intermittent G
	Incoloy (800, 825, etc.)	1 Line with Intermittent A
	Inconel (600, 625, etc.)	1 Line with Intermittent G
Aluminum Alloy	6061-T6	1 Line with Solid T
	5083-O	1 Line with Intermittent T
CPVC	CPVC (Chlorinated Polyvinyl Chloride)	None (by Tag)
HDPE	HDPE (High- Density Polyethylene)	None (by Tag)

Notes: *DSAW* double-side SAW welding, *IT* impact-tested or exempt from code requirements, *LTCS* low temperature carbon steel impact-tested by code
(1)After cut the pipe by the intended length, the remained piece without color and heat number shall be marked as the same as original under the witness of certified inspector
(2)“A” through “W”: initials for different colors. The more detail material group and colors to be classified and selected by end-user

(c) Anti-stick coating should be applied to both sides of all flat ring and full-face gaskets.
(d) All spiral wound gaskets should be color coded in accordance with *ASME B16.20*.
(e) Flexible graphite should contain:
  – A minimum of 95% pure carbon
  – Nominal density of 1121.33 kg/m^3 (70 lb./ft^3) ± 5%
  – Sulfur ≤700 ppm
  – Maximum leachable chlorides plus fluorides ≤100 ppm
  – No oxidation catalysts such as sodium (Na) and no minerals that promote galvanic corrosion, such as magnesium (Mg)

Table 3.13 Color table of bolting materials (only for reference)(1)(2)(3)

Material Group	Material (ASTM)	Color on Head(4)	Notes
CS-for structure	A307-B Bolt with A563-A Nut, PTFE Coated	None (by Tag)	(1) Stud Bolts should have paint applied to one end as per the following schedule. (2) Nuts should also be color coded. (3) Machine Bolts and Cap Screws should have paint applied to the hex head. (4) "A" through "R": Initials for different colors. To be selected by end-user. (5) Stamping instead of color also may be used by material supplier.
CS-high strength	A193-B7 Stud with A194-2H Nuts	None (by Tag)	
	A193-B7M Stud with A194-2H Nuts	A	
LTCS	A320-L7 Stud with A194-4 Nuts	W	
	A193-L7 Stud with A194-4 Nuts	Y	
LAS	A 193-B16 Stud with A194-4 Nuts	R	
ASS	A193-B8 Cl.1 Stud with A-194-8 Nuts	G	
	A193-B8 Cl.2 Stud with A-194-8 Nuts	G	
	A320-B8 Cl.1 Stud with A194-8 Nuts	B	
	A320-B8 Cl.2 Stud with A194-8 Nuts	G	
	A 193-B8M2 Stud with A194-8 M Nuts	P	
Ni Alloy	B 473-N08020 Stud and Nuts	B	
	A453-660 (S66286) Stud and Nuts	Y	
Al Alloy	B637-N07718 with B637-N07718 Nuts	Orange	

Table 3.14 Color table of gasket materials (only for reference)

Material	Color on Metal
304 SS Winding w/Flexible Graphite filler, CS centering ring, SS inner ring	Green with Gray & Purple Stripes
304 SS Winding w/Flexible Graphite filler, SS centering ring, SS inner ring	Green with Gray & Red Stripes
304 SS Grooved Ring w/Flexible Graphite cover	Green
304 SS Winding w/Mica/Flexible Graphite/Mica, SS centering ring, SS inner ring	Green with Pink & Blue Stripes
304 SS Winding w/Flexible Graphite filler, CS centering ring, SS inner ring	Yellow with Gray & Purple Stripes
304 SS Winding w/Flexible Graphite filler, SS centering ring, SS inner ring	Yellow with Gray & Red Stripes
304 SS Grooved Ring w/Flexible Graphite cover	Yellow with Pink & Green Stripes
Soft Iron Oval Ring	None (by Tag or Stamp)
Flexible Graphite sheet w/316SS Metal Insert	None (by Tag)
Compressed Non-asbestos sheet	None (by Tag)
Neoprene sheet	None (by Tag)

General notes:
(1) Spiral wound type gaskets will require a color code in accordance with ASME B16.20, Metallic Gaskets for Pipe Flanges

Where "Mica/Flexible Graphite/Mica" is specified, the flexible graphite should be oxidation inhibited. Gasket containing graphite deserve attention because graphite is very noble and is an efficient reducer of dissolved oxygen, the cathodic reaction in seawater systems. Graphite gasket will stimulate acidification and thus exacerbate crevice corrosion in chlorinated seawater.

(f) The hardness of ring gasket should be less than that of the connected flange face (at least 15 BHN less is preferable). See Table 5.32 for more details.
(g) Typically gaskets for metallic flanges are supplied as 3.2 mm (1/8 in.) in thickness except 1.6 mm (1/16 in.) or 3.2 mm (1/8 in.) for utilities (fresh water, air, nitrogen, etc.) and low pressure cryogenic service (Class $\leq$ #300).
(h) Typically gaskets for nonmetallic flanges are supplied as full-face type, 3.2 mm (1/8 in.) in thickness, and made from EPDM, Buna-N, neoprene, viton, or polytetrafluoroethylene, 1.6 mm (1/16″) or 3.2 mm (1/8 in.) as needed. The material should be compatible with both the flange material and the service fluid and suitable for the minimum and maximum expected temperatures.
(i) In systems hydrotest between 150psig (10.3 bar) and 225psig (15.5 bar), either full-face 3.2 mm (1/8 in.) thick flat rubber gaskets (neoprene, red rubber, etc.) or gaskets with better sealing properties may be used.

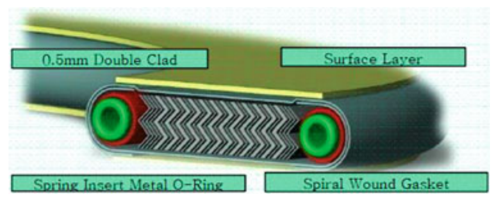
    In systems hydrotest only up to 150psig (10.3 bar), full-face 3.2-mm (1/8 in.)-thick rubber gaskets are recommended. Shore "A" hardness values can range from 60 to 80, although values down to 50 may be suitable as well as higher values.
(j) The maximum temperature (as DT) limitations of several gasket materials (Table 3.15)
(k) Nonmetallic gaskets (typically up to 300 °C (572 °F) except graphites) and ring gasket do not have fire resistance.
(l) For flat-faced flanges, the gasket should cover the full face.
(m) The gasket factor (m) and design seating stress value (y) should meet the ASME Sec. VIII, Div.1, Table 2.5.1 as a minimum. Otherwise the m and y values provided by gasket supplier should be approved by end-user.
(o) See API 661, Table A.3, for the gasket minimum width and thickness per gasket type in air coolers.
(p) See ASME B31.1, Table 112-1, for piping flange bolting, facing, and gasket requirements in power piping.

Table 3.15 Maximum temperature (DT) limitations of several gasket materials (only for reference)

DT, °C (°F)	Gasket Materials & [2nd Symbol for Table 3.16]	General Notes
93 (200)	Neoprene [W], Buna-N [X]	1. The materials should not be used when the MDMT (DMT) is less than −46 °C (−50 °F) unless complied with Sect. 2.1.9, Table 2.15, or approved by the responsible material engineer. 2. The maximum temperature limitations can be reduced per the service and operating condition. 3. The temperature limitation in each piping material class should not be above this temperature unless approved by the responsible material engineer. 4. The crevice corrosion between metal gasket and metal flange during the service should be evaluated before the selection. 5. Other materials to match the service condition may be selected if approved by responsible material engineer.
121 (250)	EPDM [U]	
177 (350)[1]	PTFE sheet [K]	
204 (400)[2]	Garlock 3000 [C] Glass reinforced polytetrafluoroethylene [M]	
427 (800)[2]	Alloy 20 [S]	
454 (850)[2]	Flexible graphite with 316 SS insert (flat or tanged) [A] Flexible graphite with 316 SS corrugated insert [B] Soft iron or low-carbon steel [D]	
482 (900)[2]	Alloy 400 (67Ni-30Cu) [H]	
583 (1000)[2]	304(L) SS [F]	
649 (1200)	4–6%Cr-Mo steel [E], Alloy 200 – pure nickel [G]	
816 (1500)	316 SS [J], 316 L SS [N], 317(L) SS [T], 347(L) SS [P]	
1093 (2000)	Alloy X-750 [L]	

Notes:
[1]Gasket service temperature may be increased to 193 °C (380 °F) for fully confined flanged joints. A fully confined flanged joint is defined as a flanged joint whereby the full thickness of the gasket after compression is confined on both the inside and outside diameter. An unconfined flanged joint is defined as a flanged joint whereby the full thickness of the gasket is not contained on both the inside or outside diameter. A standard ASME B16.5 flange with raised or flat face is considered unconfined

[2]Hiflex® Gasket (see below figure) may be considered for −240 °C (−400 °F) to 1000 °C (1832 °F) and up to 35 MPa (5076 psi), m = 3.75, y = 63.3 MPa (9000psi)



3.2.6.2 Specific Requirements for Certain Services (Recommendation)

(a) Oxygen Service

Gaskets should comply with the applicable requirement in CGA G- 4.4, Section 5.6.

Gaskets for oxygen service should be marked "Cleaned for Oxygen Service" as required in CGA G-4.1, Section 12.2 and individually packaged in sealed packaging.

(b) Other Services (Table 3.16)

Table 3.16 (1/2) Selection of gaskets in refinery and petrochemical plants (only for reference)[2]

Service & Flange Materials	For FF Type Flange	RF Type Flange				Gasket for RTJ Type Flange[6][7]
		DT ≤454 °C (850 °F)			DT > 649 °C (1200 °F)[1]	
		Class ≤ #300	All Classes	Class ≥ #300		All Classes
Carbon Steel, Impact- Tested Carbon Steel, Cast Iron						
Ammonia	2B	13F1	3F1	–	–	10D
Amine (MEA, DEA, MDEA, etc.)	2B	13F1	3F1	–	–	10D
Catalyst	–	13F1	3F1	–	–	10D
Caustic	2B	13F1	3F1	–	–	–
Ethylene oxide	–	13F2	3F2	–	–	–
Hydrocarbon (non-corrosive)	2B	13F1	3F1	–	–	10D
Hydrocarbon (corrosive)	–	13F1	3F1	–	–	10D
Hydrochloric acid and chlorine	2 K	1K		–	–	–
Hydrogen and hydrogen-hydrocarbon mixtures	–	13F1	3F1	–	–	10D
Nitrogen, gaseous oxygen	2B	13F1	3F1	–	–	10D
Phenol and phenol mixtures	2B	13F1	3F1	–	–	10D
Steam	2B	13F1	3F1	–	–	10D
Sulfuric acid	2 K	13F2	–	–	–	–
Sulfur dioxide	2 K	13F2	–	–	–	–
Water (fresh), utility air, instrument air	2C	1C	3F1	–	–	–
Cr-Mo Steel (up to 9Cr) for Flange Material						
Hydrocarbon (non-corrosive)	–	13F1	3F1	3 N4	–	10E
Hydrocarbon (corrosive)	–	13F1 or 13 N1	3F1 or 3 N1	3 N4 or 3 J4	–	10 N
Hydrogen and hydrogen-hydrocarbon mixtures	–	13F1 or 13 N1	3F1 or 3 N1	3 N4 or 3 N4[3]	–	10 N
Steam	–	13F1	3F1	3 N4	–	10E

FF = flat face, RF = raised face, RTJ = ring type joint[5], DT = design temperature

Table 3.16 (2/2) Selection of gaskets in refinery and petrochemical plants (only for reference)[2]

Service & Flange Materials[9]	For FF Type Flange[8]	RF Type Flange				Gasket for RTJ Type Flange[6][7]
		DT ≤454 °C (850 °F)		649 °C (1200 °F) ≥ DT >454 °C (850 °F)[1]	DT > 649 °C (1200 °F)[1]	
		Class ≤ #300	Class > #300	Class ≥ #300		All Classes
MSS & FSS Cladding or Lining for Flange Material						
Hydrocarbon (non-corrosive)	–	13F1	3F1	3 N4	–	–
Hydrocarbon (corrosive)	–	13F1	3F1	3 N4	–	–
Hydrogen and hydrogen-hydrocarbon mixtures	–	13F1	3F1	3 N4[3]	–	–
Steam	–	13F1	3F1	3 N4	–	–
304(L) SS Solid or Cladding/Lining for Flange Material						
Amine (MEA, DEA, MDEA, etc.)	2B	13F1	3F1	3 N4	3 L4	10F
Cryogenic Service[4]	–	13F1	3F1	–	–	–
Ethylene oxide	–	13F2	3F2	–	–	–
Hydrocarbon (non-corrosive)	2B	13F1	3F1	3 N4	3 L4	10F
Hydrocarbon (corrosive)	–	13F1	3F1	3 N4	3 L4	10F
Hydrogen and hydrogen-hydrocarbon mixtures	–	13F1 or 13 N1	3F1 or 3 N1	3 N4 or 3 N4[3]	3 L4	10 N
Phenol and phenol mixtures	2 K	13F2	–	–	–	–
Steam	2B	13F1	3F1	3 N4	3 L4	–
Water (fresh), utility air, instrument air	2B	13F1	3F1	–	–	–
316(L)SS & 317(L) SS Solid or Cladding/Lining for Flange Material						
Acetic acid, chemicals	2B	13 N1	–	–	–	–
Amine (MEA, DEA, MDEA, etc.)	2B	13 N1	3 N1	–	–	–
Hydrocarbon (corrosive)	2B & 2 T	13 N1 & 13 T1	3 N1 & 3 T1	3 N4 & 3 T4	3 L4	10 N & 10 T
Hydrogen and hydrogen-hydrocarbon mixtures	–	13 N1 & 13 T1	3 N1 & 3 T1	3 N4 & 3 T4[3]	3 L4	10 N & 10 T
Phosphoric acid	2B	13 N1	–	–	–	–
Urea	2B	13 N1	3 N1	3 N4	3 L4	10 N & 10 T
Water (fresh), utility air, instrument air	2B	13F1	3F1	–	–	–
Aluminum Alloys for Flange Material						
Cryogenic services[4]	2B	1B	1B	3F1	–	–
Alloy 20 Solid or Cladding/Lining for Flange Material						
Sulfuric acid	2 K	13S2	–	–	–	–
Sulfur dioxide	2 K	13S2	–	–	–	–
Nickel Alloy & Monel Solid or Clad/Lining for Flange Material						
Caustic	2 K	13H2	3H2	–	–	–
Sulfuric acid	2 K	13H2	3H2	–	–	–
Brine	2 K	13H2	3H2	–	–	–
Aluminized Carbon and Low Alloy Steel for Flange Material						
Hydrocarbon (corrosive)	–	13F1	3F1	3 N4	3 L4	10F

FF = flat face, RF = raised face, RTJ = ring type joint[5], DT = design temperature

Notes: Symbols (Table 3.16a): e.g., 13F2: 13, 1st; F, 2nd; 2, 3rd

[1]Above 454 °C (850 °F) and up to 649 °C (1200 °F), use 316 L SS windings in spiral wound gaskets Type 3CN4. Type 3CN4 may also be used for Class 150 up to 538 °C (1000 °F) maximum. Above 649 °C (1200 °F), use Alloy X-750 windings in spiral wound gaskets Type 3CL4

[2]See Project Piping Material Classes and Gasket Specification for project application. Consult with responsible metallurgist for gasket material in other service and/or combined conditions

[3]RTJ flanges should be used for hydrogen service in Class 600 and higher. [See the project specification for the definition of hydrogen service.] See Sect. 2.6.2.4 General Note n

[4]Cryogenic Service: Liquefied Gases, such as LNG, LPG, Ammonia, Ethylene, Liquefied Oxygen/Nitrogen, etc. See Table 2.120 for more details for liquefaction temperature and available materials

[5]Types of RTJ (Ring Type Joint) gaskets: See Fig. 3.13 types of RTJ Gaskets (R/RX/BX) and Sect. 2.6.2.4 General Note n

[6]Other type RTJ gaskets (other than octagonal) may be selected per project specification and field experience

[7]Hardness Requirements for RTJ gaskets: See Table 5.32 for maximum hardness of ring gaskets

[8]FF Flanges: Typically applied for Class ≤ #150, non-hydrocarbon, and/or utilities

[9]Gaskets for Oxygen Service: See Sect. 3.2.6.2(a)

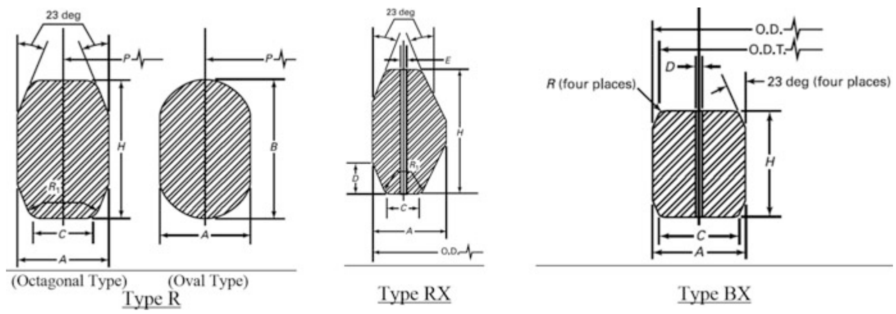


Figure 3.13 Type of RTJ Gaskets (R/RX/BX)

Table 3.16a Type of Construction and Dimensional Standard

Symbol	Type of Construction and Dimensional Standard
1	Flat ring for RF flanges (ASME B16.21)
2	Full face for FF flanges (ASME B16.21)
3	Spiral wound metal flat ring gasket with a solid inner ring, nonmetallic filler, and an outer solid ring type centering device for RF flanges (ASME B16.20). (Materials as specified)
4	Spiral wound metal flat ring gasket, nonmetallic filler, and a solid ring type centering device, for RF flanges (ASME B16.20). (Materials as specified)
5	Flat metal jacketed gasket, nonmetallic filler, completely enclosed within a fully annealed double metal jacket, for RF flanges (ASME B16.20)
6	Corrugated metal jacketed gasket, nonmetallic filler, completely enclosed within a fully annealed double metal corrugated jacket for RF flanges (ASME B16.20)
7	Corrugated metal gasket fully annealed corrugated metal with filler material cemented to the corrugations on both faces for RF flanges (ASME B16.20)
8	Solid metal flat ring for small tongue and groove flanges
9	Solid metal flat ring for large tongue and groove flanges
10	Solid metal RTJ octagonal ring (ASME B16.20)
11	Solid metal RTJ oval ring (ASME B16.20)
12	Fully annealed corrugated metal for RF flanges
13	Spiral wound metal flat ring with solid inner ring, nonmetallic filler, and an outer solid ring type centering device for ASME Class 150 RF flanges. (Low seating stress design, "Flexitallic LSI" or approved equal.) (ASME B16.20) (Materials as specified)
14	Grooved metal flat ring with solid metal centering ring (integral or loose as specified) and nonmetallic filler on both sides (Camprofile) (Materials as specified)

FF = flat face, RF = raised face
First Symbol (numbers) – Table 3.16a
Second Symbol (alphabet) – Material group (basic, wining, or jacket): See Table 3.15, Gasket Material Symbol []
Third Symbol (numbers) – Filler material (when required by the first symbol)
None: No filler required (e.g., 2B, 2C, 2 K, 10D, etc.)
1. Flexible graphite
2. PTFE
3. Oxidation inhibited flexible graphite for hot temperature with mica (inner and outer shielding)
4. Exfoliated vermiculite, Flexitallic Thermiculite® (alternatives require purchaser's written approval)

References

– ASME Sec. VIII, Div.1, MA-2 Rules for Bolted Flange Connections with Ring Type Gaskets
– ASME B16.20 – Metallic Gaskets for Pipe Flanges – Ring Joint, Spiral Wound and Jacketed
– ASME B16.21 – Nonmetallic Flat Gaskets for Pipe Flanges
– ASME B31.3 and B31.1 Process Piping and Power Piping
– MSS SP65 – Flanges and Threaded Stubs for Use with Lens Gaskets
– ASTM C564 Rubber Gaskets for Cast Iron Soil Pipe and Fittings
– CGA G-4.1 – Cleaning Equipment for Oxygen Service
– CGA G-4.4 – Industrial Practices for Gaseous Oxygen Transition and Distribution Piping Systems
– ANSI/AWWA C111/A21.11-00 Rubber Gasket Joints for Ductile-Iron Pressure Pipe and Fittings
– PIP PNSM0105 Purchasing Requirements for Gaskets
– NACE MP Vol.50, No.8 (Aug. 2011), p32 Causes of Flange Isolation Gasket, Sleeve and Washer Failure.
– NACE MP Vol.46, No.10 (Oct. 2007), p50 Gasket Selection for Stainless Steels in Seawater
– API 661 – Air Coolers-Gasket Minimum Width and Thickness per the Type

3.3 Other Fabrication

3.3.1 Insulation, Refractory Lining, and Fireproofing

See Sect. 2.6.2.7 unless otherwise noted below (materials related requirements).

3.3.1.1 Insulation

(a) See Sect. 2.4.2.13 for CUI (corrosion under insulation) and its applicable codes and standards (including recommended insulation materials and requirements).
(b) The purpose, thermal conductivity, useful temperature range, hygroscopicity, asbestos-free, required thickness, type (block, spray form, blanket, wool, etc.), etc. for the insulation material may be the key factors. The required thickness of insulation is introduced from the company insulation specifications which are based on the materials, service temperature, facility type, size of equipment, and piping. All surfaces to be insulated should be clean and dry. Normally the industrial standards do not much cover the fabrication and construction of insulation, refractory lining, and fireproofing. The following requirements are commonly applied as a minimum unless otherwise approved or specified by the end-user/purchaser:
    1. When insulation provides for the combined function of thermal and acoustic insulation, the system should be designed for the more stringent design conditions.
    2. The applied temperature for selection of insulation materials is normally based on the maximum operating temperature or maximum external metal skin temperature for hot service and the min. operating temperature for cold service unless otherwise required/specified.
    3. Selection of insulation materials should take into account any additional constraints such as, resistance to chemicals or corrosion, and temperature or mechanical strength requirements, together with any safety requirements.
    4. Significant variations in temperature above normal process conditions (e.g., auto-regeneration conditions) should require a review of the specific insulation system design.
    5. The heat tracing tubes and cables should not be directly contacted with the main body (equipment and piping).
    6. When used to insulate austenitic stainless steel surfaces, insulation materials should meet ASTM C795 (Thermal Insulation for Use in Contact with ASS), C692 (Test Method for Evaluating the Influence of Thermal Insulations on the External SCC Tendency of ASS), C871 (Test Method of Chemical Analysis for Thermal Insulation Materials for Leachable Chloride, Fluoride, Silicate and Sodium Ions) unless otherwise approved or specified.
    7. All insulation and nonmetallic accessory materials should be manufactured without the addition of asbestos, tremolite, anthophyllite, actinolite, chrysotile, crocidolite, amosite, or a combination of these minerals.
    8. Insulation materials, such as calcium silicate and perlite, which contain sodium silicate inhibitors should not be used on ASS when maximum operation temperature > 621 °C (1150 °F). Insulation for such applications should be mineral wool or ceramic fiber blankets.
    9. Refractory Ceramic Fiber (RCF) insulation should not be used for pipe insulation as a substitute for calcium silicate.
    10. When required to be insulated, flanges, flanged valves, manways, and rotary equipment should be insulated with flexible, removable, and reusable insulation covers in accordance with ASTM C1695 (Fabrication of Flexible Removable and Reusable Blanket Insulation for Hot Service). Such covers consist of fibrous insulation cores, such as glass fiber mat, mineral wool, or ceramic fiber blanket, covered with silicone-coated fiberglass cloth and manufactured using sewn seam construction.
    11. Insulation for piping sizes up to and including NPS 12 should be supplied in two-piece sectional. Insulation for piping sizes over NPS 12 should be supplied in blanket form, sized per manufacturer's standard dimensions. Pipe sizes greater than NPS 36 should be insulated with blocks chamfered and butted to follow closely the radius of the pipe.
    12. The compatibility of the cladding material with the insulation should be checked, and an inside protective coating, aluminum foil, or moisture barrier should be specified where required.
    13. Galvanized steel and aluminum cladding should not be directly in contact with ASS pressure equipment and piping.
    14. Thermal cement for use on bottom heads of equipment, inside vessel skirts, should be in accordance with ASTM C449 (Mineral Fiber Hydraulic-Setting Thermal Insulating and Finishing Cement).
    15. Expansion joints should be provided at the tangent of each elbow when the pipe temperature exceeds 150 °C (300 °F), and at the spacing between tangent points, and should be filled with glass wool, to allow the insulation to expand without leaving gaps in the insulation.
    16. All metallic accessory materials, such as bands, seals, screws, springs, and wire, should be ASS.
    17. All pipe fittings should be insulated to the same grade as the straight sections of the pipe.
    18. Acoustic insulation should be sealed to prevent noise leakage.
    19. All insulation of 75 mm (3 in.)* thickness or less is to be installed as one layer.
        *Insulation of thickness greater than 75 mm (3 in.) may be installed with multi-layers.
        *100 mm (4 in.) may be applicable for blanket type insulation. The insulation which is also used for fire protection should have double layer or higher. All joints of multi-layers insulation should be staggered.
    20. All stiffening rings should be fully insulated.
    21. All insulation materials should be asbestos-free.

22. The small bore manhole, handhole, and H/EX channel covers may not be insulated.
23. Vapor barrier or vapor retardant finish may be applicable on the metal surface to be insulated when the moisture on the metal surface is frequently expected.
24. All bolting materials embedded in the insulation in sour service should be softened type per ANSI/NACE MR0175/ISO15156 and ANSI/NACE MR0103/ISO 17945.
25. Pumps and turbines when the maximum operating temperature is 204 °C (400 °F) and greater. Insulation materials for pumps should be blanket insulation. Blanket insulation should be fitted to the curvatures and contours of the parts.
26. The scope of insulation should be clearly defined in the insulation drawings, e.g., flanges, valves, external bolting, horizontal/vertical equipment, and piping parts applied by personal protection (PP).
27. The inspection windows should be provided per the designated TML (thickness measurement location) or CUI inspection location.
28. Aluminum alloys (AL 3003 or 3105 with temper H14)/galvanized steel/ASS jacket [minimum 0.4 mm (0.016 in.) thickness], ASS bands, ASS wire mesh (min. 16 gauge), and mastics should be installed completed per the applicable insulation specification. Aluminum alloys that are subject to environmental corrosion as well as flammable environment or fire protection should not be used for jacketing.
29. Caulking and mastic sealants should include one type suitable for use on surfaces with temperatures up to 200 °C (395 °F).
30. Bands should be ASS or aluminum alloy. Minimum band width 12 mm (0.5 in.) and maximum band centers 230 mm (9 in.) for up to 150 mm (6 in.) diameter above 150 mm (6 in.) band centers maximum 300 mm (12 in.)

(c) Table 3.17 shows the applicable standards per the most common insulation materials and the purpose.

Table 3.17 Purpose and characteristics of the most common nonmetallic materials for insulation

Purpose [initial]	Materials[(1)]
[HC] Hot Conservation and Fire Protection including Heat Conservation of Steam/Electric Tracing ≥60 or 65 °C (140 or 150 °F)	Calcium Silicate-ASTM C533/BS 3958 Pt 2 [≤650–927 °C (1200–1700 °F) per type], Mineral Wool-ASTM C553/C764 [≤232–650 °C (450–1200 °F) per type], Mineral Fiberglass-ASTM C547 [≤454–760 °C (850–1400 °F) per type], Rock Wool-ASTM C592 [≤454–650 °C (800–1200 °F) per type], Ceramic Fiber-ASTM C892 [≤732–1649 °C (1350–3000 °F) per type], Expanded Perlite-ASTM C549 [≤760 °C (1400 °F)], Urethane-ASTM C1029 [≤107 °C (225 °F)]
[CC] Cold Conservation <13 °C (55 ° F)	Perlite -ASTM C549, Cellular Glass -ASTM C522, Phenolic Foam – rigid – ASTM C1126/BS EN 13166, Polyisocyanurate Foam – rigid – ASTM C591/BS 5608, Polyurethane Foam – rigid – ASTM C1289/BS 5608, etc.
[PP] Personnel Protection when the temperature ≥ 60 or 65 °C (140 or 150 °F)	Calcium Silicate – ASTM C533/BS 3958 Pt 2 Mineral Wool – ASTM C764/C547/C553/C592, etc.
[FP] Freeze Protection including Winterproofing	Cellular Glass – ASTM C522, etc.
[AH or AC] Acoustic Materials	Calcium Silicate-ASTM C533/BS 3958 Pt 2, Mineral Wool -ASTM C764/C547/C553/C592, etc.

Note: [(1)] See Sect. 2.6.2.7 for more details

3.3.1.2 Refractory Lining

The basic requirements for refractory lining are high-temperature strength and insulation as well as heat and abrasion (erosion) resistance with sufficient life time. Also, anchors (metallic or refractory device) should retain the refractory or insulation to the shell of vessels or piping stably.

(a) Refractory Types
1. Firebrick: Constructed of individual brick shapes and used primarily in areas where ceramic bonded products are necessary to withstand environmental and mechanical conditions of the equipment. Reliability of brick linings is highly dependent on the skill of the bricklayer (installer) and is more complicated than monolithic construction techniques.
2. Insulating firebrick (IFB): Class of lightweight bricks that has relatively low thermal conductivity and is used as insulating backup linings for dense refractory brick linings systems. IFBs also are used as primary (hot face) linings for fired heaters and furnaces and primary reforming furnaces in which lining integrity and insulation value are both important.
3. High-Temperature Refractory Insulation Wools
   (a) Alumina Silicate Glass Wool (ASGW) – Fig. 3.14 through Fig. 3.16: Also known as Refractory Ceramic Fibers (RCF) which are amorphous fibers produced by melting a combination of Al_2O_3 and SiO_2, usually in a weight ratio 50:50. Products made of alumina silicate wool are generally used at application temperatures of greater than 900 °C and in intermittently operating equipment and critical application conditions. Man-made vitreous (silicate) fibers (MMVF) are composed primarily of alumina and silica. Additives, such as Cr_2O_3 and ZrO_2, develop enhanced physical properties. Fibers are produced by spinning and blowing molten alumina silica compositions, forming 2.5 to 3.5 μm (98 to 138 μin) diameter fibers. RCF exhibits excellent

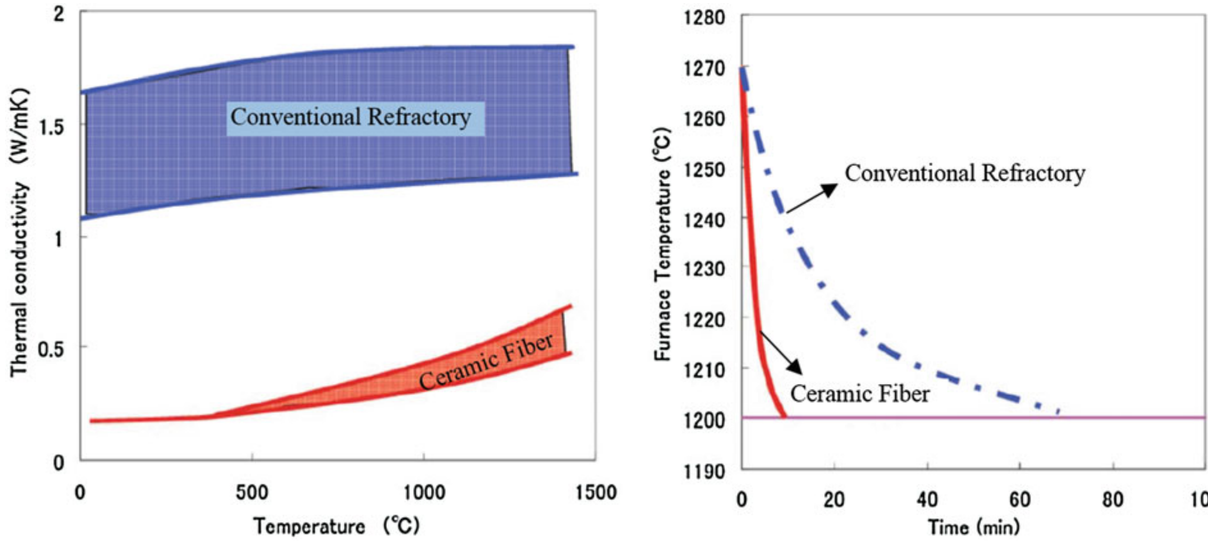


Figure 3.14 Comparison ceramic fiber and conventional refractory. (Source: Ceramic Fiber and Development of Insulation Technology Article, Nippon Steel Report, Jul. 1998)

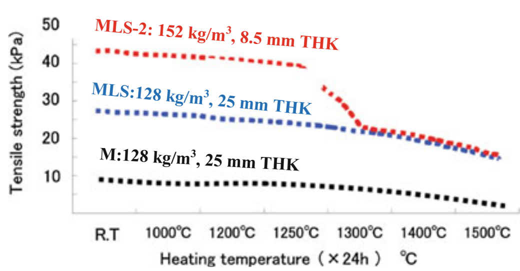


Figure 3.15 TS of Typical Crystalline Ceramic Fiber. (Source: Ceramic Fiber and Development of Insulation Technology Article, Nippon Steel Report, Jul. 1998) MLS: Multi-layer System, MLS-2: Multi-layer System-Customer Grade

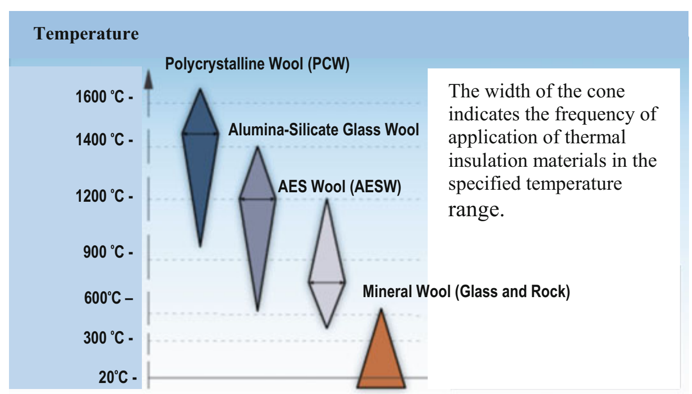


Figure 3.16 High-Temperature Properties of Several Refractory Insulation Materials. (Source: PTCH Consultancy report, 2010)

thermal conductivity (insulating value). RCF is classified as a Class 2E carcinogen, and certain restrictions apply to its use. Application forms include bulk, blanket, paper, modules, rope, and vacuum formed shapes. MMVF can cause irritation of the skin, eyes, and upper respiratory tract, many being fine enough to be inhaled and deposited in the lungs.

(b) Polycrystalline Wool (PCW) – Fig. 3.16: PCW consists of fibers containing greater than 70 wt% Al_2O_3. They are produced by a "sol-gel method" from aqueous spinning solutions. The water-soluble green fibers obtained as a precursor are crystallized by means of heat treatment. PCW is generally used at application temperatures greater than 1300 °C (2372 °F) and in critical chemical and physical application conditions, also at lower temperatures.

(c) Alkaline Earth Silicate Wool (AESW) – Fig. 3.16: Also known as high-temperature glass wool. AESW consists of amorphous fibers, which are produced by melting a combination of CaO^-, MgO^-, SiO_2, and ZrO_2. Products made from AES are generally used at application temperatures less than 900 °C (1652 °F) and in continuously operating equipment and domestic appliances. This family of products was developed to provide a ceramic fiber that is soluble in body fluids of the lung. This fiber material has been thoroughly tested and does not require the hazard label common with RCF. Thermal Ceramics produces a product called Superwool, and Unifrax produces a product called Insulfrax.

4. Anchors and Ferrules: Size, materials, layout, welding procedure, and installation procedures should be set up before the construction.
5. Inspection plan and procedure for construction and during operation should be prepared. Especially hot spot should be periodically detected during operation.

(b) Typical Refractory Classification per Density
1. Lightweight class – Installed fired density of 800–1070 kg/m3 (50–67 lb./ft3)
2. Medium weight class – Installed fired density of 1090–1440 kg/m3 (68–90 lb./ft3)

3. Moderate density class – Installed fired density of 1460–1920 kg/m3 (91–120 lb./ft3)
4. Heavy weight class – Installed fired density of 1940–2400 kg/m3 (121–150 lb./ft3)
5. Dense refractory class – Installed fired density of greater than 2400 kg/m3 (150 lb./ft3)

(c) Refractory Castables
1. Organic fiber, such as polypropylene fibers in castable products, is designed to enhance the escape of moisture during the initial heating of cast or gunited linings. Organic fibers disappear at low temperatures, less than 150 °C (300 °F), which provides capillaries that enable moisture in steam form to escape and thereby prevents the buildup of steam pressures that cause explosive spalling.
2. The aluminum phosphate binder for refractory castables is designed to provide excellent strength and erosion resistance.
3. Plastic refractory is tempered with water and extruded. Extruding develops a level of workability, permitting ramming with pneumatic tools to form a monolithic structure. Plastic refractory mixes are prepared at a manufacturer facility, extruded into columns, sliced, and packaged.
4. Stainless steel fibers are an additive to refractory castables and plastic refractories that improves lining integrity and assists in crack distribution.
5. Refractory placement technique, whereby materials with plastic like consistencies are rammed into an anchoring system with pneumatic rammers to form a refractory lining free of voids.

(d) Refractory Dryout
1. Burners for dryout of the installed refractory emit a long-flame at high firing conditions. This has been observed in numerous dryouts along with a mock-up that was performed by a dryout contractor normally. The extension tube eliminates exposure of the refractory lining to flame, which reduces the potential for explosive spalling during the drying process. The burner extension may be shortened or eliminated if dryout temperatures are below 430 °C (800 °F) and flame impingement is not possible, such as in furnace components.
2. Dryout temperature should not exceed 650 °C (1200 °F) and the normal operating temperature of the refractory lining.
3. Heating rates should be controlled by thermocouples placed closest to heat source.
4. Hold temperatures and durations should be controlled by thermocouples placed closest to exhaust or furthest from heat source.
5. During soak periods, temperature difference of refractory surfaces should be within 55 °C (100 °F).
6. Dryout schedule and curing procedure (heating/cooling rate, holding temperature/time) should be set up in accordance with refractory type before the construction.

3.3.1.3 Fireproofing

Fireproofing is for temporary fire protection during a few hours to avoid the damage or degradation of the substrate material until the firefighters are effectively working the while refractory is for continuous heat resistance (or long-term fire protection), so that the substrate material can be sustained at lower temperature continuously. The fire protection for building and any other utilities is not considered in this book.

There are several regulations for fireproofing in America and states. However, most local locations in foreign countries, states, provinces, and territories have their own regulations which may be governed preferentially.

See Sect. 2.4.2.13 for CUF (corrosion under fireproofing).

(a) Goal of Fireproofing

Methods of fireproofing should result in a three (3)-hour rating in most cases: Normally 75 mm (3 in.) thickness for heavy concrete and approximately 25 mm to 50 mm (1 in. to 2 in.) thickness for lightweight concrete as required. Thickness should be determined by probed measurements in accordance with the recommended procedure of ASTM E605 or other methods approved in writing.

(b) Materials Requirements
1. Concrete materials should be designed and proportioned so that the concrete should have a minimum compressive strength of 3000 lb./in^2 at minimum 28 days. (20.68 MN/mm^2) when spray applied and 1.0 N/mm^2 when manually applied.
2. Lightweight cement should be in accordance with ASTM Specification C150.
3. Aggregate should be per ASTM C33, having a maximum size of 9.5 mm (3/8 in.) of gravel.
4. All steel surfaces to be fireproofed should be hot dip galvanized per ASTM A123 or sandblasted and primed with a primer that is compatible with the fireproofing. (Note that some materials cannot be applied over zinc primers.)
5. Reinforced concrete structures may be substituted for fireproofed structural steel. Reinforced concrete structures should have a minimum clear cover of 65 mm (2.5 in.) of concrete over all reinforcing steel in parts of structure which may be exposed to fire.
6. Coating for fireproofing instead of conventional concrete materials may be applied if all test data are proved and the end-user agrees.

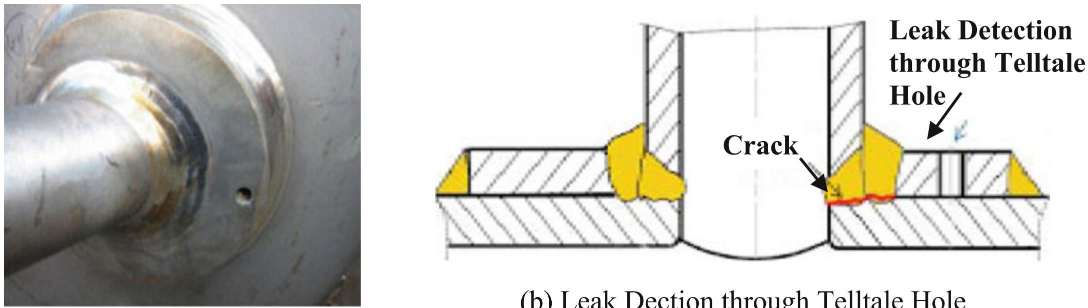
(c) Application
1. Fireproofing should normally be reinforced concrete (Carboline Pyrocrete 241 or equal), with minimum thickness to maintain a 1.5–3.0 hour rating. Substituted materials should have written approval by company prior to use and should include detailed thickness with application procedures from the manufacturer indicating compliance which will provide the specified fire ratings (2.5 hour rating) per UL (Underwriters Laboratories Inc. Fire Resistive Directory).
2. Guniting should not be carried out in the vicinity of disconnected piping where rebound and splatter can enter unless the openings in such lines are closed with wooden plugs or other suitable shields.
3. The top of fireproofing on vertical structural columns, the top of horizontal beams, and other surfaces exposed to weather should be coated with a weatherproofing mastic.

4. When supporting fire potential equipment within the battery limits, columns and the beams transmitting the equipment load to the columns should be fireproofed from their bases to a minimum height of 10.7 m (35 feet) above grade.
5. Both the vertical and the horizontal members of pipe rack located in fire potential areas should be fireproofed. Pipe rack structures more than 15.25 m (50 feet) from any fire potential equipment does not need fireproofing unless unusual conditions of exposure or loading exist.
6. All lugs, brackets, skirts, and legs supporting fire potential equipment located within the fire potential area and below a minimum height of 10.7 m (35 feet) should be fireproofed.
7. Saddles supporting equipment and measuring more than one foot in height at their lowest points should be fireproof within the fire potential area.
8. Skirts of pressure vessels in fire potential areas; outside only unless otherwise required.
   (a) The inside of skirts over 1.22 m (4 feet) in diameter and the bottom heads of uninsulated vessels on skirts over 4 feet in diameter should be fireproofed.
   (b) Skirts four 1.22 m (4 feet) in diameter and smaller, containing more than one access opening and where such openings cannot be sealed while equipment is in service, should be fireproofed also on the interior surface of the skirt. All annular pipe space openings in the skirt should be suitably plugged to prevent drafts. If these openings cannot be plugged, the interior of the skirt should be fireproofed in the same manner as the exterior.
   (c) The fireproofing, exterior and interior, should extend from the bottom of the insulation (or the tangent line)
   (d) to the foundation, including the base ring and anchor bolt chairs.
9. Air-cooled exchangers should have their legs including knee braces protected by fireproofing.

(d) Regulations
- API RP2218 Fireproofing Practices in Petroleum and Petrochemical Processing Plants
- API STD 2510 Design and Construction of LPG Installations-Fireproofing for LPG Storage Vessels
- API 2510A Fire Protection Considerations for the Design and Operation of Liquefied Petroleum Gas (LPG) Storage Facilities
- API Spec 6A Wellhead and Christmas Tree Equipment-Fire Test for Valves
- NFPA 30 Flammable and Combustible Liquids Code
- NFPA 58 Storage and Handling of Liquefied Petroleum Gases
- NFPA59 Storage and Handling of Liquefied Petroleum Gases at Utility Gas Plants
- NFPA 59A Production, Storage and Handling of Liquefied Natural Gas (LNG)
- NFPA 70 National Electrical Code
- NFPA 701 Fire Tests for Flame Propagation of Textiles and Films
- FAA AC 23-2A Flammability Test
- ACI 318 Building Code Requirements for *Reinforced Concrete*
- UL 1709 Rapid Temperature Rise Fire Testing Standard for Fireproofing Materials
- ULC Fire Resistance Directory
- ASTM E-119 (UL 263) Test Methods for Fire Tests of Building Construction and Materials with Acceptable Time-Temperature Curve
- ASTM C150 Specification for Portland Cement
- ASTM E605 Test Methods for Thickness and Density of Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members

3.3.2 Shop Isolation

1. Stainless Steels and Alloy Metals
   The fabrication shop for these materials should be isolated from the shop for carbon and low alloy steels to avoid the possibility of the pickup of iron and other contaminants. The following cautions are to be considered.
   (a) All wire brushes must be made from stainless steels and alloy metal.
   (b) All tools used to grind or polish stainless steel/alloy metals must be appropriately suited to and dedicated to stainless steel/alloy metal and not used for other metals.
   (c) Where guillotines or shear blades are used they should be thoroughly cleaned to remove any carbon steel chips or shavings from the area prior to working with stainless steel/alloy metal. To minimize pickup from the blade, if possible the guillotines or shear blades should be kept in a dedicated area and made from hard Cr plated steel or high-carbon, high-Cr steel.
   (d) Rolls, forming mandrels, press brakes, etc., should only be used when they have been thoroughly cleaned to remove any CS particles. If possible, the tool should be kept in a dedicated area and made from hard
   Cr plated tool steel, high-carbon, high Cr-steel or from one of the aluminum bronze tool materials.
2. Painting shop (blasting and painting) should be isolated from the shop for facilities fabrication shop to avoid metal loss and sand/metal/coating contamination.
3. Radiographic test should be performed at separated shop or isolated shop from workers to avoid exposure from radioactivity.



(a) Telltale Hole (b) Leak Dection through Telltale Hole

Figure 3.17 Vent hole and leak detection in reinforcing pad

3.3.3 Telltale and Vent Holes

The term of telltale holes has been widely used for metal loss/weep indication as well as vent hole. Currently ASME decided to classify two different terms, such as a telltale hole for metal loss/weep indication and a vent hole for gas emission, while API still sustains a single term as a telltale hole. ASME Sec. VIII, Div.1, UG-25(e) states that telltale holes (also called weep hole) may be used to provide some positive indication when the thickness has been reduced to a dangerous degree (i.e., to reduce significant releases and/or catastrophic events that are related to internal corrosion/erosion of process sides). Telltale holes should not be used in vessels that are to contain lethal substances [see Sect. 1.1.9.2 in this book], except as permitted by ASME Sec. VIII, Div.1, ULW-76 for vent holes in layered construction. When telltale holes are provided, they should have a diameter of 1.5 to 5 mm (1/16 to 3/16 in.) and have a depth not less than 80% of the thickness required for a seamless shell of like dimensions. These holes should be provided in the opposite surface to that where deterioration is expected [e.g., for telltale holes in clad or lined pressure vessels, see ASME Sec. VIII, Div.1, UCL-25(b)]. Meanwhile, vent holes (Fig. 3.17) on the reinforcing pad serve as a vent during welding for entrapped gases and prevents the reinforcing pad from becoming a jacketed vessel. ASME Sec. VIII, Div.1, UG-37 (g) states that reinforcing plates and saddles attached to the outside of a vessel should be provided with at least one vent hole [max. OD of 11 mm (7/16 in.), preferable 6 mm (1/4 in. diameter)] that may be tapped with straight or tapered threads. These vent holes may be left open or may be plugged when the vessel is in service. If the holes are plugged, the plugging material used should not be capable of sustaining pressure between the reinforcing plate and the vessel wall. Vent holes should not be plugged during heat treatment. This telltale/vent holes are also used for pneumatic leak test of the reinforced pad. API 660, 10.3.7 indicates that nozzle reinforcement pads should be pneumatically tested at 170 kPa (25 psi) gauge. API 650 and 620 (storage tanks) also requires one 6 mm (0.25 in.) diameter telltale hole as a vent hole in the reinforcing plate of nozzles and manholes.

3.3.4 Hot Box

A specific consideration for skirt supported-insulated vessels to be operated at elevated temperature should be given to add an insulating bulkhead below the bottom head to introduce a Hot Box (Fig. 3.18) keeping the top portion of the skirt hot. In such cases, the buckling resistance of the skirt should be evaluated.

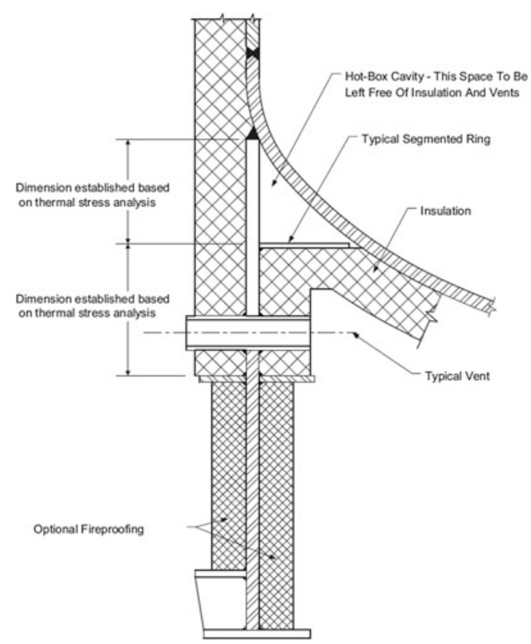


Figure 3.18 Hot Box at Bottom Head/Skirt Insulated. (Source: ASME PCC-2/ASME Sec. VIII, Div.2, Fig. 4.15.8)

3.3.5 Bolts Tensioning and Torqueing

Bolting materials can be readily stress-relaxed due to over torque and/or repeated fastening & unfastening. The control by sound tensioning procedure is greatly required to extend the life time. Joint integrity requirements and procedures are required for the tightening of flange bolting using spanners, wrenches, torque wrenches (manual and hydraulic), and hydraulic bolt tensioning equipment, providing guidance on the method of flange tightening to be used, and the bolt stresses and torques required to ensure a lasting leak-free joint. The method of flange tightening and ultrasonic measurement requirements is dependent upon bolt size, system pressure rating, temperature, and system service.

3.3.5.1 Hand Tightening

Flange bolts may be tightened by conventional combination and hammer wrenches on Class 150 and Class 300 utility piping systems only.

3.3.5.2 Torque Wrenches

Flange bolts should be tightened by torque wrenches on all hydrocarbon systems in all pressure ratings and utility systems Class 600 and above. The hammer tightening of bolts in hydrocarbon systems is not permitted.

3.3.5.3 Bolting Torqueing

Torqueing methods used to tighten bolted connections utilize the inclined plane of a thread to convert rotary motion of the nut into axial motion of the bolt. To achieve bolt stress through torqueing, it is essential that each bolt, nut, and washer is in good condition (clean, no damage, etc.) and well lubricated.

For all flange bolting on Class 150 and Class 300 utility piping, tightening may be carried out by combination and hammer wrenches. Torqueing can be carried out using either manual, calibrated air, or hydraulic torque wrenches. The method chosen is dependent upon bolt loading, access, clearance, and tooling availability, which can be determined by the site personnel. When the bolt loading requires a torque figure of more than 678 N-m (500 lb-ft) to be applied, hydraulic torqueing is recommended, using hydraulic torque wrenches.

(a) Controlled torqueing (with ultrasonic extension meter bolt stress measurement) can be carried out on the following flanged connections:
   1. Bolt sizes less than 30.8 mm (1.375 in.) diameter for all service ratings up to and including Class 400, except Class 150 utility services (see above).
   2. Bolt sizes less than 28.6 mm (1.125 in.) diameter for all service ratings Class 600 and above.

(b) Target Prestresses (Table 3.18)

   Prestress (Preload) is the term used for a bolt's clamp force.

   Reference: http://www.boltscience.com/pages/basics1.htm

Table 3.18 Reference values for calculating target torque values for low alloy steel bolting based on Target Prestress of 345 MPa (50 ksi) (root area)

Nominal Bolt Size, Inch	Target Torque, ft-lbf (m-kgf)		Notes (See General Notes Below as well)
	Non-coted Bolts(1)	Coted Bolts(1),(2),(3)	
1/2	60 (8.3)	45 (6.2)	(1) The tabulated Target Torque values are based on "working" surfaces that comply with ASME PCC-1, Section 4 (Cleaning and Examination of Flange and Fastener Contact Surfaces) and ASME PCC-1, Section 7 (Lubrication of "Working" Surfaces). The Target Torque values were computed using nut factors selected to achieve a Target Prestress of 345 MPa (50 ksi). The torques were adjusted based on industry experience and verified by bolt elongation measurements. (2) The coating on coated bolts is polyimide/amide and is considered to be the sole source of "working" surface lubrication; the application of a lubricant to the coated surfaces can result in a considerable reduction in the assumed coefficient of friction of approximately 0.12. (See ASME PCC-1, Appendix K for equivalent nut factor.) (3) Coated torque values apply only for initial tightening of new, coated bolts using the torque increment rounds shown in Table 3.19 (Torque Increments). For second and subsequent tightening by torqueing methods, use of lubricants and torque values as specified for non-coated bolts is recommended.
5/8	120 (16.6)	90 (12.4)	
3/4	210 (29.0)	160 (22.1)	
7/8	350 (48.4)	250 (34.6)	
1	500 (69.1)	400 (55.3)	
1 1/8	750 (103.7)	550 (76.0)	
1 1/4	1050 (145.2)	800 (110.6)	
1 3/8	1400 (193.6)	1050 (145.2)	
1 1/2	1800 (248.9)	1400 (193.6)	
1 5/8	2350 (324.9)	1800 (248.9)	
1 3/4	2950 (407.8)	2300 (318.0)	
1 7/8	3650 (504.6)	2800 (387.1)	
2	4500 (622.1)	3400 (470.1)	
2 1/4	6500 (898.6)	4900 (677.4)	
2 1/2	9000 (1244,3)	6800 (940.1)	
2 3/4	12,000 (1659.0)	9100 (1258.1)	
3	15,700 (2170.5)	11,900 (1645.2)	
3 1/4	20,100 (2778.8)	15,300 (2115.2)	
3 1/2	25,300 (3497.7)	19,100 (2640.6)	
3 3/4	31,200 (4313.4)	23,600 (3262.7)	
4	38,000 (5253.5)	28,800 (3981.6)	

Source: ASME PCC-1, Table 1

General Notes

(a) The values shown are based on a Target Prestress of 345 MPa (50 ksi) (root area)

(b) See ASME PCC-1, Section 12 for Target Torque Determination and Instruction on how to use this values. The root areas are based on coarse-thread series for sizes 1 in. and smaller, and 8-pitch thread series for sizes 1 1/8 in. and larger.

(c) The Reference Torques for a Target Prestress of 345 MPa (50 ksi) (root area) are given in Table 3.18. Target Torques for different Target Prestress levels may be obtained by reducing (or increasing) the values in Table 3.18 by the ratio: Target Prestress (ksi)/50 (ksi) or Target Prestress (MPa)/345 (MPa)

(d) The metric bolt size (root area) is not the same as US customary bolt size (root area)

Table 3.19 Torque increments for legacy cross-pattern tightening using a single tool

Step	Loading Methods
Install	Hand tighten, then "snug up" to 10 ft-lb (15 N-m) to 20 ft-lb (30 N-m) (not to exceed 20% Target Torque). Check flange gap around circumference for uniformity. If the gap around the circumference is not reasonably uniform, make the appropriate adjustments by selective tightening before proceeding.
Round 1	Tighten to 20% to 30% Target Torque (see ASME PCC-1, Sec.12). Check flange gap around circumference for uniformity. If the gap around the circumference is not reasonably uniform, make the appropriate adjustments by selective tightening/loosening before proceeding.
Round 2	Tighten to 50% to 70% Target Torque (see ASME PCC-1, Sec. 12). Check flange gap around circumference for uniformity. If the gap around the circumference is not reasonably uniform, make the appropriate adjustments by selective tightening/loosening before proceeding.
Round 3	Tighten to 100% Target Torque (see ASME PCC-1, Sec. 12). Check flange gap around circumference for uniformity. If the gap around the circumference is not reasonably uniform, make the appropriate adjustments by selective tightening/loosening before proceeding.
Round 4	Continue tightening the bolts, but on a circular clockwise pattern until no further nut rotation occurs at Round 3 Target Torque value. For indicator bolting, tighten bolts until the indicator rod retraction readings for all bolts are within the specified range.
Round 5	Time permitting, wait a minimum of 4 hr. and repeat Round 4; this will restore the short-term creep relaxation/embedment losses. If the flange is subjected to a subsequent test pressure higher than its rating, it may be desirable to repeat this round after the test is done.

Source: ASME PCC-1, Table 2

(c) Calculation of Target Torque (ASME PCC-1, Appendix J and ASME B1.7)

The Target Torque required to tighten bolting is computed as follows:

$$T = \frac{F}{2}\left[d_n f_n + d_2\left(\frac{f_2 + \cos\alpha\tan\lambda}{\cos\alpha - f_2\tan\lambda}\right)\right]$$

Where dn = mean diameter of the nut (or bolt head) bearing face, mm (in.) (this diameter is equal to the simple average of the diameter of the nut washer face and the nominal bolt size)

d_2 = pitch diameter (or mean thread contact diameter), mm (in.) (see Fig. 3.19)

F = Target bolt tensile load, N (lb)

f_n = coefficient of friction between the bolt nut (or bolt head) and the flange (or washer), (dimensionless)

f_2 = coefficient of friction between bolt/nut threads, (dimensionless)

T = Target Torque, N-mm (in.-lb)

α = thread flank angle, deg. (see Fig. 3.19)

λ = lead angle, deg. (see Fig. 3.19)

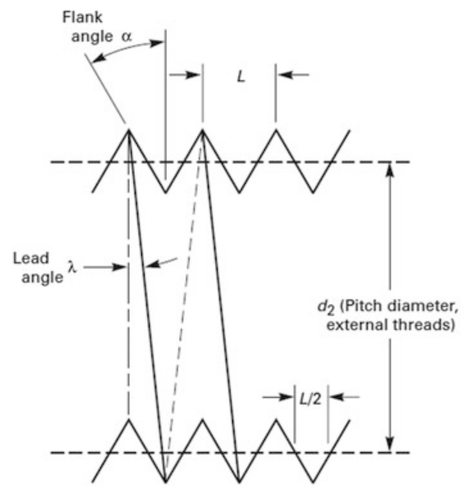


Figure 3.19 Thread Profile of Bolt. (Source: ASME PCC-1, Fig. J-1)

For metric and unified screw threads, the flank angle, α, is equal to 30 deg., the lead angle, λ, is equal to $\tan^{-1}(L/\pi d_2)$, and the lead, L, is equal to the pitch of the threads (e.g., for unified 8-thread series, this will be 1/8 in.).

L = axial movement of a threaded part when rotated one turn in its mating thread.

3.3.5.4 Controlled Sequence of Bolting

To achieve joint tightness, it is important that the following procedure is adhered to:

(a) Check and ensure that the general requirements above have been satisfied.

(b) To achieve uniform joint load/stress distribution, the bolts should be tightened in three stages, representing 30%, 60%, and 100% of the Target Torque values. At each stage of tightening, when using a single tool, bolts should be tightened in a controlled sequence as follows:
(Bolts numbered clockwise around the flange)

4-bolt flange	1, 3, 2, 4.
8-bolt flange	1, 5, 3, 7 → 2, 6, 4, 8.
12-bolt flange	1, 7, 4, 10 → 2, 8, 5, 11 → 3, 9, 6, 12
16-bolt flange	1, 9, 5, 13 → 3, 11, 7, 15 → 2, 10, 6, 14 → 4, 12, 8, 16
20-bolt flange	1, 11, 6, 16 → 3, 13, 8, 18 → 5, 15, 10, 20 → 2, 12, 7, 17 → 4, 14, 9, 19
24-bolt flange	1, 13. 7, 19 → 4, 16, 10, 22 → 2, 14, 8, 20 → 5, 17, 11, 23 → 3, 15, 9, 21 → 6, 18, 12, 24
28-bolt flange	1, 15, 8, 22 → 4, 18, 11, 25 → 6, 20, 13, 27 → 2, 16, 9, 23 → 5, 19,12, 26 → 7, 21, 14, 28 → 3, 17, 10, 24
32-bolt flange	1, 17, 9, 25 → 5, 21, 13, 29 → 3, 19, 11, 27 → 7, 23, 15, 31 → 2, 18, 10, 26 → 6, 22, 14, 30 → 4, 20, 12, 28 → 8, 24, 16, 32

See ASME PCC-1 for alternative sequence, larger sizes and detail information.

(c) Finally the bolts should be tightened sequentially around the flange using the 100% torque value stated in the project specification until no nut movement occurs.
(d) Bolt tensioning may be used in place of torqueing at the option of the end-user.

3.3.5.5 Tightening Method and Load-Control Technique Selection

Table 3.20 shows an example of an approach to selecting the tools, tightening method, and load-control technique suitable to the need.

Table 3.20 Recommended tool, tightening method, and load-control technique selection based on service applications (ASME PCC-1, Table 3 modified)

Service(1)	Tools(2)	Tightening Method	Load-Control Technique
Mild Service	Manual- or auxiliary-powered tools	Pattern single or multi-bolts tightening procedures	Consistent procedures per industry best practices or torque control
Intermediate Service	Manual- or auxiliary-powered tools or torque or tension measuring tool	Pattern single or multi-bolts tightening procedures	(3)
Critical Service	Torque or tension measuring tools	Pattern single or multi-bolts tightening procedures	Torque or tension control with final bolt elongation/load verification optional(4)

Notes:
(1)Service applications should be designated by the user and should consider governing design conditions (pressure, temperature, etc.), mechanical criteria (bolt diameter, flange diameter, gasket type, etc.), joint leakage history, and fluid service category
(a) An example of Mild Service could include Category D Fluid Service as defined in ASME B31.3
(b) An example of Intermediate Service could include Normal Fluid Service as defined in ASME B31.3
(c) Examples of Critical Service could include service requirements as defined by local jurisdictional requirements [example for United States is CFR 1910.119 (OSHA PSM rule)], lethal substance service as defined in the ASME Section VIII, Division 1 Code, or Category M Fluid Service as defined in ASME B31.3
(2)All tools are to be regularly and properly maintained and calibrated
(3)It is recognized that many joints are regularly tightened using impact wrenches or manual tools with no precise load control. Experience may prove this is sufficient for certain applications but unmeasured tightening is not recommended for intermediate service applications without careful consideration of the risks
(4)Where past practice with specific or similar equipment warrant or where testing/research validates, elongation and load verification may be waived
Commentary Notes (in Addition to Note (1) Above):
(1) Mild Service: And when the corrosion allowance is 1.6 mm (0.063 in.) or below
(2) Intermediate Service: And when the corrosion allowance is above 1.6 mm (0.063 in.) and non-cracking service (other than below in (3) below)
(3) Critical Service: And when the corrosion allowance is above 1.6 mm (0.063 in.) and cracking service (see Sect. 2.4.2 in this book)

References

– ASME PCC-1, Guidelines for Pressure Boundary Bolted Flange Joint Assembly
– ASME B1.1, Unified Inch Screw Threads
– TEMA, Shell and Tube Type Heat Exchangers

3.4 Cleaning, Finishes, and Coating of Metal Surfaces

Fouling and scaling are the accumulation of unwanted material on the internal surfaces of equipment. As a result, the process operation may not be effectively performed (e.g., higher pressure drop, insufficient heat transfer, etc.), and the premature failure can be taken place (e.g., under deposit corrosion, turbulent flow-induced erosion, etc.). Therefore, a periodical cleaning application is a very important maintenance step to prolong the design lives of the facilities.

One of the important points in cleaning is to apply the appropriate procedure without side effects, such as excessive metal thickness reduction and/or undesirable chemical reaction chemically and mechanically. In addition, the cleaning should be performed in accordance with environment health and safety regulations and standards. So, the cleaning places should have proper fencing and signage and controlled by the workers with sufficient PPE after completed removed the remaining flammable or harmful gases.

The intelligent pigging system for piping and pipelines provides the internal inspection (remained thickness and crack detection) as well as internal cleaning at the same time. The layout, routing, internals, internal weld deposits, connections, bends, and accessibility at launcher and receiver of piping and pipelines should be accordingly designed after considered the running of the applicable pigging system.

Table 3.21 shows summary of common inorganic scale forming compounds and Tables 3.22 and 3.23 show typical surface finishes after several working of stainless steel bars and plates, respectively. The scales or surface finishes should be treated, removed, cleaned, or passivated in accordance with the requirements in codes, standards, and purchaser's specifications.

References for Cleaning of Equipment and Piping

– MTI Publication 51 Cleaning of Process Equipment and Piping, 1997
– NiDI Report 10,068 Specifying Stainless Steel Surface Treatment
– SSINA (The Specialty Industry of North America) Handbook for Care and Cleaning of SS

Table 3.21 The Summary of Common Inorganic Scale Forming Compounds

Mineral Name	Common Name	Chemical formula
	Hydrous Ferrite Oxide	FeOOH
	Iron Chromium Spinels	$CrFe_2O_4$
Acmite	Sodium Iron Silicate	$NaFe(SiO_3)_2$
Analcite	Sodium Aluminum Sulfate	$NaAlSi_2O_6\ H_2O$
Anhydrite	Calcium Sulfate	$CaSO_4$
Aragonite	Calcium Carbonate-Rhombic	$CaCO_3$
Barite	Barium Sulfate	$BaSO_4$
Brucite	Magnesium Hydroxide	$Mg(OH)_2$
Chalcocite	Copper Sulfide	Cu_2S
Chalcopyrite		$CuFeS_2$
Copper		Cu
Covellite	Copper Sulfide	CuS
Cuprite	Copper Oxide	Cu_2O
Hematite	Ferric Oxide	Fe_2O_3
Hydromagnesite	Magnesium Carbonate and Hydroxide	$2MgCO_3\ Mg(OH)_2\ 3H_2O$
Hydroxyapatite	Calcium Phosphate	$Ca_{10}(OH)_2(PO_4)_6$
Magnesia	Magnesium Oxide	MgO
Magnetite	Ferric-Ferrous Oxide	Fe_3O_4
Montmorillonite	Aluminum Silicate	$Al_2O_3\ 4SiO_2\ 4H_2O$
Noselite	Sodium Aluminum Silicate	$Na_8Si_2O_7O_{24}\ H_2O$
Pyrolusite	Magnesium Dioxide	MnO_2
Serpentine	Magnesium Silicate	$Mg_3Si_2O_7\ 2H_2O$
Silica	Quartz	SiO_2
Sodalite	Sodium Aluminum Silicate	$Na_8Al_6Si_6O_{24}Cl_2$
Troilite, Pyrrhotite	Iron Sulfide	FeS
Wüsite	Ferrous Oxide	FeO

Source: NACE Paper 98,338

Table 3.22 Surface finishes after work of SS bars

Working type	Hot-worked only	Annealed or otherwise heat treated	Annealed and cold-worked to high tensile strength [(3)]
Stainless steel Surface finishes[(1)]			
(a) Scale not removed (excluding spot conditioning)	√	√	
(b) Rough turned	√[(2)]	√	
(c) Pickled or blast cleaned and pickled	√	√	
(d) Cold drawn or cold rolled		√	√
(e) Centerless ground		√	√
(f) Polished		√	√

Source: SSINA-The Care and Cleaning of SS
Notes: Blank = none
(1) Surface finishes (b), (e), and (f) are applicable to round bars only
(2) Bars of the 4xx series SS which are highly hardenable, such as 414 SS, 420 SS, 420F SS, 431 SS, 440A SS, 440B SS, and 440C SS, are annealed before rough turning. Other hardenable grades, such as 403 SS, 410 SS, 416 SS, and 416Se SS, may also require annealing depending on their composition and size
(3) Produced in 302 SS, 303Se SS, 304(L) SS, and 316(L) SS

Table 3.23 Surface finishes after work of SS plates

Working Type	Stainless Steel Surface Finishes
Hot-rolled	Scale not removed. Not heat treated. Plates not recommended for final use in this condition.[(1)]
Hot-rolled, annealed or heat treated	Scale not removed. Use of plates in this condition is generally confined to heat resisting applications. Scale impairs corrosion resistance.[(1)]
Hot-rolled, annealed or heat treated, blast cleaned, or pickled	Condition and finish commonly preferred for corrosion resisting and most heat resisting applications.
Hot-rolled, annealed, descaled, and temper passed	Smoother finish for specialized applications.
Hot-rolled, annealed, descaled optionally temper passed	Smooth finish with greater freedom from surface imperfections than the above.
Hot-rolled, annealed or heat, and polished	Polished finishes: See Sect. 3.4.5.2.

Source: SSINA-The Care and Cleaning of SS
Note: (1) Surface inspection is not practicable on plates which have not been pickled or otherwise descaled

3.4.1 *Mechanical or Physical Cleaning*

3.4.1.1 Conventional Mechanical Cleaning

Scraping, brushing, drilling, pigging (Fig. 3.20), or shot-blasting with abrasives are conventional mechanical cleaning methods to remove the deposits on the metal surfaces. Brushing is most commonly used for the removal of relatively soft deposits. In using any of these methods great care should be taken not to damage (e.g., metal loss or notches) the metal surfaces. For the cleaning of the inside of heat exchanger tubes, special cleaning brushes with extension rod assemblies are available. Care should be taken to avoid mechanical damage to the tubes due to bending of the extension rods.

Figure 3.20 Pigging System. (Source: Metropolitan Engineering Consulting & Forensics brochure, 2008)

The tube internals of heat exchangers, boilers, and furnace tubes can be cleaned by high-pressure water jetting, hydraulic pigging, or others.

3.4.1.2 Steam Cleaning

A mixture of steam and water or with a cleaning agent to remove fouling deposits may be used by spraying. It is commonly used for caustic or coke handling equipment and piping. It is a mobile device in which steam and a cleaning agent are mixed in an injector; the solution is then sprayed onto the fouled equipment via a hose and a spray gun. The temperature and the flow rate of the solution are controlled by the pressure and quantity of the steam and cleaning agent. Additional safety relief valves may be required to protect commercial steam cleaners.

Steam cleaning may be suitable for the external surfaces of most plant equipment, e.g., finned air coolers, tanks, aluminum sheeting, etc.

3.4.1.3 Shot Jet Cleaning

Shot jet cleaning is similar with shot-blasting, using round steel shot propelled by a high-velocity gas stream (generally nitrogen) for pipe cleaning. The kinetic energy of the shot sweeps away deposits. After shot jet cleaning, spray water should be used to remove the remained shot/deposit mixture dust.

The major difference between shot jet cleaning and conventional shot-blasting is the incidence angle of the abrasive particles. With conventional blasting, the abrasive strikes the surface perpendicularly, while the controlled flow of abrasive shot in shot jet cleaning impinges on the pipe surface at a low incidence angle. This method may be applied for the followings:

– To remove non-ductile coke in the heater tubes up to 150 mm (6 in.) diameter.
– To remove inorganic deposits in tube material. It has advantages over steam-air decoking.
– To remove deposits from the inside of air cooler tubes, using air instead of nitrogen.

Shot jet cleaning should be carried out only by contractors with suitable experience.

Nitrogen which is an inert gas can cause asphyxiation. Hence appropriate personnel protection should be considered.

3.4.1.4 High-Pressure Water Jet Cleaning

High-Pressure (HP) water jet cleaning is the most common method of conventional mechanical cleaning for many purposes (Fig. 3.21). It is also often used to complete a chemical cleaning process.

The water jet impinges on the deposits, breaks through to the underlying metal, and lifts off the debris. To obtain optimum results, adequate water pressure and water flow should be established for each cleaning operation. It is mainly used for the cleaning of heat exchanger tubes. For equipment and of piping with hard deposits higher water pressures and delivery rates are required. Cleaning action can be further enhanced by the use of cavitation heads or abrasive entrainment. See Sect. 3.4.1.10 for Overall Cleaning of H/EX Tube Bundles.

For HP water jet cleaning, operators should be adequately trained. Also, safe procedures should be taken.

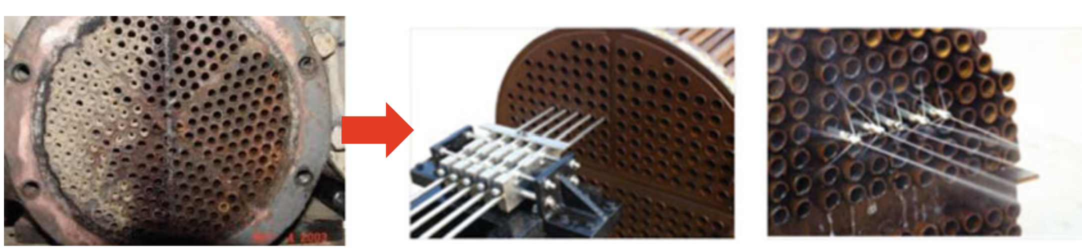


Figure 3.21 High-pressure water jet cleaning for fouled H/EX tubes. (Source: Clean-Co Systems brochure, 2008)

3.4.1.5 Induced Wave Cleanings

These cleaning techniques are based on inducing waves (ultrasonic, acoustic, or shock waves) or pressure pulses. Their application is currently limited to the cleaning of the inner surface of fouled tubes in heat exchangers, boilers, and piping systems.

3.4.1.6 Sponge Jet Cleaning

This is a modern technique which employs commercial abrasives embedded in particulate polyurethane sponge to clean and, if required, profile surfaces from 0 to 100+ microns (4+ mils). A range of abrasive grades is available allowing for all degrees of surface cleanliness (Sa 1, 2, 2 ½, and 3 –see Table 3.33 surface preparation).

On impact of the abrasive with the substrate, the sponge draws dust and debris into the cell structure and absorbs the inertial energy associated with blasting, thus giving rise to a safer, cleaner blasting procedure.

Experience has shown that Sponge Jetting is a viable alternative to open grit blasting and power/hand tool cleaning in a range of applications. Sponge Jet has been shown to be both technically and economically advantageous when blasting in shutdown and for maintenance painting or cleaning in operational environments, especially in the vicinity of sensitive equipment. When used instead of mechanical cleaning, it is both faster and yields a higher-quality surface finish, which in turn generates substantial savings in maintenance costs over paint lifetimes.

Reference: http://www.spongejet.com

3.4.1.7 Online Treatment of Fired Heaters

This is to remove fired heater tube scale and fouling without shutdown during furnace operation.

(a) Hot Tube Descaling Process (HTD) -
  Reference: http://www.ceteklimited.com/Industries/Refining/Hot_Tube_Descaling.aspx
(b) The Neutramex ® Process
  Reference: http://www.ctp-environnement.com/en/page/our-specialties/online-treatment-of-fired-heaters.html

3.4.1.8 "Between Fins" Cleaning

It is to clean Furnace/Fired Heaters Tubes (Finned Convection Section).

Reference: http://www.tubetech.com/case-studies/25_furnace-fired-heaters-tubes-finned-convection-section-cleaned-in-scotland/

3.4.1.9 Fired Heater Robotic Cleaning

A robotic cleaning technology was developed to clean deep in between both square and triangular pitch rows of convection tubes within their fired heater in order to improve poor cleanliness achieved using traditional water jetting and chemical service contractors.

Reference: http://www.tubetech.com/case-studies/17_furnaces-fired-heater-convection-bank-cleaned-robotically-on-german-refinery/

3.4.1.10 H/EX Tube Bundles Cleaning

The design of H/EXs should be considered about the maintenance cleaning with accessibility. The process contact surfaces of H/EXs should be kept reasonably clean to assure satisfactory performance – e.g., minimize fouling and deposits (corrosion under deposits) and maximize heat transfer. H/EXs may have to be cleaned by either chemical or mechanical methods for sound maintenance. The methods should be selected by the operator of the plant and will depend on the deposit type, facilities available, process performance, and turn around schedule in the plant. Cleaning method is normally decided by the several steps, such as (i) review of all inspection reports of tube externals and internals, (ii) if only water jet is enough or not, (iii) if bundle dismantlement is required or not, (iv) how many and which tubes will be dummy if required, (v) decision of cleaning methods and chemicals, and (vi) cleaning schedule and vendor selection.

This cleaning methods may be also applicable for new construction.

The following cleaning procedures (mechanically and/or chemically) and Table 3.24 may be considered partially or entirely.

(a) Circulating hot wash oil or light distillate through tubes or shell at high velocity may effectively remove sludge or similar soft deposits.
(b) Some salt deposits may be washed out by circulating hot fresh water.
(c) Commercial cleaning compounds are available for removing sludge or scale provided hot wash oil or water is not available or does not give satisfactory results.
(d) High-pressure water jet cleaning. The pressure should be decided to avoid any deformation as well.
(e) Scrapers, rotating wire brushes, and other mechanical means for removing hard scale, coke, deposits, or other foreign materials.
(f) A qualified organization should be kept the cleaning services. These organizations will check the nature of the deposits to be removed, furnish proper solvents, and/or acid solutions containing inhibitors and provide equipment and personnel for a complete cleaning job.

The following cautions during cleaning are also to be considered.

– Tubes should not be cleaned by blowing steam through individual tubes since this heats the tube and may result in severe expansion strain, deformation of the tube, or loosening of the tube to tubesheet joint.
– When mechanically cleaning a tube bundle, care should be exercised to avoid damaging the tubes.
– Cleaning compounds must be compatible with the metallurgy of the H/EX.
– All cleaned surfaces by acidic chemicals should be completely neutralized at the end of the cleaning process.

Table 3.24 Typical cleaning methods for shell and tube type H/EXs in refinery (only for reference)[3]

Type of Deposit[5]	Materials	Recommended Cleaning Method	Circulating Time and Temperature
Algae	CS & LAS	Algae Removal: water jet[1]	at room temp.
		Degreasing: steam cleaning	2 hours at 80 °C (176 °F)
		Acid cleaning (pH 2–3): 2% inhibited HCl acid[2] – Scalzo, etc.	6 hours
		Neutralizing: 1–2% Na_2CO_3 (sodium carbonate) solution[4]	1–2 hours at room temp.
Light oil[5]	Most Metals	Degreasing: steam cleaning	8 hours at 80 °C (176 °F)
Heavy oil[5] (shell side)	Most Metals	10% carbon stripper nanofiltration	8 hour at 45 °C (113 °F)
Light oil[5] (inside tubes)	Most Metals	Steam or liquid cleaning	8 hours at 85 °C (185 °F) or per condition
Scale (Fe_2O_3, FeS, salts, cokes, asphaltens, polymerization, etc.)[2]	CS & LAS	Water jet[1]	at room temp.
		Degreasing: steam cleaning	2 hours at 80 °C (176 °F)
		Acid cleaning (pH 2–3): 2% inhibited HCl acid[2] – Scalzo, etc.	6 hours
		Neutralizing: 1–2% Na_2CO_3 (sodium carbonate) solution[4]	1–2 hours at room temp.
Scale/sludge	Copper Alloys (Al-brass, Monel, Cupro-nickel)	Water jet[1]	at room temp.
		Degreasing: steam cleaning	2 hours at 80 °C (176 °F)
		Acid cleaning (pH 2–3): 2% inhibited HCl acid[2] – Scalzo, etc.	6 hours
		Neutralizing: 1–2% Na_2CO_3 (sodium carbonate) solution[4]	1–2 hours at room temp.

Notes

(1)See Sect. 3.4.1.4 for water jet cleaning of H/EX tube bundles. Other cleaning methods, such as immersion cleaning, media blast (abrasive) cleaning for tube inside, and cleaning by thermal decomposition may be also considerable per the fouling type and severity. The jetting time and pressure depends on the remained thickness and scale condition

(2)All acid cleaning should be maintained with low circulation velocity ($\leq$0.5 m/s). H_2S can be formed when HCl acid cleaning is performed to remove FeS deposits. In this case, the bolts (AISI 4140 or 5 Cr-0.5 Mo) of girth flanges and flanges of expansion bellows (5 Cr-0.5Mo) may be susceptible to SSC. Such H/EX should therefore be dismantled and cleaned by immersion after removal of the bolts and expansion bellows. Produced H_2S should be vented safely

(3)Toxic gas containing service. In case of HF service, tube bundles should be made safe for withdrawal by soaking in, or circulating with, a solution of 2.5 wt % Na_2CO_3 (sodium carbonate) for 1 hour at a temperature of 50 °C (122 °F), pH >10. After draining the solution, the bundles may be withdrawn and then cleaned with high-pressure water. After neutralization, all residual HF should be removed and measured prior to safe access the H/EX.

(4)To be a pH 7 (± pH 1) after neutralizing. Sufficiently rinse the interior of the heat exchanger with clean water after neutralization work

(5)Light crude oil is liquid petroleum that has low density and that flows freely at room temperature. It has low viscosity, low specific gravity, and high API gravity due to the presence of a high proportion of light hydrocarbon fractions. It generally has a low wax content as well. On the other hand, heavy crude oil or extra heavy crude oil is any type of crude oil which does not flow easily. It is referred to as "heavy" because its density or specific gravity is higher than that of light crude oil. Heavy crude oil has been defined as any liquid petroleum with an API gravity less than 20°. Extra heavy oil is defined with API gravity below 10.0 °

API. (API gravity is a measure of how heavy or light a petroleum liquid is compared to water. If its API gravity is greater than 10, it is lighter and floats on water; if less than 10, it is heavier and sinks)

3.4.2 *Chemical Cleaning*

3.4.2.1 Overview

The chemical cleaning of metals has a number of advantages over mechanical cleaning methods. The greatest advantages are that the metal equipment and structures to be cleaned do not need to be dismantled and reassembled, and the cleaning doesn't damage the equipment, leaving areas that are more vulnerable to corrosion than before. Weld flux, metal shavings, coatings on fittings, sand, dirt, and other foreign materials that are not soluble in chemical cleaning solutions should be removed prior to fabrication. The descaled and cleaned pipe should be free of scale, rust, weld flux, oil, grease, and other foreign materials and should be equivalent to the surface described by the Steel Structures Painting Council as SP-8 if acid pickled or SP-6 if abrasive blasted.

Table 3.25 shows the chemical cleaning solutions for specific scales on the steels. Specific methods of cleaning of SS only for nonchemical process/medical products are as in Table 3.26.

3.4.2.2 Chemical Cleaning

The chemical cleaning is one of the best solutions to remove the mill scale and all other foreign materials on the metal. In addition, the passivation treatment will promote more sound passivation film (i.e., stable Cr-oxides) on the stainless steel (Fig. 3.22).

Table 3.25 Chemical cleaning solutions for specific scales

Scale Component	Solvent	Conditions
Copper, Copper Oxides	Thiourea Derivative in HCl Ammoniacal Bromate Ammonium Persulfate Ammonium Carbonate/O_2/NH_3	66–77 °C (150–170 °F) 50–82 °C (120–180 °F) < 38 °C (100 °F) < 66 °C (150 °F) 50–77 °C (120–170 °F)
	Monoammoniated Citric Acid	60–82 °C (140–180 °F), pH 9 to 11
	Ammonium EDTA (with Fe & Oxidizer)	50–77 °C (120–170 °F), pH 9 to 11
Ca/Mg Carbonate, $CaCO_3$, $MgCO_3$	5% to 15% HCl	< 66 °C (150 °F)
	7% to 10% Sulfamic Acid	< 60 °C (140 °F)
	Tetrasodium EDTA	82–149 °C (180–300 °F) circulating
Calcium Phosphate Compounds	5% to 10% HCl	38–66 °C (100–150 °F)
	7% to 10% Sulfamic Acid	< 60 °C (140 °F)
	Tetrasodium EDTA	82–149 °C (180–300 °F), circulating
Calcium Sulfate, $CaSO_4$	Tetrasodium EDTA	82–149 °C (180–300 °F), circulating
	1% NaOH, then 5% HCl	38–66 °C (100–150 °F), circulating
	EDTA -Organic Acid Mixtures	50–66 °C (120–150 °F), circulating
Disulfides FeS_2 marcasite FeS_2 pyrite	Chromic Acid, CrO_3 followed by HCl	Boiling 7 to 10% chromic acid followed by HCl inhibited
Fe_3O_4 magnetite or mill scale	2% Hydroxyacetic/1% Formic Acid	82–104 °C (180–220 °F), circulating
	Monoammoniated Citric Acid	82–104 °C (180–220 °F), circulating
Fe_2O_3 red iron oxide or red rust	Ammonium EDTA	77–149 °C (170–300 °F), circulating
	EDTA Organic Acid Mixtures	38–66 °C (100–150 °F), circulating
Hydroxyapatite or Phosphate Compounds, $Ca_{10}(OH)_2\ (PO_4)_6$	5% to 10% HCl Sodium EDTA Sulfamic Acid 7 to 10%	Preferable not above 66 °C (150 °F) Undesirable to add fluoride, 66–149 °C (150–300 °F), circulating < 60 °C (140 °F)
Iron Oxide	5% to 15% HCl Hydroxyacetic/Formic Acids Monodiammonium Citrate Monosodium Citrate Ditetraammonium EDTA EDTA -Organic Acid Mixtures Sodium HEDTA, pH 1.4 Triammonium EDTA/N_2H_4	66–82 °C (150–180 °F) 82–93 °C (180–200 °F), circulating 82–135 °C (180–275 °F), circulating 82–93 °C (180–200 °F), circulating 93–149 °C (200–300 °F), circulating 66–93 °C (150–200 °F), circulating 38–66 °C (100–150 °F), circulating 82–93 °C (180–200 °F), circulating
Organic residues, Organo lignins algae, Some polymeric residues	Potassium Permanganate ($KMnO_4$) followed by HCl containing Oxalic Acid	Circulate not 100 °C (212 °F) at 1 to 2% $KMnO_4$ solution. Oxalic acid added to HCl controls release of toxic chlorine gas
Organic Deposits	Detergents Terpene Emulsions Organic Solvents (including Chlorinated) Alkaline $KMnO_4$, followed HCl and Oxalic Acid	66–121 °C (150–250 °F), circulating
Pectolite, 4Ca $Na_2O{\cdot}6SiO_2H_2O$ Serpentine. $Mg_3Si_2O_2{\cdot}2H_2O$	HCl containing Ammonium Bifluoride	66–80 °C (150–175 °F)
Silica & Silicate Compounds, e.g., Acmite. $NaFe(SiO_3)_2$ Analcite, $NaAlSi_2O\ 5H_2O$	Prolonged treatment with 0.5 to 1% soda ash at 345 kPa (50 psi) follows with HCl containing fluoride	Alkaline preboil at 345–690 kPa (50–100 psi) for 12–16 hours
Sulfides, Ferrous Trolite, FeS Pyrrhotite. FeS	5% to 10% HCl inhibited 5% to 10% HCl with aldehydes 5% to 10% H_2SO_4 with aldehydes	Heat slowly to avoid sudden release of toxic H_2S gas 38–71 °C (100–160 °F) 38–71 °C (100–160 °F)

Source: NACE Paper 98,338 & Publication 3 M182-1982 modified
*The chemicals are to be considered possible solvents only. There are many alternative solvents for each deposit listed. NACE Publication 3 M182 (T-3 M committee): Corrosion Testing of Chemical Cleaning Solvents Publication, 1982

Table 3.26 Typical cleaning methods of stainless steel (SS) (nonchemical process/medical products)[(1)]

Problems	Cleaning Agents	Comments
Adherent hard water scales and mortar/ cement splashes	10–15 volume % solution of phosphoric acid. Use warm, neutralize with dilute ammonia solution, rinse with clean water, and dry[(4)]. Alternatively soak in a 25% vinegar solution and use a nylon brush to remove deposits.	Proprietary formulations available with surfactant additions. Take special care when using hydrochloric acid based mortar removers under the approval of responsible engineer.
Badly neglected surfaces with accumulated grime deposits	A fine, abrasive paste as used for car body refinishing, e.g., "T-cut®" (Automotive Chemicals Ltd.) rinsed clean to remove all paste material and dried.	May brighten dull finishes. To avoid a patchy appearance, the whole surface may need to be treated.
Burnt on food or carbon deposits	Presoak in hot water with detergent or ammonia solution. Remove deposits with nylon brush and fine scouring powder if necessary.	Repeat if necessary and finish with "routine cleaning." Abrasive souring powder can leave scratch marks on polished surfaces.
Fingerprints	Detergent and warm water, alternatively, organic solvent (e.g., acetone, alcohol, methylated spirits)	Rinse with clean water and wipe dry. Proprietary spray-applied polishes available to clean and minimize remarking.
Heating (welding or heat treatment) or heavy discoloration	(a) Non-scratching cream or polish, e.g., Solvol Auto Chrome Metal Polish® (Hammerite Products Ltd.) (b) Nylon-type pad, e.g., "'Scotch-Brite"[(2)]	(a) Creams are suitable for most finishes, but only use Solvol Auto Chrome Metal Polish® (Hammerite Products Ltd.) on bright polished surfaces. Some slight scratching can be left. (b) Use on brushed & polished finishes along the grain.
Lime deposits from Hard water	Solution of one part vinegar to three parts water.	Soak in solution then brush to loosen. Rinse well with clean water.
Localized rust stains caused by CS contamination	Proprietary gels, or 10% phosphoric acid solution (followed by ammonia and water rinses), or oxalic acid solution (followed by water rinse).[(4)]	Small areas may be treated with a rubbing block comprising fine abrasive in a hard rubber or plastic filler. CS wool should not be used nor should pads that have previously been used on CS. A test should be carried out to ensure that the original surface finish is not damaged.
Oil and grease marks	Organic solvents (e.g., acetone, alcohol, methylated spirits, proprietary "safety solvents"). Baked-on grease can be softened beforehand with ammonia.	Organic solvents (e.g., acetone, alcohol, methylated spirits, proprietary "safety solvents"). Baked-on grease can be softened beforehand with ammonia. Alkaline formulations are also available with surfactant additions, e.g., D7 Polish® (Diversey Ltd.).
Paint, graffiti	Proprietary alkaline or solvent paint strippers, depending upon paint type. Use soft nylon or bristle brush on patterned surfaces.	Apply as directed by manufacturer.
Routine cleaning of light soiling	Soap, detergent, or dilute ($\leq$1%) ammonia solution to be used.	Apply with a clean sponge, soft cloth, or soft fiber brush then rinse in clean water (warm) and dry[(3)].
Rust and other corrosion products Embedded or adhering "free iron"	Rust stains can be removed by adding one part of nitric acid to nine parts of warm water. Leave for 30 to 60 minutes, then wash off with plenty of water, and flush any drains thoroughly.	Rinse well with clean water. Wear rubber gloves, mix the solution in a glass container, and be very careful with the acid. (See Precautions for acid cleaners.)
Scratches on Polished (Satin) Finish	Slight scratches – use impregnated nylon pads. Polish with scurfs dressed with iron-free abrasives for deeper scratches. Follow polish lines. Then clean with soap or detergent as for routine cleaning.	Do not use ordinary steel wool – iron particles can become embedded in stainless steel and cause further surface problems. Stainless steel and "Scotch-Brite" scouring pads are satisfactory.
Stubborn spots, stains[(4)], and light discoloration Water marking[(5)] Light rust staining	Mild, non-scratching creams and polishes. Apply with soft cloth, soft sponge, or fiber brush (soft nylon or natural bristle. An old toothbrush can be useful) and rinse off residues with clean water and dry. Follow polish lines	Avoid cleaning pastes with abrasive additions. Suitable cream cleansers are available with soft calcium carbonate additions, e.g., Jif® (Lever Brothers) or with the addition of citric acid, e.g., Shiny Sinks® (Home Products Ltd.).
Tannin (tea) stains and oily deposits in coffee urns	Tannin stains – soak in a hot solution of washing soda, i.e., sodium carbonate. Coffee deposits – soak in a hot solution of baking soda (sodium bicarbonate).	These solutions can also be applied with a soft cloth or sponge. Rinse with clean water. Satisfactory on most surfaces.

Source: SSINA-The Care and Cleaning of SS and BSSA Cleaning Guides modified

General Notes: SSINA = The Specialty Steel Industry of North America, BSSA = British Stainless Steel Association

a. Solvents should not be used in enclosed areas

b. Do not use chloride solutions

c. The registered agents are only for reference and recommendation

d. When cleaning a surface with any chemical preparation or abrasive medium, a trial should be done on a small, unobtrusive hidden, or non-critical area of the surface, to check that the resulting finish matches with the original

Notes:

[(1)]It was based on US Defense Department standard QQ-P-35C

[(2)]Nylon abrasive pads should be adequate for dealing with most deposits. If a more severe treatment is needed to mask coarse scratches or physical damage on a surface, use the finest abrasive medium consistent with covering the damage marks. With directional brushed and polished finishes, align and blend the new "scratch pattern" with the original finish, checking that the resulting finish is aesthetically acceptable. Silicon carbide media may be used, especially for the final stages of finishing. Avoid using hard objects such as knife blades and certain abrasive/souring agents as it is possible to introduce surface scuffs and scratches. Scratching is particularly noticeable on sink drainer areas. These are usually superficial and can be removed with proprietary SS cleaners or, alternatively, with a car paint restorer, such as "T-cut"

(3)To avoid water marks, use clean rinsing water, such as reasonable quality potable (tap) water. Drying marks may be avoided using an air blower or wiping with clean disposable wipes

(4)Rust marks or staining on SS is unlikely to be the result of corrosion to the SS itself (similar marks may also be found on porcelain and plastic sinks). These marks are likely to result from small particles of CS brush

(5)To avoid water marks, use clean rinsing water, such as reasonable quality potable (tap) water. Drying marks may be avoided using an air blower or wiping with clean disposable wipes

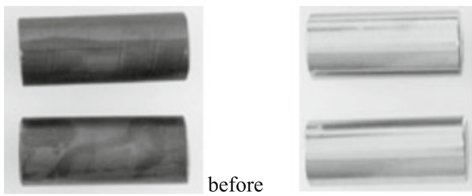


Figure 3.22 The parts on the left have clean, shiny, corrosion-resistant surfaces after proper passivating

The pickling solution should be properly controlled to avoid excessive corrosion of the metal by the pickling solution. Contractor/technician for acid cleaning should ensure that test samples (corrosion coupons) representative of all materials in the equipment and piping system are exposed to the pickling solution used in the piping. Exposure of the test coupons must be for the entire time of the pickling operation, to monitor the corrosive effect of the solution on the piping system, to avoid excess corrosion. Pickling solutions should not be allowed to contact any parts of process machinery.

The following formulas show the typical reactions during acid cleaning.

[Desirable Reaction]

$$: \underset{\text{Rust}}{Fe_2O_3} + \underset{\text{Acid}}{6H^+} \rightarrow \underset{\text{Ferric Iron}}{2Fe^{3+}} + \underset{\text{Water}}{3H_2S} \quad \text{(Eq. 3.1)}$$

[Undesirable Reaction by Over-cleaning]

$$: \underset{\text{Iron}^*}{Fe} + \underset{\text{Acid}}{2H^+} \rightarrow \underset{\text{Ferrous Iron}}{Fe^{2+}} + \underset{\text{Hydrogen Gas}^{**}}{H_2} \quad \text{(Eq. 3.2)}$$

*From base metal

*Can be a source of hydrogen embrittlement

Table 3.27 shows the simplified suitability table of chemical cleaning agents for various structural metals. In addition, the holding time and neutralization/rinsing procedure should be carefully selected.

Table 3.27 Suitability (typical) of chemical cleaning agents (general guidance for structural metals)(8)

	Concent. (wt%)	Max. temperature °C (°F)(7)	CS and LAS(3)	Cast Iron(3)	12-Cr MSS	ASS (300 s SS)	Cu-Ni	Aluminum	Monel 400	Al-Brass
Inhibited hydrochloric (HCl) acid(4),(5)	2–5	65 (150)	√	√	**R**(1)	**U**	**R**	**U**	**U**	**U**
Inhibited citric ($C_6H_8O_7$) ammoniated acid(6)	5–6	82–93 (180–200) as a preferable range	√	√	**R**(2)	√	√	**R**	√	√
Inhibited phosphoric (H_3PO_4) acid	15–70 (20% preferable)	50 (122)	√	√	√	√	**R**	**U**	**U**	**U**
Inhibited sulfuric (H_2SO_4) acid(4),(5)	4–10	75 (167)	√	√	√	√	√	**U**	√	**U**
Alkaline solutions	–	70 (158)	√	√	√	√	√	**U**	√	**R**
Organic solvents (organic acids or chelating agents)	–	–	√	√	√	√	√	√	√	**U**
Nitric/citric acid	See Table 3.31a									

Legend: √ = generally suitable, **R** = restricted, **U** = unsuitable due to severe corrosion

Notes: (sources: ASTM A380/A967, ASTM STP538, MIL-STD-171F, SAE AMS-2700, NiDI Publ. 9001/10004/10068)

(1)Ambient temperature only (but, not recommended)

(2)60 °C (140 °F) maximum. Alkaline boiling-out may be required prior to HCl acid cleaning to remove calcium sulfate and silicate deposits

(3)Normally chemical cleaning is not applicable unless purchaser requires

(4)When cleaning by circulation, the velocity should be max. 0.5 m/s because at higher velocities the efficiency of the inhibitor will be reduced. Fe ion should be controlled 0.4 wt% and below because of severe corrosion

(5)Ammonium bifluoride (typically 1 wt% as NH_4HF_2 or $NH_4F{\cdot}HF$) may be added to the acid to remove SiO_2 (silica)

(6)It is applied for the removal of mill scale and foreign materials in new boilers and delicate equipment such as turbine rotors. Although corrosion rates are low, effective inhibitors should be used

References: ASTM A967 (Specification for Chemical Passivation Treatments for SS Parts), MIL-STD-171F (Finishing of Metal and Wood Surfaces), and SAE AMS-2700 (Passivation of Corrosion-Resistant Steels)

(7)The holding time should not exceed the limitation per the standard and followed by neutralizing and rinsing immediately to avoid Eq.2 reaction above

(8)The cautions for safety during acid cleaning process performed by circulation and immersion, respectively, should be complied. Normally the detail cautions may be prepared by chemical cleaning agent supplier and/or facility end-user

(a) Acid Cleaning of Carbon and Low Alloy Steel

1. Pre-cleaning
   Circulate a 2% (wt.) trisodium phosphate solution with wetting agent (surfactant) to remove grease and oil films from the pipe before pickling. Mix the solution in accordance with the manufacturer's instructions, and treat the pipe for 1 to 2 hours at 60 to 71 °C (140 to160°F). All oil and grease must be removed before pickling.
2. Rinsing (after pre-cleaning)
   After removing the pre-cleaning solution, the system should be rinsed with clean, potable-quality fresh water until the pH of the effluent rinse is within one pH of the fresh rinse water.
3. Descaling in acid for carbon and low alloy steels
   Pickle the system with one of the following solutions: 10% sulfuric acid [4 to 6 hours at 66 °C (150 °F)]. When mixing acid with water, be sure to add the acid to the water, not water to acid. Seven percent hydrochloric acid [4 to 6 hours at 66 °C (150 °F)]. Alloy valve trim will pit in this solution. HCl is an acceptable alternative when valves can be temporarily removed. Ammoniated citric acid (inhibited; 3 to 5%; 6 hours at 82 to 93 °C (180 to 200 °F). After the citric acid and inhibitor are mixed into the water, add ammonia to adjust the pH to between 4 and 5. Use of ammoniated citric acid is a convenient procedure that will allow both pickling and passivating with the same solution. Agitate as necessary during circulation to flush out loose scale. Use inhibitor in accordance with the manufacturer's instructions.
   Recommended inhibitors are:
   – Armohib 31 or equivalent for sulfuric or citric acid
   – Rodine #213 or 214 or equivalent for hydrochloric acid
   Acid solution should be drained under a nitrogen purge.
4. Rinsing (after descaling/pickling)
   After pickling for the required time period, rinse as per above 2. The rinse should be removed under a nitrogen purge. When using the ammoniated citric acid, this step should be deleted.
5. Neutralization
   Circulate a neutralizing solution of 2% soda ash (sodium carbonate) to remove all traces of acid from the system. Circulate for 1 hour at 49 °C (120 °F). Drain under a nitrogen purge. When using ammoniated citric acid, this step should be deleted.
6. Rinsing (after neutralizing)
   After neutralizing, rinse with water until all traces of acid and neutralizing solution have been removed. Drain under a nitrogen purge. When using ammoniated citric acid, this step should be deleted. pH of final rinse water should be between 6 and 8 for most applications or 6.5 to 7.5 for critical applications.

(b) Chemical Cleaning of Stainless Steels
   The chemical cleaning for stainless steels is more frequently applied than CS, LAS, or nickel alloys. Washing with soap or a mild detergent and warm water followed by a clean water rinse is usually quite adequate for domestic and architectural equipment. An enhanced appearance will be achieved if the cleaned surface is finally wiped dry. Table 3.28 shows general verification test methods for contamination detecting on the stainless steel surfaces before chemical passivation.

Tables 3.29 and 3.30 show Acid Descaling (Pickling) and Acid Cleaning of Stainless Steel in ASTM A380, respectively. In many cases, Table 3.29 (ASTM A380) is applied for process equipment and piping which are in contact with the process service, while Table 3.30

Table 3.28 (1/2) Verification tests on SS surfaces contamination before passivation (ASTM A967 modified)(1)(2)

Practice	Test Source	Targets	Test Method(1)
A	Water Immersion	To detect free iron or any other anodic surface contaminants on SS.	Alternately immersed in a non-rusting tank of distilled water for 1 h and allowed to dry in air for 1 h. This cycle should be repeated a minimum of twelve (12) times.
B	High Humidity		Be performed using a humidity cabinet capable of maintaining the specified test conditions. Be cleaned by immersion in acetone or methyl alcohol or by swabbing with a clean gauze saturated with acetone or methyl alcohol and dried in an inert atmosphere or desiccated container. The cleaned and dried part should be subjected to 94–100 humidity at 35–40 °C [95–105 °F] for a min. 24 hours.
C	Salt Spray		Be tested by the salt spray test conducted per ASTM B117 for a minimum of 2 hours using a 5% salt solution.
D	Copper Sulfate	To detect free iron for 200 and 300 series ASS, DSS, PHSS, and FSS (Cr ≥ 16%)(3). Should not be applied to parts to be used in food processing.	4 g of copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) in 250 mL of distilled water to which 1 mL of 96 to 100% sulfuric acid (H_2SO_4) has been added. The solution is swabbed and applying additional solution as needed to keep the surface wet for a period of at least 6 minutes. At the end of this period, the surface should be carefully rinsed and dried with care taken not to disturb copper deposits if present.
E	Potassium Ferricyanide-Nitric Acid	To detect a very small amounts of free iron on 200 and 300 ASS. Not used in MSS & FSS(3) as well as food processing.	10 g of chemically pure potassium ferricyanide to 500 mL of distilled water, adding 30 mL of 70% nitric acid, agitating until all of the ferricyanide is dissolved, and diluting to 1000 mL with distilled water. The test solution should be mixed fresh on the day of the test since it changes color on standing and is swabbed on the surface of the sample representing the lot of passivated parts. The formation of a dark blue color within 30 seconds denotes the presence of metallic iron.

Table 3.28 (2/2) Verification tests on SS surfaces contamination before passivation (ASTM A967 modified)[(1)(2)]

Practice	Test Source	Targets	Test Method[(1)]
F	Damp Cloth	Useful for large parts that have been uniformly cleaned but that are inconvenient for reasons of size of equipment or ease of handling of the part to place in the environments defined in Practice A or B. Unless otherwise specified by the purchaser, the number of tests and the locations of the tests should be at the option of the processor to assure a representative testing of the part.	Be performed by placing a clean cloth pad that has been thoroughly soaked with distilled or demineralized water on the surface of the part at a part temperature of 10 °C [50 °F] or greater for a period of not less than 60 minutes. The cloth should be in contact with the steel for an area of at least 130 cm^2 [20 $in.^2$]. The pad should be maintained wet through the test period, either by a method of retarding external evaporation, by further addition of potable water, or by backing the pad with a sponge or similar water source. The cloth pad used should be used for only one such test, being changed for each test so as to avoid risk of contamination. After removal of the cloth pad, the surface of the part should be allowed to dry in air before inspection.
G	Boiling Water Immersion	To detect free iron or any other anodic surface contaminants on SS.	The sample shall be immersed in a non-rusting container of distilled water which is then heated to a temperature in the range from 95 to 100 °C [200 to 212 °F] and maintained within that range for a period of at least 30 minutes, while ensuring the sample remains immersed. At the end of this period, the container shall be removed from the heat source and be allowed to cool for a period of 3 hours ±15 minutes. The sample is then removed from the container and set on a towel to air dry (ambient air) for 2 hours ±10 minutes.

Notes

(1)Acceptance

A, B, C, F and G: The tested sample should not exhibit rust or staining attributable to the presence of free iron particles embedded in the surface

D: The tested sample should not exhibit copper deposits

E: The tested sample should not exhibit the dark blue color indicative of free iron on the surface. When the test is negative, the surface should be thoroughly washed with warm water to remove the test solution. When the test is positive, the dark blue stain should be removed with a solution of 10% acetic acid and 8% oxalic acid, followed by a thorough hot water rinse

(2)If the test sample container is metal, the parts shall not be in contact with each other, and the container should have a temperature-resistant polymeric support

(3)This test is not recommended for all 400 series MSS or for 400 series FSS with less than 16% Cr because these steels may give a positive indication irrespective of the presence or absence of anodic surface contaminants

Table 3.29 Acid Descaling (Pickling) of Stainless Steel (ASTM A380) – See General Notes

			Treatment		
SS[(1)(8)]	Condition[(2)]	Code	Solution. Volume[(3)]	Temperature °C (°F)	Time Minutes
200, 300, and 400 series, precipitation hardening, and maraging alloys (except free-machining alloys)	Fully annealed only	A	H_2SO_4, 8–11%[(4)] followed by treatment D or F, Annex A2, as appropriate	66–82 (150–180)	5–45[(5)]
200 and 300 series: 400 series containing Cr 16% or more; precipitation hardening alloys (except free-machining alloys)	Fully annealed only	B	HNO_3. 10–15% plus HF, 1–8%[(6),(7)]	21–60 (70–140)	5–30[(5)]
All free-machining alloys and 400 series containing less than Cr 16%	Fully annealed only	C	HNO_3, 10–15% plus HF, ½ –1 1/2%[(6),(7)]	21 (70) [up to 60 (140)]	5–30[(5)]

General Notes:

(a)Nitric-hydrofluoric acid solution should be carefully controlled and is not recommended for descaling sensitized ASS or hardened MSS or where it can come into contact with CS parts, assemblies, equipment, and systems. Instead, these materials should be cleaned by mechanical descaling or grinding followed by cleaning by scrubbing with hot water and fiber brushes and finally followed by rinsing with clean, hot water. Especially, the hardened MSS (Cr < 16%) are subject to hydrogen embrittlement or intergranular attack when they are exposed to acidic solutions that can generate hydrogen during cleaning

Notes:

(1)This table is also applicable to the cast grades equivalent to the families of wrought materials listed

(2)Other heat treatments may be acceptable if proven by experience: see 5.2.1, A2.4, and A2.5 in ASTM A380 for further information

(3)Solution prepared from reagents of following weight %: H_2SO_4, 98; HNO_3, 67; HF, 70

(4)Tight scale may be removed by a dip in this solution for a few minutes followed by water rinse and nitric-hydrofluoric acid treatment as noted

(5)Minimum contact times necessary to obtain the desired surface should be used in order to prevent over-pickling. Tests should be made to establish correct procedures for specific applications

(6)For reasons of convenience and handling safety, commercial formulations containing fluoride salts may be found useful in place of HF for preparing nitric-hydrofluoric acid solutions

(7)After pickling and water rinsing, an aqueous caustic permanganate solution containing NaOH, 10 weight %, and $KMnO_4$, 4 weight %, 71 to 82 °C (160 to 180 °F), 5 to 60 min, may be used as a final dip for removal of smut, followed by thorough water rinsing and drying

(8)Cleaning by mechanical methods or other chemical methods is recommended for hardenable 400 series, maraging, and PHSS materials. If acid treatment is unavoidable, this table may be used under the user's approval. When these solutions are used, the post-cleaning thermal treatment (at 120 to 150 °C [250 to 300 °F] for 24 h) is not required because they do not lead to the generation of hydrogen

Cautions for Code:

Code B & C: HNO_3 + HF solutions may intergranularly corrode certain alloys if they have been sensitized by improper heat treatment or by welding. Crevices resulting from intergranular corrosion attack (IGC) can collect and concentrate halogens under service conditions or during cleaning or subsequent processing with certain chemicals; these halogens can cause SCC. The applicable materials should generally not be acid-pickled while in the sensitized condition. Consideration should be given to stabilized or low-carbon grades if acid pickling after welding is unavoidable

Table 3.30 Acid cleaning of stainless steel (ASTM A380)

SS	Condition	Code	Treatment: Solution, Volume, wt%[(1)]	Treatment: Temperature °C (°F)	Treatment: Time, Minutes
Part I – Cleaning with Nitric-Hydrofluoric Acid					
Purpose – For use after descaling by mechanical or other chemical methods as a further treatment to remove residual particles of scale or products of chemical reaction (i.e., smut) and to produce a uniform: "white pickled" finish					
200 and 300 series, 400 series containing Cr 16% or more, and precipitation hardening SS (except free-machining SS).	Fully annealed only	D	HNO_3, 6–25% + HF, 0.5 to 8 [(2),(3)]	21–60 (70–140)	As Necessary
Free-machining SS, maraging alloy, and 400 series SS containing less than Cr16%	Fully annealed only	E	HNO_3, 10% + HF, 0.5–1.5% [(2),(3)]	21 (70) [up to 60 (140)]	1–2
Part II – Cleaning Passivation with Nitric Acid Solution (See Specification ASTM A967 for Passivation Specifications)					
Purpose – For removal of soluble salts, corrosion products, and free iron and other metallic contamination resulting from handling, fabrication, or exposure to contaminated atmospheres (see A380, 6.2.11)					
200 and 300 series, 400 series, precipitation hardening, and maraging SS containing Cr 16% or more (except free-machining SS).[(4)]	Annealed, cold-rolled, thermally hardened, or work-hardened, with dull or non-reflective surfaces	F	HNO_3 20–50%	40–71 (120–160) 21–38 (70–100)	10–30 30–60[(3)]
	Annealed, cold-rolled thermally hardened, of work-hardened with bright-machined, or polished surfaces	G	HNO_3 20–40% + $Na_2Cr_2O_7$ $2H_2O$, 2–6%	49–69(120–155) 21–38 (70–100)	10–30 30–60[(3)]
400 series SS, maraging, and precipitation hardening SS containing less than Cr 16% high-carbon-straight Cr SS (except free-machining SS).[(4)]	Annealed or hardened with dull or non-reflective surfaces	H	HNO_3, 20–50%	43–54 (110–130) 21–38 (70–100)	20–30 60
	Annealed or hardened with bright-machined or polished surfaces	I[(5)]	HNO_3, 20–25% + $Na_2Cr_2O_7 2H_2O$, 2–6%	49–54(120–130) 21–38 (70–100)	15–30 30–60
200,300, and 400 series free-machining SS.[(4)]	Annealed or hardened, with bright-machined or polished surfaces	J[(5)]	HNO_3, 20–50% + $Na_2Cr_2O_7 2H_2O$, 2–6%[F]	21–49 (70–120)	25–40
		K[(7)]	HNO_3, 1–2% + Na_2Cr_2O-$2H_2O$, 1–5%	49–60(120–140)	10
		L[(5)]	HNO_3, 12% + $CuSO_4$ $5H_2O$, 4%	49–60 (120–140)	10
Part III – Cleaning with Other Chemical Solutions					
200, 300, and 400 series (except free-machining SS), precipitation hardening, and maraging SS	Purpose-General cleaning. Fully annealed only	N	Citric add, 1 wt% + $NaNO_3$, 1 wt%	21 (70)	60
		O	Ammonium citrate, 5–10 wt %	49–71(120–160)	10–60
Assembles of SS and CS (e.g., H/EX with SS tubes and CS shell)	Sensitized	P	Inhibited solution of hydroxyacetic acid, 2 wt% and formic acid, 1 wt%	93 (200)	360 (6 hrs)
		O	Inhibited ammonia-neutralized solution of EDTA followed by hot-water rinse and dip in solution of 10 ppm ammonium hydroxide +100 ppm hydrazine	up to 121 (250)	360 (6 hrs)

***General Notes**:*

(a) Nitric-hydrofluoric acid solution should be carefully controlled and is not recommended for descaling sensitized ASS or hardened MSS or where it can come into contact with CS parts, assemblies, equipment, and systems. Instead, these materials should be cleaned by mechanical descaling or grinding followed by cleaning by scrubbing with hot water and fiber brushes, and finally followed by rinsing with clean, hot water. Especially, the hardened MSS (Cr < 16%) are subject to hydrogen embrittlement or intergranular attack when they are exposed to acidic solutions that can generate hydrogen during cleaning

(b) After acid cleaning, the cleaned surfaces shall be inspected by ASTM A380, 7.2. Normally visual test is performed ASTM A380, 3.4.2.5 unless otherwise required, such as copper-sulfate test, ferroxyl test, or others in ASTM A380, 7.2

Notes:

[(1)] Solution prepared from reagents of following: 67 wt% HNO_3, 70 wt% HF

[(2)] For reasons of convenience and handling safety, commercial formulations containing fluoride salts may be found useful in place of HF for preparing nitric-hydrofluoric acid solutions

[(3)] After acid cleaning and water rising, a caustic permanganate solution containing NaOH, 10 weight %, and $KMnO_4$, 4 weight %, 71 to 82 °C (160 to 180 °F), 5 to 60 min, may be used as a final dip for removal of smut, followed by thorough water rinsing and drying

[(4)] Cleaning by mechanical methods or other chemical methods is recommended for hardenable 400 series, maraging, and PHSS materials. If acid treatment is unavoidable, this table may be used under the user's approval. When these solutions are used, the post-cleaning thermal treatment (at 120 to 150 °C [250 to 300 °F] for 24 h) is not required because they do not lead to the generation of hydrogen

If the purchaser specifies the option of specifying in his purchase documents that all 400 series FSS and MSS parts receive additional treatment as follows: within 1 hr. after the water rinse following the specified passivation treatment, all parts should be immersed in an aqueous solution containing 4 to 6 weight % $Na_2Cr_2O_7 \cdot 2H_2O$, at 60 to 71 °C (140 to 160 °F), 30 min. This immersion should be followed by thorough rinsing with clean water. The parts then should be thoroughly dried

(5) See ASTM A380, A2.2
(6) If flash attack (clouding of stainless steel surface) occurs, a fresh (clean) passivating solution or a higher HNO_3 concentration will usually eliminate it
(7) Shorter times may be acceptable where established by test and agreed upon by the purchaser

Cautions for Code:

Code D & E: Nitric acid (HNO_3) + hydrofluoric acid (HF) solutions may intergranularly corrode certain alloys if they have been sensitized by improper heat treatment or by welding. Crevices resulting from intergranular corrosion attack (IGC) can collect and concentrate halogens under service conditions or during cleaning or subsequent processing; these halogens can cause SCC. Such alloys should not be cleaned with nitric-hydrofluoric acid solutions while in the sensitized condition. Consideration should be given to use of stabilized or low-carbon alloys if this kind of cleaning after welding is unavoidable

Code F & H: Nitric acid (HNO_3) solutions are effective for removing free iron and other metallic contamination, but are not effective against scale, heavy deposits of corrosion products, temper films, or greasy or oily contaminants. Any scale, heavy deposits of corrosion products or heat-temper discoloration must be removed per Table 3.29 *before acid cleaning. Use conventional degreasing methods for removal of greasy or oil contaminants before any acid treatment*

Code N: Citric acid ($C_6H_8O_7$) + sodium nitrate ($NaNO_3$) treatment is the least hazardous for removal of free iron (Fe) and other metallic contamination and light surface contamination. Spraying of the solution, as compared to immersion, tends to reduce cleaning time

(ASTM A967) is applied for non-process equipment, structures, and piping which are not in contact with the process service. For more detail information, see industrial standards and reports, e.g., ASTM A380 (cleaning, descaling, and passivation of SS parts, equipment, and systems), A967 (chemical passivation treatments for SS parts), ASTM STP 538 (cleaning SS), European SS Development Association, and NiDI Handbook No. 9001 (cleaning and descaling SS) and CRA mill supplier's manual/handbooks.

As a common rule, hardenable 400 Series, maraging, and precipitation hardening alloys (PHSS) in the hardened condition are subject to hydrogen embrittlement or intergranular corrosion attack (IGC) when exposed to acids that can cause the generation of hydrogen on the item being cleaned. Cleaning by mechanical methods or other chemical methods is recommended for these materials. If acid treatment is unavoidable, parts should be heated at 120 to 150 °C [250 to 300 °F] for 24 h immediately following acid cleaning to drive off hydrogen and reduce susceptibility to embrittlement unless otherwise noted.

Also, for all stainless steels, severe pitting may result from prolonged exposure to certain acids if the solution becomes depleted or if the concentration of metallic salts becomes too high as a result of prolonged use of the solution; the concentration of iron should not exceed 2 wt %; take care to avoid overexposure.

In current practice for chemical cleaning of structural stainless steels, any one of three approaches is usually used nitric acid passivation, nitric acid with sodium dichromate passivation, and citric acid passivation as seen in Table 3.31. Which bath and composition to use depends on the grade of stainless steel and prescribed acceptance criteria. After thorough cleaning, the stainless steel part or component may have to be ready for immersion in a passivating acid bath to improve the corrosion resistance.

Table 3.31 Chemical passivation treatment of stainless steel (ASTM A967) – *Note 4, 5, 6*

Practice	Test Solution	Time and Temperature	Remark
Nitric Acid Solutions (HNO_3)		*Note 1*	
Nitric 1	20–25 vol% HNO_3 + 2.0–3.0 wt% Sodium Dichromate	Immersed for min. 20 minutes in 50–55 °C (120–130 °F)	
Nitric 2	20–45 vol% HNO_3	Immersed for min. 30 minutes in 20–30 °C (70–90 °F)	
Nitric 3	20–25 vol% HNO_3	Immersed for min. 20 minutes in 50–60 °C (120–140 °F)	
Nitric 4	45–55 vol% HNO_3	Immersed for min. 30 minutes in 50–55 °C (120–130 °F)	
Nitric 5	Other combination with HNO_3 solution plus accelerants, inhibitors, or proprietary solutions, capable of producing parts that pass the specified test requirements		
Water Rinsing	*Note 2*		*Note 2*
Citric Acid Solutions ($C_6H_8O_7$)		*Note 3*	
Citric 1	4–10 wt% Citric Acid Solution	Immersed for min. 4 minutes in 60–70 °C (140–160 °F)	
Citric 2	4–10 wt% Citric Acid Solution	Immersed for min. 10 minutes in 50–60 °C (120–140 °F)	
Citric 3	4–10 wt% Citric Acid Solution	Immersed for min. 20 minutes in 20–50 °C (70–120 °F)	
Citric 4	Other combination with HNO_3 solution (or plus accelerants, inhibitors, or proprietary solutions, capable of producing parts that pass the specified test requirements)		
Citric 5	Other combination with HNO_3 solution (or plus accelerants, inhibitors, or proprietary solutions, capable of producing parts that pass the specified test requirements) at a pH of 1.8–2.2.		
Water Rinsing	*Note 2*		*Note 2*

Notes
1. See SAE AMS QQ-P-35A (Passivation Treatments for Corrosion-Resistant Steel) and BS EN 2516 (Passivation of Corrosion Resisting Steels and Decontamination of Nickel-Base Alloys)
2. Immediately after passivation. And thoroughly rinsed, using stagnant, countercurrent, or spray washes singly or in combination, with or without a separate chemical treatment for neutralization of the passivation media with a final rinse being carried out using water with a maximum total solids content of 200 ppm
3. This method is being promoted because citric acid is safer to use than nitric acid, is biodegradable, produces fewer effluent concerns, and is also used as a food ingredient. Citric acid does an excellent job of removing iron from surfaces, which is the first step of traditional passivation. It is not an oxidizer and so it cannot oxidize Cr which is the second step of classic passivation. Therefore, it cannot build up the protective passivation layer, so this process depends on natural air oxidation
   Citric acid is mostly used on small parts that will not be used in aggressive chemical or physical environments. NASA applies citric acid treatment on the surfaces of 304 SS, 410 SS, and 17-4 PHSS
4. Refer SAE AMS 2700 (Nitric/Citric Acid Passivation Treatment of Corrosion-Resistant Steels)
5. See Table 3.31a below for Recommended Nitric/Citric Acid Passivation Treatment for Several Stainless Steels
6. See ASTM A967, Table X1.1 for Recommended Nitric Acid Passivation Treatment for Different Grade (UNS No.) of Stainless Steels

Table 3.31a Recommended nitric/citric acid passivation treatment for several stainless steels (ASTM A967) √: applicable

SS Group		Nitric 1	Nitric 2	Nitric 3	Nitric 4	Nitric 5	Citric 1 to 5
Free-machining grades including ASS, FSS, MSS, in other words, containing high amount (value not set to a maximum) of Sulfur, any Selenium, or both		√	–	–	–	√	√
ASS	ASS with high Carbon ("H" grade)	–	√	–	√	√	√
	Other ASS	–	√	√	–	√	√
DSS, Lean DSS, Super DSS		–	√	√	–	√	√
PHSS		√	–	–	√	√	√
MSS	MSS containing high amount Carbon and < 15% Cr (e.g., 420 SS)	√	–	–	–	√	√
	Other MSS	√	–	–	√	√	√
FSS	<15% Cr	√	–	–	√	√	√
	≥15% Cr	√	–	√	–	√	√

Table 3.32 Comparison of passivation and electropolishing

	Passivation	Electropolishing
Process	A chemical process developed surface quality (to fine and thicker Cr_2O_3 film) to remove surface contamination and increase the corrosion resistance of SS surfaces	An electrochemical process provides a variety of benefits including deburring, microfinish improvement, and corrosion resistance improved by eliminating embedded contaminants and surface imperfections. The part is submerged in a chemical bath and treated with electricity to make uniform layer of surface material. See ASTM B912
Pre-cleaning	Required	Not Required
Brightens and Polishes	Not expected	Greatly expected
Microfinish, Deburring, Heat Tint	May not be expected	Greatly expected
Limits of Materials	A certain free-machining SS or MSS may not be easy	All grades of SS may be available

See Table 3.32 for the comparison of passivation and electropolishing. The detail information for electropolishing other than Table 3.32 is not included in this book.

(c) Acid Cleaning of Nickel Alloys
Sodium hydride baths are necessary to descale this alloy. After the sodium hydride treatment, the material should be immersed in a sulfuric acid bath 74 °C (165 °F) for approximately 3 minutes. A 25-minute immersion in a nitric-hydrofluoric bath 63 °C (145 °F) is then necessary. Rinse. Sulfuric solution: 16% by weight, H_2SO_4. Nitric solution: 8% HNO_3 by weight and 3% HF by weight. Acid etching for macro-inspection-expose material electrolytically to a 3-to-1 HCl to HNO_3 solution, saturated with $CuCl_2$ at a current density of 0.645 amp/in^2 (25.4 A/m^2). For other procedures, see BS EN 2516 (Passivation of Corrosion Resisting Steels and Decontamination of Nickel-Base Alloys) and ASTM B380 (same as for stainless steel).
(d) Descaling and Cleaning of Titanium and Titanium Alloys: See ASTM B600. However, any type of cleaning of titanium which causes disturbance of the initially formed protective film should be avoided, since serious corrosion may occur.
(e) Descaling and Cleaning of Zirconium and Zirconium Alloys: See ASTM B614.
(f) Chemical Cleaning of Columbium and Tantalum Alloys: See NASA Lewis Specification No. RM-1.
(g) Tantalum should not be cleaned with acids or alkaline solutions because acids may cause embrittlement due to absorption of the released hydrogen, and alkaline solutions will cause serious corrosion.
(h) Limitation of Cleaning on Nonmetals:
    1. Glass-lined equipment should not be cleaned with alkaline solutions, and its steel jackets should not be cleaned with acids.
    2. Graphite equipment should not be cleaned with oxidizing chemicals or with cleaning solutions containing phenolic or cresolic compounds.
    3. For certain coatings and linings, acid cleaning of the uncoated side should not be performed. The hydrogen gas formed may penetrate through the steel wall and cause loosening and/or spalling of the coating or lining, so that acid cleaning should not be used on the H/EX shell side having a baked-on coating on the tube side.

3.4.2.3 Alkaline Cleaning on Stainless Steels

Alkaline solutions are used to remove oily, semisolid, grease, and soil contaminants from metal surfaces. Such cleaning is needed to fully expose metal surfaces to the more aggressive chemicals that are required to facilitate the removal of mineral deposits and mill scale. Spray or soak alkaline cleaning also can be used as a pre-cleaning stage followed by additional alkaline cleaning, if the soil/metal lend themselves to this treatment.

Chemicals used in alkaline cleaning include trisodium phosphate (Na_3PO_4), sodium carbonate (Na_2CO_3), sodium hydroxide (NaOH), and sodium silicate (Na_2SiO_3). These chemicals are often used in combination with a surfactant. To a great extent, the solutions used depend on their detergent qualities for cleaning action and effectiveness. Agitation and temperature of the solution are important. After cleaning and draining of the system, flush the piping system with water to remove any remaining alkaline cleaning solution. This flushing minimizes the risk of alkaline SCC. The flushing should be with potable water for stainless steel surfaces. Drying should be thoroughly performed after flushing. See ASTM B322 and A380 for more information.

3.4.3 Surface Preparation Before Coating

Table 3.33 shows several classes per standards of surface preparation before coating. Table 3.34 shows the application matrix of the surface preparation per the substrate.

Table 3.33 Comparison of surface preparation standards

System	SSPC	NACE	CGSB	SIS/ISO 8501	BS (old version) See Table 3.35 for current BS STD	Remark
Solvent Cleaning	SP-1	–	–	–	–	See Fig. 3.23 for Comparison of Surface Preparation Standards See Note below for several SSPC standards.
Hand Tool Cleaning	SP-2	–	31 GP 401	St.2/St.3	–	
Power Tool Cleaning	SP-3	–	31 GP 402	St.2/St.3	–	
Flame Cleaning (New Steel)	SP-4	–	31 GP 403	F-1	–	
White Metal Blast	SP-5	#1	31 GP 404-Type 1	Sa.3	BS4232, 1st Quality	
Commercial Blast	SP-6	#3	31 GP 404-Type 2	Sa.2	BS4232, 3rd Quality	
Brush-Off Blast	SP-7	#4	31 GP 404-Type 3	Sa.1	Light Blast to Brush-off	
Pickling	SP-8	–	–	–	–	
Weather & Blast	SP-9	–	–	–	–	
Near- White Blast	SP-10	#2	–	Sa. 2 1/2	BS4232 2nd Quality	
Power Tool Cleaning to Bare Metal	SP-11	–	–	–		
Water Jetting	SP-12	#5	–	–	–	
For Concrete	SP-13	#6	–	–	–	
Industrial Blast	SP-14	#8	–	–	–	
Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, SS, and Nonferrous Metals	SP-16	–	–	–	–	

Abbreviation: *SSPC* Steel Structure Painting Council (The Society for Protective Coatings), *NACE* National Corrosion Engineers' Association, *CGSB* Canadian General Standards Board, *SIS* Swedish Standard Institute, *BS* British Standards

Notes: See Fig. 3.23 for Comparison of Surface Preparation Standards and Table 3.34 Application of Surface Preparation

SP-1 (Solvent Cleaning): Removal of all visible oil, grease, soil, drawing and cutting compounds, and other soluble contaminants from steel surfaces with solvent, vapor, cleaning compound, alkali, emulsifying agent, or steam

SP-2 (Hand Tool Cleaning): Removing of all loose rust, loose mill scale, loose paint, and other loose detrimental foreign matter by hand chipping, scraping, sanding, and wire brushing

SP-3 (Power Tool Cleaning): Removing of all loose rust, loose rust, loose paint, and other loose detrimental foreign matter by power wire brushing, power sanding, power grinding, power tool chipping, and power tool descaling

SP-5 (White Metal Blast Cleaning): Blast cleaning to pure metal. Free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter

SP-6 (Commercial Blast Cleaning): Thorough blast cleaning. Free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter of at least 66.6% of unit area, which should be a square 3 in. × 3 in. (9 in^2). Light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating in less than 33.3% of the unit area is acceptable

SP-7 (Brush-Off Blast Cleaning): Free of all visible oil, grease, dirt, dust, loose mill scale, loose rust, and loose coating. Tightly adherent mill scale, rust, and coating may remain on the surface. Mill scale, rust, and coating are considered tightly adherent if they cannot be removed by lifting with a dull putty knife. May be applicable to the stainless steel surface before the coating

SP-10 (Near-White Blast Cleaning): Very thorough blast cleaning. Free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter of at least 95% of each unit area. Staining should be limited to no more than 5 percent of each unit area and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coatings. Unit area should be approximately 3 in. × 3 in. (9 in^2)

SP-11 (Power Tool Cleaning to Bare Metal): Free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products, and other foreign matter. Slight residues of rust and paint may be left in the lower portion of pits if the original surface is pitted. The surface profile should not be less than 1 mil (25 microns). May be applicable to the stainless steel surface before the coating

SP-12 (Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Water Jetting Prior to Recoating): requires water jetting at high- or ultrahigh-pressure to prepare a surface for recoating using pressure above 10,000 psi. Water jetting will not produce a profile; rather, it exposes the original abrasive-blasted surface profile. Water jetting should be performed to meet four conditions: WJ-1, WJ-2, WJ-3, and WJ-4, and a minimum acceptable surface should have all loose rust, loose mill scale, and loose coatings uniformly removed

WJ-1: Waterjet Cleaning of Metals-Clean to Bare Substrate – Surface should be free of all previously existing visible rust, coatings, mill scale, and foreign matter and have a matte metal finish

WJ-2: Waterjet Cleaning of Metals-Very Thorough Cleaning– Surface should be cleaned to a matte finish with at least 95% of the surface area free of all previously existing visible residues and the remaining 5% containing only randomly dispersed stains of rust, coatings, and foreign matter

WJ-3: Waterjet Cleaning of Metals-Thorough Cleaning – Surface should be cleaned to a matte finish with at least two-thirds of the surface area free of all previously existing visible residues (except mill scale), and the remaining one-third containing only randomly dispersed stains of previously existing rust, coatings, and foreign matter

WJ-4: Waterjet Cleaning of Metals-Light Cleaning – Surface should have all loose rust, loose mill scale, and loose coatings uniformly removed

SP-13 (Surface Preparation of Concrete): Surface preparation of concrete by mechanical, chemical, or thermal methods prior to the application of bonded protective coating or lining systems

SP-14 (Industrial Blast Cleaning): Removal of all visible oil, grease, dust and dirt, when viewed without magnification. Traces of tightly adherent mill scale, rust, and coating residues are permitted to remain on 10% of each unit area of the surface if they are evenly distributed. Shadows, streaks, and discoloration caused by stains of rust, stains of mill scale, and stains of previously applied coating may be present on the remainder of the surface

SP-16 (Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, SS, and Nonferrous Metals): Free of all visible oil, grease, dirt, dust, metal oxides (corrosion products), and other foreign matter. Intact, tightly adherent coating is permitted to remain. A coating is considered tightly adherent if it cannot be removed by lifting with a dull putty knife. Bare metal substrates should have a minimum profile of 19 micrometers (0.75 mil)

St.2 Thorough hand and power tool cleaning

St.3 Very thorough hand and power tool cleaning

Sa 1 Light blast cleaning

Sa 2 Thorough blast cleaning

Sa 2 ½ Very thorough blast cleaning

Sa 3 Blast cleaning to visually clean steel

SSPC-VIS 1 Visual Standard for Abrasive Blast Cleaned Steel

SSPC-VIS 2/NACE VIS 2 Standard Method for Evaluating Degree of Rusting on Painted Steel Surfaces

SSPC-VIS 3 Visual Standard for Power- and Hand Tool Cleaned Steel

SSPC-VIS 4/NACE VIS 7 Interim Guide and Visual Reference Photographs for Steel Cleaned by Water Jetting

SSPC-VIS 5/NACE VIS 9 Guide and Reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning

SSPC PA1 Shop, Field, and Maintenance Coating of Metals

SSPC PA2 Procedure for Determining Conformance to Dry Coating Thickness Requirements

SSPC PA6 Fiberglass-Reinforced Plastic (FRP) Linings Applied to Bottoms of Carbon Steel Aboveground Storage Tanks – NACE No. 10

SSPC PA7 Applying Thin Film Coatings to Concrete

SSPC PA8 Thin Film Organic Linings Applied in New Carbon Steel Process Vessels – NACE No. 10

SSPC PA9 Measurement of Dry Coating Thickness Using Ultrasonic Gauges

SSPC PA14 Application of Thick Film Polyurea and Polyurethane Coatings to Concrete and Steel Using Plural-Component Equipment

SSPC PA15 Material and Preparation Requirements for Steel Test Panels Used to Evaluate the Performance of Industrial Coatings

SSPC PA16 Method for Evaluating Scribe Undercutting on Coated Steel Test Panels Following Corrosion Testing

SSPC PA17 Procedure for Determining Conformance to Steel Profile/Surface Roughness/Peak Count Requirements

SSPC-PA Guide 4 Guide to Maintenance Repainting with Oil Base or Alkyd Painting Systems

SSPC-PA Guide 5 Guide to Maintenance Coating of Steel Structures in Atmospheric Service

SSPC-PA Guide 9 Measurement of Dry Coating Thickness on Cementitious Substrates Using Ultrasonic Gauges

SSPC-PA Guide 10 Guide to Safety and Health Requirements for Industrial Painting Projects

SSPC-PA Guide 11 Protecting Edges, Crevices, and Irregular Steel Surfaces by Stripe Coating

SSPC-PA Guide 13 Guide for Application of Coating Systems with Zinc-Rich Primers to Steel Bridges

Class	SP-1/ISO 8504	SP-7/NACE #4 /Sa-1	SP-14/NACE #8	SP-6/NACE #3 /Sa-2	SP-10/NACE #2/Sa-2.5	SP-5/ NACE #1/Sa-3
Condition	Solvent Cleaning	Brush Off	Industrial Blast Cleaning	Commercial Blast Cleaning	Near White Blast Cleaning	White Metal Blast
Loose Material	100%	0%	0%	0%	0%	0%
Tight Material	100%	100%	10%	0%	0%	0%
Strains, Shadows	100%	100%	100%	≤ 33%	≤ 5% for SP-10 ≤ 15% for Sa 2.5	0%

Figure 3.23 Microscophic comparison of surface preparation standards. (Source: SSPC)

Table 3.35 shows relative ranking of SSPC surface preparation grade for steel based on thoroughness of cleaning.
Table 3.36 shows the summary of BS standards-surface preparation.
Table 3.37 shows the table of each SSPC spec related with galvanizing ASTM standard practices.

Table 3.34 Application of surface preparation per substrate

SSPC Spec	Iron or Steel	Galvanized Surfaces	Aluminum	Prefinished Metals	SS	Nonferrous Metals	Plastic-PVC/FRP	Concrete[1]	Pre-coated Metals
SP-1 (Solvent Cleaning)	√	√	√	√	√	√		√	√
SP-2 (Hand Tool Cleaning)	√	√							
SP-3 (Power Tool Cleaning)	√	√						√	
SP-5 (White Metal Blast Cleaning)	√								
SP-6 (Commercial Blast Cleaning)	√								
SP-7 (Brush-Off Blast Cleaning)	√	√	√	√	√	√		√	√
SP-10 (Near-White Blast Cleaning)	√								
SP-11 (Power Tool Cleaning to Bare Metal)	√								
SP-12 (Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Water Jetting Prior to Recoating)	√			√			√	√	√
SP-13 (Surface Preparation of Concrete)								√	
SP-14 (Industrial Blast Cleaning)	√								
SP-16 (Brush-Off Blast Cleaning of Galvanized Steel, SS, Nonferrous Metals)		√	√		√	√			√

Source: https://coastalone.com/media/wysiwyg/product_resources/surface_preparation_standards
Notes: √ = applicable, blank = not applicable
[1]Concrete can also be cleaned and prepared using ASTM D 4260 (Acid Etch – Floors), ASTM D 4258 (Solvent Cleaning), ASTM D 3359 (To Check Adhesion), and ASTM D 4259 (To Abrade Concrete)

Table 3.35 Relative ranking of SSPC surface preparation grade for steel based on thoroughness of cleaning[1]

Thorough Cleaning	SSPC Grade	Dry Abrasive Blast	Wet Abrasive Blast (WAB)	Hand and Power Tool	Water Jetting (WJ)
Strong ↑	White Metal Blast Cleaning	SP-5	SP 5 (WAB)/NACE WAB-1		SP WJ-1/NACE WJ-1
	Near-White Blast Cleaning	SP-10	SP 10 (WAB)/NACE WAB-2	SP 11	SP WJ-2/NACE WJ-2
	Commercial Blast Cleaning	SP-6	SP 6 (WAB/NACE WAB-3		SP WJ-3/NACE WJ-3
	Industrial Blast Cleaning	SP-14	SP 14 (WAB)/NACE WAB-8	SP 15	
	Brush-Off Blast Cleaning	SP-7	SP 7 (WAB)/NACE WAB-4		SP WJ-4/NACE WJ-4
	Power Tool Cleaning			SP-3	
	Hand Tool Cleaning			SP-2	

Source: SSPC SP-COM modified
Notes: Blank = not applicable
[1]This ranking is not meant to imply that different methods of cleaning on the same level are equivalent. For example, SP 10 is not the same as SP 11, nor are either of these the same as WJ-2. If SP 10 is desired, but abrasive blast cleaning is not possible, then the closest alternatives would be SP 11 or WJ-2

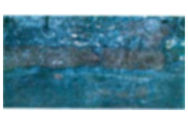
Table 3.36 (1/2) The summary of BS standards-surface preparation

Standards	Old References	(Part) Titles
BS 7079	7079-0	**Preparation of steel substrates before application of paints and related products – Introduction**
BS EN ISO 8501	**Preparation of steel substrates before application of paints and related products – Visual assessment of surface cleanliness**	
Part 1	7079-A1 & Supplement 1	Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings – Note 1
Part 2	7079-A2	Preparation grades of previously coated steel substrates after localized removal of previous coatings
Part 3	7079-A3	Preparation grades of welds, edges, and other areas with surface imperfections
Part 4	7079-A4	Initial surface conditions, preparation grades, and flash rust grades in connection with high-pressure water jetting
BS EN ISO 8502	**Preparation of steel substrates before application of paints and related products – Tests for assessment of surface cleanliness**	
Part 2	7079-B2	Preparation grades of previously coated steel substrates after localized removal of previous coatings
Part 3	7079-B3	Preparation grades of welds, edges, and other areas with surface imperfections
Part 4	7079-B4	Initial surface conditions, preparation grades, and flash rust grades in connection with high-pressure water jetting
Part 5	7079-B5	Rust and preparation grades of uncoated steel substrates and steel substrates after overall removal of previous coatings
Part 6	7079-B6	Preparation grades of previously coated steel substrates after localized removal of previous coatings
Part 8	7079-B8	Preparation grades of welds, edges, and other areas with surface imperfections
Part 9	7079-B9	Initial surface conditions, preparation grades, and flash rust grades in connection with high-pressure water jetting
Part 11	7079-B11	Field method for the turbidimetric determination of water-soluble sulfate
Part 12	7079-B12	Field method for the titrimetric determination of water soluble ferrous ions

Table 3.36 (2/2) The summary of BS standards-surface preparation

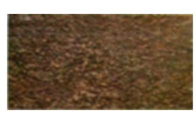
Standards	Old References	(Part) Titles
BS EN ISO 8503	**Preparation of steel substrates before application of paints and related products – Surface roughness characteristics of blast-cleaned steel substrates**	
Part 1	7079-C1	Specifications and definitions for ISO surface profile comparators for the assessment of abrasive blast-cleaned surfaces
Part 2	7079-C2	Method for the grading of surface profile of abrasive blast-cleaned steel – Comparator procedure
Part 3	7079-C3	Method for the calibration of ISO surface profile comparators and for the determination of surface profile – Focusing microscope procedure
Part 4	7079-C4	Method for the calibration of ISO surface profile comparators and for the determination of surface profile – Stylus instrument procedure
Part 5	7079-C5	Replica tape method for the determination of the surface profile
BS EN ISO 8504	**Preparation of steel substrates before application of paints and related products – Surface preparation methods**	
Part 1	7079-D1	General principles
Part 2	7079-D2	Abrasive blast cleaning
Part 3	7079-D3	Hand and power tool cleaning
BS EN ISO11124	**Preparation of steel substrates before application of paints and related products – Specs for metallic blast cleaning abrasives**	
Part 1	7079-E1	General introduction and classification
Part 2	7079-E2	Chilled iron grit
Part 3	7079-E3	High-carbon cast-steel shot and grit
Part 4	7079-E4	Low-carbon cast-steel shot
BS EN ISO11125	**Preparation of steel substrates before application of paints and related products – TM for metallic blast cleaning abrasives**	
Part 1	7079-E6	Sampling
Part 2	7079-E7	Determination of particle size distribution
Part 3	7079-E8	Determination of hardness
Part 4	7079-E9	Determination of apparent density
Part 5	7079-E10	Determination of percentage defective particles and of microstructure
Part 6	7079-E11	Determination of foreign matter
Part 7	7079-E12	Determination of moisture
BS EN ISO11126	**Preparation of steel substrates before application of paints and related products – Specs for nonmetallic blast cleaning abrasives**	
Part 1	7079-F1	General introduction and classification
Part 3	7079-F3	Copper refinery slag
Part 4	7079-F4	Coal furnace slag
Part 5	7079-F5	Nickel refinery slag
Part 6	7079-F6	Iron furnace slag
Part 7	7079-F7	Fused aluminum oxide
Part 8	7079-F8	Olivine sand
Part 9	7079-F9	Staurolite
Part 10	7079-F10	Almandite garnet
BS EN ISO11127	**Preparation of steel substrates before application of paints and related products – TM for nonmetallic blast cleaning abrasives**	
Part 1	7079-F11	Sampling
Part 2	7079-F12	Determination of particle size distribution
Part 3	7079-F13	Determination of apparent density
Part 4	7079-F14	Assessment of hardness by a glass slide test
Part 5	7079-F15	Determination of moisture
Part 6	7079-F16	Determination of water-soluble contaminants by conductivity measurement
Part 7	7079-F17	Determination of water-soluble chlorides
DD ISO/TR 15235	**Preparation of steel substrates before application of paints and related products – Collected information on the effect of levels of water-soluble salt contamination**	

Note 1: ISO 8501 identifies the following four rust grades which are normally found on uncoated steel surfaces and on stored steel surfaces

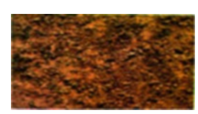


Grade A Steel surface largely covered with adhering mill scale but little, if any, rust.

Grade B Steel surface which has begun to rust and from which the mill scale has begun to flake.



Grade C Steel surface on which the mill scale has rusted away or from which it can be scraped but with slight pitting visible under normal vision.



Grade D Steel surface on which the mill scale has rusted away and on which general pitting is visible under normal vision.

Table 3.37 Table of each SSPC spec related with galvanizing ASTM standard practices

SSPC Spec	**ASTM A780** Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings	**ASTM D6386** Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Painting	**ASTM D7803** Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Powder Coating
SP-1 (Solvent Cleaning)	–	5.3.2 Surface cleaning prior to surface preparation	5.1.2.3 Surface cleaning step removing oil and grease
SP-2 (Hand Tool Cleaning)	A2.1.2 Clean areas when circumstances do not allow blast or power tool cleaning	5.2.1 Removal of zinc high spots 5.3.3 Cleaning of light deposits of zinc reaction products	5.1.1 Surface smoothing and removing loose particles
SP-3 (Power Tool Cleaning)	–	5.2.1 Removal of zinc high spots 5.3.3 Cleaning of light deposits of zinc reaction products	5.1.1 Surface smoothing and removing loose particles
SP-5 (White Metal Blast Cleaning)	A3.3 Prepare surface for zinc spray	–	–
SP-7 (Brush-Off Blast Cleaning)	–	5.4.1 Acceptable surface preparation standard for profiling surface of newly galvanize metal	–
SP-10 (Near-White Blast Cleaning)	A2.1.2 Prepare surface for zinc-rich paint repair	–	–
SP-11 (Power Tool Cleaning to Bare Metal)	A2.1.2 Prepare surface for zinc-rich paint repair in less critical field exposure conditions	5.4.21 Acceptable surface preparation standard for profiling surface of newly galvanized metal	–
SP-12 (Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh- Pressure Water Jetting Prior to Recoating)	–	–	5.3.2 Cleaning fully weathered galvanized steel to maintain existing profile
SP-16 (Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, SS, and Nonferrous Metals):	–	–	5.1.3.1 Sweep blasting newly galvanized metal after to add surface profile

3.4.4 Paint Color Code Standards

3.4.4.1 Munsell Color System

Developed by Dr. Munsell in the USA. Used world widely. The color codes are based on three color dimensions, such as Hue, Value (lightness), and Chroma (color purity), Fig. 3.24.

(a) Hue – Five principal types: **R**ed, **Y**ellow, **G**reen, **B**lue, and **P**urple, along with five intermediate hues (e.g., **YR**) halfway between adjacent principal hues. Each of these 10 steps, with the named hue given number 5, is then broken into 10 sub-steps, so that 100 hues are given integer values. In practice, color charts conventionally specify 40 hues, in increments of 2.5, for example 10R to 2.5YR.

(b) Value (lightness) – Varies vertically along the color solid, from black (value 0) at the bottom, to white (value 10) at the top. Neutral grays lie along the vertical axis between black and white.

(c) Chroma (color purity) – *M*easured radially from the center of each slice, represents the "purity" of a color (related to saturation), with lower chroma being less pure (more washed out, as in pastels). Note that there is no intrinsic upper limit to chroma. Different areas of the color space have different maximal chroma coordinates.

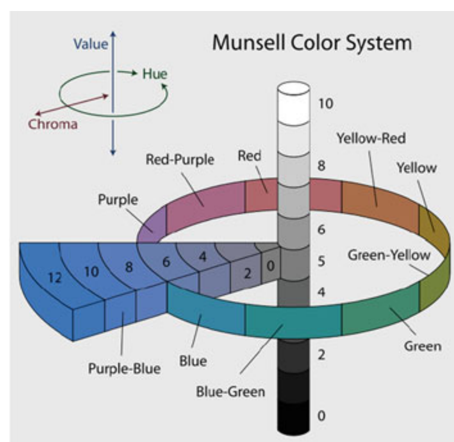


Figure 3.24 Munsell Color System Principal. (Source: Munsell color – Wikipedia)

3.4.4.2 US Federal Standard 595 Color Classes

FS vwxyz

v: 1 = gloss, 2 = semi-gloss, 3 = matt

w: 0 = brown, 1 = red, 2 = orange, 3 = yellow, 4 = green, 5 = blue, 6 = gray, 7 = other (white, black, violet, metallic), 8 = fluorescent

xyz: The numbers indicate the intensity. Lower value indicates a darker color and higher value, a lighter color, with no other significance. The numbers have been assigned with gaps to allow addition of new colors. Fed-Std-595 is a color collection, not a complete color system.

Fed-Std-595 provides the color search from the Fed number in http://www.colorserver.net/.

Table 3.38 RAL color code classes (RAL standard)

Range	Range Name	First	Last	Quantity
RAL 1xxx	Yellow	RAL 1000 Green Beige	RAL 1037 Sun Yellow	30
RAL 2xxx	Orange	RAL 2000 Yellow Orange	RAL 2013 Pearl Orange	14
RAL 3xxx	Red	RAL 3000 Fire Red	RAL 3033 Pearl Pink	34
RAL 4xxx	Violet	RAL 4001 Red Purple	RAL 4012 Pearl Black Berry	12
RAL 5xxx	Blue	RAL 5000 Violet Blue	RAL 5026 Pearl Night Blue	25
RAL 6xxx	Green	RAL 6000 Patina Green	RAL 6038 Luminous Green	36
RAL 7xxx	Gray	RAL 7000 Squirrel Gray	RAL 7048 Pearl Mouse Gray	38
RAL 8xxx	Brown	RAL 8000 Green Brown	RAL 8029 Pearl Copper	20
RAL 9xxx	White/Black	RAL 9001 Cream	RAL 9023 Pearl Dark Gray	14

3.4.4.3 RAL Color System

Developed by the German RAL gGmbH. Mostly used in Europe (Table 3.38).

3.4.4.4 RGB (Red-Green-Blue) Color System

The three principal colors (**R**ed-**G**reen-**B**lue) are combined with Hue (H), Saturation (S), and Value (V) to designate the color code.

3.4.5 Surface Finish

3.4.5.1 Definitions and Types of Surface Roughness

The metal surface roughness is normally required for the functional purpose of the following components of equipment and piping, while the brightness is normally for aesthetic purpose.

- Flange face (for gasket contact): per codes and company specifications (to minimize sliding and leaking).
- Pipe/Tube Internals: per ASME B46.1 and/or end-user's specifications (to minimize erosion/corrosion rate and deposits/fouling).
- External surface to be painted: per painting specification (to make anchor effect of the coating).
- Machined parts (i.e., shaft, pin, bearing, etc.) to be metallically contacted/assembled: per codes, manufacturer's standards, and/or end-user's specifications (for tight contact).
- Machined parts (i.e., flange external surfaces, etc.) not to be metallically contacted/assembled: per company specifications or supplier's standards – In this case, "no requirements" or "max. 500 AARH" may be recommended unless otherwise required.
- Weld bevel surfaces: "as ground" or "max. 500 AARH" may be recommended unless otherwise required.

(a) All materials have some roughness on the surfaces. The surfaces can be typically classified by the following definitions.
   - ***Surface:*** the boundary that separates an object from another object, substance, or space.
   - ***Nominal surface:*** the intended surface boundary (exclusive of any intended surface roughness), the shape, and extent of which is usually shown and dimensioned on a drawing or descriptive specification (see Fig. 3.25).
   - ***Real surface:*** the actual boundary of an object. Its deviations from the nominal surface stem from the processes that produce the surface.
   - ***Measured surface:*** a representation of the real surface obtained by the use of a measuring instrument.

   Figure 3.25 shows schematic diagram of metal surface characteristics.

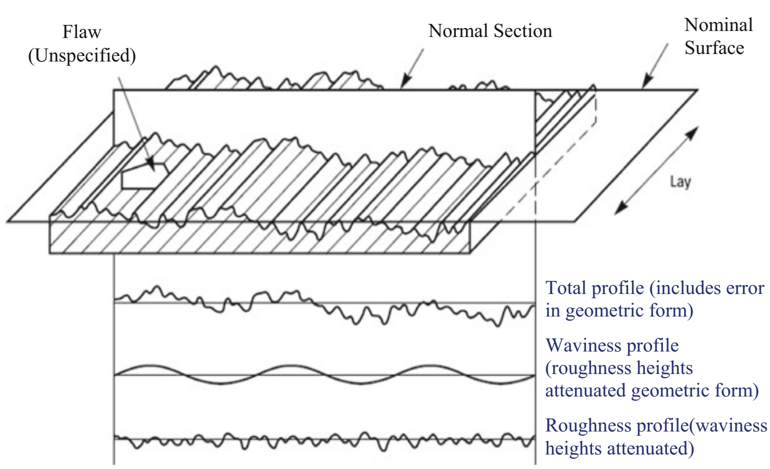
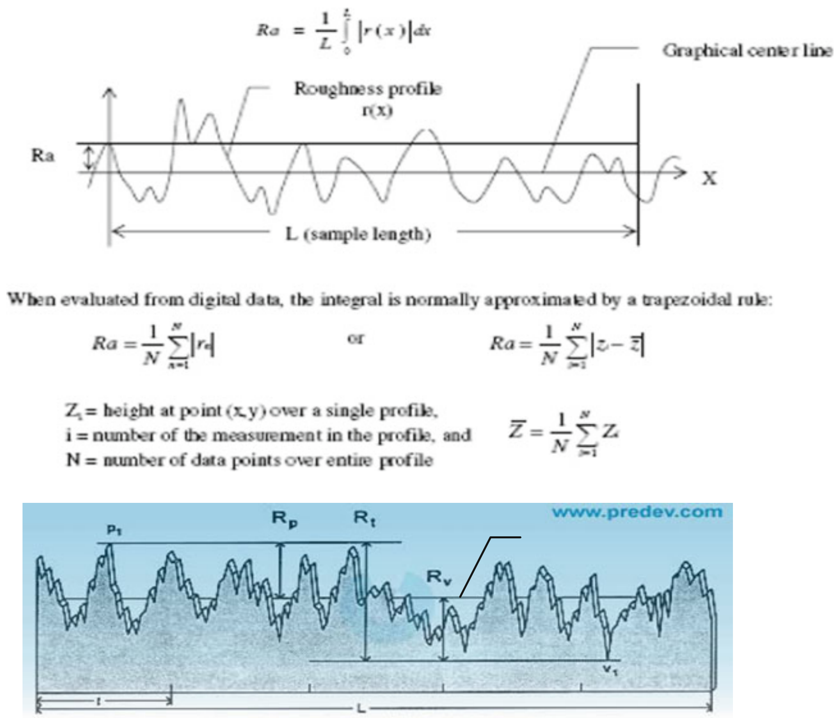


Figure 3.25 Schematic Diagram of Surface Characteristics (ASME B46.1)



(a) Ra

(b) Rp, Rv, and Rt

Figure 3.26 Roughness of Ra, Rp, Rv, and Rt. (Source ASME B46.1 – modified)

Figure 3.26 shows (a) Ra which is average (mean) roughness from average deviation from the mean of all profile heights and (b) Rap, Rv, and Rt;

Rp: The height of the highest peak in the roughness profile over the evaluation length (p1): Rp $= |\max[r(x)]|$, $0 < x < L$

Rv: The depth of the deepest valley in the roughness profile over the evaluation length (v1): Rv $= |\min[r(x)]|$, $0 < x < L$

Rt: The vertical distance from the deepest valley to the highest peak, the sum of Rt and Rv Mean line: Rt = Rp + Rv

(b) Components of the Real Surface

The real surface differs from the nominal surface to the extent that it exhibits surface texture, flaws, and errors of form. It is considered as the linear superposition of roughness, waviness, and form with the addition of flaws. ASME B46.1 defines that:

– ***Surface texture:*** the composite of certain deviations that are typical of the real surface. It includes roughness and waviness.
– ***Roughness:*** the finer spaced irregularities of the surface texture that usually result from the inherent action of the production process or material condition. (see Fig. 3.29 in this book)
– ***Waviness:*** the more widely spaced component of the surface texture. Waviness may be caused by such factors as machine or workpiece deflections, vibration, and chatter. Roughness may be considered as superimposed on a wavy surface.
– ***Lay:*** the predominant direction of the surface pattern, ordinarily determined by the production method used (See Fig. 3.25).
– ***Error of form:*** widely spaced deviations of the real surface from the nominal surface, which are not included in surface texture. The term is applied to deviations caused by such factors as errors in machine tool ways, guides, or spindles, insecure clamping or incorrect alignment of the workpiece, or uneven wear. Out-of-flatness and out-of-roundness are typical examples.
– ***Flaws:*** unintentional, unexpected, and unwanted interruptions in the topography (three-dimensional representation of geometric surface irregularities; see ASME B46.1, Fig. 1-20) typical of a surface. However, these topographical interruptions are considered to be flaws only when agreed upon in advance by buyer and seller. If flaws are specified, the surface should be inspected by some mutually agreed upon method to determine whether flaws are present and are to be rejected or accepted prior to performing final surface roughness measurements. If specified flaws are not present, or if flaws are not specified, then interruptions in the surface topography of an engineering component may be included in roughness measurements.

(c) Definitions of Profiles

The profiles which are the curves of intersection of a normal sectioning plane with the surface (see Fig. 3.25) can be classified as below.

– ***Nominal profile:*** a profile of the nominal surface; a straight line or smooth curve (see Fig. 3.27 in this book).
– ***Real profile:*** a profile of the real surface.
– ***Measured profile:*** a representation of the real profile obtained by a measuring instrument (see Fig. 3.28). The profile is usually drawn in a *x-z* coordinate system.
– ***Form-suppressed profile:*** a modified profile obtained by various techniques to attenuate dominant form such as curvature, tilt, etc. An example of a mechanical technique involves the use of a skidded instrument (see Sect. 4).

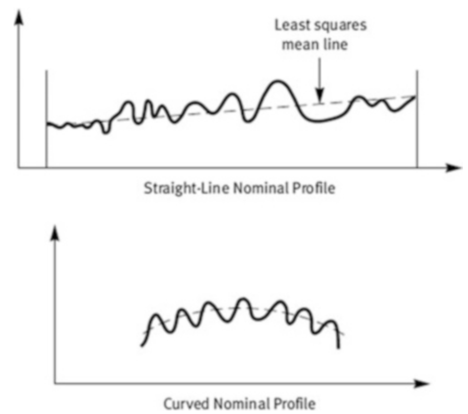


Figure 3.27 Nominal Profile (ASME B46.1, Fig. 1-4)

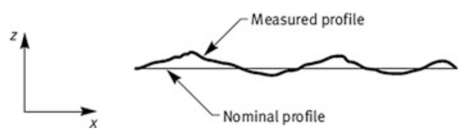


Figure 3.28 Measured Versus Nominal Profile (ASME B46.1, Fig. 1-2)

– ***Primary profile:*** a modified profile after the application of the short wavelength filter, _s (see Sect. 9). This corresponds to *P* (profile) parameters per ISO 4287.
– ***Modified profile:*** a representation of the measured profile for which various mechanisms (electrical, mechanical, optical, or digital) are used to minimize certain surface texture characteristics and emphasize others. Modified profiles differ from unmodified, measured profiles in ways that are selectable by the instrument user, usually for the purpose of distinguishing surface roughness from surface waviness. By previous definition (see ASME B46.1, para. 1-2.2), roughness irregularities are more closely spaced than waviness irregularities. Roughness can thus be distinguished from waviness in terms of spatial wavelengths along the path traced. See ASME B46.1, para. 1-3.4 for a definition of spatial wavelength. No unique spatial wavelength is defined that would distinguish roughness from waviness for all surfaces.
– ***Roughness profile:*** the modified profile obtained by filtering to attenuate the longer spatial wavelengths associated with waviness (see ASME B46.1, Fig. 1-1).
– ***Waviness profile:*** the modified profile obtained by filtering to attenuate the shorter spatial wavelengths associated.

3.4.5.2 Surface Finishing/Polishing (Brightness) for Flat-Rolled Stainless, Heat-Resisting Steel Plate, Sheet, and Strip

ASTM A480 designates the definition for classes of finishing of sheet metal surfaces as below.

No. 1 Finish (Hot-rolled, annealed, and descaled.) – This is pickled or descaled and a dull, non-reflective finish.
No. 2D Finish (Cold-rolled, dull finish.) – A smooth, non-reflective cold-rolled annealed and pickled or descaled finish. This non-directional finish is favorable for retention of lubricants in deep drawing applications.
The profiling can be performed by a surface scanning measurement technique that produces a two-dimensional graph or profile of the surface irregularities as measurement data.
Figure 3.29 shows surface roughness (Ra) produced by common production methods (source: ASME B46.1).
Figure 3.30 shows surface roughness (Ra) produced by several grinding grits and other methods (source: NACE MP, Aug, 1990).
See Sect. 2.4.5.2(d) for surface relative roughness, wall shear stress, and Moody Diagram for the internals of piping, pipelines, and tubes.

No. 2B Finish (cold-rolled, bright finish.) – A smooth, moderately reflective cold-rolled annealed and pickled or descaled finish typically produced by imparting a final light cold-rolled pass using polished rolls. This general purpose finish is more readily polished than No. 1 or 2D finishes. Product with 2B finish is normally supplied in the annealed plus lightly cold-rolled condition unless a tensile-rolled product is specified.
Bright Annealed Finish: A smooth, bright, reflective finish typically produced by cold rolling followed by annealing in a protective atmosphere so as to prevent oxidation and scaling during annealing. A bright cold-rolled finish retained by final annealing in a controlled atmosphere furnace.
No. 3 Finish (intermediate polished finish, one or both sides) – Also known as grinding, roughing, or rough grinding. A linearly textured finish that may be produced by either mechanical polishing or rolling. Average surface roughness (Ra) may generally be up to 40 micro-inch). A skilled operator can generally blend this finish. Surface roughness measurements differ with different instruments, laboratories, and operators. There may also be overlap in measurements of surface roughness for both No. 3 and No. 4 finishes.

These finishes are coarse in nature and usually are a preliminary finish applied before manufacturing. An example would be grinding gates off of castings, deburring, or removing excess weld material. It is coarse in appearance and applied by using 36–100 grit abrasive. The polished finish of stainless steel strip is also available in polished finishes such as No. 3 and No. 4.

When the finish is specified as No. 3, the material is polished to a uniform 60–80 grit.

No. 4 Finish (General purpose polished finish, one or both sides) – A linearly textured finish that may be produced by either mechanical polishing or rolling. Average surface roughness (Ra) may generally be up to 25 micro-inch. A skilled operator can generally blend this finish. Surface roughness measurements differ with different instruments, laboratories, and operators. There may also be overlap in measurements of surface roughness for both No. 3 and No. 4 finishes. The polished finish of stainless steel strip is also available in polished finishes such as No. 3 and No. 4.
Architectural Finish (directional or satin finish) – Also known as brushed. A #4 architectural finish is characterized by fine polishing grit lines that are uniform and directional in appearance. It is produced by polishing the metal with a 120–180 grit belt or wheel finish and then softened with an 80–120 grit greaseless compound or a medium non-woven abrasive belt or pad.
Dairy or Sanitary Finish **–** This finish is commonly used for the medical and food industry and almost exclusively used on stainless steel. This finish is much finer than a #4 architectural finish. One takes great care to remove any surface defects in the metal, like pits, that could

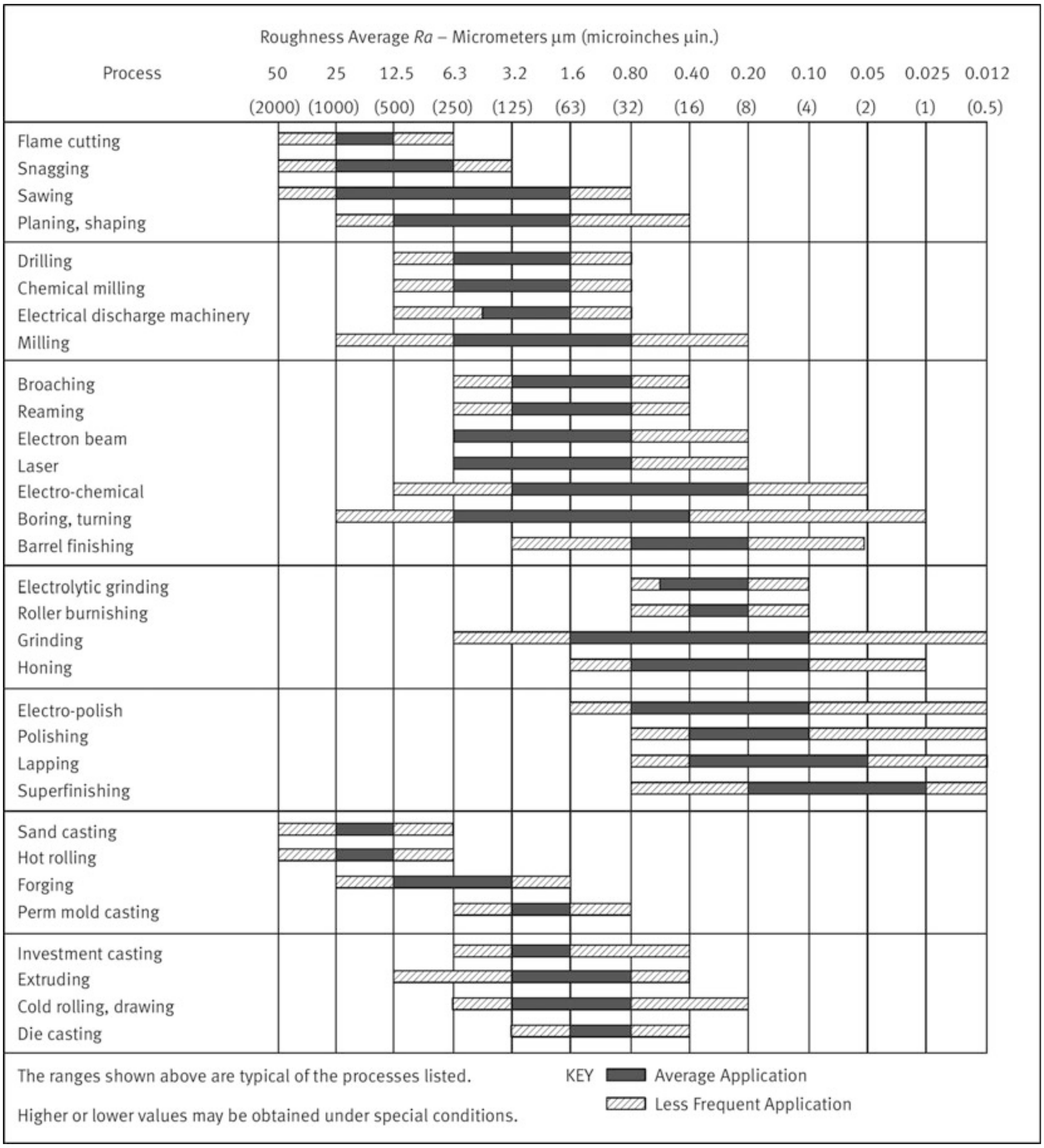


Figure 3.29 Surface Roughness (Ra) Produced by Common Production Methods (source: ASTM B46.1)

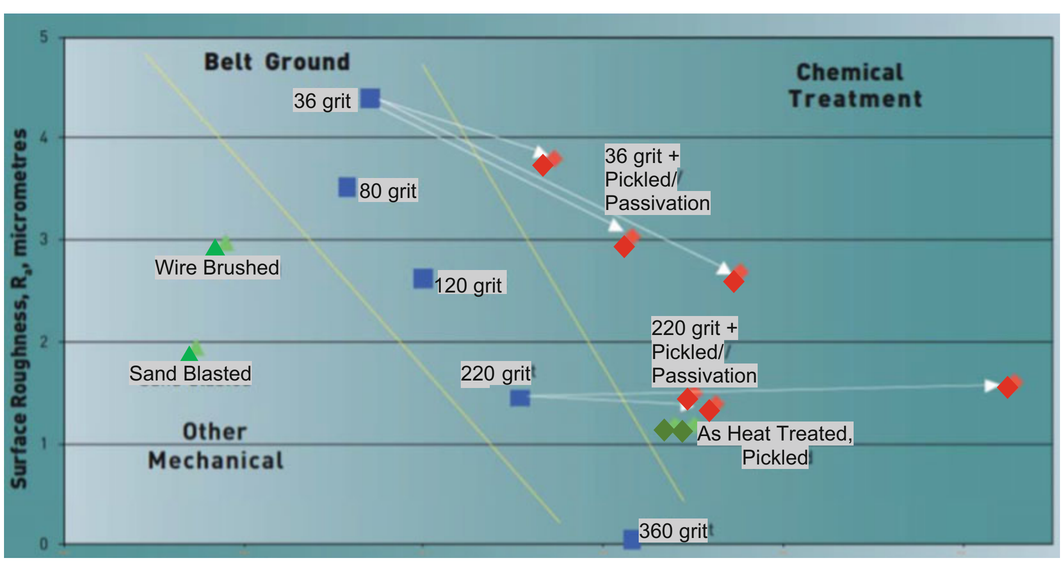


Figure 3.30 Surface Roughness (Ra) Produced by Grinding and Other Methods. (Source: NACE MP, Aug, 1990)

allow bacteria to grow. A #4 dairy or sanitary finish is produced by polishing with a 180–240 grit belt or wheel finish softened with 120–240 grit greaseless compound or a fine non-woven abrasive belt or pad.

No. 6 Finish (dull satin finish, tampico brushed, one or both sides) – This finish has a soft, satin appearance typically produced by tampico brushing a No. 4 finish. This finish is produced by polishing with a 220–280 grit belt or wheel softened with a 220–230 greaseless compound or very fine non-woven abrasive belt or pad. Polishing lines will be soft and less reflective than a #4 architectural finish.

No. 7 Finish (high luster finish-high degree of reflectivity) – This finish is produced by polishing with a 280–320 belt or wheel and sisal buffing with a cut and color compound. This is a semi-bright finish that will still have some polishing lines, but they will be very dull. It is produced by buffing a finely ground surface, but the grit lines are not removed. It is chiefly used for architectural or ornamental purposes. CS and iron are commonly polished to No. 7 finish before chrome plating. This finish can be made bright by color buffing with coloring compound and a cotton buff. This is commonly applied to keep polishing costs down when a part needs to be shiny but not flawless.

No. 8 Finish (mirror finish) – This is a highly reflective, smooth finish typically produced by polishing with successively finer grit abrasives, then buffing. Typically, very faint buff of polish lines may still be visible on the final product. Blending after part assembly may be done with buffing. This finish is produced by polishing with at least a 320 grit belt or wheel finish. Care will be taken in making sure all surface defects are removed. The part is sisal buffed and then color buffed to achieve a mirror finish. The quality of this finish is dependent on the quality of the metal being polished. Some alloys of steel and aluminum cannot be brought to a mirror finish. Castings that have slag or pits will also be difficult, if not impossible, to polish to a No. 8.

TR Finish **–** The finish resulting from the cold rolling of an annealed and descaled or bright annealed product to obtain mechanical properties higher than that of the annealed condition. Appearance will vary depending upon the starting finish, amount of cold work, and the alloy.

Architectural Finishes (called as No. 5 finish) – Sometimes described as a No. 5 finish, these are a separate category and may be negotiated between buyer and seller, as there are many techniques and finish variations available throughout the world.

Bright Annealed Finish **–** A bright cold-rolled finish retained by final annealing in a controlled atmosphere furnace.

3.4.5.3 Conversion/Comparison of Standards-Surface Finishing/Polishing

Table 3.39 shows the conversion/comparison table of several standards for surface finish.

Table 3.39 Comparison chart of surface finish standards

Grit No.	USA Finish#	Common Name	Ra µinch	E/P Range Ra, µinch	Ra, µm	Rmax µinch	Rmax µm	Approx RMS µinch	ISO No.	ASTM STD Ra, µm	Japanese STD
			2000		50	7875	200		N12		
			1000		25	3940	100		N11		
			500		12.5	1988	50		N10		
60	1	Mill Plate	250	50 max.	6.3	985	25		N9		
			125		3.2	492	12.5		N8		
80	2	Satin Sheet	70 max. 40–60					80			
			63		1.60		6.3		N7		
00 to 120	3		52					58			
120	4	Commercial #4	40–60 typ.								
150	4	3A Sanitary Finish	42 max. 30–35					42.47		45 max.	
		ANSI #4	32		0.8	126	3.2		N6		
180	4	Sanitary Finish	20–30	15–20				34		25 max.	Buff #100
200 to 220	4	Biotech Finish	20–25								
240	6		15–20	10–15				17		8–20	
			16		0.40	63	1.60	17 max.	N5	6–15	
320	7		8–12					14			
			12		0.30	59	1.50	13–14			Buff #200
			8		0.20	31	0.80	9	N4		Buff #300
400	8	Mirror Finish	4–8								
500	8	Super Mirror Finish	<4 3–8								
500	8	Super Mirror Finish	4		0.10	16	0.40	4–10	N3		Buff #400 (approx.)
			2		0.050	8	0.20		N2		
			1		0.025	4	0.10		N1		

Source: JVNW Inc. technical report, 2004

Reference Standards for Surface Finish

ASME B46.1 Surface Texture (Surface Roughness, Waviness, and Lay)

ISO 1302 Geometrical Product Specifications (GPS) – Indication of surface texture in technical product documentation

ISO 4287 Geometrical Product Specifications (GPS) – Surface Texture: Profile Method – Terms, Definitions and Surface Texture Parameters

ASTM A480 General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip – para.11

3.4.5.4 Roughness and Serration of the Surface of Flange Gasket Contact Face

The gasket contact surfaces have some roughness and serration to avoid the gasket sliding and leakage, the requirements are shown in Table 3.40. Serration is measured by number (N) of machined waives per width as seen in Fig. 3.31. Concentric serration grooves have more leakage resistance than that of spiral serration groves so that concentric type is recommended for lethal or smaller molecular gas services (e.g., H_2, He, etc.).

Table 3.41 shows the roughness requirements for gasket contact faces of H/EXs in API 660. Table 3.42 shows the conversion of the roughness values for machined faces.

Table 3.40 Roughness and serration requirements for flange gasket contact face

Flange Face Type	Required Roughness[3]	Remark[2]
Ring Joint	≤1.6 μm (63 μ inch RMS)	–
Tongue and Groove and Small Male and Female.	≤3.2 μm (125 μ inch RMS)	–
Other Flange Facings	3.2 to 6.3 μm (125 to 250 μ inch RMS)	A result of either a serrated concentric or serrated spiral finish

Notes: (Sources: ASME B16.5 and B16.47)
[1]Ra Standard: Average Roughness – See ASTM B46.1 (See Figs. 3.27 and 3.28 in this book)
[2]Serration: The cutting tool employed should have an approximate 1.5 mm (0.06 in.) or larger radius, and there should be from 1.8 grooves/mm through 2.2 grooves/mm (45 grooves/in. through 55 grooves/inch)
[3]API 6A, Type 6BX RTJ flanges: All 23° surfaces on ring grooves shall have a surface finish no rougher than 0.8 μm *Ra* (32 μin RMS)
API 6A, Type 6B flanges for R and RX gasket: All 23° surfaces on ring grooves shall have a surface finish no rougher than 1.6 μm *Ra* (64 μin RMS)

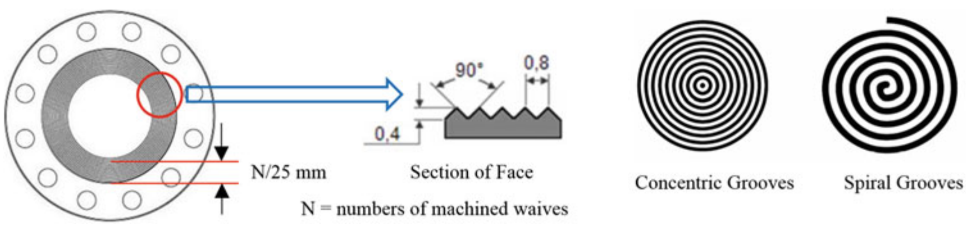


Figure 3.31 Serration for flange gasket contact face

Table 3.41 Roughness requirements for gasket contact faces of H/EXs (API 660)

Gasket Type	Required Roughness of Flange Face
Solid flat metal gaskets	≤1.6 μm (63 μinch)
Double-jacketed gaskets	1.6–3.2 μm (63 to 125 μinch)
Spiral wound gaskets	3.2–6.3 μm (125 to 250 μinch)
Serrated gaskets or corrugated metal gaskets with soft gasket-seal facing	

Note: Ra Standard – Average Roughness (see ASTM B46.1)

Table 3.42 Roughness conversion table of machined faces

Ra, μm (μinch)	RMS	CLA	Rt	N	Cutoff Length, mm (inch)
0.025 (1)	1.1	1	0.3	1	0.08 (0.003)
0.05 (2)	2.2	2	0.5	2	0.25 (0.01)
0.1 (4)	4.4	4	0.8	3	0.25 (0.01)
0.2 (8)	8.8	8	1.2	4	0.25 (0.01)
0.4 (16)	17.6	16	2.0	5	0.25 (0.01)
0.8 (32)	32.5	32	4.0	6	0.8 (0.03)
1.6 (63)	64.3	63	8.0	7	0.8 (0.03)
3.2 (125)	137.5	125	13	8	2.5 (0.1)
6.3 (250)	275	250	25	9	2.5 (0.1)
12.5 (500)	550	500	50	10	2.5 (0.1)
25 (1000)	1100	1000	100	11	8.0 (0.3)
50 (2000)	2200	2000	200	12	8.0 (0.3)

CLA Center Line Average (μ inch), *Cutoff Length* Length required for sample, *N* New ISO Grade (scale number), *Ra* Roughness Average, *RMS* Root Mean Square (μ inch), *Rt* Roughness Total

3.4.6 Thermal Spray Coating (TSC)

Thermal spraying techniques are spray coating processes by melted materials on the substrate. The substrate is heated by electrical (plasma or arc) or chemical means (combustion flame). Thermal spraying can provide thick coatings (thickness is 20 μm to several mm, depending on the process and feedstock), over a large area at high deposition rate as compared to other coating processes such as electroplating, physical and chemical vapor deposition. Here are introduced for chemical means (combustion flame) as shown in Table 3.43. Table 3.44 shows the characteristics of TSA (Thermal Spray Aluminum) coating. See Sects. 2.1.7.7 hardfacing and 2.4.5.3 erosion prevention for electrical (plasma or arc) thermal spray coating.

Table 3.43 Requirements for each step of thermal spray coating[(1)]

Step	Hold Points	Requirements	Acceptance Tests
1. Preparation	Proper Feedstock	Per contact requirement	AWS C2.25/(M) or ASTM B833
	Ambient Condition	Temperature of the substrate; min. 3 °C (5 °F) higher than the dew point	ASTM E337
	Cleanliness of Abrasive	SSPC-AB 1,2,3 as applicable	SSPC-AB 1,2, or 3 as applicable
	Cleanliness of Compressed Air	Free of contaminant	ASTM D4285
2. Surface Preparation of Substrate	Surface Cleanliness	NACE No.2/SSPC-SP 10 as a minimum NACE No.1/SSPC-SP 5 for immersion service	NACE No.2/SSPC-SP 10 para.2 NACE No.1/SSPC-SP 5
	Water Soluble Contaminants	Per contract requirement	SSPC-Guide 15
	Surface Profile	65–125 μm (2.5–5.0 mil)	ASTM D4417 (Method B or C) per SSPC-PA 17
3. Thermal Spray Coating	Coating Thickness (min. & max.)	Per contract requirement	SSPC-PA 2-inspection level 4
	Applied Coating Appearance	Smooth and uniform, No blisters, cracks, loose particles, or exposed steel	Per job spec.
	Tensile Adhesion	Zn: $\geq$ 500 psi (3.35 MPa) Al: $\geq$ 1000 psi (6.89 MPa) 85Zn/15Al: $\geq$ 700 psi (4.83 MPa)	ASTM D4541 (method C,D,E, or F) per job spec.

Source: NACE No.12/AWS C2.23 modified
Note [(1)] See Sect. 3.4.3 for SSPC classes and NACE No.12/AWS C2.23 for more details
Commentary Notes
ASTM B833 Standard Specification for Zinc and Zinc Alloy Wire for Thermal Spraying
ASTM C633 TM for Adhesion or Cohesion Strength of Thermal Spray Coating
ASTM D1210 TM for Fineness of Dispersion of pigment – Vehicle Systems by Hegman-Type Gauge
ASTM D4285 TM for Indicating Oil or Water in Compressed Air
ASTM D4417 TM for Field Measurement of Surface Profile of Blast Cleaned Steel
ASTM D4541 TM for Pull-Off Strength of Coating Using Portable Adhesion Testers
ASTM D4940 TM for Conductimetric Analysis of Water Soluble Ionic Contamination of Blasting Abrasives
ASTM E337 TM for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
AWS C2.18 Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites

Table 3.44 Characteristics of thermal spray aluminum (TSA)

Advantages	Disadvantages or Cautions
– Long life times (>> 10 yrs) with minimum need for maintenance,	– High initial costs compared with painting (i.e., higher standard of surface preparation required and more expensive application),
– Resistance to mechanical damage,	– Very expensive repair work (e.g., after the installation of new welded supports),
– No health hazard from solvents or other organic substances,	– Pretreatment to Sa 3 (SSPC SP-5) and high surface roughness/sharpness normally required,
– No drying/curing times after application,	– Possible chronic strain injury to manual operators,
– Coatings exposed to dry atmospheres can withstand temperatures up to the melting point for aluminum (660 °C/1120 °F),	– High level of personal protection required (against noise, dust, ultraviolet/infrared radiation, ozone, and nitrogen oxide gases),
– Coating has sacrificial anode effect on steel in marine environments, which means the coating will corrode in preference to the steel substrate. Hence, any small areas of bare steel will receive limited cathodic protection and be protected against corrosion.	– Signs of surface rust can occur when coating thickness is less than approximately 150 μm, and the process creates large amounts of aluminum and aluminum oxide dust, which can be explosive if not handled properly due to its reactive nature and small particle size.
– The application process can be mechanized.	– Aluminum will be anode against base metal (cathode), and then greatly to be corroded once the coating is locally failed.

3.4.7 Repair of Galvanized Steel

See Sect. 2.6.2.6, general note r and s for cautions of several plating. Any damage to galvanizing should be repaired in accordance with ASTM A780. In addition, the following guidelines are recommended.

1. Before repair of damaged galvanized coating, the work surface needs to be very clean. If there is any oxidation or other buildup in the repair area, it must first be cleaned by grinding or wire brushing. Any material that may contain a secondary surface coating such as phosphate, chromate, oily, or other coatings over the galvanizing may require solvent cleaning.
2. When surface defects exceed 2% of originally galvanized area, the defects should be repaired by re-dipping the member in the zinc bath.
3. Cold repair using an organic zinc-rich coating is allowed if the total damaged area is less than 1% of the total coated area of the parts being repaired and no single repair is greater than 1300 mm^2 (2 in^2) or 300 mm (12 in.) long. The dry film thickness should be 0.05 to 0.08 mm (2 to 3 mils) and contain a minimum of 65 wt% zinc dust.
4. Hot repair should be made in the shop if any of the following conditions exist:
   (a) Total damaged area is greater than 1%, but less than 2%, of the total coated area of the member being repaired.
   (b) Any single repair is at least 1300 mm^2 (2 in^2) in area.
   (c) Any single repair is 300 mm (12 in.) long or more.
5. Hot repair should be made using zinc alloy powder-manufactured for the repair of galvanized steel.
6. Galvanized steel that has been rejected should be stripped, re-galvanized, and submitted again for inspection.
7. Correction of excessive warpage (that exceeds the limits in ASTM A6) should be by press straightening when possible. The application of localized heating to straighten should be approved by the responsible engineer.
8. If galvanized tension control bolts are used, all bare steel surfaces (i.e., bolt ends) should be repair galvanized.

3.5 Materials Protection During Transportation or Storage

3.5.1 Rust Prevention

During fabrication, transportation, construction, and mothballing of industrial facilities, much of metal loss may be expected due to corrosion (rust) of iron and steel. When exposed to moisture and oxygen, iron and steel will react, forming an oxide. This oxide does not firmly adhere to the surface of the metal and will flake off, causing pitting. Extensive pitting eventually results in weakness and disintegration of the metal, leading to failure. Traditionally the external surfaces are well controlled the corrosion prevention by coating; however, the prevention of internals surfaces may have been disregarded. Therefore, the internal surfaces of equipment and piping should be prevented accordingly.

Obviously, because of the involvement with water, rust occurs much more rapidly in moist conditions. However, there are a few other factors that determine the rate of corrosion. One example is the presence of salt. Dissolved salt increases the conductivity of the aqueous solution formed at the surface of the metal and enhances the rate of electrochemical corrosion. Another factor is heat. The higher the temperature is, the higher the corrosion rate will be.

Corrosion inhibitors are available in many forms with various functions to protect equipment. Liquid-phase corrosion inhibitors ensure surfaces covered by the liquid will be protected by the strong additives in the fluid. Vapor-phase protection may be included with the liquid-phase protection or used in dry reservoirs. It works by filling the headspace with a vapor that prevents corrosion. Surface coatings protect the systems by adhering to the surface. Generally, surface coatings repel water from the surface and include an additive to reduce corrosion at the surface.

The best way to stop rust and corrosion is not to allow the metal to come in contact with water, oxygen, or acid. In essence, this is exactly what rust and corrosion inhibitors do. These additives are typically compounds that have a high polar attraction towards metal surfaces. They chemically bond to the metal surface, forming a protective film over the underlying metal. This film acts as a barrier that does not physically allow the metal to come in contact with anything that could promote corrosion. Some popular compounds being used are amine succinates and alkaline earth sulfonates. Equipment suppliers may select an equivalent solvent which has the similar features in Tables 3.45 through 3.48 if required in the purchase order. See MIL-STD-2073, JIS K-2246 or VCI supplier's data for more details. See NACE Paper 10147 and 03485 for several test methods and their application standards in VCI quality.

3.5.2 Packing and Shipping for Oversea Transportation

Packing and shipping for oversea transportation is very important because the metal surfaces can be readily impaired during/after transportation as seen in Fig. 3.32. Hence specific prevention should be provided even though codes and standards do not designate the requirements.

Here are the most common requirements (recommendations) of project specifications of end-users.

Table 3.45 Rust preventive oil classification (foreign standard)

Classification	JIS K2246 Symbol[(1)]	Features
Fingerprint removal type rust preventive oil	NP-0	It coats metal products at ordinary temperature. It forms extremely thin oil film and has capability of removing fingerprints.
Solvent dilution type rust preventive oil	NP-1	It coats metal products at ordinary temperature. It forms thick hard film. It is suitable for the outdoor storage of metal products. It is often not required to wrap them with greaseproofed barrier materials.
Solvent dilution type rust preventive oil	NP-2	It coats metal products at ordinary temperature. It forms thick soft film. It applies to metal products or the like stored indoors required for easy removal. It is, as a rule, required to wrap the metal products with greaseproofed barrier materials.
Volatile corrosion inhibitor	NP-18-1[(2)]	It is used at ordinary temperature. It is powdery and has volatile rust preventive quality.
Volatile corrosion Inhibitor treated paper	NP-18-2[(2)]	It is used at ordinary temperature. It is the paper coated with volatile corrosion inhibitor or infiltrated therewith.
Solvent dilution type rust preventive oil	NP-19	It coats metal products at ordinary temperature. It forms hard, transparent, dry film. It is suitable for the outdoor storage of metal products or the like. It is often not required to wrap them with greaseproof barrier materials.
Volatile rust preventive oil	NP-20 −1 or 2	It coats metal products at ordinary temperature. It has especially light lubricating oil as basic oil, forms very thin oily film and has volatile rust preventive performance for neutralization of acid and performance for substitution of water.

Notes:
[(1)]Refer to Tables 3.46, 3.47, and 3.48 for each symbol. See JIS K2246 latest version for more details
[(2)]NP-18-1 and 2 (Shell VPI 260 or EQ.): These symbols are based on the old version. For the actual practice with additional symbols and classes, the current version of JIS K2246 should be used

Table 3.46 Characteristic and quality of the fingerprints removal type rust preventive oil

Item \ Symbol		NP-0
Flashing point, °C		38 and over
Kinematic viscosity, mm^2/s {cSt} (at 40.0 °C)		12 and below
Separation stability		No phase change or separation are permissible
Fingerprints removability		No fingerprints & rust are permissible
Film removability	After moistening	The film must be removed
Corrosivity	Mass change mg/cm^2	Al ± 0.1 Cu ± 0.1 Cu-Zn ±1.0 Pb ±45.0 Zn ± 3.0
Rust Preventive Characteristics (for No Rust)	Moistened	min. 168 Hours

Table 3.47 Characteristic and quality of the solvent dilution type rust preventive oil

Item \ Symbol		NP-1	NP-2	NP-19
Flashing point, °C		38 and over		
Drying characteristics		No cohesive condition	Soft condition	Finger touch drying condition (4 hours) no cohesive condition (24 hours)
Flow point, °C		80 and over	–	80 and over
Cold temperature cohesive characteristics		No cohesion of film is permissible.		
Sprayability		Film is continuous.		
Separation stability		No phase change or separation are permissible.		
Film removability	After anti-seasoning	Film not removed 30 times	–	–
	After packing	–	Film not removed to 15 times	Film not removed to 15 times
Transparent characteristics		–	–	Stamp to be seen.
Corrosivity	Mass change, mg/cm^2	Cu ±0.2		Al ±0.2
		Zn ±7.5		Cd ±5.0
		Mg ±0.5		No luster is faded.
		(Zn + Cu) ± 1.0		
Film thickness, μm		100 and below	50 and below	50 and below
Rust preventive Characteristics (for No Rust)	Moistened	–	min. 720 hours	min. 720 hours
	After sprayed chloric water	min. 336 hours	min. 168 hours	min. 336 hours
	After anti-seasoning	min. 600 hours	–	–
	After packing	–	min. 12 months	min. 12 months

Table 3.48 Characteristic and quality of volatile rust preventive oil

Item \ Symbol		NP-20-1	NP-20-2
Flashing point, °C		115 and over	120 and over
Pour point, °C		−25 and below	−12.5 and below
Kinematic mm^2/s	100 °C	–	8.50 ~ 12.98
Viscosity {cSt}	40 °C	10 and above	95 ~ 125
Volatile components, %		15 and below	5 and below
Viscosity change, %		−5 ~ 20	
Settling value, ml		0.05 and below	
Acid neutralization characteristics		No rust, skin rough & contamination are permissible.	
Hydraulic substitution characteristics			
Solubility in hydrocarbon permissible.		No phase change or separation is permissible.	
Corrosivity	Mass change, mg/cm^2	Steel: ±0.1 Cu: ±1.0 Al: ±0.1	
Rust preventive Characteristics (for No Rust)	Moistened	min 200 Hours	
	Volatile rust preventive property	min. 12 months	
	Volatile rust preventive property after wetting		
	Volatile		

(a) Tubes just opened from packing box (b) Rusted stainless casting alloy tube surfaces

Figure 3.32 Rusted stainless steel tube surfaces after oversea transportation

3.5.2.1 Preparation

(a) Equipment should be free of loose scale, dirt, and foreign material.
(b) Liquid used for testing or cleaning should be completely drained and dried.
(c) High alloy vessels should be blown dry with ambient temperature air, only after all standing water has been removed.
(d) All nozzle, manhole, vent, and connection openings should be blanked, plugged, or capped to prevent the entry of moisture.
(e) Protection for flange faces, threaded connections, weld bevels, etc. should be as follows:
   1. All machined and threaded surfaces of CS and ferritic alloy steel materials, except weld bevels, should be coated with rust preventive coating approved by the purchaser.
   2. Weld bevels should be free of dirt, oil, grease, scale, rust, and other foreign materials. Weld bevels of CS and ferritic alloy steel materials should be coated, after cleaning, on the inside and outside for a distance of approximately 75 mm (3 in) from the end of the weld bevel with a weldable rust preventive approved by the purchaser.
   3. All weld bevels should be closed with metal or plastic caps to prevent damage or entrance of foreign materials.
   4. Threaded openings, if any, should be plugged with round headed threaded plugs of the same material as the connected part and sealed with polytetrafluoroethylene (PTFE) tape thread sealant or joint compound.
   5. Flanged openings should be protected and made waterproof with plastic or plywood [20 mm (3/4 in.) thick for openings NPS 18 in. in diameter and greater, otherwise 10 mm (3/8 in.) thick] flange covers or full size 3 mm (1/8 in.) or 10 gauge minimum thickness steel covers and 3 mm (1/8 in.) thick rubber gaskets between the flange and cover.
      (a) When wood flange covers are used there should be a plastic interface between the flange face and plywood cover.
      (b) If steel flange covers are furnished, they should be secured with appropriately sized machine bolts per c. or d. below:
      (c) For flanges having 4 to 28 bolt holes, a bolt should be placed in at least every other hole, with a minimum of 4 bolts.
      (d) For flanges having more than 28 bolt holes, bolts should be placed in at least every fourth bolt hole.

(f) Manways should have blind flange, gasket, and pressure bolting of type and material specified on the vessel drawings.

(g) Telltale holes in reinforcing pads on ferritic vessels should be plugged with heavy grease, if they will not be fitted with vent lines that protrude through the insulation.
(h) Equipment fabricated with ASS should be protected from exposure to salt water, salt spray, and chlorides during ocean or over the road shipment. The external protective coatings used against such exposure should be subject to approval. If the surface is applicable to CUI protection, the metal surfaces should be coated per NACE SP0198 and/or API RP583 at shop before the transportation. If the long pressure vessel is oversea-shipped as segment (multi-pieces), the shell length should have sufficient cutting margin, and a protected steel cover should be continuously welded on the end of each segment to avoid internal rust and contamination.
(i) Equipment that will undergo ocean shipment should have a preparation and shipping plan submitted for approval. For H/EX, nitrogen charging which is dew point-controlled is recommended. If nitrogen is used, the equipment should be clearly marked identifying that nitrogen is present. The method and location of such marking should be agreed upon between manufacturer and purchaser.

3.5.2.2 Packing and Shipping

(a) Equipment or materials that contain or are coated with any of the following should be prominently tagged at openings to indicate nature of contents and precautions for shipping, storage, and handling:
  – Insulating oils
  – Corrosion inhibitors
  – Antifreeze solutions
  – Desiccants
  – Chemical substances
  – Hydrocarbon substances
(b) Material Safety Data Sheets (MSDS) should fully comply with regulations for MSDS preparation specified by entity that has jurisdiction and should include a statement that the substance is considered hazardous by regulation.
(c) If any products are exempt from regulation, a statement to that effect should be included.
(d) Before shipment, MSDSs should be forwarded to the receiving facility.
(e) At shipment, MSDS in protective envelopes should be affixed to the outside of the shipment.
(f) The supplier should be responsible for suitably packaging each vessel or component and adequately supporting and securing all vessel internals to protect them from damage or loss during handling and shipment in accordance with the purchase order and the following requirements:
  1. All material and methods of packing should conform to the specifications referenced in the purchase order.
  2. Packages should include lifting lugs or designated lifting points.
(g) All tools and machines which are using for shipping and transportation should be not be directly contacted with the equipment unless otherwise corrosion protected.
(h) The supplier should provide any special protection or packaging and details of any storage, shelf life, or maintenance instructions which are not within the scope of the purchase order but which pertain to the manufacturer's guarantee or are otherwise necessary for protection of the vessel.
(i) Unless otherwise agreed, all packaging and protection should be suitable for outdoor storage for a minimum period of 12 months.

3.5.2.3 Marking

(a) Stamping of all materials should be with "low stress" steel stamps having round or "U" shaped cross sections or with "interrupted-dot" die stamps.
(b) Marking paint or water insoluble ink for use on austenitic and high-nickel alloy steels should not contain any deleterious substances (e.g., metallic pigments, sulfur or chlorides) which would be harmful to these materials at ambient or elevated temperatures. The manufacturer should submit analysis of marking material to the purchaser. The submittal should demonstrate (by chemical analysis and history of use) that the material meets these requirements.
(c) Internals, clips, lugs, or other similar attachments that are removable and are to be assembled by others should be marked with piece numbers or identification in assembly and match-marked.
(d) For pressure vessels that have received, the following sign should be painted on the vessel after heat treatment. The sign should be clearly marked in approximately 150 mm (6 in.) high letters in white paint unless otherwise required.
  "POSTWELD HEAT TREATED...NO WELDING OR BURNING PERMITTED"
  1. On vertical vessels, this sign should be located on two opposite sides near the bottom tangent line and repeated at approximately each 3 m (10 ft) of height, but rotated 90 degrees.
  2. On horizontal vessels, the sign should be located on both sides near the horizontal centerline.
(e) The North and East orientations should be center-punched on the outside of each vertical vessel approximately 150 mm (6 in.) above the bottom tangent line and 150 mm (6 in.) below the top tangent line. The punch marks should be circled with white paint unless otherwise required.
(f) All temporary support components required for maintaining vessel roundness or shipping should be painted yellow and marked:
  "SHIPPING/FABRICATION DEVICE. REMOVE BEFORE UNIT STARTUP".
(g) The center of gravity of the vessel should be marked in white paint unless otherwise required.
(h) When specified, a certified weight should be obtained for major vessels involving heavy lifts or other lifts to be made in congested or critical areas, as determined by project site-specific lifting and erection policies.

Table 3.49 Rust removal methods on stainless steels/alloys

Method	Comments	Effectiveness
1. SS Wire Brushing	Often used for cleaning welds. If used for heat tint removal can deform surface and may lead to surface staining unless used in conjunction with a more effective treatment.	Least
2. Grinding by aluminum oxide discs or flapper wheels)	Do not smear or overheat surfaces by worm abrasives or excessive pressure.	
3. Blasting (glass bead, garnet, walnut shells-no free iron) at dry condition	Avoid CS shot or blast media contaminated with iron.	
4. Chemical descaling per ASTM A380, Sect. 5.2.	Immersion, circulation, spray, or paste methods are available. Use 10% nitric acid-2% HF acid solution. Rinse with clean water. Confirm removal with ferroxyl test per ASTM B912, Appendix X3. Remove all traces of ferroxyl test solution with clean water or diluted nitric acid or acetic acid solution.	
5. Electro-polishing per ASTM B912	Site or shop treatment	Best

3.5.2.4 Removal of Dusts on Metal Surfaces

Once the metal surfaces are dusted as seen in Fig. 3.32 and the end-user cannot agree the dusted condition for the performance of plant operation, the effective dust removal is required by one or multiple methods in Table 3.49.

3.5.3 Mothballing

The guideline for mothballing provides specification for decommissioning and preservation of equipment including instrumentation and electrical distribution systems that will be idle, out of service or abandoned for various durations. It also addresses pre-commissioning and mechanical integrity processes (inspection and testing, etc.) for safely returning idle equipment to operating status. Normally the mothballing specification should be applied when the equipment is to be out of service for 6 months or more. However, the specification may also be applicable for short term (1 to 6 months) idle equipment exposed in the severe weather/environment condition.

The following requirements from shutdown to storage should be performed as general guidelines.

1. Temperature gradients and depressurizing rates should be considered for each piece of equipment being shutdown. When hydrogen is present, heavy equipment walls must be cooled and degassed slowly to reduce the possibility of overpressure in laminations and voids within the metal. Similarly, when equipment containing a lining or protective coating is depressurized, a reasonable depressurizing rate reduces the likelihood of bulging and blistering caused by unequalized pressure behind these barriers.
2. Some materials become embrittled and are highly susceptible to cracking during exposure to normal ambient temperatures. This susceptibility to brittleness is especially serious in colder climates when temperatures are low. If impact test results are not available, but equipment materials are likely to have high transition (behavior change from ductile to brittle) temperatures in the ambient temperature range, heat must be supplied during periods of special stress, such as maintenance work, hydrostatic testing, and the like. In cold climates additional protective measures, such as draining all low points and cleaning, must be taken to prevent freezing or other damage.
3. Shutdown environments, which may also involve deposits accumulated during operation, can be far more hostile to equipment construction materials than the process environment. Some deposits can be removed most effectively during shutdown or before the equipment is opened. Other deposits should be removed as soon as the equipment is opened. Consideration should be given to the immediate removal of all harmful deposits, such as pyrophoric iron sulfide and other corrosive materials, from opened equipment. Equipment in acid services should be washed and completely drained. Such equipment may be further protected by washing with a neutralizing solution.
4. Austenitic stainless steels (ASS) are subject to stress corrosion cracking and pitting when exposed to certain aqueous or ionic solutions. Deposits of chlorides and/or sulfide scales may form during the process operations. If these deposits are not washed away or neutralized before they are exposed to moisture and oxygen, serious cracking or pitting can be caused by the chloride solutions or weak sulfur (polythionic) acids. (See NACE SP0170, Protection of ASS in Refineries against SCC by Use of Neutralizing Solutions during Shutdown for details of these corrosion mechanisms.)
5. ASS equipment that need not be opened or that cannot be easily drained and purged (such as vertical U-bend heater tubes) can be purged most easily with nitrogen, which expels moisture and oxygen. In addition, such equipment should be kept warm and stored under positive nitrogen pressure for the duration of the shutdown. Before startup, austenitic stainless steel equipment must be tested with a compatible medium such as low chloride water.
6. Sulfur deposits, which can occur in heater and boiler convection sections, breechings, and stacks may become actively corrosion during shutdown periods. These areas should be thoroughly cleaned and maintained at temperatures that will exclude moisture precipitation.
7. Moisture is the most common cause of deterioration in idle equipment. When moisture combines with oxygen, serious pitting, rusting, and microbiological induced corrosion (MIC) can result. Hence equipment removed from service should be completely drained,

cleaned, isolated, and properly protected. During the preservative preparations, the most important factor is to establish a barrier between the equipment, moisture, and oxygen.

8. The continued effectiveness of even properly applied protection can be ensured only by a program of periodic inspection and planned maintenance.
9. In most cases, equipment may be stored in a sealed room or constructed containers with desiccants. When possible, desiccants should be used in such a manner that there is no need to open the package (barrier) to check the indicator.
10. Properly mothballed and stored equipment can remain in its original condition for a long period of time (6–8 years), with a well-planned maintenance program.
11. Heavy equipment should be stored on proper dunnage and/or a suitable foundation to ensure the equipment does not sink over a long period of time.
12. Stored mothballed equipment should be plainly identified on the outside of the package, for easy identification without the need for opening or handling.
13. Storage areas should have proper drainage or run off and enough room between equipment for periodic maintenance.
14. Equipment to be stored outside should be elevated above the normal maximum snow depth.
15. Protective coverings should be constructed to allow free air circulation, and not sealed against the ground.
16. Powdered volatile corrosion inhibitors (VCI) are a more efficient means of conservation of vessels and columns than nitrogen or inhibited oil or gas.
17. VCI products are almost entirely nontoxic, biodegradable, nonflammable, and nonexplosive.
18. All safety precautions should be considered the followings. See the company specifications and/or references below for more information.
    (a) Toxicity is very important in selection of preservation material and methods of application. Therefore, equipment should be well vented and normal precautions taken against fires during applications of preservatives.
    (b) All mothballed, sealed vessels should be vented and drained for a minimum of 24 hours before being moved from their storage location.
    (c) Equipment should not be shipped or erected in a mothballed condition.
    (d) Hydrocarbons should never be used in protective coatings of compressors in oxygen (or almost exclusively oxygen) service. For compressors that merely handle normal amounts of oxygen, thorough removal of hydrocarbons before a return to service is extremely important.

References

– MTI 34 Guidelines for the Mothballing of Process Plants
– MIL–B–121–F Barrier Material, Greaseproofed, Waterproofed, Flexible
– MIL–G–10924F Grease, Automotive and Artillery
– MIL–L–21260D Lubricating Oil, Internal Combustion Engine, Preservative and Break-In
– API Guide for Inspection of Refinery Equipment, Chapter XVIII-Protection of Idle Equipment
– NACE SP0170 Protection of ASS and Other Austenitic Alloys from Polythionic Acid Stress Corrosion Cracking during Shutdown of Refinery Equipment

3.5.4 Winterization

The main purpose of winterization is to protect facilities from ambient temperatures that could cause congealing or freezing of contents, interfere with operation, or cause damage to facilities, also to prevent any brittle failure of materials which was not considered on the facilities' design. The most critical factors are the field weather condition, process characteristics, and plant operating plan.

3.5.4.1 The Oil and Gas Plants Should be Considered the Following Conditions for Winterization

(a) Operation and startup under severe winter conditions
   1. Solidification or congealing of viscous fluids.
   2. Condensation that may lead to corrosive compounds. The facilities should be adequately dried to maintain a water or hydrocarbon dew point at least 10 °C (18 °F) below the design minimum ambient temperature (at system operating pressure). See Table 2.136 for dew point control in normal operation.
   3. Any undesirable separation that may occur at low ambient temperatures.
   4. Hydrate formation.
   5. Pour point suppression.
   6. Protection against freezing.
   7. Minimum Pressurization Temperature (MPT) – see Sect. 1.3.6.

3.5.4.2 Critical Temperature

It may be defined as the minimum and/or maximum fluid temperature which can increase the risk of failure and corrosion in the following conditions.

(a) In liquid phase:
   1. Too great a heat loss to maintain correct process stability
   2. Viscosity of circulating fluid too high for satisfactory operation
   3. Setting-up (API pour point)
   4. Freezing point of liquid
   5. Freezing point of free water from the liquid
   6. Crystallization and precipitation
   7. Other undesirable separation due to cooling
(b) In gases or multi phases:
   1. Formation of corrosive compound upon condensation
   2. Formation of hydrates upon condensation

3.5.4.3 Considerable Facilities that Require Protective Heating

Special attention should be given to the following facilities to determine during startup, operation, and shutdown periods.

(a) Equipment and piping in water service when intermittent operation or minimum flow will not maintain the temperature above freezing
(b) Water seals
(c) Relief valves and their discharge lines
(d) Instrument leads, orifice taps and pressure taps
(e) Field instruments
(f) Auto-refrigeration at control valves and letdown stations
(g) Piping and equipment that may contain significant amounts of moisture during startup or upsets
(h) Undrained low points in equipment and piping and dead-ended pipes or legs
(i) Drains on pipelines, pumps, tanks, hydraulic power systems, and other equipment
(j) Lube and seal oil systems
(k) Closed-system cooling water tanks for compressors in wet gas service
(l) Fuel oil and diesel fuel tanks and lines
(m) Diesel-driven equipment, particularly fire pumps and emergency generators
(o) Concentrated sulfuric acid and caustic soda solutions as used in demineralized water treatment
(p) Drains/traps at low points in compressed air lines and drains of fuel gas knockout pot
(q) Pipeline pigging operations
(r) Produced gas that is used as a power source for remote equipment and instruments
(s) Inlet air systems of turbine
(t) Air or water exchangers in condensing service
(u) Natural gas cooler tubes when hydrate formation is possible
(v) Buy-back gas used for cold start that is purchased from departing pipelines
(w) Suction piping to compressors in saturated gas service
(x) Fire foam lines
(y) Aboveground fire water supply tanks
(z) Submerged pipeline crossings in rivers and streams

3.5.4.4 Protection

Winterization is generally accomplished by one or more of the following methods depending upon the nature of the equipment, piping or instrumentation, the characteristics of the fluid to be protected, and some analysis of cost, both installed and operational.

(a) Application to retain heat:
   1. Application of external heat through tracing and/or insulation and/or heaters
   2. Elimination of dormant sections of pipe
   3. Maintaining a partial circulation in dormant sections of piping such as firewater systems
   4. Recirculating and bypassing flow around equipment or piping that is temporarily out of service.
   5. Use of antifreeze solutions or diluting streams with lighter, nonfreezing fluids.
   6. Draining, purging, and flushing of piping and equipment; however, this should not be used as a primary means of protection and must be kept to a minimum.
   7. Agitation or intermittent flow through idle piping and equipment.
   8. Providing suitable housing (sheltering) with heat if required.
   9. Cutting heavy stocks with lighter products
(b) Application of heating:
   Piping for offshore platforms often involves numerous deck penetrations, which can present unique accessibility challenges. The design of heat tracing systems should consider the installation, operations, and maintenance challenges in these areas, especially the areas below decks. If an entire piping system requires heat tracing, it is generally unacceptable to provide for heat tracing only on the piping that is above deck.

General Heating Conditions

1. For process systems that carry fluids with critical temperatures (pour point, freeze point, flow point) above 52 °C (126 °F) the heat tracing system should have sufficient capability to maintain the fluid 28 °C (50 °F) above the critical temperature.
2. For process systems that carry fluids with critical temperatures (pour point, freeze point, flow point) above the design cold weather temperature but less than 52 °C (126 °F) the heat tracing system should have sufficient capability to maintain the fluid temperature 14 °C (25 °F) above the critical temperature.
3. The heat tracing system (steam tracing, electric tracing, solvent tracing, steam jacketing, and internal coils or heaters) should have the capability to heat a line sufficiently to permit initial circulation after the line has cooled to the winter design temperature.

(c) All piping should be buried to the project specified depth for freeze protection.
(d) Air coolers should comply with API 661.

References

– API 661, Annex C Winterization of air-cooled heat exchangers
– DNV-OS-A201 Winterization for Cold Climate Operations

3.5.5 External Coating on Metal Surfaces

The appropriate external coating can greatly extend the life of the metal facilities. Tables 3.50 and 3.51 show typically applied coating systems for onshore and offshore facilities, respectively. The detail coating systems are not considered in these Tables. Meanwhile, ASME STS-1, Appendix C suggests the suitability of various coatings and linings for steel stacks to withstand chemical and moderate/high-temperature environments of flue gases.

Table 3.50 Typical coating system for onshore pressure containing facilities (only for reference)

Material	Insulated	Environment	Operating Temperature, °C[(2)]	Coating Required[(3)]
CS or LAS	No	All	≥ −5 °C (22 °F)	Yes
CS or LAS	Yes[(1)]	All	≤150 °C (300 °F)	Yes
300 series SS	No	Nonmarine, Non-coastal or Low chloride	All	No
300 series SS	No	Coastal or Moderate/High chloride	≥50 °C (122 °F)	Yes
300 series SS	Yes[(1)]	All	All	Yes
Super ASS (≥6%Mo), DSS	No	Nonmarine, Non-coastal or Low chloride	–	No
Super ASS (≥6%Mo), DSS	No	Coastal or Moderate/High chloride	≥70 °C (158 °F)	Yes
Super ASS (≥6%Mo), DSS	Yes[(1)]	All	All	Yes
Super DSS	No	Nonmarine, Non-coastal or Low chloride	–	No
Super DSS	No	Coastal or Moderate/High chloride	≥80 °C (176 °F)	Yes
Super DSS	Yes[(1)]	All	All	Yes

Notes
[(1)]See API RP583 and NACE SP0198 CUI standards for more detail application or compliance
[(2)]The temperature and period during upset or shutdown may have to be considered in accordance with company's or user's experience
[(3)]Some companies may apply the coating system selectively when the average relative humidity is 55% and below

Table 3.51 Typical coating system for offshore topside facilities (only for reference) [(1) (2)]

Material	Insulated	Environment	Operating Temperature, °C[(2)]	Coating Required
CS or LAS	No	All	All	Yes
CS or LAS	Yes[(1)]	All	All	Yes
300 series SS	No	Nonmarine, Non-coastal or Low chloride	–	No
300 series SS	No	Marine, Coastal, or Moderate/High chloride	≥50 °C (122 °F)	Yes
300 series SS	Yes[(1)]	All	All	Yes
Super ASS (≥6%Mo), DSS	No	Nonmarine, Non-coastal or Low chloride	–	No
Super ASS (≥6%Mo), DSS	No	Marine, Coastal, or Moderate/High chloride	≥70 °C (158 °F)	Yes
Super ASS (≥6%Mo), DSS	Yes[(1)]	All	All	Yes
Super DSS	No	Nonmarine, Non-coastal or Low chloride	–	No
Super DSS	No	Marine, Coastal, or Moderate/High chloride	≥80 °C (176 °F)	Yes
Super DSS	Yes[(1)]	All	All	Yes

[(1)]Notes: See the notes in Table 3.50
[(2)]See NACE SP0108 for Corrosion Control and Test Methods (for Aging Stability, Cathodic Disbondment, Dimensional Stability, Edge Retention, Flexibility, Hot/Wet Cycling, Impact Resistance, Impact Strength, Rust Creepage Resistance, Thermal Cycling Resistance, Thick-Film Cracking, and Water Immersion) of Offshore Structures by Protective Coatings

3.5.6 Corrosion Protection of Bolting Materials

Bolted materials are normally exposed to strong tensile stress which are susceptible to SCC or hydrogen embrittlement. Where more stringent control of joint stresses is required, flange/anchor bolting should, whenever practical, be tightened by using hydraulic tensioning equipment.

3.5.6.1 Coating of Carbon and Low Alloy Steel Bolting Materials in Onshore Non-coastal Environment

Onshore non-coastal environments typically do not require bolt coatings for in-service corrosion protection but may require coatings for protection during storage and to facilitate installation. See Table 3.52 for several types of coating.

Table 3.52 Coating of bolting materials

Type of Coating	Application Method	Remark
(Hot) Dip galvanized	Dipping	For large size bolts. Zinc thickness: 10–200 micron
Dip-spin galvanized	Special equipment	Even coating thickness Zinc thickness: about 40 microns
Sherardizing	Special equipment	Even coating thickness. Zinc thickness: 10–50 microns
Electrodeposited (Zn or Cd*)	Electrolytic	Low zinc thickness Zinc thickness: 2–25 microns
Phosphate	Dipping	As pretreatment to additional coating application
Al-based coating	Spraying techniques	Low coating thickness
Zinc-silicate	Spraying techniques	–
Fluoropolymer (PTFE)	Spraying techniques	Provided electrical continuity is verified by measurements
Thermoplastic	Spraying techniques	With inhibitor. Can also be used for maintenance
Wax system	Spraying techniques	Also for maintenance use

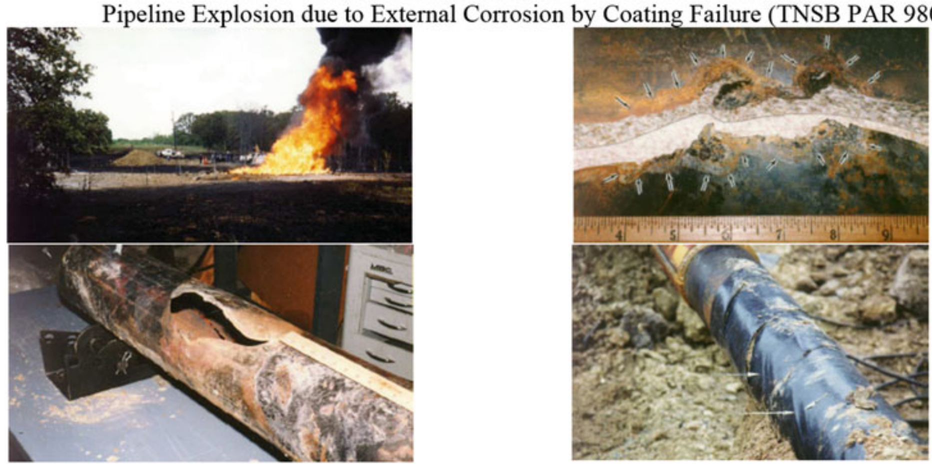
*Cadmium plating should not be used (due to environmental and worker health problems associated with the coating process)

3.5.6.2 Coating of Carbon and Low Alloy Steel Bolting Materials in Offshore or Coastal Environment

(a) Coating performance on bolts can be specific to site location. Acceptable bolt coatings have been found to include hot-dip spun galvanized in North Sea environments and Cermet coatings in Gulf of Mexico. The use of hot-dip spun galvanized bolts has led to threading issues during manufacturer, and extra care is warranted when using this approach. Cermet coatings are thinner and do not require re-thread by the coatings applications and have found better success and reliability.
(b) Cadmium plating should not be used.
(c) To mitigate the risk of bolt failures due to hydrogen embrittlement, high strength fasteners (actual yield strength exceeding 950 MPa or hardness exceeding 34 HRC/325 Hv10) should not be used for:
   1. Joints retaining hazardous fluids
   2. For pressure retaining connections in an external environment outside of a dry habitat.

Classic Case Study 3

Pipeline Explosion due to External Corrosion by Coating Failure (TNSB PAR 98025)



Chapter 4
Welding and Heat Treatment Requirements in Shop and Field

4.1 Standards and Weldability

4.1.1 Codes & Standards and Terms for Welding

4.1.1.1 Codes and Standards for Welding

There are several industrial standards. Some companies'/countries' standards (e.g., DNV, Lloyd, ABS, Norsok-Norway, RCC-M-France, etc.) are also recognized as project engineering standards in certain industries (e.g., offshore, shipbuilding, nuclear power, etc.). Tables 4.1, 4.2, 4.3, 4.4, and 4.5 show the codes and standards and classes of welding in the USA, UK, and Canada.

Table 4.3 shows comparison of soldering, brazing, and welding.

Figure 4.1 indicates typical welding costs excluding base metal cost. The labor cost has more than 80% of all welding work. So, the minimizing repair welding may be the most important QA-QC program. The rate of labor cost will be increased per the location and work environments (e.g., cold weather, subsea, field welding, 6G/6GR position, etc.).

4.1.1.2 Terms and Definitions for Welding: See AWS A3.0, API 660, TEMA, etc. for More Details

(a) Seal Welding

Any weld intended primarily to provide a specific degree of tightness against leakage. This term is also used for H/EX tube-to-tubesheet weld joint (normally fillet welds) of unspecified strength applied between the tubes and tubesheets for the sole purpose of reducing the potential for leakage. Normally the PWHT for the seal welding of CS may be exempt in accordance with the applicable codes.

Reference: D. Miller, Use Caution when Specifying "Seal Welds", Welding Innovation Vol. XVI, No.2

(b) Strength Welding

This term may be used for all weld joints which are required the strength calculation. Especially in H/EXs, it is used for tube-to-tubesheet weld joint (TTTWJ – normally partial bevel fillet welds) when the design strength of TTTWJ is equal to, or greater than, the axial tube strength specified by the pressure design code. Normally the PWHT for the strength welding of CS may or may not be exempt in accordance with the applicable codes.

(c) Continuous Welding

A weld extending continuously from one end of a joint to the other. Where the joint is essentially circular, it extends completely around the joint. It should be used for low temperature, fatigue, EAC, and lethal services or conditions as a minimum.

(d) Full Penetration (Fullpen) Welding

A complete joint penetration through the weldable thickness. Commonly used for butt welding in pressure-containing joints. It should be used for low temperature, fatigue, EAC, and lethal services or conditions as a minimum.

(e) Brazing

A joining process in which the brazing filler metal having a liquidus above 450 °C [840 °F] and below the solidus of the base metal is deposited in the joint without capillary action or melting of the base material. The brazing filler metal is distributed and retained between the closely fitted faying surfaces of the joint by capillary action. There are several different types of brazing welding, such as arc braze welding, carbon arc braze welding, electron beam braze welding, exothermic braze welding, flow welding, and laser beam braze welding. See Sect. 4.11.14 for more detailed guidelines of brazing.

(f) Soldering

A group of joining processes in which the workpiece(s) and solder are heated to the soldering temperature below 450 °C (840 °F) to form a soldered joint. The soldering filler metals have a liquidus below 450 °C (840 °F).

4.1.1.3 Welding Positions and Symbols

See AWS A2.4, EN ISO 2553/BS EN 22553, DIN EN ISO 6947, AS 3545 (Australian), etc.

J.-C. Eun, *Handbook of Engineering Practice of Materials and Corrosion*,
https://doi.org/10.1007/978-3-030-36430-4_4

Table 4.1 Welding codes and standards-short list (USA and UK) – See Notes

Application	Application code/standard	Welding standards for approval	
		Procedure approval	Welder approval
Pressure vessels	ASME VIII BS 5500	ASME IX BS EN 288	ASME IX BS EN 287
Process piping	ASME B31.1 ASME B31.3 BS 2633 BS 4577 BS 2971	ASME IX BS EN 288 (Part 3) BS EN 288 (Part 4) (if required)	ASME IX BS EN 287 (Part 1) BS EN 287 (Part 2) BS EN1418 Operator BS 4872
Storage tanks	API 620/650 BS 2654 BS 2594	ASME IX BS EN 288 (Parts 3 & 4)	ASME IX BS EN 287
Structural Fabrication	AWS D1.1 AWS D1.2 BS 5135 BS 8118	AWS D1.1 AWS D1.2 BS EN 288 (Part 3) BS EN 288 (Part 4)	AWS D1.1 AWS D1.2 BS EN 287 BS 4872
Common requirements/ guidance	API RP582 guidelines API 1104 pipelines API RP577 welding processes,, inspection, and metallurgy	ASME Sec. II, Part C fillers ASTM A488 cast welding BS EN 729 quality BS EN 970 NDE	BS EN 1011 Guidance BS EN ISO 13916 Quality

Notes:

1. Reference should be made to the application codes/standards for any additional requirements to those specified in BS EN 287, BS EN 288, and ASME IX
2. Some BS standards have not been revised to include the new BS EN standards: BS EN 287 and BS EN 288 should be substituted, as appropriate, for BS 4871 and BS 4870, respectively, which have been withdrawn
3. Safety Standards of the KTA (Nuclear Safety Standards Commission) to be applied for nuclear industries

Table 4.2 Lists of major AWS codes

AWS No.	Title	AWS No.	Title
B 2.1	Standard for WPS & PQR	D10.13	Tube brazing (copper)
D1.1	Structural welding (steel)	D10.18	Pipe welding (stainless steel)
D1.2	Structural welding (aluminum)	D11.2	Welding (cast iron)
D1.3	Structural welding (sheet steel)	D14.1	Industrial mill crane welding
D1.4	Structural welding (reinforcing steel)	D14.3	Earthmoving & agricultural equipment welding
D1.5	Bridge welding	D14.4	Machinery joint welding
D1.6	Structural welding (stainless steel)	D14.5	Press welding
D1.7	Structural welding (strengthening and repair)	D14.6	Industrial mill roll surfacing
D1.8	Structural welding seismic supplement	D15.1	Railroad welding
D1.9	Structural welding (titanium)	D15.2	Railroad welding practice supplement
D8.1	Automotive spot welding	D16.1	Robotic arc welding safety
D8.6	Automotive spot welding electrodes supplement	D16.2	Robotic arc welding system installation
D8.7	Automotive spot welding recommendations supplement	D16.3	Robotic arc welding risk assessment
D8.8	Automotive arc welding (steel)	D16.4	Robotic arc welder operator qualification
D8.9	Automotive spot weld testing	D17.1	Aerospace fusion welding
D8.14	Automotive arc welding (aluminum)	D17.2	Aerospace resistance welding
D9.1	Sheet metal welding	D18.1	Hygienic tube welding (stainless steel)
D10.10	Heating practices for pipe and tube	D18.2	Stainless steel tube discoloration guide
D10.11	Root pass welding for pipe	D18.3	Hygienic equipment welding
D10.12	Pipe welding (mild steel)		

Table 4.3 Comparison of soldering, brazing, and welding

Parameter	Process		
	Soldering	Brazing	Welding
Joint formed	Mechanical	Metallurgical	Metallurgical
Filler metal melt temperature, °C (°F)	<450 °C (<840 °F)	>450 °C (>840 °F)[(a)]	>450 °C (>840 °F)[(b)]
Base metal	Not melt	Not melt	Melt
Fluxes used to protect and to assist in wetting of base metal surfaces	Required	Optional	Optional
Typical heat sources	Soldering iron, ultrasonic, resistance, oven	Furnace, chemical reaction, induction, torch, infrared	Plasma, electron beam, tungsten and submerged arc, resistance, laser
Tendency to warp or burn	A typical	A typical	Potential distortion and warpage of base metal likely
Residual stresses	–	–	Likely around weld area

Source: ASM Metal Handbook Vol. 6
Notes
[(a)]Less than melting point of base metal
[(b)]Higher than or equal to melting point of base metal

Table 4.4 ASME/AWS filler metal specifications per material and welding process [ASME Sec. II-C (SF-) & AWS]

	OFW	SMAW	GTAW GMAW PAW	FCAW	SAW	ESW	EGW	Brazing
Carbon steels	A5.2	A5.1	A5.18, A5.36	A5.20, A5.36	A5.17	A5.25	A5.26	A5.8, A5.31
Low alloy steels	A5.2	A5.5	A5.28, A5.36	A5.29, A5.36	A5.23	A5.25	A5.26	A5.8, A5.31
Stainless steels		A5.4	A5.9, A5.22	A5.22	A5.9	A5.9	A5.9	A5.8, A5.31
Cast Iron	A5.15	A5.15	A5.15	A5.15				A5.8, A5.31
Nickel alloys		A5.11	A5.14	A5.34	A5.14			A5.8, A5.31
Aluminum alloys		A5.3	A5.10					A5.8, A5.31
Copper alloys		A5.6	A5.7					A5.8, A5.31
Titanium alloys			A5.16					A5.8, A5.31
Zirconium alloys			A5.24					A5.8, A5.31
Magnesium alloys			A5.19					A5.8, A5.31
Tungsten electrodes			A5.12					
Brazing alloys and fluxes								A5.8, A5.31
Surfacing alloys	A5.21	A5.13	A5.21	A5.21	A5.21			
Consumable inert			A5.30[(1)]					
Shielding gases			A5.32	A5.32			A5.32	

Legend
PAW plasma arc welding, *SMAW* shield metal arc welding (or *MMA* manual metal arc welding), *SAW* submerged arc welding, *GTAW Gas Tungsten Arc Welding* (or *TIG* tungsten inert gas), *GMAW* gas metal arc welding (two types: *MIG* metal inert gas/*MAG* metal active gas), *FCAW* flux-cored arc welding, *ESW* electroslag welding, *EGW* electrogas welding
Note: [(1)]It is typically applicable for GTAW of CS, Cr-Mo LAS, SS, Ni alloys, and Cu-Ni alloys unless otherwise proved the suitability. Use of this inserts may be limited in company/project specifications

Table 4.5 Welding standards in Canadian Standards Association

Code	Description
CSA W47.1	Certification of companies for fusion welding of steel
CSA W59	Welded steel construction (metal arc welding)
CSA W59.2	Welded aluminum construction

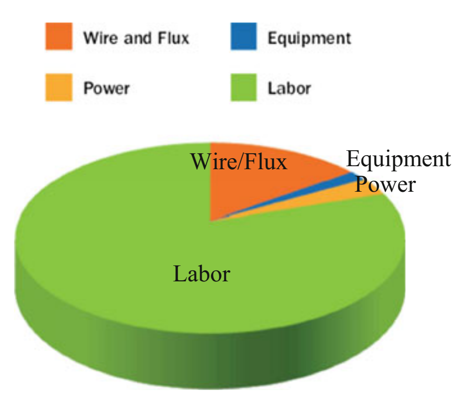


Figure 4.1 Typical welding costs. (Source: AWS & CWB, report, 2008)

Table 4.6 Weldability and joinability of several materials per welding process

Material / Welding process	Arc	Oxyacetylene	EBW	RW	Brazing	Soldering	Adhesive bonding
Cast iron	7	10	1	1	3	1	7
Carbon steel, low alloy steel	10	10	7	10	10	3	7
Stainless steel	10	7	7	10	10	5	7
Aluminum	7	7	7	7	7	1	10
Magnesium	7	7	7	7	7	1	10
Copper, copper alloys	7	7	7	7	10	10	7
Nickel, nickel alloys	10	7	7	10	10	5	7
Titanium	7	1	7	7	3	1	7
Lead	7	7	1	3	1	10	10
Zinc	7	7	1	3	1	7	10
Thermoplastics	10[a]	10[b]	1	7[c]	1	1	7
Thermosets	1	1	1	1	1	1	7
Elastomers	1	1	1	1	1	1	10
Ceramics	1	1	7	1	1	1	10
Dissimilar metals	3	3	7	3	3–7	N/A	10

Source: ASM Welding H/B
Note: 10 = Excellent, 5 = Fair, 1 = Seldom/never used. EBW, electron beam welding, RW, resistant welding
[a]Heated tool
[b]Hot gas
[c]Induction

4.1.2 Definition and Comparison of Weldability

The "weldability" is simply regarded as a measure of how easy it is to make a weld in a particular material without cracks. If it is easy to avoid cracking, the material is deemed "weldable." For a weld to be truly successful, however, it is also necessary for it to have adequate mechanical properties and to be able to withstand degradation in service (e.g., corrosion damage). Thus, a good weldability is a measure of how easy it is to:

Deformation ↓
Spatter ↓
Porosity ↓
Segregation and Precipitation ↓
HAZ (coarse grain, residual stress, hardness, etc.) ↓
Melting Efficiency ↑
Brittleness and Crack ↓
Solidification (Hot) Crack ↓

Weldability is not a fixed parameter for a given material but will depend on material combination/chemical composition (base metals and fillers), joint details, welding sequence, service requirements, welding processes, and welding facilities available. The most critical issues for weldability are to avoid cracks due to solidification, liquation, reheat, lamellar, chevron, hydrogen-assisted cold cracking (hydrogen embrittlement), restraint stresses, residual stresses as well as deformation, contraction, inclusions, undesirable precipitation, etc. Table 4.6 shows the weldability and joinability of several materials per welding process. Adhesive bonding has very wide weldability and joinability, while EBW has very limited characteristics. Several weld cracking tests are introduced in Sect. 4.2.9.

Figure 4.2 shows a sample for the difference of weldability after the first pass welding between thick wall and thin wall. After the first pass welding for both with same heat input (100 cal), the cooling rate on thick wall is faster than that on thin wall because the heat loss by conduction is passed out through *x*, *y*, and *z* direction in thick wall, while the heat loss by conduction is passed out through *x* and *y* direction in thin wall. As a result, the faster cooling rate on thick wall can produce the hardened microstructure (bainite or martensite) which is very brittle and susceptible to crack. So as the wall is thicker, the higher preheat is required to prevent the crack. Cooling time control ($T_{8/5}$) per three-dimensional heat flow for thick wall and two-dimensional heat flow for thin wall can be used to prevent cracking during/after welding (see Sect. 4.2.5).

This variability in weldability is illustrated in the following examples:

Figure 4.3 shows a sample for the difference of weldability after the finish pass welding between thick wall and thin wall. After the finish pass welding, the total heat inputs between both are greatly different (e.g., if 10,000 calories at thick wall and 2000 calories at thin wall). Even though three-way (x, y, and z direction) drain valves are in the thick wall, the drainage speed at thick wall will be low because the total energy at thick wall is greatly reserved compared to that at thin wall during welding. So the finish pass is not controlled by preheat for continuous welding. From this sample, we can recognize the importance of the preheat (or slow cooling) during first pass welding.

Meanwhile the joint quality factors according to weld joint type, radiographic test (RT), and others have been addressed in Sect. 1.2.7.

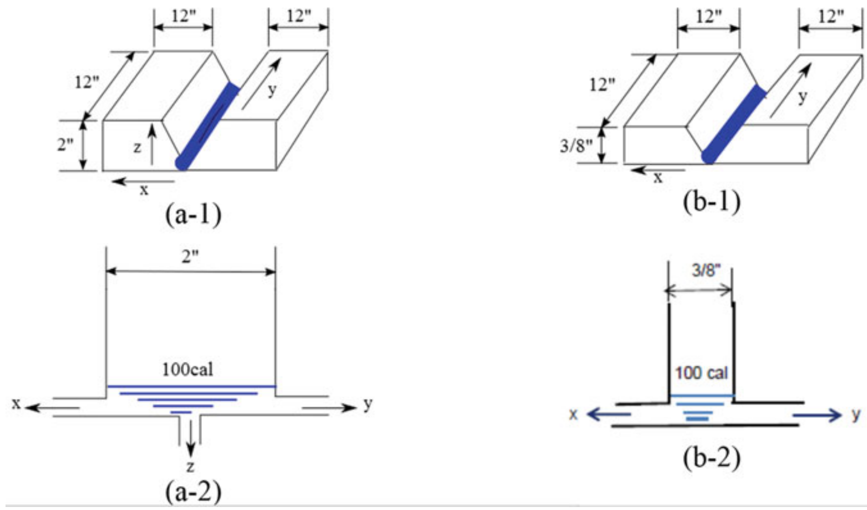


Figure 4.2 Weldability after first pass

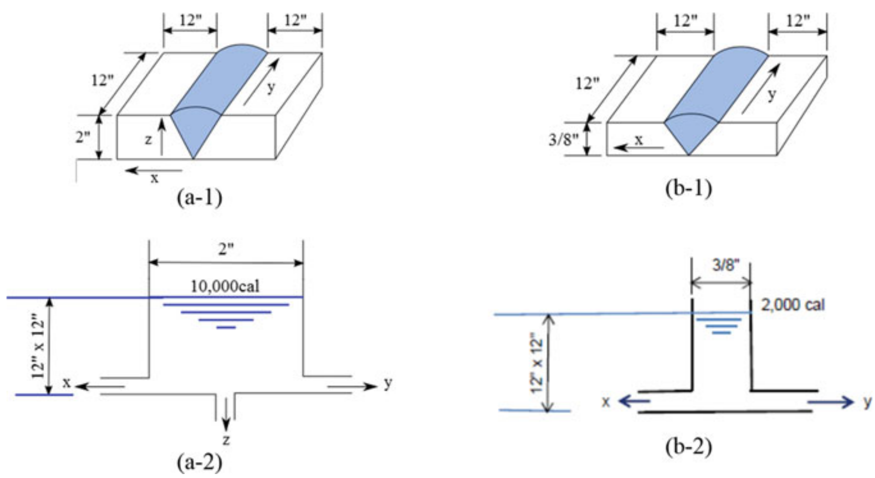


Figure 4.3 Weldability after complete welding

4.1.3 *Factors Affected to Weldability*

1. Materials – Ceq, Pcm, impurity.
2. Joints and Geometry Effect – tee, branch, heavy wall, etc.
3. Position* – flat (1G, 1F), horizontal (2G, 2F, 2FR), vertical (upwards and downwards – 3G, 3F), overhead (4G, 4F), pipe fixed horizontal (5G, for girth weld; 5F, for plate to pipe fillet weld). Pipe fixed with 45° angle (upwards and downwards – 6G/6F), pipe fixed with 45° angle and obstacle plate and rotating weld (6GR).
   *G = groove weld, F = fillet weld, R = rotation
4. Appropriate Welding Process and Certified WPS/PQR.
5. Welding Sequence and Decision of Closing Seam: for effective welding, minimizing deformation and defects.
6. Use of Approved Essential Variables (see Sect. 4.9.1.).
7. Chemical Elements in Base Metal, Welding Electrodes, Fillers, and Flux – see Table 2.7 for the effects of each element on welding of CS and LAS.
8. Welder Workmanship and Training.
9. Welding Shop Environment (wind, humidity, moisture in fillers/electrodes, etc.).
10. Cleanliness of Weld Bevels.
11. QA/QC Including Qualified Inspectors, Calibration, and NDE System.

4.1.4 *Alignment Tolerance and Reinforcement on Weldment*

Tables 4.7 and 4.8 show ASME BPVC requirements for alignment tolerance and max. reinforcement thickness in finished longitudinal and circumferential butt weld, respectively. ASME B31.3, 328.4.3 states the requirements for weld joint alignment.

Table 4.7 Max. allowable offset (misalignment) (ASME Sec. VIII, Div. 1 Table UW-33)[a]

Section thickness,	Joint categories	
t mm (in.)	A	B, C, & D
$t \leq 12.7$ (1/2)	¼ t	¼ t
12.7 (1/2) < $t \leq$ 19 (3/4)	3.2 mm (1/8 in.)	6.4 mm (1/4 in.)
19 (3/4) < $t \leq$ 38 (1 ½)	3.2 mm (1/8 in.)	4.8 mm (3/16 in.)
38 (1 ½) < $t \leq$ 50.8 (2)	3.2 mm (1/8 in.)	1/8 t
50.8 (2) < t	Lesser of 1/16 t; or 9.5 mm (3/8 in.)	Lesser of 1/8 t; or 19 mm (3/4 in.)

Notes for Table 4.7 & 4.8: t nominal thickness (thinner section of butt weld)
[a]Same requirements in ASME Sec. VIII, Div. 2, Table 6.4
[b]Same requirements in ASME Sec. VIII, Div. 2, Table 6.6

Table 4.8 Max. allowable reinforcement thickness, in finished long. & circum. welds (ASME Sec. VIII, Div. 1, UW-35)[b]

Section thickness, t mm (in.)	Joint categories	
	Categories B, C	Other welds
$t \leq 2.4$ (3/32)	2.4 mm (3/32 in.)	0.8 mm (1/32 in.)
2.4 (3/32) < $t \leq$ 4.8 (3/16)	3.2 mm (1/8 in.)	1.6 mm (1/16 in.)
4.8 (3/16) < $t \leq$ 12.7 (½)	4 mm (5/32 in.)	2.4 mm (3/32 in.)
12.7 (½) < $t \leq$ 25.4 (1)	4.8 mm (3/16 in.)	2.4 mm (3/32 in.)
25.4 (1) < $t \leq$ 50.8 (2)	6.4 mm (1/4 in.)	3.2 mm (1/8 in.)
50.8 (2) < $t \leq$ 76.2 (3)	6.4 mm (1/4 in.)	4 mm (5/32 in.)
76.2 (3) < $t \leq$ 101.6 (4)	6.4 mm (1/4 in.)	5.6 mm (7/32 in.)
101.6 (4) < $t \leq$ 127 (5)	6.4 mm (1/4 in.)	6.4 mm (1/4 in.)
127 (5) < t	8 mm (5/16 in.)	8 mm (5/16 in.)

4.1.5 Joint Details for Specific Welds

There are many types of weld joints, such as butt (full penetration and partial penetration with several bevel types), tee (plug, fillet, bevel-groove, slot, flare bevel-groove, J-groove, etc.), lap (similar kinds of tee joint), edge (bevel-groove, square-groove, J-groove, edge-flange, U-groove, corner-flange, etc.), and corner joint (spot, fillet, V-groove, square-groove, U-groove, bevel-groove, flare-V-groove, corner-flange, edge, etc.). This section is only addressed for more specific weld joints, such as clad with cutback and narrow gap butt welding. Also, the controlled deposit welding (CDW) and buttering welding are introduced in Sect. 4.5.

4.1.5.1 Definitions of Weld Joint Types

Most industrial codes and standards have their own definitions and acceptable weld joint details. ASME Sec. VIII, Div. 1 and 2 state the weld categories (A to E) and joint types [(1) through (10)] in Table 1.54 in this book. ASME Sec. VIII requires the acceptable weld joint details for each weld category and joint type which are not shown in this book.

ASME Sec. VIII, Div. 2 states the definitions of weld joint types as below.

(a) *Butt Joint* – A butt joint is a connection between the edges of two members with a full penetration weld. The weld is a double-sided or single-sided groove weld that extends completely through both of the parts being joined.
(b) *Corner Joint* – A corner joint is a connection between two members at right angles to each other in the form of an L or T that is made with a full or partial penetration weld or fillet welds. Welds in full penetration corner joints shall be groove welds extending completely through at least one of the parts being joined and shall be completely fused to each part.
(c) *Angle Joint* – An angle joint is a connection between the edges of two members with a full penetration weld with one of the members consisting of a transition of diameter. The weld is a double-sided or single-sided groove weld that extends completely through both of the parts being joined.
(d) *Spiral Weld* – a weld joint having a helical seam.
(e) *Fillet Weld* – A fillet weld is a weld that is approximately triangular in cross section that joins two surfaces at approximately right angles to each other.
(f) *Gross Structural Discontinuity* – A gross structural discontinuity is a source of stress or strain intensification which affects a relatively large portion of a structure and has a significant effect on the overall stress or strain pattern or on the structure as a whole. Examples of gross structural discontinuities are head-to-shell and flange-to-shell junctions, nozzles, and junctions between shells of different diameters or thicknesses.
(g) *Lightly Loaded Attachments* – Weld stress due to mechanical loads on attached member not over 25% of allowable stress for fillet welds and temperature difference between shell and attached member not expected to exceed 14 °C (25 °F) shall be considered lightly loaded.
(h) *Minor Attachments* – Parts of small size, less than or equal to 10 mm (0.375 in.) thick or 82 cm^3 (5 $in.^3$) in volume, that carry no load or an insignificant load such that a stress calculation in designer's judgment is not required; examples include nameplates, insulation supports, and locating lugs.
(i) *Major Attachments* – Parts that are not minor or lightly loaded as described above.

4.1.5.2 Cutback Detail of Clad Butt Weld (Recommendation)

Figure 4.4 shows the typical configurations for backfilling on stainless steels or nickel alloy cladding in butt joints. If the maximum operating temperature is above 232 °C (450 °F), FEA may be considered additionally. Strip back cladding to a minimum of 12 mm (0.5 in.) is shown in Figure (a). Chipped, gouged, or ground surface shall be cleaned of all residual alloy and its removal verified with a $CuSO_4$ etching. Depth of base material below clad interface shall not exceed 0.8 mm (0.03 in.). If chip back or gouge is done from inside, as shown in Figure (b), 5 mm (3/16 in.) minimum shall be left between edge of chipped or gouged surface and cladding. Final base material weld deposit from inside shall not contact cladding and shall be ground flush before depositing alloy. If initial welding is done from inside, space

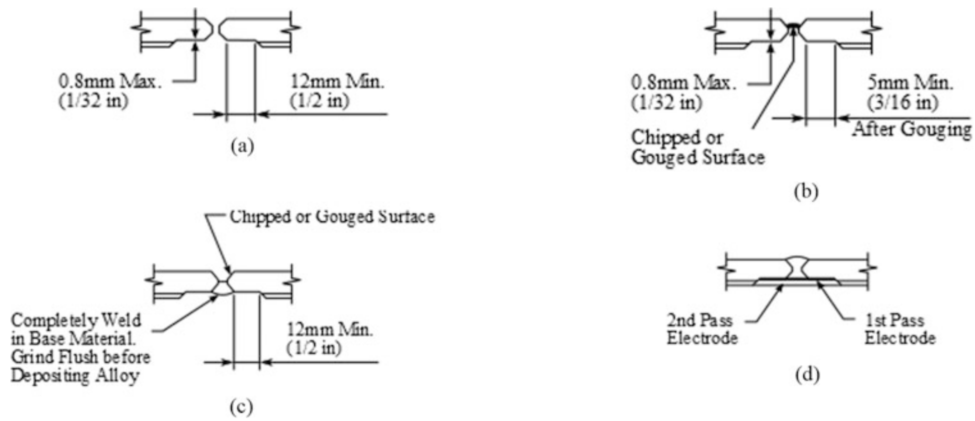


Figure 4.4 Backfilling on stainless steels or nickel alloy cladding in butt joint. (**a**) Machining. (**b**) Root pass*. (**c**) Main fill & back-gouge*. (**d**) Backfill & cladding. **The minimum distance (5 mm) between the end of the bevel/gouged and the end of clad at cutback to be kept to avoid alloy contamination, so that large diameter gouging stick should be carefully selected before gouging*

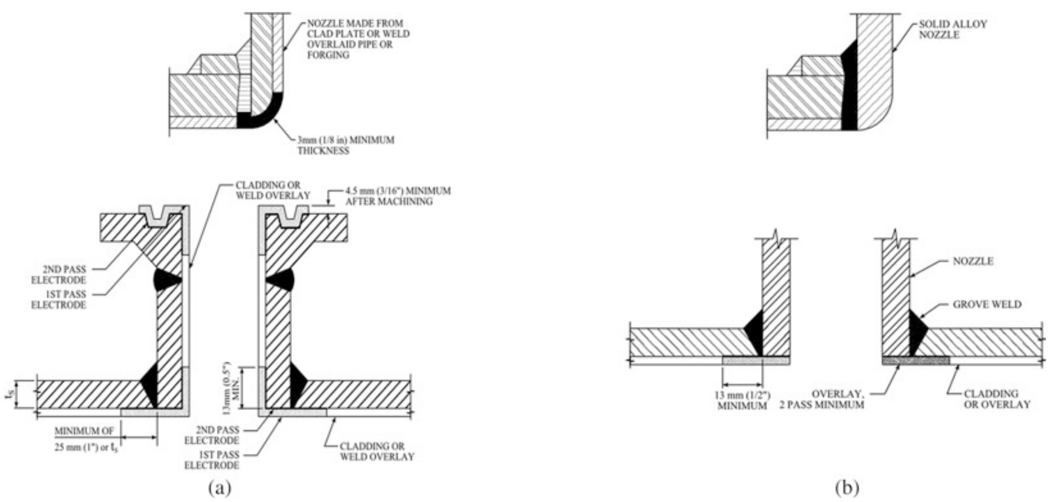


Figure 4.5 Backfilling on stainless steels or nickel alloy cladding in nozzle joint. (**a**) Nozzle detail (≥NPS 2–3). (**b**) Nozzle detail (<NPS 2–3)

between edge of base material weld deposit and edge of cladding shall not be less than 3 mm (0.125 in.), as shown in Figure (c). Completed weld on the inside shall be ground flush before alloy welding. Weld shall be completed with alloy rod first and second electrode; see Figure (d). Figure 4.5 shows backfilling on stainless steels or nickel alloy cladding in nozzle joint. Figure 4.6 shows attachment detail on stainless steels or nickel alloy cladding. Figure 4.7 shows detail of titanium cladding.

In a vacuum service, the vents shall be capped with a threaded end piece CS.

4.1.5.3 Narrow Gap for Heavy Wall Pressure Vessel Weld

Conventional arc welding techniques make use of wider weld grooves with included angles of 60–90° for plate thickness up to 50 mm (2 in.) in general. For higher thickness, the edge preparation comprises a relatively wider root preparation with 2–10° bevel for each side angle (Fig. 4.8). The edge preparations call for considerable deposition of weld metal and consumption of flux. Modern fabrication techniques aim at maximizing productivity (very short welding time) and cost savings as well as minimizing distortion. Narrow gap welding technique applied to conventional arc welding processes is a potential tool for welding fabrication industry for achieving this goal especially for welding of thick-section joints using submerged arc welding. Narrow gap technology for heavy wall weld has been established for butt welding steel plates up to 300 mm (12 in.) thickness and SAW (mainly), GMAW, and GTAW. The productivity has been greatly developed by tandem welding (Fig. 4.9). However, this process has some disadvantages below.

- Mainly available for position 1G. Greatly limited for position 2G.
- Specific equipment (i.e., very accurate turning rollers and/or fixtures) are required.
- The weld is more prone to defects for certain welding processes – especially lack of sidewall fusion*.

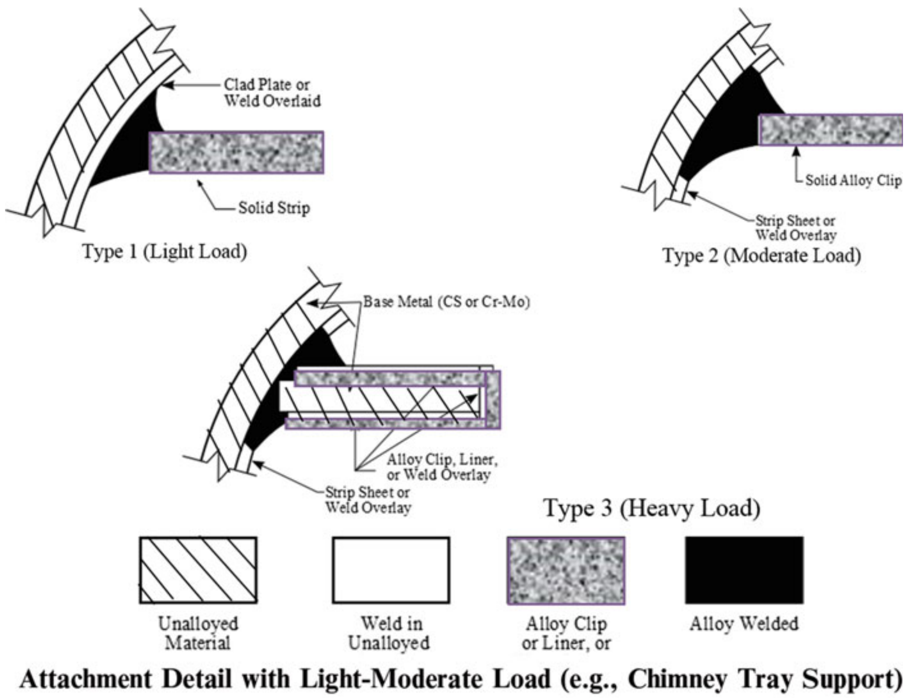


Figure 4.6 Attachment detail on stainless steels or nickel alloy cladding. Attachment detail with light-moderate load (e.g., chimney tray support)

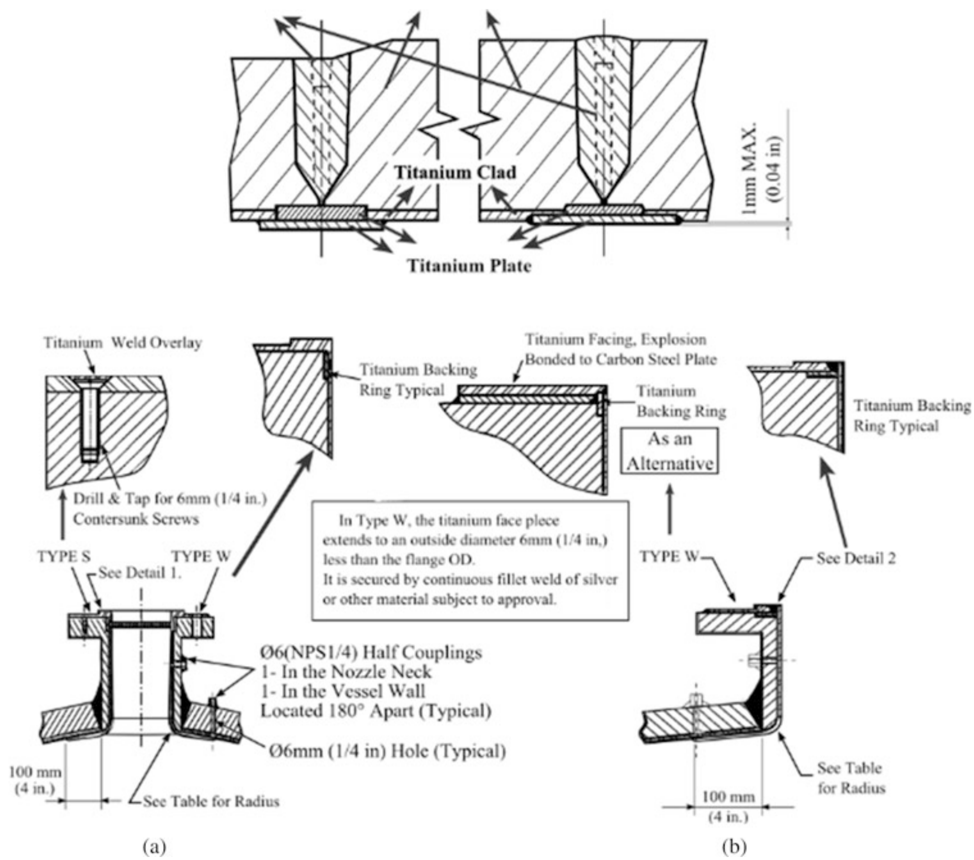


Figure 4.7 Titanium cladding details. (**a**) Nozzles DN 80 (NPS 3) and larger. (**b**) Nozzles DN 50 (NPS 2) and smaller

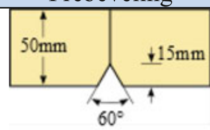
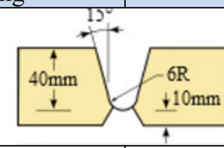
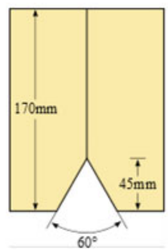
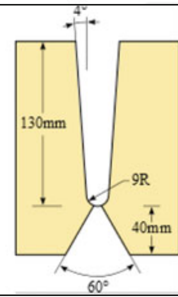
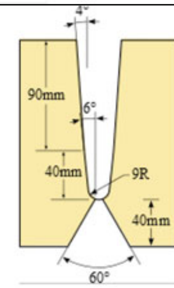
Base Metal	Prebeveling	Machining	
Carbon Steel (T ≤ 50mm)			
Carbon Steel (T > 50mm) Low Alloy Steel Stainless Steel			

Figure 4.8 Typical weld bevel details for narrow gap in heavy wall

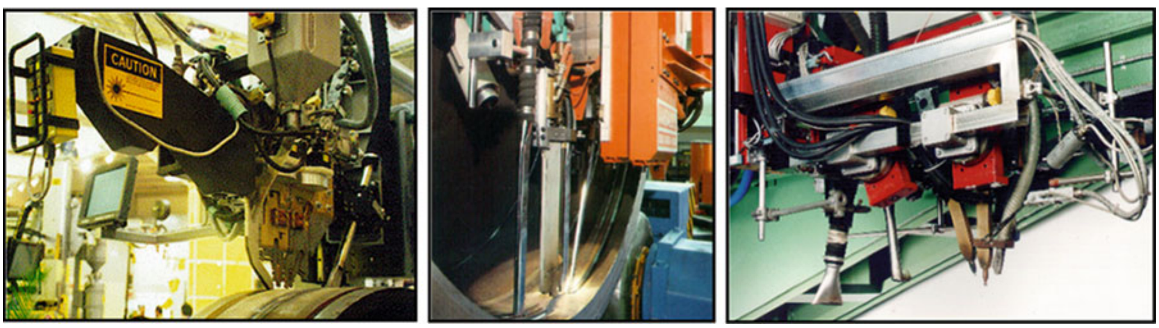


Figure 4.9 Several welding machines for tandem SAW (an example)

– It is difficult to remove any defects when detected, because of poor joint accessibility.
– The J (or U)-groove preparations must be machined onto the parent materials, so that the tolerance of the machined dimensions of both parent materials as well as the tolerance of the formed dimensions of the parent materials shall be minimized, unless use of a backing bar is permitted. This will affect the economics of the process.

*The risk of lack of sidewall fusion can be reduced in narrow gap welding by several methods:

(i) Using two electrodes in tandem (Fig. 4.9) with each electrode oriented so that a weld bead is directed towards each sidewall (SAW and GMAW)
(ii) (ii) Using an electrode that has been bent into a wave form (GMAW). This should make the arc move from side to side across the joint
(iii) Using two electrodes that are twisted around each other to oscillate the arc (GMAW)
(iv) Using an angled contact tip, which automatically aims the electrode at one sidewall and then the other (GMAW)
(v) Use of seam tracking to ensure alignment of the arc with the sidewall

4.1.6 Closure Seam Weld

The closure weld is a common description for fabrication of pressure vessels or piping which is for the last weld joint in pressure-retaining parts. Normally this joint has some limitations to access, test, or inspect after welding as well as to weld.

The closing weld of pressure vessels and piping should be carefully selected, designed, and controlled with the following.

– Closure weld selection
– Weld joint preparation
– Welding process
– NDE and Inspection
– PWHT
– Documentation

The main purpose of closure weld control is somewhat different between pressure vessels and piping. The pressure test is a main issue for piping, while NDE, inspection, PWHT, welding sequence, and hydrotest are main issues for pressure vessels.

4.1.6.1 Closure Weld in Field Piping System

Closure welds should not be allowed in shop fabricated spools or within the boundaries of an individual module fabrication.

The closure weld in this section designates that the final weld connecting piping systems and components in field will not be leak tested in accordance with ASME B31.3, para. 345.4, 345.5 or 345.6:

– Between two piping systems made of new materials that have not been in service and have separately been successfully leak tested
– Between a piping system made of new materials that has not been in service and has been successfully leak tested and a piping system that either is or has been in service. In this case the condition of the portion of the piping system that is or has been in service is important to the quality of the closure weld.

The butt welds of pipe-to-pipe, pipe-to-flange/fitting, and pipe-to-other component may be considered as closure welds.

(a) Closure Weld Seam Selection and Welding
  1. The location of each closure weld in each system should be logged and traceable to the examination reports.
  2. Welds should be multipass with the root pass welded with GTAW.
(b) Closure Weld Control System
  1. The closure weld tracking program should be retrievable.
  2. Welds in nonflammable services may be incorporated into a closure weld administration program without further evaluation.
  3. Closure welds in flammable services.
     – For maximum operating pressures ≤50 psig; may be included in the closure weld administration program without further restriction.
     – For maximum operating pressures >50 psig; should be individually reviewed.
  4. Closure welds should not be allowed in piping systems classified by the end-user as Category M or high pressure fluid service.
(c) NDE and Inspection
  1. All NDE for closure welds should be documented and traceable.
  2. Each closure weld should be examined in-process, in accordance with B31.3, para. 344.7.
  3. All weld preparations shall be subject to WCMT (wet contrast MT) or PT.
  4. Each closure weld should be tested by100% RT or 100% UT, in accordance with B31.3, para. 344.5 or 344.6, respectively.
  5. Final volumetric examination should be performed after any required heat treatment, regardless of material type.
  6. All NDE personnel should be qualified and certified to their employer’s written practice which should meet ASNT SNT-TC-1A, CP-189 and/or certified NDE inspectors by end-user.
  7. Personnel interpreting NDE should, as a minimum, be qualified and certified Level II in the applicable NDE method.
  8. Where the closure welds as golden welds are permitted in lieu of pressure testing, the following additional inspection should be performed:
     • Welds shall be multipass with the root pass welded with GTAW.
     • All weld preparations shall be subject to WCMT (wet contrast MT) or PT.
     • The completed weld shall be subject to 100% RT and WCMT/PT.

4.1.6.2 Closure Weld Control in Pressure Vessels

(a) Closure Weld Selection
  Furnace size for PWHT, scope of supply, transportation, pressure test, and other requirements will be the factors to select the weld seam. The location of any required closure weld shall be defined on the appropriate drawing and other documents.
(b) Weld Joint Preparation
  Single bevel, double bevel, back-gouging location, weld joint gap, final contraction, and NDE/inspection should be considered. For instance, the major V bevel of closing weld seam may be provided on the outside due to safety reasons (fumes), while that should be provided inside the shell to reduce the distortion.
(c) Welding
  If the back chipping or gouging is not available on the inside of equipment, GTAW or GMAW-S may be used.
(d) NDE and Inspection
  Appropriate NDE and accessible inspection should be selected. For instance, UT in lieu of RT may be applicable.
(e) PWHT for Closing Seam – Sample Check Sheet for ASME Sec. VIII, Div. 1 Application
(f) Table 4.9 shows the checklist for closing weld seam design of ASME Sec. VIII, Div. 1 pressure vessels.
(g) Documentation (Recommendation)
  1. Closure welds shall be tracked in accordance with the project field weld tracking program. Additionally, all aspects associated with each closure weld shall be tracked such that all details and documents can be retrieved and bundled as part of the final package for project closure welds.
     See Sect. 4.12.6 for more details on local PWHT.

Table 4.9 Checklist for closing seam design of pressure vessels (ASME Section VIII, Div. 1)

Code requirements
Paragraph UW-40 – Procedure for PWHT
Para. UW-40 (a) – Soak band is defined as the volume of metal required to meet or exceed the minimum PWHT temperatures listed in Table UCS-56. As a minimum, the soak band shall contain the weld, HAZ, and a portion of the base metal adjacent to the weld being heat treated. The minimum width of this volume is the widest width of the weld plus 1*t* or 50 mm (2 in.) whichever is less on each side or end of the weld. The term "*t*" is the nominal thickness defined in para. UW-40 (f).
• Heating a circumferential band containing nozzle or other welded attachments that require PWHT in such a manner that the entire band shall be brought up uniformly to the required temperature and held for the specified time. The soak band shall extend around the entire vessel and shall include nozzle or attachment weld requiring PWHT, provided the required soak band around the nozzle or attachment weld is heated to the required temperature and held for the required time.
Para. UW-40(c) – Where more than one pressure vessel or pressure vessel part are PWHT in one furnace charge, thermocouples shall be placed on vessels at the bottom, center, and top of the charge or in other zone of possible temperature variation so that the temperature indicated shall be the true temperature for all vessels or the components in those zones.
Para. UW-40 (d) – When pressure parts of two different P-numbers groups are joined by welding, the PWHT shall be that specified for the material requiring the higher PWHT temperature.
Paragraph UCS-56 – Requirements of PWHT
Para. UCS-56 (d) (1) – The temperature of the furnace shall not exceed 425 °C (800 °F) at the time the vessel or part is placed in the furnace.
Para. UCS-56 (d) (2) – Above 425 °C (800 °F), the rate of heating shall not be more than 222 °C/hr (400 °F/hr) divided by the maximum metal thickness[(1)] of the shell or head plate in inch, but no more than 222 °C/hr (400 °F/hr).
• During the heating period, there shall not be a greater variation in temperature throughout the portion of the vessel being heated than 139 °C (250 °F) within any 4.6 m (15 ft) interval of length.
Para. UCS-56 (d) (3) – The vessel shall be held at or above the temperature specified in UCS-56 for the period of time specified in the tables unless otherwise noted.
• During the holding period, there shall not be a greater difference than 83 °C (150 °F) between the highest and lowest temperature throughout the portion of the vessel being heated.
Para. UCS-56 (d) (4) – During the heating and holding periods, the furnace atmosphere shall be so controlled so as to avoid excessive oxidation of the surface of the vessel.
Para. UCS-56 (d) (5) – Above 425 °C (800 °F), cooling shall be done in a closed furnace or cooling chamber at a rate not greater than 278 °C/hr (500 °F/hr) divided by the maximum metal thickness[(1)] of the shell or head plate in inch, but in no case more than 278 °C/hr (500 °F/hr). From 425 °C (800 °F), the vessel may be cooled in still air.

Note [(1)] The maximum metal thickness is defined as the thickest nominal thickness per ASME Sec.VIII, Div.1, UW-40 (f) among all weld joints heat-treated in the furnace.

2. A document package shall be prepared for each weld as soon as practical after a weld has been selected and designated as a closure weld and prior to beginning any welding.

   Associated documents shall be added to each package as soon as available. All reports and records associated with closure weld activity, including any repairs and associated NDE, shall be included in the document package. Each package shall include, as a minimum:

   (a) An isometric drawing showing the closure weld, its location, and its weld number.
   (b) Statement of justification for use of the closure weld designation, rather than the required leak test (these justifications may be standardized).
   (c) A summary of the analysis and results for any specific design review required (such as a stress analysis).
   (d) A weld map or weld description sheet showing the welding procedure(s) used for the closure weld.
   (e) Completed and signed leak test records for the adjoining piping.
   (f) Individual NDE records for completed NDE.
   (g) The closure weld inspection record. This document should be the original, be kept with the rest of the package, and be updated as the required examinations are completed.

       Individual closure weld documentation packages may be combined to reduce volume and redundancy, as permitted by the project specification for closure welds.

       However, the location of each closure weld, within each system, shall be specifically recorded and easily traceable to all visual and volumetric examination reports for that weld.
3. The final assembled data package for a closure weld program shall include all individual closure weld packages and a table in the front of the package listing the weld identifier, service or system, pipe class, and pipe size.
4. Closure weld documentation maintenance and review

   The audit/review by end-user and/or representative should be documented and the results reported for all welding and NDE for closure welds.

4.2 Deformation and Crack of Metal due to Heat

4.2.1 General Defects by Welding

Figure 4.10 and Table 4.10 show typical weld defects and abbreviations used in the welding documents. Table 4.11 shows the typical cause and correction of several weld defects.

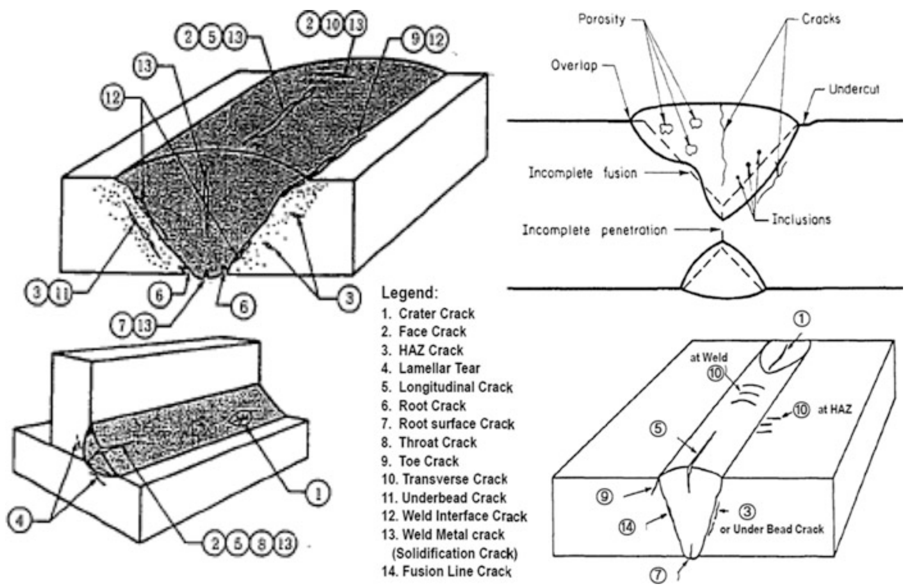


Figure 4.10 General defects by welding

Table 4.10 Types and typical abbreviation of weld defects

Defects	Abbreviation	Meaning	Defects	Abbreviation	Meaning
Gas cavity	GP	Gas pore	Crack	KL	Longitudinal crack
	PG	Localized porosity		KT	Transverse crack
	PL	Linear porosity		KG	Crater crack
	EC	Elongated cavity		KE	Edge crack
	WH	Worm hole	Surface imperfection	SXP	Excess penetration bead
	PU	Uniform porosity		SXR	Excess reinforcement
	CP	Crater pipe		SRC	Root concavity
Solid inclusion	IN	Slag inclusion		SGI	Incompletely filled groove
	IL	Linear inclusion		SGS	Shrinkage groove
	IC	Copper inclusion		SUC	Undercut
	IT	Tungsten inclusion		SSP	Spatter
	IO	Oxide inclusion		SED	Excessive dressing
Lack fusion	LS	Lack of side fusion		SMG	Grinding mark
	LR	Lack of root fusion		SMT	Tool mark
	LI	Lack of inter-run fusion		SMH	Hammer mark
	LP	Incomplete root penetration		SRS	Torn surface
	LF	Incomplete root		SPT	Surface pitting
	NSD	Nonsignificant defect		BT	Burn-through
	NAD	No apparent defect		DM	Diffraction mottling
				FM	Film mark

Table 4.11 Typical cause and correction of weld defects (simple summary for all welding processes)

	Causes	Action to avoid
A. Porosity		
1	Contamination of workpiece	Clean joint area.
2	Excessive moisture pickup in electrode covering	Follow manufacturers recommended re-baking procedure.
3	Moisture on work surfaces	Use preheating/warm-up workpiece.
4	High sulfur content	Use basic coated base metal electrodes.
5	(a) A long arc length (b) Excessive current (c) Higher travel speed	Change welding parameters and technique.
6	High solidification rate	Use preheat/increase heat input.
B. Inclusions		
1	Improper cleaning procedure	Clean work surfaces and each weld run thoroughly. If available, use power wire brush, grinders, and chisel to ensure thorough removal of slag.
2	Improper welding technique (a) Long arc length (b) High travel speed (c) Slag flooding ahead of welding arc	Improve welding technique. Reposition work to prevent loss of slag control wherever possible. Restrict weaving to minimum.
3	Narrow, inaccessible joints	Increase the angle of groove joint.
C. Incomplete fusion		
1	Improper joint design	Increase the angle of groove joint.Change the groove design to “J” or a “U” type.
2	Presence of slag or oxide film	Clean weld surfaces prior to welding.
3	Incorrect electrode position and operating current	Maintain proper electrode position and current.
4	Improper manipulation of arc	Use correct manipulation techniques to melt the joint faces properly.
D. Inadequate penetration		
1	Improper joint preparation	
	(a) Excessively thick root face (b) Insufficient root opening (c) Bridging of root opening	Use proper joint geometry. Reduce root face height. Use wider root opening.
2	Electrode diameter too large	Use smaller electrode in root. Increase root opening.
3	Inadequate current	Follow correct welding current and technique.
E. Cracks		
1	High rigidity of joint	Use preheat, relieve the residual stresses. minimize shrinkage stresses, and use backstep or block welding sequences.
2	Poor joint fit-up (tack welding)	Adjust root opening of all alignment.
3	Higher carbon content of weld metal and/or hardenable base material	Use proper electrode. Use buttering layers wherever necessary.
4	Too small a weld bead	Decrease travel speed to increase cross section of bead. Increase electrode size.
5	High sulfur content in base level of sulfur of weld metal element like Mn	Use filler with high level of sulfur fixing element like Min.
6	Hot cracking	Reduce the heat input/minimum joint restraints.
7	Cracking at the crater	Fill up the crater before withdrawing the electrode. Use taper poor control device/use backstep welding technique.
8	High hardenability	Preheat the joint. Perform the PWHT per code.
9	Hydrogen-induced cracking/delayed cracking	Use low-hydrogen welding electrode. Use suitable preheat and postweld heat treatment.
10	Presence of brittle phases in the microstructure of the base material	Soften the material before welding.
11	Low ductility of the base material	Use preheat/anneal the base metal/use ductile weld metal.
12	High residual stresses	Redesign the weld metal and reduce restraints. Change welding sequence. Use intermediate stress relief heat treatment.
13	Excessive dilution	Change welding current. Use buttering technique wherever possible.

4.2.2 Deformation and Crack of Metal

Figure 4.11a shows that as the bar is uniformly heated, it expands in all directions, as shown in (a). As the metal cools to room temperature, it contracts uniformly to its original dimensions. If the steel bar is restrained – as in a vise – while heated, as shown in (b), lateral expansion cannot take place. But, since volume expansion must occur during the heating, the bar expands in a thickness direction and becomes thicker. As the deformed bar returns to room temperature, it will still tend to contract uniformly in all directions, as in (c). The bar is now shorter, but thicker. It has been permanently deformed or distorted.

Figure 4.12 shows how and why bulging and cracking occur in bars which are free and fixed at the end of one side and both sides during heating. The bulging occurs due to heating and restricted condition. The swelled part remained as a permanent deformation at the restricted condition during/after heating. After cool down, the swelled (bulged) area will remain, and then the length will shorten due to the contraction under “C”–“B” condition, and the crack may take place due to the restricted contraction under “C”–“C” condition.

Figure 4.13 shows typical types of weld deformations.

Figure 4.14 shows the deformed angle of single-bevel groove after SMAW for carbon steel as a sample case. Typically, the distortion is proceeding forwards the major welding side.

Figure 4.15 shows a typical effect of weld area on transverse shrinkage.

4.2.3 Hardness Effect on Weldments

Figure 4.16 shows a typical hardness profile in HAZ and butt welds of high tension carbon steels. The HAZ has the highest hardness values due to coarse grain and highly tangled dislocation (residual stresses).

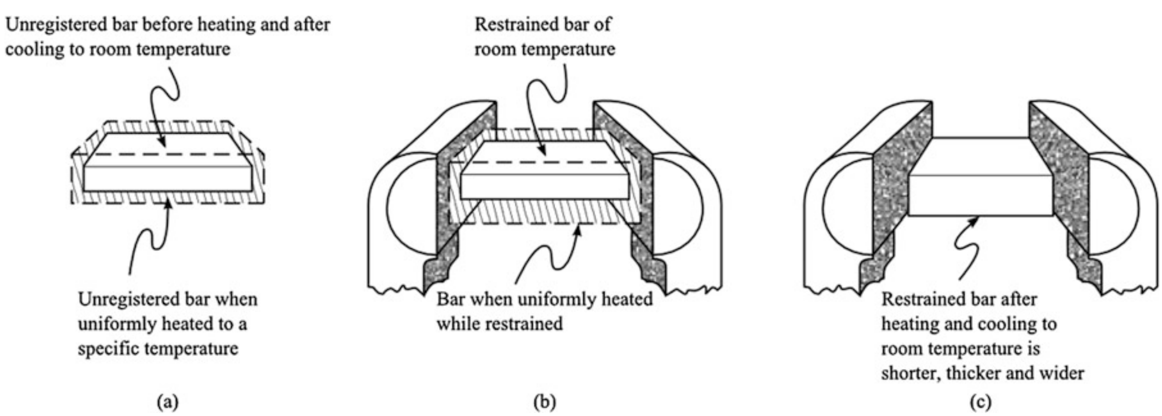


Figure 4.11 How and why distortion occurs. (Source: Lincoln Electric manual, 2005)

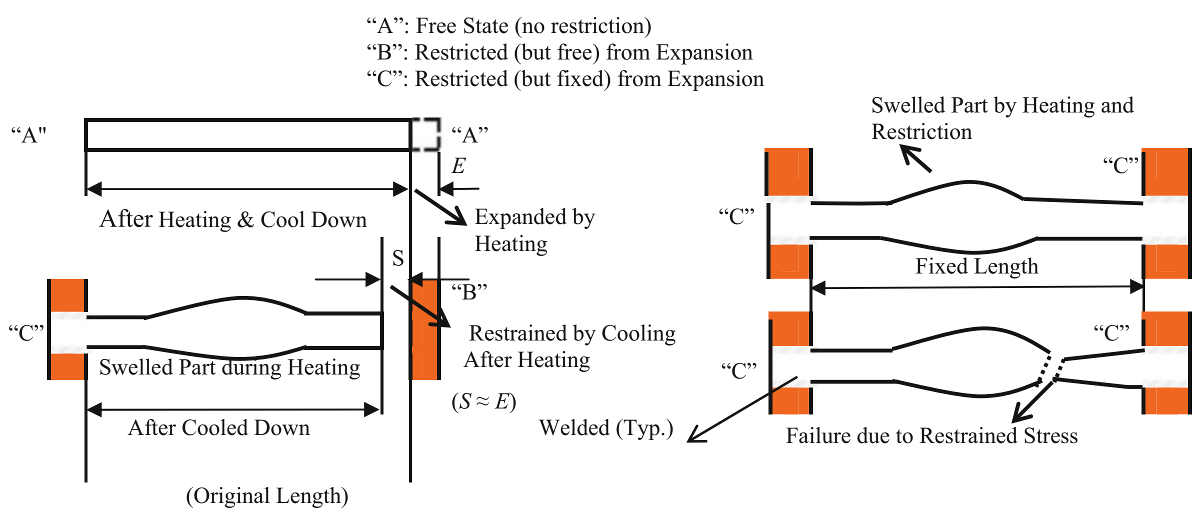


Figure 4.12 How and why bulging and cracking occur

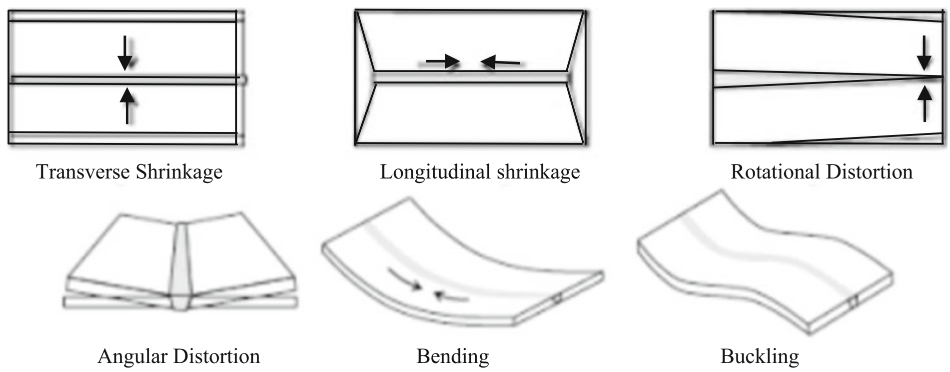


Figure 4.13 Typical types of weld deformations on welds

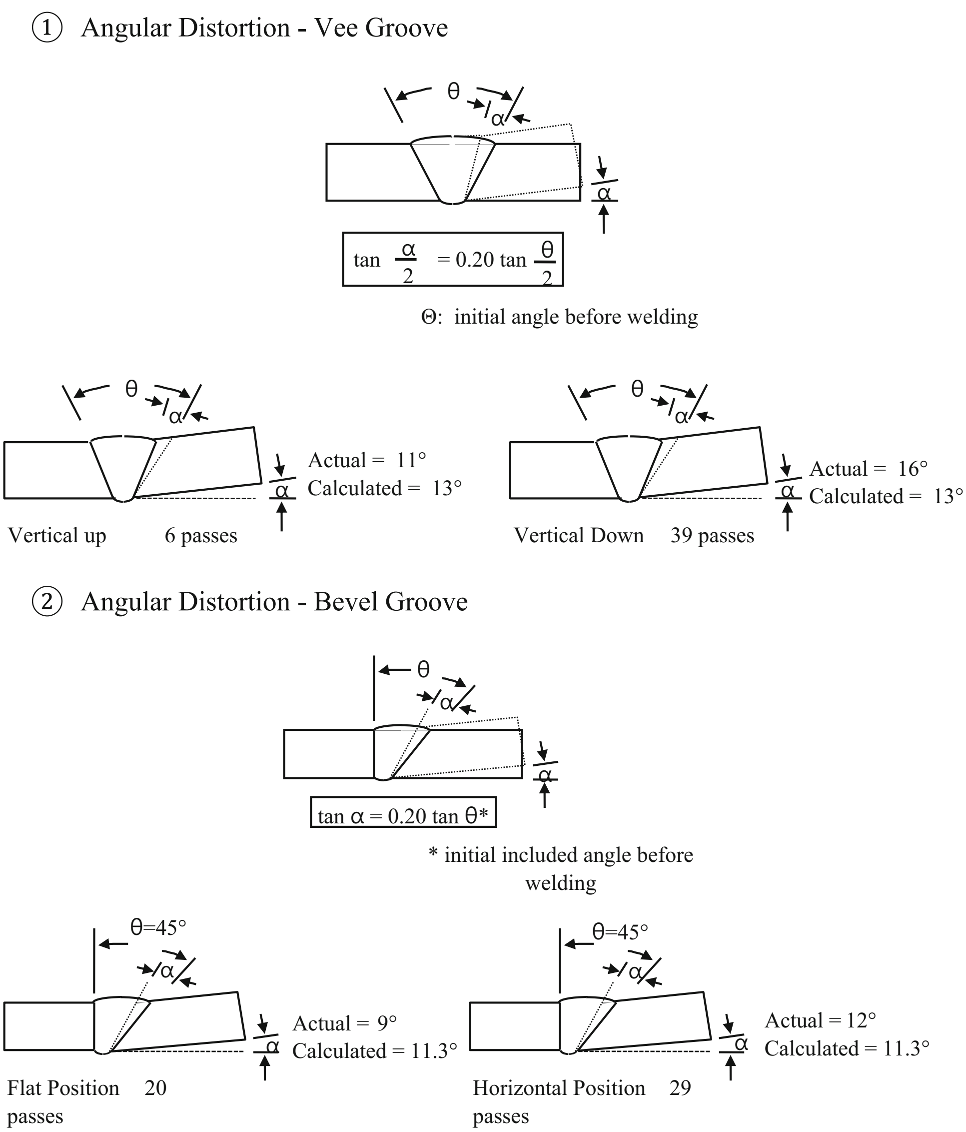


Figure 4.14 Deformed angle of single-bevel groove

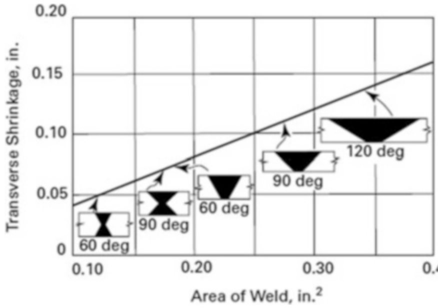


Figure 4.15 Effect of weld area on transverse shrinkage on butt welds. (Source: ASME PCC-2, Fig. 2)

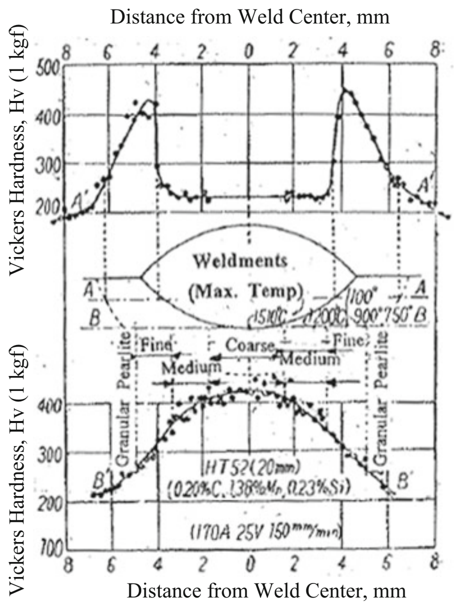
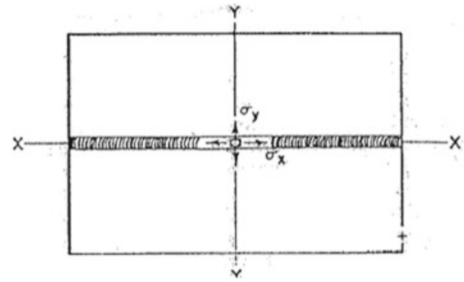
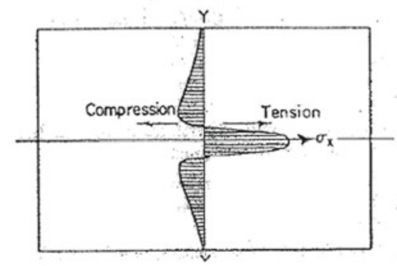


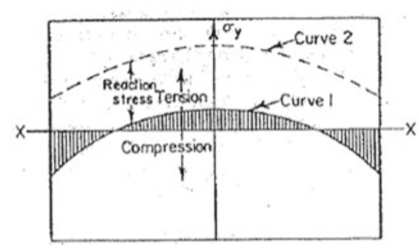
Figure 4.16 Hardness in HAZ and weldments in high tension carbon steels



(1) Butt Weld



(2) Distribution of σ_y along Y-Y



(3) Distribution of σ_y along X-X

Figure 4.17 Typical distribution of residual stressed in butt weld

4.2.4 Residual Stress on Weldments

Figure 4.17 shows a typical distribution of residual stresses in HAZ and butt welds. Normally the highest stresses come from the tensile stress in the weld direction.

The residual stresses can be reduced/minimized/removed by the following treatments.

- PWHT or solution heat treatment
- Evacuation of hydrogen from weld metal
- To use lower carbon equivalent or tensile strength material
- Softening of hardened HAZ
- To avoid cold work
- To avoid the close of neighbor weld joints
- Effective weld joint preparation
- To avoid restriction of weld structures

The residual stress can be measured by (1) X-ray diffraction (XRD) technique [effective for fine- and medium-grain materials – see ASTM E915 TM for verifying the alignment of X-ray diffraction instrumentation for residual stress measurement, ASTM E1426 TM for determining the X-ray elastic constants for use in the measurement of residual stress using X-ray diffraction techniques, ASTM E2860 TM for residual stress measurement by X-ray diffraction for bearing steels, and ISO/TS 21432 NDE-TM for determining residual stresses by neutron diffraction], (2) hole drilling method [effective coarse grain materials-casting or weldments – see ASTM E837 TM for determining residual stresses by hole drill strain gauge method], and (3) others [ASTM E1928 Standard Practice for Estimating the Approximate Residual Circumferential Stress in Straight Thin-walled Tubing].

4.2.5 Cooling Time Control ($T_{8/5}$) for Ferritic Steel

4.2.5.1 Definition and Background

There are several methods to prevent cracking and/or control hardness on weldment of ferritic steel.

One of them is to control the cooling time from 800 °C to 500 °C to minimize the peak hardness in the HAZ in which the most important structural changes occur in the steel welding. The cooling rate depends on the material, its grade, geometry, and thickness of weld joint as well as preheat and heat input.

– If the period is very short (rapid cooling), the hardness of ferrous steel increases due to bainitic and martensitic structure formation so that the weld can be readily cracked during/after welding.
– If the period is very long (slow cooling), only ferrite and perlite can form from the austenite, and this reduces the hardness. There is also the risk of coarse grain formation, and this has negative effects on the mechanical properties of the steel.

BS-EN 1011-2 and NACE SP0472 define "Cooling Time $t_{8/5}$" which is a time taken, during cooling, for a weld run and its HAZ to pass through the temperature range from 800 °C to 500 °C.

This method is qualified by carrying out a PQR with pre-production weld test on representative parent material using the fastest cooling rate at which the HAZ hardness is acceptable for the code and standard requirements. Normally several tests may be required. A successful test qualifies all other production welds made with cooling rates slower than that of the test piece, calculated from the Eq. 4.1, 4.2, and 4.3 below. This may require the welders to be specifically trained to deposit weld metal within very tight limits on travel speed, weaving, etc. and will require close supervision during production welding.

If cooling time control is used, eventually the WPS shall control production welding such that the calculated $t_{8/5}$ is equal to or greater than the $t_{8/5}$ calculated for the procedure qualification specimen. The user may specify a minimum $t_{8/5}$ required for future repair or alteration scenarios.

4.2.5.2 Determination of Cooling Time ($T_{8/5}$)

There are three steps in determining $t_{8/5}$ for a given set of weld joint configuration and welding conditions.

The first step: to determine the type of heat flow during welding, that is, whether the heat flow is either two (*2*)- or three (*3*)-dimensional
The second step: to calculate the heat input
The third step: to determine $t_{8/5}$ using either the calculation method or the graphical method

Step 1—Determining two- or three-dimensional heat flow

The determination of the type of heat flow during welding, whether two (*2*)- or three (*3*)-dimensional, depends on the thickness of the components that impact the heat flow, as shown conceptually in Fig. 4.18.

Figure 4.19 is a diagram that provides information regarding the relationship between the transition thickness (*d*t, in mm), heat input (*Q*, in kJ/mm), and preheat temperature (*T*p, °C), for any type of weld and any welding process. This diagram indicates whether the heat flow is two (*2*)- or three (*3*)-dimensional for any particular combination of plate thickness, heat input, and preheat temperature.

Step 2—Calculating the heat input

The heat input (*Q*, in kJ/mm) can be calculated by using Eq. 4.1 below: See Sect. 4.4.4 for general application of heat input (*ε*, thermal efficiency is not considered).

$$Q = \varepsilon \times V \times (I/v)/1000\ (\mathrm{kJ/mm}) \quad \text{See Step 3 for the effect of joint shape factors.} \qquad \text{(Eq. 4.1)}$$

where

Q = total welding heat input
V = welding voltage (V)

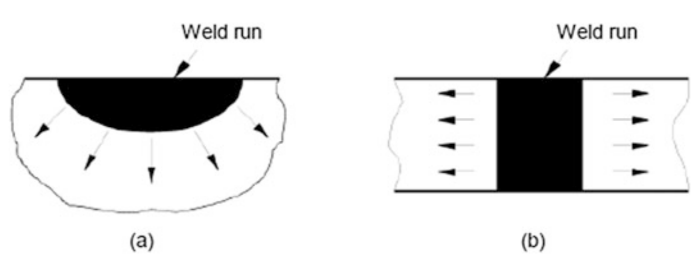


Figure 4.18 Types of heat flow during welding. *Keys*: (**a**) Three (*3*)-dimensional heat flow. Relatively thick plates; plate thickness does not affect cooling time. (**b**) Two (*2*)-dimensional heat flow. Relatively thin plates; plate thickness has a decisive influence on cooling time. (Source: NACE SP0472 and BS EN 1011-2)

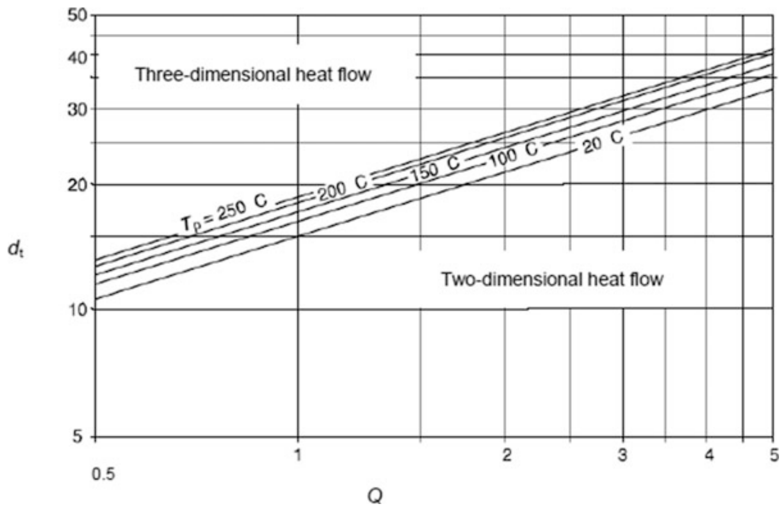


Figure 4.19 Transition plate thickness (*dt*, mm) from three (*3*)-dimensional to two (*2*)-dimensional heat flow as a function of heat input (*Q, kJ/mm*) for different preheat temperatures (*T*p, °C). Key: *dt* transition thickness (mm), *Q* heat input (kJ/mm). (Source: NACE SP0472 and BS EN 1011-2)

I = welding current (A)
v = travel speed (mm/s)
ε = thermal efficiency* of the welding procedure (simplified for cooling time determination)

SAW	$\varepsilon = 1.0$	FCAW	$\varepsilon = 0.8$
SMAW	$\varepsilon = 0.85$	GTAW	$\varepsilon = 0.48$ for NACE SP0472 and 0.6 for BS EN 1011-2
GMAW	$\varepsilon = 0.85$	PAW	$\varepsilon = 0.6$

*See Table 4.41 in this book for other resources (for reference).

Step 3a—Determining $t_{8/5}$ by the calculation method

The relationship between the welding conditions and $t_{8/5}$ can be described by equations that differentiate between two (*2*)- and three (*3*)-dimensional heat flow.

(i) For three-dimensional heat flow in unalloyed and low-alloyed steels, $t_{8/5}$ can be determined using Eq. 4.2:

$$t_{8/5} = (6700 - 5T_p) \times Q \times \left(\frac{1}{500 - T_p} - \frac{1}{800 - T_p}\right) \times F_3 \quad \text{(Eq. 4.2)}$$

where

$t_{8/5}$ = cooling time (second)
Tp = preheat temperature (°C)
Q = heat input (kJ/mm) calculated in accordance with Eq. 4.1
$F3$ = appropriate shape factor for three-dimensional heat flow from Table 4.12

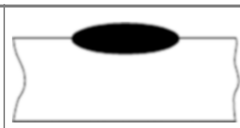
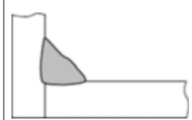
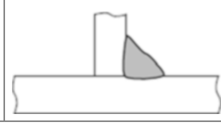
(ii) For two-dimensional heat flow in unalloyed and low-alloyed steels, $t_{8/5}$ can be determined using Eq. 4.3:

$$t_{8/5} = (4300 - 4.3T_p) \times Q \times 10^5 \times \frac{Q^2}{d^2} \times \left[\left(\frac{1}{500 - T_p}\right)^2 - \left(\frac{1}{800 - T_p}\right)^2\right] \times F_2 \quad \text{(Eq. 4.3)}$$

where

$t_{8/5}$ = cooling time (s)
Tp = preheat temperature (°C)
Q = heat input (kJ/mm) calculated in accordance with Eq. 4.1
d = thickness, mm (thickness selected by user to reflect heat sink of the weld)
$F2$ = appropriate shape factor for two-dimensional heat flow from Table 4.12

Table 4.12 Shape factors for influence of the form of weld on $t_{8/5}$

Weld shape		Shape factor	
		$F2$, two-dimensional heat flow	$F3$, three-dimensional heat flow
Run on plate		1	1
Between runs in butt welds		0.9	0.9
Single run fillet weld on a corner joint		0.9–0.67	0.67
Single run fillet weld on a T-joint		0.45–0.67	0.67

Source: NACE SP0472 and BS EN 1011-2
*See Table 4.42 in this book for other resources (for weld position of FCAW)

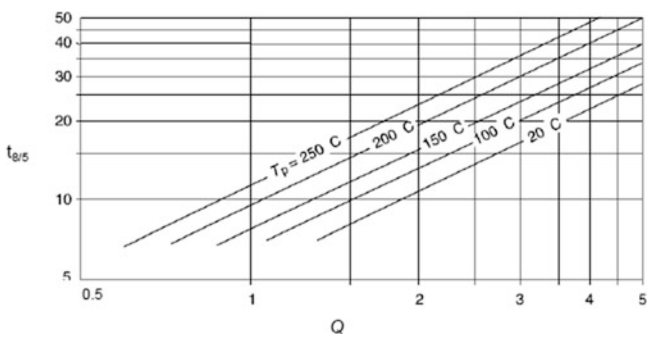


Figure 4.20 Cooling time ($t_{8/5}$, second) for three-dimensional heat flow as a function of heat input (Q, kJ/mm) for different preheat temperatures (Tp, °C). Keys: $t_{8/5}$ cooling time (second), Q heat input (kJ/mm). (Source: NACE SP0472 and BS EN 1011-2)

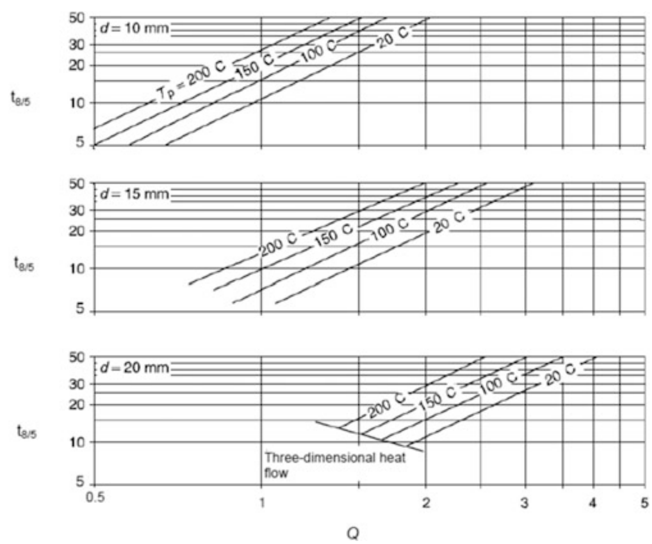


Figure 4.21 Cooling time ($t_{8/5,}$ second) for two-dimensional heat flow as a function of heat input (Q) for different preheat temperatures (Tp) and plate thicknesses (d). Keys: $t_{8/5}$ cooling time (second), Q heat input (kJ/mm). (Source: NACE SP0472 and BS EN 1011-2)

Step 3b—Determining $t_{8/5}$ by the graphical method

The cooling time ($t_{8/5}$) can be determined using Fig. 4.20 (for three-dimensional heat flow) and Fig. 4.21 (for two-dimensional heat flow) below, having first established the type of heat flow using Fig. 4.18 and calculated the heat input (Q) using Eq. 4.1. Figures 4.20 and 4.21 can also be used to determine the heat input for a given cooling time.

(i) For three (*3*)-dimensional heat flow, the relationship between the cooling time ($t_{8/5}$), the heat input (Q), and the preheat temperature (Tp) is given in Fig. 4.20 for a run on plate weld with a shape factor of 1.0. Figure 4.20 is based on Eq. 4.2. If Fig. 4.20 is applied to another form of weld, consideration should be given to the corresponding shape factor (F_3) given in Table 4.12. If the cooling time is to be determined for a particular combination of heat input and preheat temperature, the heat input should first be multiplied by F_3. If, however, the heat input is to be determined for a particular combination of cooling time and preheat temperature, it should be divided by F_3.

(ii) For two (*2*)-dimensional heat flow, the relationship between the cooling time ($t_{8/5}$), the heat input (Q), and the preheat temperature (Tp) is given in Fig. 4.21 for a run on plate weld with a shape factor of 1.0 for different plate thicknesses (d). Figure 4.21 is based on Eq. 4.3. If Fig. 4.21 is applied to another form of weld, consideration should be given to the factor (F_2) given in Table 4.12. If the cooling time is to be determined for a particular combination of heat input and preheat temperature, then the heat input should first be multiplied by $(F_2)^{1/2}$. If, however, the heat input is to be determined for a particular combination of cooling time and preheat temperature, then it should be divided by $(F_2)^{1/2}$.

If, in the case of two (2)-dimensional heat flow, the actual plate thickness does not correspond exactly to the plate thickness shown on one of the diagrams in Fig. 4.21, the diagram closest to the actual plate thickness should be used. The cooling time should then be corrected in accordance with the plate thickness ratio. To do this, the cooling time taken from the diagram is multiplied by the square of the plate thickness taken from the diagram and then divided by the square of the actual plate thickness.

4.2.6 Lamellar Tearing

When welding, the weld shrinkage stresses impose tensile strains in CS or LAS plate or on inclusions paralleled to the rolling direction of the plate. The tensile strains (high through thickness) can separate the inclusions causing cracks (lamellar tearing). Excessive strains can further elongate the cracks (Fig. 4.22). In general, the type, shape, and distribution of nonmetallic inclusions, mainly of the MnS, MnSi, and oxide types, control the reduction in ductility. The inadequate deoxidization formed in steels at the mill is sensitive to lamellar tearing. The potential for lamellar tearing increases with the amount of inclusions in the plates being welded.

Normally the lamellar tearing occurs in rolled or forged (thick) products when fusion line is parallel to the surface (Fig. 4.23) or the welds caused by elongated sulfide inclusions (FeS) in the rolling direction. Lamellar tearing occurs mainly during production and not during service. More resistant materials might not tear unless used in situations which impose very high through-thickness strains.

The susceptibility can be determined by Short Transverse Reduction of Area (STRA).
Test per EN 10164, EN 895, AS 1855, AS 2205.2.1, or Lehigh Test. If the reduction in area as a result is:

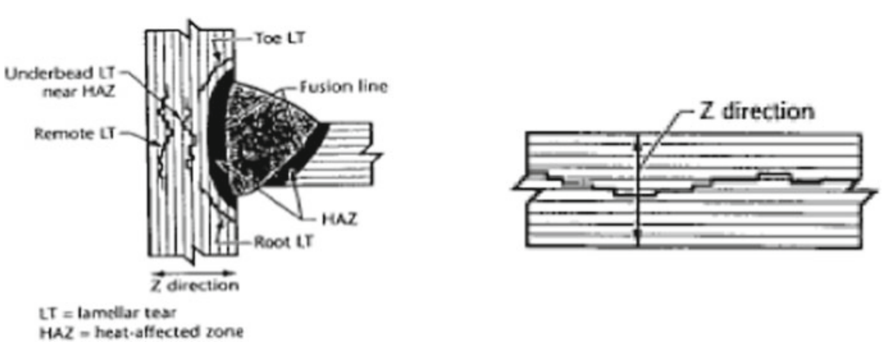
$>$15%: not susceptible
5–15%: moderately susceptible
$<$5%: highly susceptible

Additional Prevention of Lamellar Tearing: with Fig. 4.24

- Selection of acceptable materials, such as lower-strength and welding consumable materials.
- Symmetrical deposition of the weld passes to balance both sides/to minimize the strain (Fig. 4.24a).
- Prior buttering of the joints with a ductile layer (Fig. 4.24b).
- Selecting a joint geometry to minimize through-thickness strains (Fig. 4.24c and d).
- Removal and replacement of the susceptible material with ductile weld metal (Fig. 4.24e).
- Use of low sulfur steel.
- Use of high-deposition, low-hydrogen consumables.
- Use of fillet or partial joint penetration groove welds (Fig. 4.24f).
- Preheating provides that additional strain is not created.
- Selection of the fabrication sequence to minimize the restraint strains at the critical location.

References

- EN 10164 Steel products with improved deformation properties perpendicular to the surface of product-technical delivery conditions
- EN 895 Destructive Tests on Welds in Metallic Materials – Transverse tensile test
- AS 1855 Methods for the determination of transverse tensile properties of round steel pipe
- AS 2205.2.1 Methods for destructive testing of welds in metal – Transverse butt tensile tests



(a) (b)

Figure 4.22 Types of Lamellar Tearing. (**a**) Typical appearance of lamellar tears. (**b**) Step-like appearance of lamellar tears

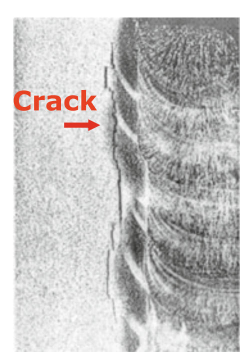


Figure 4.23 Lamellar tearing along to fusion line

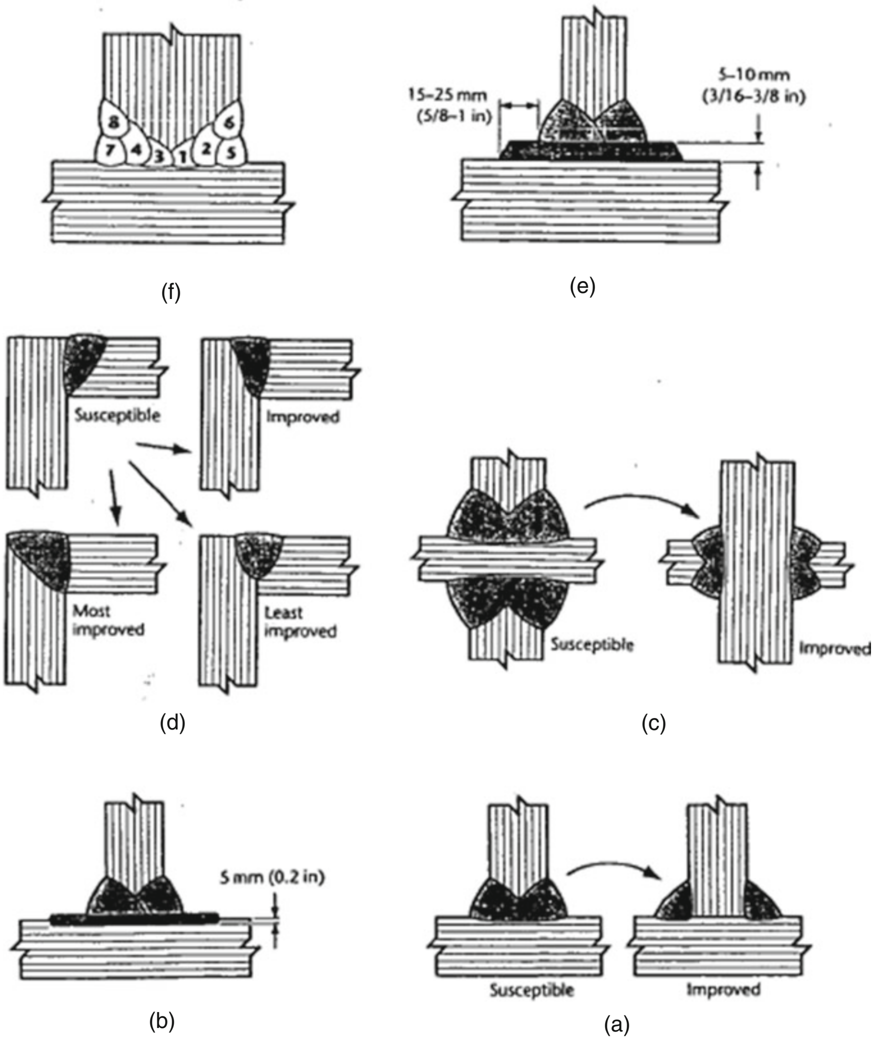


Figure 4.24 Prevention of lamellar tearing. (**a**) Use of fillet welds in preference to complete joint penetration groove welds. (**b**) Buttering of a joint by removal of susceptable material. (**c**) Reducing the weld size by placing in the thinner plate. (**d**) Selecting a joint to minimize through thickness strain. (**e**) Buttering of the joint. (**f**) Symmetrical deposition of weld passes. (Source: ASM Metal Handbook, Vol. 6)

– J.C.M. Farrar et al., Lamellar Tearing in Welded Steel Fabrication, TWI (1972)
– Significance and Control of Lamellar Tearing of Steel Plate in the Shipping Industry, SSC-290 (1979)
– A.D. Hattangadi et al., Lamellar tearing in fillet weldments of pressure vessel fabrication. Weld. J. 89s–96s (1983)
– L. Malik et al., Effect of joint restraint on lamellar tearing susceptibility in steel plates. Weld. J. 12s–20s (1979)

4.2.7 Solidification (Hot) Cracking of Carbon Steel

Solidification (hot) cracking of the weld metal is usually recognized as centerline cracking as seen in Fig. 4.10, Legend 13. It is more often found in root runs and, although frequently open at the surface and visible after deslagging, can be just below the surface and covered by up to 0.5 mm of sound metal. Solidification cracks can be deep and can seriously reduce the efficiency of a joint. When welding C-Mn steels, this type of cracking is most commonly found in SAW, rarely with SMAW, but it can sometimes be a problem with GMAW or FCAW. Solidification cracking is associated with impurities, particularly S and P (same mechanism with the solidification crack of ASS weld in Sects. 2.1.6.1 and 4.2.8), and is promoted by carbon picked up from the parent metal at high dilution levels, while Mn reduces the risk of cracking. The solidification crack susceptibility of weld metal is affected by both its composition and weld run geometry (depth/width ratio = D/W = 1.0–0.7 preferable). The open bevel angle of 75° for butt welding of piping spool normally can reduce the solidification cracking in geometry point of view (Fig. 4.25).

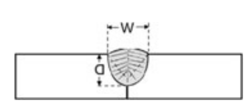


Figure 4.25 Width and depth on butt weld

The chemical composition of weld metal is determined by the composition of the filler material and the parent metal and the degree of dilution. The degree of dilution and weld run geometry both depend on the joint geometry (angle of bevel, root face and gap) and the welding parameters (current and voltage).

For SAW, the following formula has been developed for CS (C-Mn steel) in which the solidification (hot) crack susceptibility in arbitrary units known as units of crack susceptibility (UCS) has been related to the composition of the weld metal. Although developed for SAW, the use of the formula can be helpful in assessing the risk of solidification cracking for other welding processes (other than SAW) and other ferritic steels. The formula is as follows:

$$\mathbf{UCS} = \mathbf{230\,C^*} + \mathbf{190\,S} + \mathbf{75\,P} + \mathbf{45\,Nb} - \mathbf{12.3\,Si} - \mathbf{5.4\,Mn} - \mathbf{1} \quad (\text{source: EN 1011-2})$$

$$(\text{element: wt\% from weld metal of SAW})$$

$$C^* = 0.08\% \text{ if } C < 0.08\%.$$

The formula is applicable for SAW and in the following ranges:

Element limits used in this formula	Other element limits not used in this formula max.	
C: 0.03 to 0.23 wt% S: 0.010 to 0.050 wt% P: 0.010 to 0.045 wt% Si: 0.15 to 0.65 wt% Mn: 0.45 to 1.60 wt% Nb: 0 to 0.07 wt%	Ni: 1 wt% Cr: 0.5 wt5 Mo: 0.4 wt% V: 0.07 wt% Cu: 0.3 wt%	Ti: 0.02 wt% Al: 0.03 wt% B: 0.002 wt% Pb: 0.01 wt% Co: 0.03 wt%

Decision of Risk:
UCS $\leq$ 10 – *Low risk*
UCS > 20 (T-fillet) and >25 (butt weld) – *High risk*

Therefore, the chemical composition of CS weld metal performed by SAW should be controlled by <10 of UCS value.

References

- EN 1011-2
- N. Bailey et al., Solidification crack ferritic steel during SAW. Weld. J. 217s–231s (1978)
- S. Ohshita et al., Prevention of solidification cracking in very low CS welds. Weld. J. 129s–136s (1983)

4.2.8 *Solidification (Hot) Cracking of Austenitic Stainless Steel (ASS)*

The conventional 300 series SS during welding have a tendency towards shot shortness or tearing. The ferrite control in base metal and welding electrodes specified in Sect. 2.1.6.1 are principal requirements to avoid the solidification (hot) cracking. In addition, the following welding techniques may reduce the susceptibility of the hot cracking:

- Stringer bead is also recommended rather than weaving or oscillating bead techniques from side to side since there is a reduction in contraction stresses during welding; hence, cooling is more rapid through the hot-short temperature range.
- Short-circuiting welding can reduce the crack because of the lower dilution of base metal.
- Preheating to about 260 °C (500 °F) also can improve bead contour and then reduce hot cracking when using the stringer bead technique on 1 inch or thicker.

4.2.9 *Weld Crack Tests*

1. Self-Restraint Tests: (a) Lehigh test, (b) Tekken test (HAZ cold crack), (c) RRC (rigid restraint cracking) test, (d) Keyhole restraint cracking test, (e) Keyhole slotted-plate restraint test, (f) Houldcroft crack susceptibility test, (g) Circular patch test
2. Externally Loaded Tests: (a) Varestraint test, (b) Implant test, (c) TRC (tensile restraint cracking) test, Sigmajig test, (e) Russell test, (f) PVR (Programmierter Verformungs-Riss) test, (g) Transvarestraint test
3. Lamellar Tearing Tests – two conditions of Lehigh test: (a) Cantilever test, (b) Cranfield test
4. Underbead Cracking Tests: (a) Longitudinal bead test, (b) Cruciform test, (c) CTS (controlled thermal severity) test
5. Simulative tests: Gleeble hot ductility test, Cast pin tear test, CLR (constant load rupture) test

See AWS B4.0, API RP577, Welding Journal (Nov. 1973), National & University Lab (Oak Ridge, US Naval Research, Battelle, Lehigh, Japan, Australia, UK, etc.), and ASM Welding Integrity and Performance for more details.

4.3 Hydrogen Effect

4.3.1 *Hydrogen-Induced Cracking in Welds*

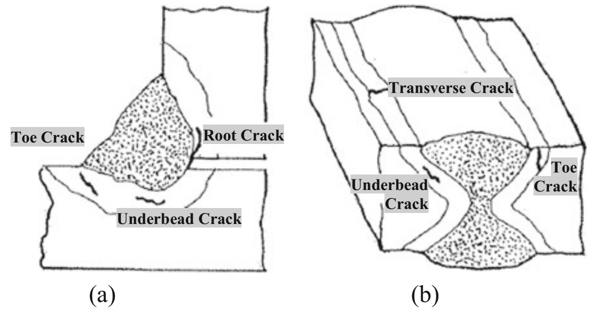


Figure 4.26 Hydrogen-induced cracking in HAZ. (**a**) Fillet welds. (**b**) Butt welds

The mechanism of hydrogen-induced cracking (also called cold cracking, delayed cracking, or HAC – hydrogen-assisted cracking from H_2O) in CS or LAS welds is somewhat different with HIC (hydrogen-induced cracking) of CS in wet H_2S (sour) service. The hydrogen in welding is picked up from the moisture of welding electrodes mostly (or uncleaned weld bevel, humid atmosphere, or service fluids for hot tap welding) as seen in Fig. 4.26, while the hydrogen in wet H_2S (sour) service comes from the dissociation of the H_2S in the condensed water. As a result, the hydrogen-induced cracking in welding normally occurs mostly at HAZs with a high carbon equivalent, high tensile strength, or high residual stress, while the HIC induced from dissociation of H_2S occurs with blistering-type cracks under the base metal surfaces or stepwise shape cracks through thickness in the base metal.

$$2H_2O \rightarrow O_2 + 2H_2$$

$H_2 \rightarrow 2H^+$: Penetrate/diffuse between lattices of metal
$2H^+ \rightarrow H_2$: metal crack due to great volume expansion

	Factors of hydrogen-induced cracking in welding	Remedy
In HAZ	1. *Hydrogen is present to a sufficient degree* (from flux or moisture in atmospheric). It is absorbed by the weld pool and some is transferred to the HAZ by diffusion. 2. *Tensile stresses act on the weld.* These arise inevitably from thermal contractions during cooling and may be supplemented by other stresses developed as a result of rigidity in the parts to be joined. 3. *Residual stresses* due to welding (from rapid cooling or restraint weld connection), cyclic load & pressure-temperature, hot temperature, and soil load/settlement in underground pipelines. 4. *A susceptibility HAZ microstructure is present.* That part of the HAZ which experiences a high enough temperature for the parent steel to transform rapidly from ferrite to austenite and back again produces microstructures which are usually harder and more susceptible to hydrogen embrittlement than other parts of the HAZ. Hydrogen cracks, when present, are invariably found in these transformed regions. 5. *A low temperature is reached.* The greatest risk of cracking occurs when the temperature near ambient is reached, and cracking may thus take place several hours (sometimes 2 or 3 days) after welding has been completed. Cracking is unlikely to occur in structural steels above 150 °C (302 °F) and in any steel above about 250 °C (482 °F).	– To reduce the sources of water entrainment to welds – To use lower T.S. steels (i.e., SMTS≤70 ksi) – To avoid the restraint weld joint or stress concentration – To stress-relieve the welds or control the cooling rate and heat input/preheat – If the PWHT is not applied (i.e., hot tapping), more careful consideration is required – Chemical control of base and weld metals (i.e., carbon equivalent: Ceq and Pcm) – To use low diffusible hydrogen containing welding consumables
In welds	Weld metal hydrogen cracking can be orientated longitudinally or transverse to the weld length, while in the transverse orientation, they can be either perpendicular or angled, typically at approximately 45° (e.g., chevron cracks), to the weld surface. The crack may be buried or may break the weld surface.	

4.3.2 *Diffusible Hydrogen (DH) Control*

Low hydrogen-containing welding consumables prevent delayed hydrogen-induced cracks in the weld metal and HAZ, which otherwise result from hydrogen charged into the metal during welding process. These cracks are difficult to detect with the nondestructive examination procedures used in most vessel fabrication shops (RT, visual, and other surface examinations typically), so that DH per below should be strongly controlled before the welding.

$$DH = (260a_1 + 30a_2 + 0.9b - 10)^{1/2} \text{ in basic flux (ml/100g of deposited metal)} \qquad \text{(Eq. 4.4)}$$

a_1: combined water in flux (%)
a_2: absorbed water in flux (%)
b: partial pressure of water vapor in atmospheric (mmHg)

Provided the HAZ has completed its transformation from austenite, an increase of temperature increases the rate of diffusion of hydrogen sufficiently to accelerate its removal from the weld. This effect is particularly marked in the range 20–150 °C (68–302 °F), as shown in Fig. 4.27.

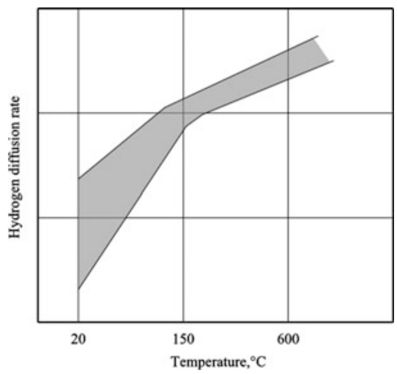


Figure 4.27 Diffusion rate of hydrogen through ferrite steels. (source: ASM, Welding steels without hydrogen cracking, 1973)

Figure 4.28 indicates the moisture chart for moisture content at each humidity per the exposed temperature.

AWS D1.1 steel structural welding code states that the maximum moisture content values of AWS A5.5 are not exceeded. Additionally, E70XX or E70XX-X (AWS A5.1 or A5.5) low-hydrogen electrode coverings shall be limited to a maximum moisture content not exceeding 0.4 wt%. Tables 4.13 shows optional supplemental diffusible hydrogen for welding electrodes of CS & LAS. Table 4.14 shows Susceptibility Index grouping as function of hydrogen level (H) and composition parameter (Pcm).

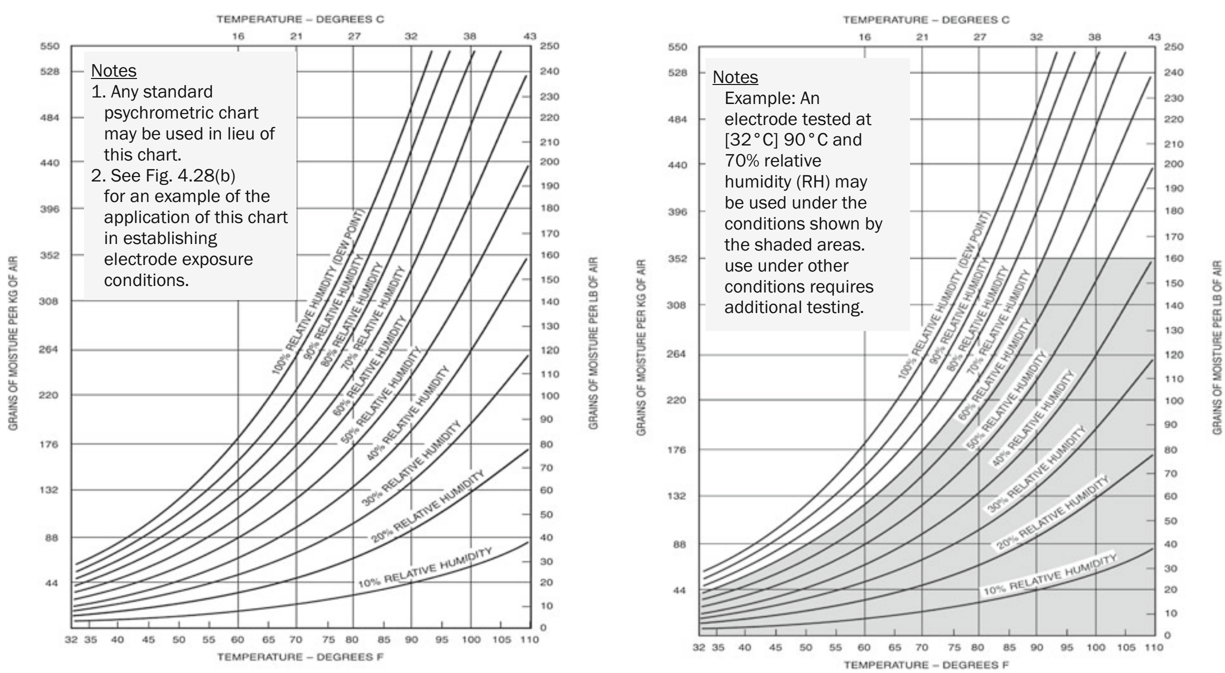
4.3.3 Hydrogen Control During Welding Process

1. General Requirements
   Electrodes should be stored in a dry environment (humidity controlled – RH $\geq$ 60%) and free of dirt grease, oil, rust, and mill scale. All low-hydrogen electrodes should be delivered in hermetically sealed containers that are free of apparent damage.
2. Main Dry Oven: maintained at a minimum 120–150 °C (248–302 °F) – e.g., AWS D1.1
3. Portable Dry Oven: maintained at a minimum 120–150 °C (248–302 °F)
4. Maximum Permissible Atmospheric Exposure (Recommended): $xx = 16$ or $18 =$ low hydrogen

$$\text{SMAW, E70}xx\text{: 4 hours; E80}xx\text{: 2 hours; E90}xx\text{: 1 hour; E100}xx\text{, E110}xx\text{, E120}xx\text{; 0.5 to 1 hour}$$

4.3.4 Hydrogen Control by Baking Out (Degassing) after Welding (Post-Heat)

In addition to hydrogen control of welding electrodes and base metal, hydrogen baking-out may be applied after repair welding of CS, LAS, and MSS used in H_2S/HF/Amine or Hydrogen Services or after new construction welding of heavy wall Cr-Mo steels, Grade 91 steel, ferritic steels with tensile properties enhanced by heat treatment (e.g., ASME Sec. VIII, Div. 1, UHT), and MSS. Hydrogen baking out calls out Post-Heat as well. See Sect. 4.4.3 Post-Heat After Welding for more details.



(a) (b)

Figure 4.28 Effectiveness of moisture per humidity and exposure time – E7018 Electrodes. (**a**) Temperature-moisture content chart to be used in conjunction with testing program to determine extended atmospheric exposure time of low-hydrogen SMAW electrodes. (**b**) Application of temperature-moisture content chart in determining atmospheric exposure time of low-hydrogen SMAW electrodes. (Source: AWS D1.1)

Table 4.13 Optional supplemental diffusible hydrogen of CS and LAS

AWS class	Optional supplemental diffusible hydrogen designator	Average diffusible hydrogen, max. (ml/100 g deposited metal)	Remark
All	H16	16.0	The suffix "R" (e.g., H4R) may be added. R identifies electrodes passing the absorbed moisture test after exposure to an environment of 80 °F (26.7 °C) and 80% relative humidity for a period of not less than 9 hours.
All	H8	8.0	
All	H4	4.0	
All	H2	2.0	

Source: ASME Sec. II, Part C and AWS
General Notes: Diffusible hydrogen test to be in accordance with AWS A4.3 and below:
– ASME Sec. II, Part C, SFA-5.1 (CS-SMAW) para. 18 and A8.2, and SFA-5.5 (LAS-SMAW) para. 17 and A8.1
– ASME Sec. II, Part C, SFA-5.17 (CS-SAW) para. 14, and SFA-5.23 (LAS-SAW) para. 14 and A9
– ASME Sec. II, Part C, SFA-5.20 (CS-FCAW) para. 16 and A8.2, and SFA-5.29 (LAS-FCAW) para. 15 and A8.2
– ASME Sec. II, Part C, SFA-5.28 (LAS-GMAW, GTAW. PAW) para. 14, and SFA-5.18 (CS-GMAW, GTAW. PAW) para. 15
– ASME Sec. II, Part C, SFA-5.36 (CS & LAS-FCAW, GMAW, GTAW. PAW) para. A2 and B9.2
– See Table 4.49 for Diffusible Hydrogen Limits for FCAW Consumables per SMYS of CS & LAS

Table 4.14 Susceptibility Index* grouping as function of hydrogen level, H, and composition parameter, Pcm

Hydrogen Level	Composition Parameter = Pcm				
	< 0.18	< 0.23	< 0.28	< 0.33	< 0.38
H1 (5ml/100g of deposited metal)	A	B	C	D	E
H2 (10ml/100g of deposited metal)	B	C	D	E	F
H3 (30ml/100g of deposited metal)	C	D	E	F	G

Source: CSA W59, Table P1 and AWS D1.1, Table H.1 Steel Structures
*Susceptibility Index = 12 Pcm + $\log_{10}$H where Pcm is from below and H is the level (1, 2, or 3)
Susceptibility Groups: A = 3.0, B = 3.1–3.5, C = 3.6–4.0, D = 4.1–4.5, E = 4.6–5.0, F = 5.1–5.5, and G = 5.6–7.0.
Note
1. Pcm = Crack Parameter in Welding; See Sect. 4.4.1 for more details
Commentary Note: The hydrogen level (H1, H2, H3) in CSA W59 is different with those (H4, H8, H16) in ASME Sec. II Part C

4.4 Preheat, Interpass Temperature, Post-Heat, Carbon Equivalent, and Heat Input

4.4.1 Carbon Equivalent (Ceq, Pcm, and CEN) and the Related Preheat Requirements

The equivalent carbon content concept as carbon equivalent is used on ferrous materials, typically carbon steel and cast iron, to determine hardenability during welding. This is then directly related to hydrogen-induced cold cracking, which is the most common weld defect for steel; thus it is most commonly used to determine weldability. Higher concentrations of carbon (C) and other alloying elements such as manganese (Mn), silicon (Si), chromium (Cr), molybdenum (Mo), vanadium (V), copper (Cu), niobium (Nb), phosphorous (P), and nickel (Ni) tend to increase hardness and decrease weldability. Carbon is the most critical element for the cold cracking, so that the limitation of sole carbon content can be also required in accordance with the experience in addition to carbon equivalent.

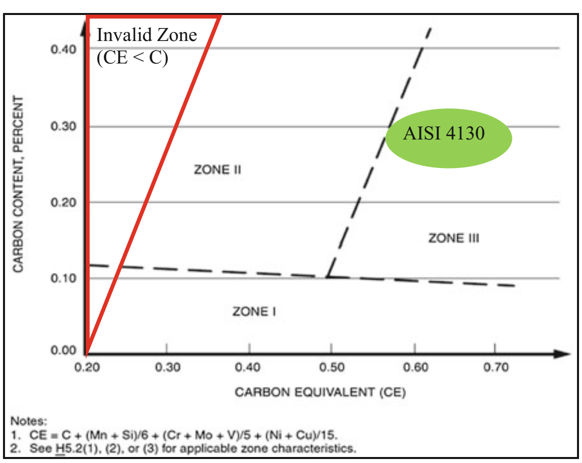


Figure 4.29 Graville diagram to check the weldability of CS. (Source: B. Graville, ASM Conference, p. 85–101, Nov. 1976 in Italy and AWS D1.1, Fig. H.1)

Figure 4.29 (Graville diagram) shows a simple weldability check of CS structure.

Zone I: Easy to Weld – Cracking is unlikely, but may occur with high hydrogen or high restraint. Use hydrogen control method to determine preheat for steels in this zone.

Zone II: Weldable – The hardness control method and selected hardness shall be used to determine minimum energy input *for single-pass fillet welds* without preheat. If the energy input is not practical, use hydrogen method to determine preheat.

For groove welds, the hydrogen control method shall be used to determine preheat.

For steels with high carbon, a minimum energy to control hardness and preheat to control hydrogen may be required for both types of welds, i.e., fillet and groove welds.

Zone III: Difficult to Weld – The hydrogen control method shall be used. Where heat input is restricted to preserve the HAZ properties (e.g., some quenched and tempered steels), the hydrogen control method should be used to determine preheat.

1. Carbon Content in Base Metal: 0.20 to 0.23% in clients' specifications
2. Carbon Equivalent (Ceq) of Base Metal

   Carbon Equivalent (Ceq) is used for the guideline for the decision of minimum preheating temperature as well as materials purchasing in order to prevent the crack of carbon steel during welding and/or on service in cracking environment (sour, caustic, etc.). Element: weight % for all formulas.

   (a) Carbon Equivalent of Cast Iron (Ceq)

$$C_{eq}/ = C + (Si + P)/3$$

(b) Carbon Equivalent (Ceq. %) and the Relative Preheat for Low Carbon Steels and Low Alloy Steels

1. Carbon Steels
   - (i) Ceq (Ceq_{IIW}) = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu) /15 → IIW, ASME, EN 1011-2 (Method A), BS2642, API 1104, API RP5C6, API 5L-PSL2 (C > 0.12%), and CSA W59
   - (ii) Ceq = C + (Mn + Si) /6 + (Cr + Mo + V) /5 + (Ni + Cu) /15 → AWS D1.1, API RP5C6, etc.
   - (iii) Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Si + Ni + Cu)/15 → API RP577, etc.
   - (iv) Ceq = C + Mn /6 + Si /24 + Ni /40 + Cr /5 + Mo /4 + V /14 → Japan JIS G 3106 & 3115
   - (v) Ceq (CEN) = C + F [Mn/6 + Si/24 + Cu/15 + Ni/20 + (Cr + Mo + V + Nb)/5 + 5B] → CSA Z245.1/11/12

C%	F	C%	F	C%	F	C%	F	C%	F
<0.06	0.53	0.09	0.62	0.13	0.80	0.17	0.94	0.21	0.99
0.06	0.54	0.10	0.66	0.14	0.85	0.18	0.96	>0.21	1.00
0.07	0.56	0.11	0.70	0.15	0.88	0.19	0.97		
0.08	0.58	0.12	0.75	0.16	0.92	0.20	0.98		

This table is based on F = 0.75 + 0.25 tanh [20 × (C% – 0.12)] by N. Yurioka et al.

   - (vi) Ceq = C + Mn /6 + (Cr -V) /10 - Mo/50 + N/20 + Cu/40 → Winterton's Formula
   - (vii) Ceq = C + Mn /6 + (Cr + Mo)/5 + V/3 + Nb/(4xC) + 0.0001/S → Cottrell's Formula
   - (viii) Ceq = C + (Mn + Cu)/20 + (Cr + V) /10 + Mo/15 + N/40+ Si/25 → Mannesmann's Formula
   - (ix) Ceq = C + Mn/16 + Cr/23 + Mo/7 + V/9 − Ni/50 + Nb/8 → Graville's Formula
   - (x) Ceq = C + Mn/20 + Ni/15 + (Cr + Mo + V)/10 → British Welding Research Association

   ASME PCC-2 recommends to preheat for CS welds as below:

   CE ≤ 0.45%; preheat is normally optional
   0.45% ≤ CE ≤ 0.60%; preheat 200–400 °F
   CE > 0.60%; preheat 400–700 °F
   where CE > 0.5, delaying final NDE for at least 24 hr

2. Low Alloy Steels (fine grained)

$$CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40 \quad \rightarrow \quad EN\ 1011\text{-}2\ (Method\ B)$$ – See Fig. 4.30.

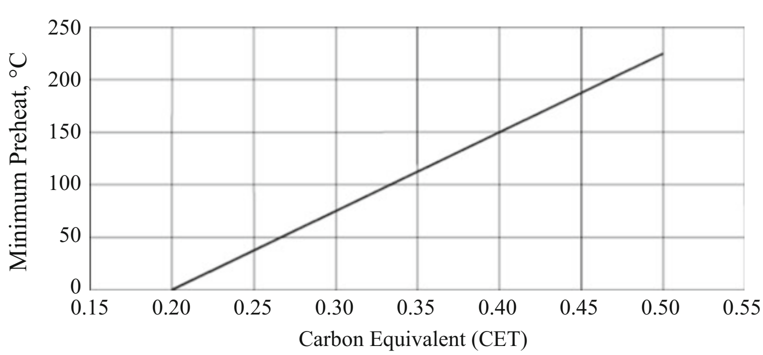


Figure 4.30 Preheat temperature as a function of CET of LAS. (Source: BS EN 1011-2 Method B)

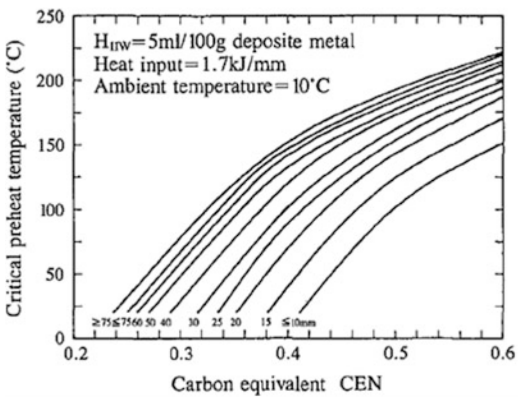


Figure 4.31 Critical curves per thickness by preheat temperature prediction method. (Source: Nippon Steel Technical Report, No.65, 1995)

where C (0.05–0.32%), Si (≤0.8%), Mn (0.5–0.9%), Cr (≤1.5%), Cu (≤0.7%), Mo (≤0.75%), Nb (≤0.06%), Ni (≤2.5%), Ti (≤0.12%), V (≤0.18%), and B (≤0.005%)

(c) Carbon Equivalent for Extremely Low Carbon Steel (ISO & Bessyo Cracking Parameter – Pcm, %)
Pcm is more appropriate than conventional carbon equivalent (Ceq) for steels, such as low carbon steels, HSLA (high strength low alloy) steels, or TMCP (thermomechanical-controlled process) steels. Pcm carbon equivalent formula was developed for steels with low carbon contents (≤0.10 or 0.12%) and with tensile strengths of 414–896 MPa (60–130 ksi) in Japan.

$$\text{Pcm}\ (\%) = \text{C} + \text{Si}/30 + (\text{Mn} + \text{Cu} + \text{Cr})/20 + \text{Ni}/60 + \text{Mo}/15 + \text{V}/10 + 5\text{B}\ [\text{element, wt\%}]$$

Pcm is typically applied for pipelines [e.g., API 5L-PSL2 (C ≤ 0.12%)], risers, and offshore structures. ASME PCC-2 allows to use this formula when the C content in the carbon steel is 0.17% and below, or where high strength steels are involved. Also, ASME PCC-2 and API RP5C6 recommend to preheat as below:

$$\text{P}_{\text{cm}} \leq 0.15\%;\ \text{preheat is normally optional.}$$
$$0.15\% < \text{P}_{\text{cm}} \leq 0.26 - 0.28\%;\ \text{preheat}\ 93 - 204^{\circ}\text{C}\ \left(200 - 400^{\circ}\text{F}\right).$$
$$\text{P}_{\text{cm}} > 0.26 - 0.28\%;\ \text{preheat}\ 204 - 371^{\circ}\text{C}\ \left(400 - 700^{\circ}\text{F}\right).$$

Dr. N. Yurioka illustrated a good correlation between CEN (Carbon Equivalent Number) and Pcm and between CEN and Ceg for structural steels, low alloy steels (Ni-Cr-Mo type), and carbon steels. From these comparisons, the following relationships were derived:

$$\text{CEN} = 2\text{P}_{\text{cm}} - 0.092\ \ (\text{where}\ \ C \leq 0.17\%)$$
$$\text{CEN} = \text{Ceg-}_{\text{IIW}} + 0.012\ \ (\text{where}\ \ C > 0.17\%)$$

Preheating temperature for fillet welds may be predicted by the Controlled Thermal Severity (CTS) test per BS 7363, while predictions for butt welds are based on several weldability tests such as the Tekken test per Japanese Standard JIS Z3703 (Welding – Guidance on the Measurement of Preheating Temperature, Interpass Temperature and Preheat Maintenance Temperature) or JIS Z3158 (Y-groove weld crack test). Figure 4.31 shows the relationship between the CEN calculated from the experimental data of various steels and the critical preheat temperature determined by the y-groove weld cracking test. The critical preheat temperature varies with the plate thickness and CEN at the fixed heat input and diffusible hydrogen content. Figure 4.31 also indicates the recommended preheating temperatures of carbon and low alloy steels according to the Pcm and thickness to avoid crack during/after welding. See Table 4.15 for Preheat Requirements per Carbon Equivalent.

The following shows the max. Pcm requirements in several codes and standards:

– API Spec 5L (Line Pipe): max. 0.25 Pcm for all PSL2 pipes
– API Spec 2W (Steel Plates for Offshore Structures, Produced by TMCP): max. 0.22–0.25 per grade and thickness
– AWS D1.1 Structural Welding Code

Table 4.15 Minimum preheat temperature per carbon equivalent (for reference)(2)

Thickness, *t* mm (in.)	IIW carbon equivalent(1), % (amb = ambient temperature)				
	<0.35	0.35–0.45	0.45–0.55	0.55–0.65	>0.65
Non-low-hydrogen processes					
t ≤ 12.7 (1/2)	amb	amb	amb-93 °C (200 °F)	93~177 °C (200–350 °F)	177~232 °C (350–450 °F)
12.7 (1/2) < *t* ≤ 25.4 (1)	amb	amb-93 °C (200 °F)	93~177 °C (200–350 °F)	177~232 °C (350–450 °F)	232~343 °C (450–650 °F)
t > 12.7 (1)	amb-93 °C (200 °F)	93~177 °C (200–350 °F)	177~232 °C (350–450 °F)	450–650 °F (232~343 °C)	232~343 °C (450–650 °F)
Low-hydrogen processes					
t ≤ 12.7 (1/2)	amb	amb	Ambient	amb-93 °C (200 °F)	93~177 °C (200–350 °F)
12.7 (1/2) < *t* ≤ 25.4 (1)	amb	amb	amb-93 °C (200 °F)	93~177 °C (200–350 °F)	177~232 °C (350–450 °F)
t > 12.7 (1)	amb	amb-93 °C (200 °F)	93~177 °C (200–350 °F)	177~232 °C (350–450 °F)	232~343 °C (450–650 °F)

Notes: (source: IIW)
(1)IIW Carbon Equivalent, Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15
(2)Preheat recommendation from Winterton's Ceq = C + Mn/6 + (Cr − V)/10 − Mo/50 + N/20 + Cu/40
<0.48 : Weldable with ordinary electrode and preheat 90–200 °C (194–392 °F) per the thickness
0.48–0.55: Weldable with low-hydrogen electrode and preheat 200–370 °C (392–698 °F) per the thickness
>0.55 : Difficult to weld. Use only austenitic electrodes, preheat >370 °C (698 °F)

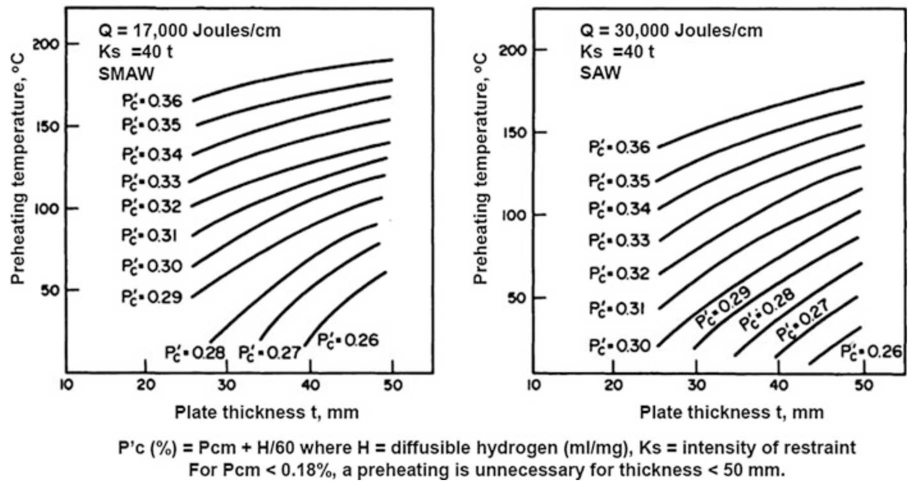


Figure 4.32 Recommended preheating temperature as per Pcm and thicknesses. (Source: Koichi Masubuchi, Analysis of Welded Structures, Elsevier, 1980)

- AWS D14.3 Specification of Welding Earth Moving and Construction Equipment
- CSA W59 Welded Steel Construction
- JIS B8285 Welding procedure qualification test for pressure vessels
- DIN EN 1011 Welding - Recommendations for welding of metallic materials
- ABS Part 2 Rules for Materials and Welding

Pcm is an accurate index to find the weldability and minimum preheating temperature of low carbon steel as seen in Fig. 4.32.

4.4.2 Preheat and Interpass Temperature for Welding

4.4.2.1 Preheat

Preheating is to prevent cracking on weld and HAZ due to remained hydrogen and/or residual stresses by high temperature gradient on welds. The preheating temperature is decided from the following factors: base metal (chemical composition and strength/hardness), welding (electrode-hydrogen contents, heat inputs, etc.), and joint configurations (thicknesses, joint configuration-restraint, residual stresses). The preheat measurement should be performed at both internal and external surfaces for heavy wall welding. BS EN 1011-2 states that the points of temperature measurement should be 75 mm (3 in.) as a minimum from the weld centerline unless otherwise required. ASME B31.3 states that the preheat zone shall extend at least 25 mm (1 in.) beyond each edge of the weld. See EN-ISO 13916 for more details.

API RP582 states the following for preheat:

(i) For pipe welding of ASME P-1, Group 1, carbon steel base metal, the root pass and second pass of single-groove welds, regardless of base metal thickness, may be welded with cellulose type coated electrodes. In addition, ASME P-1, Group 2, materials may have the root and hot pass welded with cellulose electrodes, provided a minimum preheat of 149 °C (300 °F) is used and maintained until the joint is completed or 13 mm (0.5 in.) of weld thickness is completed.
(ii) Preheat, where required, applies to all welding, tack welding, and thermal cutting. Minimum preheat requirements shall follow the applicable code and recommended practice such as ASME Sec. VIII, Div. 1 Appendix R, ASME B31.3 Table 330.1.1, API 934-A, API 934-C, AWS D1.1 Annex XI, etc.
(iii) Any recommendations or requirements for preheat listed in the relevant code shall be considered mandatory.
(iv) The preheat temperature shall be applied and, for low alloy steels, maintained until PWHT throughout the entire thickness of the weld and at least 75 mm (3 in.) on each side of the weld. Consideration should be given to lowering the preheat temperature below Mf (martensite finish point) prior to PWHT.

(a) Benefits of Preheat
    Table 4.16 shows a summary for the mechanisms and benefits of preheat prior to welding.
(b) Applicable Codes for Preheat and/or Interpass Temperature of Welding
    - All Welding in ASME: ASME Sec. II, part C – See SFA-5.4/5.5/5.10/5.18/5.22/5.23/5.28/5.29/5.36.
    - Boilers: ASME Sec. 1, Appendix R (Table 4.17 in this book).
    - Boilers: ASME Sec. I, PW-40.2 (Table 4.18 in this book).
    - Boilers: ASME Sec. I, Appendix A-100 (Table 4.19 in this book).
    - Pressure Vessels: ASME Sec. VIII, Div. 1, Nonmandatory Appendix R (Table 4.20 in this book).
    - Pressure Vessels-Alternative: ASME Sec. VIII, Div. 2 Table 6.7 (Table 4.21 in this book).
    - Piping for Process: ASME B31.3, Table 330.1.1 (Tables 4.22 and 4.23 in this book).

Table 4.16 Benefits and mechanisms of preheat before welding

Benefits	Mechanism
Reduce the level of thermal stress	Thermal stresses are set up as a molten weld pool cools. Cracking can occur both during and after welding when the colder parent metal resists the inevitable contraction of the weld metal. Preheat reduces the temperature differentials between the weld metal and the parent metal, thus minimizing the tendency to crack.
Compensate for high heat loss	Thick-section carbon steel and copper and aluminum alloys having high thermal conductivity benefit from preheat before welding. The cooling rate of the deposited weld metal is reduced allowing time for the weld metal to fuse properly with the adjacent base metal.
Minimize the rate of welding hardening	Weld metal and the adjoining HAZ can harden and crack when rapidly cooled from high temperature. Preheating the weld and HAZ generally prevents both from becoming extremely hard by reducing the rate of cooling.
Reduce porosity	Water is broken down into its elements, hydrogen and oxygen, by the welding arc ($H_2O \rightarrow 2H + 1/2O_2$). The hydrogen easily dissolves in the weld metal at its high temperatures and can produce weld porosity during solidification. Preheating drives off moisture from the joint surface eliminating a prime source of water.
Reduce hydrogen cracking	Electrode coatings and fluxes can often introduce moisture directly to the arc and weld pool. The resulting hydrogen increases greatly the porosity of weld and/or HAZ cracking. Preheat slows down the cooling rate allowing the hydrogen to escape.
Improve microstructure of HAZ	Low alloy steels containing such elements as Cr, Ni, Mo, and V are susceptible to cracking in the HAZ. Preheating improves the microstructure of this zone by reducing the postweld cooling rate, thus leading to formation of more desirable and more ductile microstructures. Cracking by hardening, particularly under the surface, is minimized.

Table 4.17 Preheat requirements – ASME Sec. I, Appendix A-100.4 (Nonmandatory)

Material	Min. preheat temperature	Notes
P-No. 1, Gr.1, 2, 3 [Cmax >0.3%, t > 25 mm (1″)]	79 °C (175 °F)	
P-No. 1 [other than above]	10 °C (50 °F)	
P-No. 3, Gr.1, 2, 3 [MSTS>480 MPa (70 ksi) or t > 16 mm (5/8″)]	79 °C (175 °F)	
P-No. 3 [other than above]	10 °C (50 °F)	
P-No. 4, Gr.1, 2, 3 [MSTS>410 MPa (60 ksi) or t > 13 mm (0.5″)]	121 °C (250 °F)	
P-No. 4 [other than above]	10 °C (50 °F)	
P-No. 5A/5B [MSTS>410 MPa (60 ksi), or min. Cr > 6% and t > 13 mm (0.5″)]	204 °C (400 °F)	
P-No. 5A/5B [other than above]	149 °C 300 °F)	
P-No. 6	204 °C (400 °F)	
P-No. 7	None	
P-No. 8	None	
P-No. 9A, Gr.1	121 °C (250 °F)	
P-No. 9B, Gr.1	149 °C (300 °F)	
P-No. 10A, Gr.1	79 °C (175 °F)	
P-No. 10B, Gr.2	121 °C (250 °F)	
P-No. 10C, Gr.3	–	(1)
P-No. 10D, Gr.4	149 °C (300 °F)	(2)
P-No. 10F, Gr.6	121 °C (250 °F)	
P-No. 10I, Gr.1	149 °C (300 °F)	(2)
P-No. 11A, Gr. 1, 2, 3	–	(1)
P-No. 11A, Gr. 4	121 °C (250 °F)	
P-No. 11A, Gr. 1, 2, 3, 4, 5, 6, 7	–	(1)
P-No. 15E [MSTS>410 MPa (60 ksi) or min. Cr > 6% and t > 13 mm (0.5″)]	204 °C (400 °F)	
P-No. 15E [other than above]	149 °C (300 °F)	

Notes: See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
(1)To give the interpass temperature for various thicknesses to avoid detrimental effects on mechanical properties
(2)Interpass temperature: 177–232 °C (350– 450 °F)
Commentary Note: Recommended to apply Table 4.33 and 4.37 for the missing P-No. materials in this table unless otherwise specified a certain code or standards

Table 4.18 Preheat requirements for repair welding of PWHT'd pressure vessels to avoid additional PWHT(1). Tube-to-header or tube-to-drum repair welded joints – ASME Sec. I, PW-40.2

Material	Min. preheat temperature for rework welding
P-No. 3 Gr.1/2	95 °C (200 °F)
P-No. 4	120 °C (250 °F)
P-No. 5A	150 °C (300 °F)

Note: See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
(1)This table is applicable for minor local repair welding without repeating the PWHT. So, the depth of any rework welding below the surface shall not exceed the smaller of 10% of the thickness of the drum or header, or 50% of the wall thickness of the tube

Table 4.19 Preheat requirements – ASME Sec. I, Appendix A-100

Material	Min. preheat temperature	Notes
P-No. 1-Gr.1, 2, 3 [Cmax > 0.3%, *t* > 1″ (25 mm)]	80 °C (175 °F)	
P-No. 1 [other than above]	10 °C (50 °F)	
P-No. 3, Gr.1, 2, 3 [MSTS > 70 ksi/ 480 MPa or *t* > 5/8″ (16 mm)]	80 °C (175 °F)	
P-No. 3 [other than above]	10 °C (50 °F)	
P-No. 4, Gr. 1, 2, 3 [MSTS > 60 ksi/ 410 MPa or *t* > 0.5″ (13 mm)]	120 °C (250 °F)	
P-No. 4 [other than above]	10 °C (50 °F)	
P-No. 5A/5B [MSTS > 60 ksi/ 410 MPa, or min. Cr > 6% and *t* > 0.5″ (13 mm)]	200 °C (400 °F)	
P-No. 5A/5B [other than above]	150 °C (300 °F)	
P-No. 6	200 °C (400 °F)	
P-No. 7	None	
P-No. 8	None	
P-No. 10I	150 °C (300 °F)	(1)
P-No. 15E [MSTS>60 ksi/ 410 MPa, or min. Cr > 6% and *t* > 0.5″ (13 mm)]	200 °C (400 °F)	
P-No. 15E [other than above]	150 °C (300 °F)	

Note: See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
(1)Interpass temperature: 175–230 °C (350–450 °F)
Commentary Note: Recommended to apply Table 4.33 and 4.37 for the missing P-No. materials in this table unless otherwise specified a certain code or standards.

Table 4.20 Preheat requirements – ASME Sec. VIII, Div. 1 (Nonmandatory Appendix R)

Material	Min. preheat temperature	Notes
P-No. 1-Gr.1, 2, 3 [Cmax > 0.3%, *t* > 25 mm (1″)]	79 °C (175 °F)	
P-No. 1 [other than above]	10 °C (50 °F)	
P-No. 3, Gr.1, 2, 3 [MSTS > 480 MPa (70 ksi) or *t* > 16 mm (5/8″)]	79 °C (175 °F)	
P-No. 3 [other than above]	10 °C (50 °F)	
P-No. 4, Gr. 1 & 2 [MSTS > 410 MPa (60 ksi) or *t* > 13 mm (0.5″)]	121 °C (250 °F)	
P-No. 4 [other than above]	10 °C (50 °F)	
P-No. 5A/5B-Gr.1 [MSTS > 410 MPa (60 ksi) or min. Cr > 6% and *t* > 13 mm (0.5″)]	204 °C (400 °F)	
P-No. 5A/5B [other than above]	149 °C (300 °F)	
P-No. 6-Gr. 1, 2, 3	204 °C (400 °F)	
P-No. 7-Gr. 1 & 2	None	
P-No. 8-Gr. 1 & 2	None	
P-No. 9A, Gr.1	121 °C (250 °F)	
P-No. 9B, Gr.1	149° (300 °F)	
P-No. 10A, Gr.1	79 °C (175 °F)	
P-No. 10B, Gr.2	121 °C (250 °F)	
P-No. 10C, Gr.3	79 °C (175 °F)	(1)
P-No. 10D, Gr.4	149 °C (300 °F)	(2)
P-No. 10I, Gr.1	149 °C (300 °F)	
P-No. 11A, Gr.1	None	(3)
P-No. 11A, Gr.2 & 3 [MSTS > 410 MPa (60 ksi) or min. Cr > 6% and *t* > 13 mm (0.5″)]	205 °C (400 °F)	
P-No. 11A, Gr.2 & 3 [other than above]	149 °C 300 °F)	
P-No. 11A, Gr.4	121 °C (250 °F)	
P-No. 11B, Gr.1, 2, 3, 4, 5, 6, 7 [MSTS > 480 MPa (70 ksi) or *t* > 16 mm (5/8″)]	79 °C (175 °F)	(3)
P-No. 11B, Gr.1, 2, 3, 4, 5, 6, 7 [other than above]	10 °C (50 °F)	
P-No. 15E-Gr.1 [MSTS > 410 MPa (60 ksi)], or min. Cr > 6% and *t* > 13 mm (0.5″)	205 °C (400 °F)	
P-No. 15E-Gr.1 [other than above]	150 °C (300 °F)	

Notes: See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
(1)Preheat is neither required nor prohibited, and consideration shall be given to the limitation of interpass temperature for various thicknesses to avoid detrimental effects on the mechanical properties of heat-treated material
(2)Interpass temperature: 177 °C (350 °F) to 232 °C (450 °F)
(3)Consideration shall be given to the limitation of interpass temperature for various thicknesses to avoid detrimental effects on the mechanical properties of heat-treated materials
Commentary Note
a. Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard.

Table 4.21 Preheat requirements – ASME Sec. VIII, Div. 2, Table 6.7

P-No.	Minimum preheat temperature
1	80 °C (175 °F) for a material which has maximum C > 0.30% and thickness at the joint of >25 mm (1 in.) 10 °C (50 °F) for all other materials
3	80 °C (175 °F) for a material which has either SMTS of >480 MPa (70 ksi) or thickness at the joint of >16 mm (5/8 in.) 10 °C (50 °F) for all other materials
4	120 °C (250 °F) for a material which has either SMTS of >410 MPa (60 ksi) or thickness at the joint of >13 mm (1/2 in.) 10 °C (50 °F) for all other materials
5A, 5B, 5C, 15E	205 °C (400 °F) for a material which has either SMTS of >410 MPa (60 ksi) or has both specified minimum Cr content of >6.0% and thickness at the joint of >13 mm (1/2 in.) 150 °C (300 °F) for all other materials
6	205 °C (400 °F)
7	None
8	None
9A and 9B	150 °C (300 °F)
10A	150 °C (300 °F) with interpass temperature maintained between 175 °C and 230 °C (350 °F and 450 °F)
11A	For 5% and 9% nickel steel preheat is neither required nor prohibited
11B Gr. Gr. 1–6	80 °C (175 °F)
21–24, inclusive	None
31–35, inclusive	None
41–44, inclusive	None

Note: See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
Commentary Note
[a]Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard

Table 4.22 Preheat and interpass temperature requirements – ASME B31.3, Table 330.1.1

Base metal, P-No.	Thickness, mm (in.)	Additional limits	Min. preheat temperature	Max. interpass temperature	Remark
1	≤25 (1.0)	C > 0.30 wt%	10 °C (50 °F)	[a]	
	>25 (1.0)	C ≤ 0.30 wt%	10 °C (50 °F)	[a]	
	>25 (1.0)	C > 0.30 wt%	95 °C (200 °F)	[a]	
3	≤13 (0.5)	SMTS ≤450 MPa (65 ksi)	10 °C (50 °F)	[a]	
	>13 (0.5)	SMTS ≤450 MPa (65 ksi)	95 °C (200 °F)	[a]	
	All	SMTS >450 MPa (65 ksi)	95 °C (200 °F)	[a]	
4	All	–	120 °C (250 °F)	[a]	
5A	All	SMTS ≤414 MPa (60 ksi)	150 °C (300 °F)	[a]	
	All	SMTS >414 MPa (60 ksi)	200 °C (400 °F)	[a]	
5B	All	SMTS ≤414 MPa (60 ksi)	150 °C (300 °F)	[a]	
	All	SMTS >414 MPa (60 ksi)	200 °C (400 °F)	[a]	
	>13 (1/2)	Cr > 6.0 wt%[1]	200 °C (400 °F)	[a]	
6	All	–	200 °C (400 °F)	315 °C (600 °F)	
9A	All	–	120 °C (250 °F)	[a]	
9B	All	–	150 °C (300 °F)	[a]	
10I	All	–	150 °C (300 °F)	230 °C (450 °F)	
15E	All	–	200 °C (400 °F)	[a]	
All others	–	–	10 °C (50 °F)	[a]	[b]

Notes: See Sect. 2.1.10.1 for more details of P-No. and Gr. No
[1]Chemical composition may be based on ladle or product analysis or per specification limits
Commentary Notes
[a]To follow the approved WPS/PQR
[b]Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard.

- Piping for Power: ASME B31.1, Table 131.4.1 (Table 4.24 in this book).
- Pipelines and Piping Systems: ASME B31.4, Transportation Systems for Liquids and Slurries, 434.8.9 and ASME B31.8 Gas Transmission and Distribution Piping Systems, B824.5, and ASME B31.12 Hydrogen Piping and Pipelines, GR-3.5 and IP-9.8 (Table 4.25 in this book).
- Welding of Pipelines and Piping Systems: API 1104, 7.11.
- Welding of Cr-Mo Steel Piping and Tubing: AWS D10.8, Table 3 (Table 4.26 in this book).
- Tanks for Low Pressure Storage: API 620, Table 6.2 (Table 4.27 in this book).
- Tanks for Welded Oil Storage: API 650, Table 7.1a (Table 4.28/4.28a in this book).
- Castings for Low Temperature Ferritic/Martensitic Steel: ASTM A352, Table 2 (Table 4.29 in this book).

Table 4.23 Preheat requirements – ASME B31.3, Table 330.1.1 (2012-Old Version – only for reference)

Base metal-no. or S-no.[(1)]	Weld metal analysis no.[(2)]	Base metal group	Nominal wall thickness		SMTS base metal		Min. temperature			
							Required		Recommended in several companies	
			mm	inch	MPa	ksi	°C	°F	°C	°F
1	1	Carbon steel	<25 ≥25 All	<1 ≥1 All	≤490 All >490	≤71 All >71	... ...	... ...	10 79 79	50 175 175
3	2,11	Alloy steels, Cr ≤1/2%	< 13 ≥13 All	<1/2 ≥1/2 All	≤490 All > 490	≤71 All >71	... ...	... ...	10 79 79	50 175 175
4	3	Alloy steels, 1/2% < Cr ≤ 2%	All	All	All	All	149	300	...	...
5A, 5B, 5C	4, 5,	Alloy steels, 2 1/4% ≤ Cr ≤ 10%	All	All	All	All	177	350	...	...
6	6	High alloy steels martensite	All	All	All	All	...	...	149[(3)]	300[(3)]
7	7	High alloy steels ferrite	All	All	All	All	...	...	10	50
8	8,9	High alloy steels austenite	All	All	All	All	...	...	10	50
9A, 9B	10	Nickel alloy steels	All	All	All	All	...	...	93	200
10	...	Cr-Cu steel	All	All	All	All	149–204	300–400	...	...
10I	...	27Cr steel	All	All	All	All	149[(4)]	300[(4)]	...	...
11A SG 1	...	8Ni, 9Ni steel	All	All	All	All	...	...	10	50
11A SG 2	...	5Ni steel	All	All	All	All	10	50	...	...
21–52	...	...	All	All	All	All	...	...	10	50

Notes
[(1)]P-Number or S-Number from ASME BPVC, Section IX, QW/QB-422. See Sect. 2.1.10.1 for more details of P-No. and Gr. No
[(2)]A-Number from Section IX, QW-442
[(3)]Maximum interpass temperature 316 °C (600 °F)
[(4)]Maintain interpass temperature between 177 °C and 232 °C (350 °F and 450 °F)
Commentary Notes
[(a)]This table is only for existing materials which were constructed before 2012. See Tables 2.99 and 2.100, and Sect. 2.6.2 in this book for all current P and Gr. Numbers
[(b)]P-No. 10 does not exist in the current version due to being withdrawn
[(c)]Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard.

Table 4.24 Preheat and interpass temperature requirements – ASME B31.1, Table 131.4.1

Base metal, P-No.	Base metal group	Thickness, mm (in.)	Additional limits	Min. preheat temperature	Max. interpass temperature
1	CS	≤25 (1.0)	C > 0.30%[(1)]	10 °C (50 °F)	[(3)]
		>25 (1.0)	C ≤ 0.30%[(1)]	10 °C (50 °F)	[(3)]
		>25 (1.0)	C > 0.30%[(1)]	95 °C (200 °F)	[(3)]
3	LAS	≤13 (1/2)	SMTS ≤450 MPa (65 ksi)	10 °C (50 °F)	[(3)]
	(Cr ≤ 0.5%)	>13 (1/2)	SMTS ≤450 MPa (65 ksi)	95 °C (200 °F)	[(3)]
		All	SMTS >450 MPa (65 ksi)	95 °C (200 °F)	[(3)]
4	LAS (0.5% < Cr ≤ 2%)	All	–	120 °C (250 °F)	[(3)]
5A	LAS	All	SMTS ≤414 MPa (60 ksi)	150 °C (300 °F)	[(3)]
		All	SMTS >414 MPa (60 ksi)	200 °C (400 °F)	[(3)]
5B	LAS	All	SMTS ≤414 MPa (60 ksi)	150 °C (300 °F)	[(3)]
		All	SMTS >414 MPa (60 ksi)	200 °C (400 °F)	[(3)]
		>13 (1/2)	Cr > 6.0%[(1)]	200 °C (400 °F)	[(3)]
6	MSS	All	–	200 °C (400 °F)	315 °C (600 °F)
9A	Ni alloy steel	All	–	120 °C (250 °F)	[(3)]
9B	Ni alloy steel	All	–	150 °C (300 °F)	[(3)]
10I	27Cr steel	All	–	150 °C (300 °F)	[(2)]
15E	9Cr-1Mo-V CSEF steel	All	–	200 °C (400 °F)	[(3)]
All others		–	–	10 °C (50 °F)	[(3)]

Commentary Notes: thickness = nominal thickness, CSEF = creep strength enhanced ferritic, element: weight %
See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
[(1)]Chemical composition may be based on ladle or product analysis, or per specification limits
[(2)]Maintain interpass temperature between 150 °C and 230 °C (300 °F and 450 °F)
[(3)]Per the approved WPS/PQR
[(4)]Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard.

Table 4.25 Preheat temperature requirements for hydrogen piping and pipelines – ASME B31.12, Table GR-3.5-1

Base metal, P-No.	Base metal group[(1)]	Thickness, mm (in.)[(2)]	Additional limits	Min. preheat temperature	Max. interpass temperature [(5)]
1	CS	<25 (1.0)	SMTS ≤490 MPa (71 ksi)	80 °C (175 °F)	[(3)]
		≥25 (1.0)	All	80 °C (175 °F)	[(3)]
		All	SMTS >490 MPa (71 ksi)	80 °C (175 °F)	[(3)]
3	LAS	≤13 (1/2)	SMTS ≤490 MPa (71 ksi)	80 °C (175 °F)	[(3)]
	(Cr ≤ 0.5%)	>13 (1/2)	All	80 °C (175 °F)	[(3)]
		All	SMTS >490 MPa (71 ksi)	80 °C (175 °F)	[(3)]
4	LAS (0.5% < Cr ≤ 2%)	All	All	150 °C (300 °F)	[(3)]
5A & 5B	LAS (2.25% ≤ Cr ≤ 9%)	All	All	175 °C (350 °F)	[(3)]
[(4)]	Nonferrous	All	All	24 °C (75 °F)	[(3)]

Commentary Notes: thickness = nominal thickness, element: weight %. See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
[(1)]Chemical composition may be based on ladle or product analysis, or per specification limits
[(2)]See ASME B31.12, GR-3.6.2 for governing thickness
[(3)]Per the approved WPS/PQR
[(4)]Nonferrous materials minimum preheat and maximum interpass temperature shall be per the applicable WPS/PQR
[(5)]Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard.

Table 4.26 Suggested minimum preheat temperature for various base metals – AWS D10.8, Table 3

Base metal	Min. preheat temperature
CS	10 °C (50 °F)
C-Mo and ½ Cr-Mo	80 °C (50 °F)
1 ¼ Cr-Mo	120 °C (250 °F)
2–3 Cr-Mo	150 °C (300 °F)
5–9 Cr-Mo	200 °C (400 °F)
9 Cr-Mo-V	200 °C (400 °F)
300 series SS	10 °C (50 °F)

Commentary Notes: a. The above temperatures should be raised for heavy wall and/or restricted structures
b. Recommended to apply Table 4.33 and 4.37 for the missing P-number materials in this table unless otherwise specified a certain code or standard.

Table 4.27 Minimum preheat temperature – API 620, Table 6-2

Material P-No. & Group No	Thickness (t) of thicker plate, mm (in.)	Minimum preheat temperature, °C (°F)
P 1 – Gr. 1	$t \leq 31.8$ (1.25)	0 (32)
	31.8 (1.25) < $t \leq$ 38.1 (1.5)	10 (50)
	$t > 38.1$ (1.5)	93 (200)
P 1 – Gr. 2 & 3	$t \leq 31.8$ (1.25)	0 (32)
	31.8 (1.25) < $t \leq$ 38.1 (2.0)	10 (50)
	$t > 38.1$ (2.0)	93 (200)

Table 4.28 Minimum Preheat Temperature – API 650, Table 7.1a

Material group Per Table 2-3	Thickness (t) of thicker plate mm (in.)	Minimum preheat temperature
Groups I, II, III & IIIA	$t \leq 32$ ($t \leq 1.25$) $32 < t \leq 38$ (1.25 < $t \leq$ 1.50) $t > 38$ ($t > 1.50$)	0 °C (32 °F) 10 °C (50 °F) 93 °C (200 °F)
Groups IV, IVA, V & VI	$t \leq 32$ ($t \leq 1.25$) $32 < t \leq 38$ (1.25 < $t \leq$ 1.50) $t > 38$ ($t > 1.50$)	10 °C (50 °F) 40 °C (100 °F) 93 °C (200 °F)

Note: See below for Material Group (see Table 4.28a). See Sect. 2.1.10.1 for more details of P-No. and Gr. No.

- Castings – Steel, MSS, and Alloy Steel for High Temperature Service: ASTM A217, Table 3 (Table 4.30 in this book).
- Castings – Fe-Cr, Fe-Cr-Ni, Corrosion Resistant, for General Application: ASTM A743, Table 3 (Table 4.31 in this book).
  - Steel Structures: CSA W59, Table 5.3 (Table 4.32 in this book). AWS D1.1. Table 3.3 (Table 4.34 in this book), Annex H for Alternative Methods for Preheat and Interpass Temperature.
  - Welding Guidelines for the Chemical, Oil, and Gas Industries: API RP582 (Table 4.33 in this book).
  - Welding Processes, Inspection and Metallurgy: API RP577 (Sect. 4.4.2.1(e) in this book).
  - Arc Welding of Ferritic Steels and Low Ni Alloy Steels: BS EN 1011-2 (Tables 4.35 and 4.36 in this book).
  - Reference for Preheating: N. Yurioka et al., Determination of Necessary Preheating Temperature in Steel Welding, WJ, June 1993, supplement p147s to 153s.
  - Reference for Interpass Temperature: See Table 4.37 in this book.

Table 4.28a (1/2) Material group of Table 4.28 (US customary)[(1)]

Group I As-rolled, Semi-killed		**Group II** As-rolled, Killed or semi-killed		**Group III** As-rolled, killed Fine-grain practice		**Group IIIA** Normalized, killed Fine-grain practice	
Material	Notes	Material	Notes	Material	Notes	Material	Notes
A283 C		A131 B	[(6)]	A573–58		A573–58	[(9)]
A285 C	[(2)]	A36	[(5)]	A516–55		A516–55	[(9)]
A131 A		G40.21-38W		A516–60		A516–60	[(9)]
A36	[(3)]	Grade 250	[(7)]	G40.21-38W	[(8)]	G40.21–38W	[(8), (9)]
Grade 235	[(3)]			Grade 250	[(8)]	Grade 250	[(8), (9)]
Grade 250	[(5)]						

Table 4.28a (2/2) Material group of Table 4.28 (US customary)[1]

Group IV As-rolled, killed Fine-grain practice		**Group IVA** As-rolled, killed Fine-grain practice		**Group V** Normalized, killed fine-grain practice		**Group VI** Normalized or quenched and tempered, killed fine-grain practice reduced carbon	
Material	Notes	Material	Notes	Material	Notes	Material	Notes
A573–65		A662C		A573–70	(9)	A131 EH 36	
A573–70		A573–70	(10)	A516–65	(9)	A633 C	
A516–65		G40.21-44W	(8),(10)	A516–70	(9)	A633D	
A516–70		G40.21-50W	(8),(10)	G40.21-44W	(8),(9)	A537 Cl.1	
A662 B		E275 D		G40.21-50W	(8),(9)	A537 Cl.2	(12)
G40.21-44W	(8)	E355 D				A678 A	
G40.21-50W	(8)	S275 J2	(8)			A678B	(12)
E275C	(8)	S355 (J2 or K2)	(8)			A737B	
E355C S275 J0 S355 J0	(8) (8) (8)					A841 Gr.A-Cl.1 A841 Gr.B-Cl.2	(11),(12),(13) (11),(12),(13)
Grade 275	(8)						

Notes: Based on API 650, Table 4.4b

(1)Most of the listed material specification numbers; see ASTM specifications (including Grade or Class); there are, however, some exceptions: G40.21 (including Grade) is a CSA specification; Grade E 275 and E 355 (including Quality) are contained in ISO 630; Grades S275 and S355 (including Quality) are contained in EN10025; and Grade 235, Grade 250, and Grade 275 are related to national standards (See API 650, 4.2.6). CVN impact test: per codes and specifications. See Sect. 2.6.2.1 in this book for more detail information of each material.

(2)Must be semi-killed or killed

(3)Thickness ≤19 mm (0.75 in)

(4)Produced by the thermo-mechanical control process (TMCP)

(5)Mn content shall be 0.80%–1.2% by heat analysis for thicknesses greater than 19 mm (0.75 in.), except that for each reduction of 0.01% below the specified C maximum, an increase of 0.06% Mn above the specified maximum will be permitted up to the maximum of 1.35%. Thicknesses ≤19 mm (0.75 in.) shall have a Mn of 0.80%–1.2% by heat analysis

(6)Thickness ≤25 mm (1 in)

(7)Must be killed

(8)Must be killed and made to fine-grain practice

(9)Must be normalized

(10)Must have chemistry (heat) modified to a maximum C content of 0.20% and a maximum Mn content of 1.60% (see API 650, 4.2.7.4)

(12)See API 650, 5.7.4.6 for tests on simulated test coupons for material used in stress-relieved assemblies

(11)Produced by the thermomechanical control process (TMCP)

(13)See API 650, 4.2.10 for impact test requirements (each plate-as-rolled tested)

Table 4.29 Minimum preheat temperature for low temperature ferritic/martensitic cast steel (ASTM A352)

Grade	Thickness, mm (in.)	Minimum preheat temperature, °C (°F)
LCA	All	10 (50)
LCB	All	10 (50)
LCC	All	10 (50)
LC1	≤15.9 (5/8) >15.9 (5/8)	10 (50) 120 (250)
LC2	All	150 (300)
LC2-1	All	150 (300)
LC3	All	150 (300)
LC4	All	150 (300)
CA6NM	All	10 (50)

Table 4.30 Minimum preheat temperature for steel castings, MSS, and alloy steel for high temperature service (ASTM A217)

Grade	Thickness, mm (in.)	Minimum preheat temperature, °C (°F)
WC1	≤15.9 (5/8) >15.9 (5/8)	10 (50) 120 (250)
WC4	All	150 (300)
WC5	All	150 (300)
WC6	All	150 (300)
WC9	All	200 (400)
WC-11	All	150 (300)
C5	All	200 (400)
C12	All	200 (400)
C12A	All	200 (400)
CA15	All	200 (400)

Table 4.31 Castings, Fe-Cr, Fe-Cr-Ni, corrosion-resistant, for general application1 (ASTM A743)

Grade	Minimum preheat temperature, °C (°F)
CA15, CA15M, CA28MWV, CA40	205 (400)
Others in ASTM A743	10 (50)

Note: ASME B31.3 has greatly updated the requirements as seen in Table 4.22. Therefore, the existing piping materials specifications in most plants may require the updating.

Meanwhile, most companies' standards state more conservative requirements which are introduced in the recommendations in Table 4.23.

Table 4.32 Minimum preheat and interpass temperature requirements – CSA W59, Table P2 and AWS D1.1, Table H.2 (Steel Structures)

a. For three levels of restraint (imperial)

Restraint level	Thickness[1], in.	Min. preheat and interpass temperature, °F						
		Susceptibility index groups						
		A	**B**	**C**	**D**	**E**	**F**	**G**
Low	<3/8	<65	<65	<65	<65	140	280	300
	3/8 to 3/4	<65	<65	65	140	210	280	300
	¾ to 1–1/2	<65	<65	65	175	230	280	300
	1–1/2 to 3	65	65	100	200	250	280	300
	>3	65	65	100	200	250	280	300
Medium	<3/8	<65	<65	<65	<65	160	280	320
	3/8 to 3/4	<65	<65	65	175	240	290	320
	¾ to1–1/2	<65	65	165	230	280	300	320
	1–1/2 to 3	65	175	230	265	300	300	320
	>3	200	250	280	300	320	320	320
High	<3/8	<65	<65	<65	100	230	300	320
	3/8 to 3/4	<65	65	150	220	280	320	320
	¾ to 1–1/2	65	185	240	280	300	320	320
	1–1/2 to 3	240	265	300	300	320	320	320
	>3	240	265	300	300	320	320	320

Notes: Thickness is that of the thicker part welded. See Table 4.14 for susceptibility index groups (A–G)

b. For three levels of restraint (metric)

Restraint level	Thickness[1], in.	Min. preheat and interpass temperature, °F						
		Susceptibility index groups						
		A	**B**	**C**	**D**	**E**	**F**	**G**
Low	<10	<18	<18	<18	<18	60	138	149
	10 to 20	<18	18	18	60	99	138	149
	20 to 40	<18	18	18	79	110	138	149
	40 to 75	18	18	38	93	121	138	149
	>75	18	18	38	93	121	138	149
Medium	<10	<18	<18	<18	<18	71	138	160
	10 to 20	<18	<18	18	79	115	143	160
	20 to 40	<18	18	74	110	138	149	160
	40 to 75	18	79	110	129	149	149	160
	>75	93	121	138	149	160	160	160
High	<10	<18	<18	<18	38	110	149	160
	10 to 20	<18	18	66	104	138	160	160
	20 to 40	18	85	116	138	149	160	160
	40 to 75	116	129	149	149	160	160	160
	>75	116	129	149	149	160	160	160

Notes: Thickness is that of the thicker part welded. See Table 4.14 for Susceptibility Index Groups (A–G) based on CSA W59

Table 4.33 Recommended maximum interpass temperatures – API RP582, Table 4

Metal	Maximum interpass temperature	Metal	Maximum interpass temperature
P-1 (carbon steels)	315 °C (600 °F)	P-8 (ASS)	175 °C (350 °F)
P-3, 4, 5A, 5B, and 5C	315 °C (600 °F)	P-10H (DSS)	(1)
P-6 (Type 410)	315 °C (600 °F)	P-41, P-42	150 °C (300 °F)
P-6 (CA6NM)	345 °C (650 °F)	P-43, 44, and 45	175 °C (350 °F)
P-7 (Type 405/410S)	260 °C (500 °F)		

Notes: See Sect. 2.1.10.1 for more details of P-No. and Gr. No.
(1)Maximum recommended interpass temperature for DSS and SDSS (API RP582 draft for next version)

Welded thickness	Maximum interpass temperature	
	2205 DSS	2507 SDSS
< 3 mm (1/8 in.)	50 °C (120 °F)	50 °C (120 °F)
< 6 mm (1/8 in.)	70 °C (160 °F)	70 °C (160 °F)
< 9.5 mm (1/8 in.)	100 °C (210 °F)	100 °C (210 °F)
≥ 9.5 mm (1/8 in.)	150 °C (300 °F)	120 °C (250 °F)

Table 4.34 (1/2) Prequalified minimum preheat and interpass temperature – AWS D1.1, Table 3.3

Category	Steel specification		Welding process	Thickness of thicker part at point of welding		Min. preheat & interpass temperature	
				mm	in.	°C	°F
A	ASTM A36		*SMAW*	$3 \le t \le 20$	$0.125 \le t \le 0.75$	0[a]	32[a]
	ASTM A53	Gr. B	with low-hydrogen	$20 < t \le 38$	$0.75 < t \le 1.5$	65	150
	ASTM A106	Gr. B	electrodes	$38 < t \le 65$	$1.5 < t \le 2.5$	110	225
	ASTM A131	Gr. A, B, CS, D, DS, E		$t > 65$	$t > 2.5$	150	300
	ASTM A139	Gr. B					
	ASTM A381	Gr. Y35					
	ASTM A500	Gr. A, B, C					
	ASTM A501	Gr. A					
	ASTM A516						
	ASTM A524	Gr. I & II					
	ASTM A573	Gr. 65					
	ASTM A709	Gr. 36					
	ASTM A1008SS	Gr. 30					
	ASTM A1008SS	Gr. 33/40 Type 1					
	ASTM A1011SS	Gr. 30, 33, 40, 45, 50, 55					
	ASTM A1011SS	Gr. 36 Type 1					
	ASTM A1018SS	Gr. 30, 33, 36, 40					
	API 5L	Gr. B, X42					
	ABS	Gr. A, B, D, CS, DS, E					
B	ASTM A36		*SMAW*	$3 \le t \le 20$	$0.125 \le t \le 0.75$	0[a]	32[a]
	ASTM A53	Gr. B	with low-hydrogen	$20 < t \le 38$	$0.75 < t \le 1.5$	10	50
	ASTM A106	Gr. B	electrodes	$38 < t \le 65$	$1.5 < t \le 2.5$	65	150
	ASTM A131	Gr. A, B, CS, D, DS, E	*SAW,*	$t > 65$	$t > 2.5$	110	225
	ASTM A131	Gr. AH 32 & 36	*GMAW,*				
	ASTM A131	Gr. DH 32 & 36	*FCAW*				
	ASTM A131	Gr. EH 32 & 36					
	ASTM A139	Gr. B					
	ASTM A381	Gr. Y35					
	ASTM A441						
	ASTM A500	Gr. A, B, C					
	ASTM A501	Gr. A, B					
	ASTM A516	Gr. 55, 60, 65, 70					
	ASTM A524	Gr. I, II					
	ASTM A529	Gr. 50, 55					
	ASTM A537	Cl. 1, 2					
	ASTM A572	Gr. 42,50,55					
	ASTM A573	Gr. 65					
	ASTM A588						
	ASTM A595	Gr. A, B, C					
	ASTM A606						
	ASTM A618	Gr. Ib, II, III					
	ASTM A633	Gr. A, B, C, D					
	ASTM A709	Gr. 36, 50, 50S, 50W, HPS 50W					
	ASTM A710	Gr. A-Cl2 (>50 mm)					
	ASTM A808						
	ASTM A913[b]	Gr. 50					
	ASTM A992						
	ASTM A1008HSLAS	Gr. 45/50/55 Cl. 1 & 2					
	ASTM A1008HSLAS-F	Gr. 50					
	ASTM A1011HSLAS	Gr. 45/50/55 Cl. 1 & 2					

Table 4.34 (2/2) Prequalified minimum preheat and interpass temperature – AWS D1.1, Table 3.3

Category	Steel specification		Welding process	Thickness of thicker part at point of welding		Min. preheat & interpass temperature	
				mm	in.	°C	°F
	ASTM A1011HSLAS-F	Gr. 50					
	ASTM A1018HSLAS	Gr. 45/50 Cl. 1 & 2					
	ASTM A1018HSLAS	Gr. 55 Cl. 1 & 2					
	ASTM A1018HSLAS-F	Gr. 50					
	ASTM A1018SS	Gr. 30.33.36.40					
	API 5L	Gr. B, X-42					
	API Spec. 2H	Gr. 42, 50					
	API 2MT1	Gr. 50					
	API 2W & 2Y	Gr. 42, 50, 50T					
	ABS	Gr. AH/DH/EH 32 & 36					
	ABS	Gr. A, B, CS, D, DS, E					
C	ASTM A572	Gr. 60, 65	*SMAW* with low-hydrogen electrodes, *SAW,* *GMAW,* *FCAW*	$3 \leq t \leq 20$ $20 < t \leq 38$ $38 < t \leq 65$ $t > 65$	$0.125 \leq t \leq 0.75$ $0.75 < t \leq 1.5$ $1.5 < t \leq 2.5$ $t > 2.5$	10[a] 65 110 150	50[a] 150 225 300
	ASTM A633	Gr. E					
	ASTM A913[b]	Gr. 60, 65, 70					
	ASTM A710	Gr. A-Cl.2 (> 50 mm)					
	ASTM A710	Gr. A-Cl.3 (> 50 mm)					
	ASTM A709[c]	Gr. HPS70W					
	ASTM A852[c]						
	ASTM A1018HSLAS	Gr. 60-Cl.2					
	ASTM A1018HSLAS	Gr. 70-Cl.2					
	ASTM A1018HSLAS-F	Gr. 60-Cl.2					
	ASTM A1018HSLAS-F	Gr. 70-Cl.2					
	API 2W	Gr. 60					
	API 2Y	Gr. 60					
	API 5L	Gr. X52					
D	ASTM A710	Gr. A (all classes)	*SMAW, SAW, GMAW, FCAW* With electrodes or electrode-flux combinations capable of depositing weld metal with a maximum DH content of H8, when tested according to AWS A4.3	$t \geq 3$	$t \geq 0.125$	32[a]	0[a]
	ASTM A913[b]	Gr. 50, 60, 65					

General and Commentary Notes: DH = diffusible hydrogen

1. For modification of preheat requirements for SAW with parallel or multiple electrodes, see AWS D1.1, 3.5.2
2. See AWS D1.1, 5.11.2 and 5.6 for ambient and base metal temperature requirements
3. *Alternative methods for determining preheat (Basic consideration: HAZ hardness control and DH control) to avoid cold crack during/after welding: See AWS D1.1, Annex H*

Notes

[a]When the base metal temperature is below 0 °C (32 °F), the base metal shall be preheated to a minimum of 20 °C (70 °F) and the minimum interpass temperature shall be maintained during welding

[b]The heat input limitation of AWS D1.1, 5.7 shall not apply to ASTM A913

[c]For ASTM A709 Gr. HPS70W and ASTM A852, the maximum preheat and interpass temperature shall not exceed 200 °C (400 °F) for thickness up to 40 mm (1.5 in.), inclusive, and 230 °C (450 °F) for greater thicknesses

(c) Preheat for Low Temperature Steels

TWI indicates that preheat for low temperature steels (LTCS and Ni alloy steels) may be required depending upon section thickness, joint type, and restraint to reduce the risk of hydrogen cold cracking. ASME B31.3 requires minimum 120 °C (250 °F) for 2 1/4Ni steel-all thicknesses, minimum 150 °C (300 °F) for 3 1/2Ni steel-all thicknesses, and 10 °C (50 °F or nil) for the 5% and 9% Ni alloy steels. The reason for this low preheat temperature is that these 5 to 9Ni content alloys contain a certain amount of austenite that can tolerate large amounts of hydrogen. This austenite therefore substantially reduces the risk of cold cracking; in addition, they are conventionally welded with nickel-based alloys that reduce the risk even further.

See Table 4.15 and Fig. 4.29 for preheat requirements per carbon equivalent.

(d) Preheat in Steel Structures: CSA W59, Table 5.3. See Table 4.32 in this book.

AWS D1.1, Table 3.3. See Table 4.34 in this book.

Table 4.35 Minimum preheating and interpass temperatures for LAS (BS-EN 1011-2, Table C.5)

Material group	Thickness, mm (in.)	Minimum preheat and interpass temperature, °C (°F)			Maximum interpass temperature, °C (°F)
		Scale-D DH ≤ 5 ml/100 g	Scale-C DH ≤ 10 ml/100 g	Scale-A DH ≤ 15 ml/100 g	
0.3Mo	≤15 (0.6) >15 (0.6), ≤30 (1.2) >30 (1.2)	20 (68) 75 (167) 75 (167)	20 (68) 75 (167) 100 (212)	100 (212) 100 (212) N/A	250 (482)
1Cr-0.5Mo 1.25Cr-0.5Mo	≤15 (0.6) >15 (0.6)	20 (68) 100 (212)	100 (212) 150 (302)	150 (302) N/A	300 (572)
0.5Cr-0.5Mo-0.25 V	≤15 (0.6) >15 (0.6)	100 (212) 100 (212)	150 (302) 200 (392)	N/A N/A	300 (572)
2.25Cr-1Mo	≤15 (0.6) >15 (0.6)	75 (167) 100 (212)	150 (302) 200 (392)	200 (392) N/A	350 (662)
5 to 7Cr-0.5Mo 9Cr-1Mo	All	150 (302)	200 (392)	N/A	350 (662)
12Cr-Mo-V	≤8 (0.3) >8 (0.3)	150 (302) 200 (392)[1] 350 (662)[2]	N/A N/A	N/A N/A	300 (572) 300 (572)[1] 450 (842)[2]

Notes: N/A = not applicable
[1]Martensitic method where the preheat temperature is below the Ms (martensite start) temperature and transformation to martensite occurs during welding
[2]Austenitic method where the preheat temperature is above the Ms temperature and the joint shall be allowed to cool to below the Ms to ensure transformation to martensite occurs before any PWHT is applied

Table 4.36 Minimum preheat/interpass temperatures-low Ni alloy steels (for low temperature) (BS-EN 1011-2, Table C.6)

Material group	Thickness, mm (in.)	Minimum preheat and interpass temperature, °C (°F)		Maximum interpass temperature, °C (°F)
		Scale-D DH ≤ 5 ml/100 g	Scale-C DH ≤ 10 ml/100 g	
3.5Ni	>10 (0.4)	100 (212)[1]	150 (302)[1]	–
5.0Ni	>10 (0.4)	100 (212)[2]	N/A	250 (482)
5.5Ni	>10 (0.4)	100 (212)[2]	N/A	250 (482)
9.0Ni	>10 (0.4)	100 (212)[2]	N/A	250 (482)

Notes: *N/A* not applicable
[1]The values for minimum preheat given are typical of normal production using matching composition consumables
[2]The level of preheat specified refers to those instances where near matching consumables or autogenous welding is involved. 5% Ni to 9% Ni steels are usually welded using Ni-based welding consumables and preheat is not normally required up to 50 mm THK

Table 4.37 Interpass temperature limitation – for reference (from several companies)

Metal (See Sect. 2.1.10.1 for more details of P-No. and Gr. No.)		Minimum interpass & Preheat temperature	Maximum interpass temperature
Cast iron, nodular cast iron	RCI & RCI-A	430–566 °C (800–1050 °F)	677 °C (1250 °F)
P-No. 1		[1]	232~260 °C (450~500 °F)
P-No. 3 & 4		121 °C (250 °F)	175 °C (350 °F)
P-No. 5A, 5B, 5C, 9B, 10C		[1]	204~232 °C (400~450 °F)
P-No. 6 (MSS)	410 filler on 410 base metal		260~316 °C (500~600 °F)
P-No. 6 (MSS)	309 filler on 410 base metal	175 °C (350 °F)	260 °C (500 °F)
P-No. 7 (FSS)		[1]	204~232 °C (400~450 °F)
P-No. 8 (ASS)			175 °C (350 °F)
P-No. 8 (overlay weld on CS & LAS)		121 °C (250 °F)	175~232 °C (350~450 °F)
P-No. 10H (DSS)	DSS 2205	[1]	150~200 °C (300~390 °F)[3]
P-No. 10H (DSS)	DSS 2507		70 °C (160 °F)
P-No.11A		[1]	150 °C (300 °F)
P-No.11B		[2]	[2]
P-No. 41 (Ni alloys)	ENiCrFe-4	[1]	204 °C (400 °F)
P-No. 42 (Ni alloys)	ENiCu-7		150 °C (400 °F)
P-No. 42 (overlay weld on CS & LAS)		121 °C (250 °F)	204 °C (400 °F)
P-No. 43 (Ni alloys)	ENiCrMo-3	[1]	175 °C (350 °F)
P-No. 43 (overlay weld on CS & LAS)		121 °C (250 °F)	175~232 °C (350~450 °F)

Notes:
[1]Minimum Interpass Temperatures may be the same as minimum required preheating temperature
[2]See ASME Sec. VIII, Div. 1, UHT-82 for ferritic steel with tensile properties enhanced by heat treatment
[3]Max. interpass temperature ≤100 °C (212 °F) for Hyper DSS (i.e., UNS S32707, S33707)

(e) Preheat in API RP577 Welding Processes, Inspection, and Metallurgy

$$Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Si + Ni + Cu)/15 \text{ in CS}$$

Ceq < 0.35: no preheat
Ceq = 0.35 to 0.55: usually require preheating
Cen > 0.55: require both preheating and a PWHT

However, requirements for preheating should be evaluated by considering other factors such as hydrogen level, humidity, and section thickness.

(f) Companies' Standards for Steel Structures (For reference)

1. When the base metal temperature is below 0 °C (32 °F), the base metal should be preheated to at least 21 °C (70 °F) and this minimum temperature maintained during welding.
2. Only low-hydrogen electrodes should be used when welded with A36 or A709 Grade 36 steel more than 25 mm (1 in.) thick for bridges.
3. Welding should not be done when the ambient temperature is lower than −18 °C (0 °F). When the base metal is below the temperature listed for the welding process being used and the thickness of material being welded, it should be preheated (except as otherwise provided) in such manner that the surfaces of the parts on which weld metal is being deposited are at or above the specified minimum temperature for a distance equal to the thickness of the part being welded, but not less than 76 mm (3 in.), both laterally and in advance of the welding. Preheat and interpass temperatures must be sufficient to prevent crack formation. Temperature above the minimum shown may be required for highly restrained welds. For quenched and tempered steel, the maximum preheat and interpass temperature should not exceed 204 °C (400 °F) for thickness up to 38 mm (1.5 in.) inclusive and 230 °C (450 °F) for greater thicknesses. Heat input when welding quenched and tempered steel should not exceed the steel producer's recommendation.
4. In joints involving combinations of base metals, preheat should be as specified for the higher-strength steel being welded.
5. The above −18 °C (0 °F) does not mean the ambient environment temperature but the temperature in the immediate vicinity of the weld. The ambient environmental temperature may be below −18 °C (0 °F), but a heated structure or shelter around the area being welded could maintain the temperature adjacent to the weldment at −18 °C (0 °F) or higher.
6. Post-heating: Sometimes it requires to be post-heated instantly after welding in accordance with the end-user's specification in hydrogen service or heavy wall thickness facilities as below:
   Post-heating should be performed minimum 1~3 hours with cloth wrapping immediately after welding. See Sect. 4.4.3 for Post-Heat After Welding.
7. Welds in TMCP steels should not be postweld heat treated unless otherwise proved the mechanical properties and toughness after PWHT.

4.4.2.2 Interpass Temperature

The term of interpass temperature in welding refers to the temperature of the material in the weld area immediately before the second and each subsequent pass of a multiple-pass weld, so that it is normally controlled in a certain temperature range. In practice, the minimum specified interpass temperature is typically equal to the minimum specified preheat temperature even though the main purpose of minimum interpass temperature control is to bake out the hydrogen while the primary purpose of preheat is to delay the cooling rate to avoid hardened structure, so that the interpass temperature designated in WPS/PQR or other documents may call for the maximum specified interpass temperature. Normally root pass may have more rapid cooling rate as well as a higher stress concentration than the remaining passes, so that the root pass may require a higher preheat temperature than minimum interpass/preheat temperature for the remained passes.

Interpass temperature is just as important as, if not more important than, preheat temperature, with regard to the mechanical and microstructural properties of weldments. For instance, the yield and ultimate tensile strengths of the weld metal are both a function of the interpass temperature. High values of interpass temperature tend to reduce the weld metal strength (i.e., ferritic steel) and produce second precipitation (some stainless steels). Additionally, higher interpass temperatures will generally provide a finer grain structure and improved CVN impact toughness transition temperatures. However, when interpass temperatures exceed approximately 260 °C (500 °F), this trend is reversed. For example, the American Welding Society (AWS) Position Statement on the Northridge Earthquake recommends that the interpass temperature should not exceed 290 °C (550 °F) when notch toughness is a requirement.

Table 4.32 shows minimum preheat and interpass temperature requirements in CSA W59 (Steel Structures), Table P2.

Table 4.33 shows recommended maximum interpass temperatures in API RP582 (Welding Guidelines for Chemical, Oil, and Gas Industries), Table 4.

Table 4.34 shows prequalified minimum preheat and interpass temperature in AWS D1.1 (Structural Welding Code-Steel), Table 3.3.

Tables 4.35 and 4.36 show minimum preheating and interpass temperatures in BS-EN 1011-2 (Welding – Recommendations for welding of metallic materials, Part 2: Arc welding of ferritic steels).

Table 4.37 shows interpass temperature limitations in several company standards, so that it may be used when the applicable industrial standards are not clearly defined.

See the following article for preheat requirement from unknown CS and LAS.

R.W. Hinton, R.K. Wiswesser, Estimating welding preheat requirement from unknown grades of CS and LAS, Weld. J. p 273s–278s (2008)

Table 4.38 Post-heating for hydrogen baking-out practice (CS and LAS)

Codes & standards	Temperature, °C (°F)	Time (hours)	Remark (as alternative)
ASME Sec. VIII, Div. 1 & 2	See remark	See remark	Use filler H4* for ASME Sec. VIII, Div. 1, UHT, ferritic steel with tensile properties enhanced by heat treatment. *for all materials in Sec. VIII, Div. 2 After completing all welding, the repair area shall be maintained at a temperature of 400 °F to 500 °F (205 °C to 260 °C) for a minimum period of 4 hr for P-No. 3, Gr.1, 2, 3
ASME Sec. III, Subsection NB	232–288 (450–550)	Min. 2 for CS Min.4 for P-No.3	For repairs made using SMAW or FCAW
API 510 pressure vessel repair, API 570 piping repair NBIC, Part RD-1000 (remark only)	232–288 (450–550)	Min. 2	Use filler H8[(1)] or lower for SMAW, GMAW, FCAW* (*only for API 570 and NBIC RD-1000), and GTAW; and the shielding gas, if applicable, shall exhibit a dew point that is no higher than −50 °C (−60 °F); or use filler H4[(1)] for SMAW and FCAW** (**only for NBIC RD-1000) with preheat of 260 °C ± 30 °C (500 °F ± 0 °F)
API RP945 amine	232–316 (450–600)	2–4	
NACE SP0296 wet H_2S (sour)	>204 (400)	Up to 4	As an industry survey data. Example on Fick's law[(2)]

Notes
[(1)]H8 and H4: diffusible hydrogen grades (see Table 4.13 for detail)
[(2)]For example of Fick's law, a 25 mm (1 in) thick plate may require 3 hours at 426 °C (800 °F) or 6 hours at 315 °C (600 °F) to reach 1 ppm of residual hydrogen. Hydrogen flux monitor may be considered for use in determining what hydrogen bake-out is sufficient. Bake-out temperatures up to those required for full PWHT may be used for holding times shorter than specified for PWHT

4.4.3 Post-Heat After Welding

The primary objective of post-heat is the removal of hydrogen and then to prevent hydrogen-induced crack (delayed crack) in welding of ferritic steels with high strength and/or heavy wall. This crack occurs most frequently in the HAZ and at times up to 48 hours (or more) after the weldment has been cooled to ambient temperature. This is a critical concern when the hydrogen potential of the welding consumables, such as moisture, oil, grease, wire drawing compounds, and contaminated by other foreign materials are remained on the metal surfaces before welding.

Frequently, post-heating is applied in situations where some delay is expected between the completion of welding and PWHT. Hydrogen baking with 204–343 °C (400–650 °F) is recommended after (repair) welding of CS, LAS, and MSS used in H_2S/HF/Amine or Hydrogen Services. The repair welding of Grade 91 steel may require the hydrogen baking which is holding in the temperature range of 260–350 °C (500–660 °F) for 1 hour minimum for thickness ≤25.4 mm (1 in.) and 2 hours for thicknesses >25.4 mm (1 in.). This hydrogen baking out may be also applicable for the new construction welding of heavy wall Cr-Mo steels, Grade 91 steel, ferritic steels with tensile properties enhanced by heat treatment (e.g., ASME Sec. VIII, Div. 1, UHT), and MSS.

Table 4.38 shows the post-heat requirements in several codes and standards for CS and LAS.

Post-heating immediately after welding is very effective for the hydrogen evolution. When the predicted necessary preheating temperature is excessively high, immediate post-heating should be employed so that the necessary preheating temperature could be reduced. Here is an example in carbon steel.

$$150^{\circ}\mathrm{C}\ \text{for}\ 95\ \text{hours},\quad \text{or}\ 200^{\circ}\mathrm{C}\ \text{for}\ 29\ \text{hours},\quad \text{or}\ 250^{\circ}\mathrm{C}\ \text{for}\ 12\ \text{hours},\quad \text{or}\ 300^{\circ}\mathrm{C}\ \text{for}\ 2\ \text{hours}.$$

4.4.4 Heat Input (Q) for Welding

An appropriate energy (heat input (Q): see below formulas and tables) is required to melt the base metal and welding consumables and to control the cooling rate for the sound welding process and the results. An increase in heat input, or an increase in volume of weld metal deposited per unit length of weld, for each process is recorded on the PQR. Table 4.39 shows general trends per the heat input in ferritic steels. See Sect. 4.2.5 for cooling time control ($T_{8/5}$) with the use of heat input formula.

[For Arc Welding] by all formulas for nonwaveform-controlled welding, by * for waveform-controlled welding.

$$Q = K \times 60 \times V \times A/\upsilon = [\text{Joule/mm}] \quad \text{(Eq. 4.5)}$$

where V = Voltage, A = Amperage, υ = Travel speed (mm/minute), and K = Net factor used only for hot tap welding = 0.85 for butt welding and 0.57 (=2/3 × 0.85) for fillet welding.

Volume of weld metal measured by (i) an increase in bead size (width × thickness) or a decrease in length of weld bead per unit length of electrode.*

Table 4.39 General trends per the heat input in ferritic steels

By	Results-increase (↑)	Results-decrease (↓)
Q ↑	Weld bead thickness, grain growth, radiation loss due to arc length (when V↑)	Crack due to high cooling rate, effective heat (due to arc length↑)
Q ↓	Crack due to low cooling rate, effective heat (due to arc length↓)	Weld bead thickness, coarse grain, radiation loss due to arc length (when V↓)

Table 4.40 Consumption of heat input (typical)

Total net heat input (Qnet) = 100%		
45~65%	20~40%	15%
To Melt Base metals, solution of flux, spatter, convection & radiation loss	To create new weld metals	To melt electrodes/ fillers

Table 4.41 Heat transfer efficiency of heat input per welding process

Welding process	Heat transfer efficiency (Qnet/Q)
SAW	0.90–0.95
FCAW	0.70–0.90
GMAW (MAG)	0.70–0.85
GMAW (MIG)	0.70–0.80
FCAW	0.70–0.80
SMAW	0.65–0.80
GTAW	0.65–0.75

Source: ASM Welding H/B
Notes: Qnet = Q – (radiation/conduction/convection heat loss)

Table 4.42 Typical heat input range for FCAW of CS (AWS A5.20 E71T-9J)

Welding position[(1)]	Heat input (kJ/mm) [mean]
1F & 1G	1.0–3.0 [2.0]
2F	1.0–2.0 [1.5]
2G	1.0–1.5 [1.3]
3F, 3G, and 4F	1.5–3.0 [2.3]

Note: (source: Kobelco)
[(1)] *1F* flat fillet, *1G* flat groove, *2F* horizontal fillet, *2G* horizontal groove, *3F* vertical fillet, *3G* vertical groove, *4F* overhead fillet

Heat input determined using instantaneous energy or power by*:

(i) for instantaneous energy measurements in joules (J) *Heat input [J/in. (J/mm)]*

$$Q = \text{Energy (J)/weld bead length (mm)} = [\text{Joule/mm}] \quad \text{(Eq. 4.6)}$$

(ii) for instantaneous power measurements in joules per second (J/s) or Watts (W) *Heat input [J/in. (J/mm)]*

$$Q = \text{Power (J/s or W)} \times \text{arc time (seconds)/Weld bead length (mm)} = [\text{Joule/mm}] \quad \text{(Eq. 4.7)}$$

[For Low-Power Density Laser Beam Welding (LLBW)]

$$Q = 60 \times \text{power (W)}/\upsilon = [\text{Joule/mm}] \quad \text{(Eq. 4.8)}$$

where W = power (Watt) and υ = travel speed (mm/minute).

Table 4.40 shows typical consumption rate of heat input, Table 4.41 shows heat transfer efficiency of heat input per welding process, and Table 4.42 shows typical heat input range per welding position. Figure 4.33 shows how heat input affects the cooling rates in welds. This figure indicates that the effect of heat input on the cooling rate is more significant in lower heat input ranges at every preheat temperature. In higher heat input, preheating does not remarkably affect the cooling rate in welds.

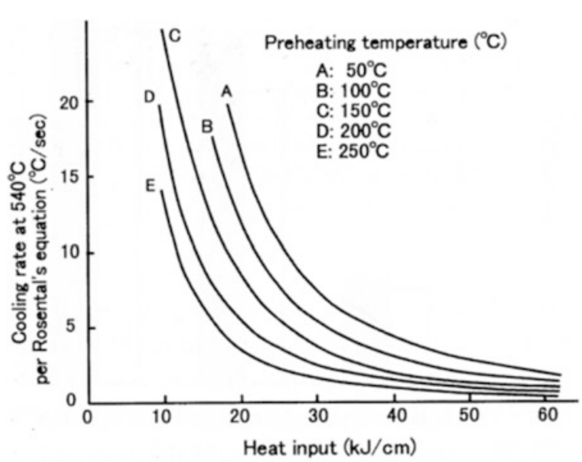


Figure 4.33 Effect of heat input on cooling rates in butt welds per preheat temperatures. (Source: Kobelco and D. Rogenthal's reports, 2005)

4.5 Controlled Deposition Welding (CDW) and Buttering Welding

CDW is a welding technique used to obtain controlled grain refinement and tempering of the underlying HAZ in the base metal. Various controlled deposition techniques, such as temper bead (tempering of the layer below the current bead being deposited) and half bead (requiring removal of one-half of the first layer), are included. It is anticipated that the techniques could replace PWHT for carbon steel of great thickness and alloy steels (less than 4Cr for Cr-Mo steels) and save the industries a lot of money. In the early days, several industrial codes and standards had developed the applications and requirements for repair welding; nowadays this technique has been extending its use to new construction as well.

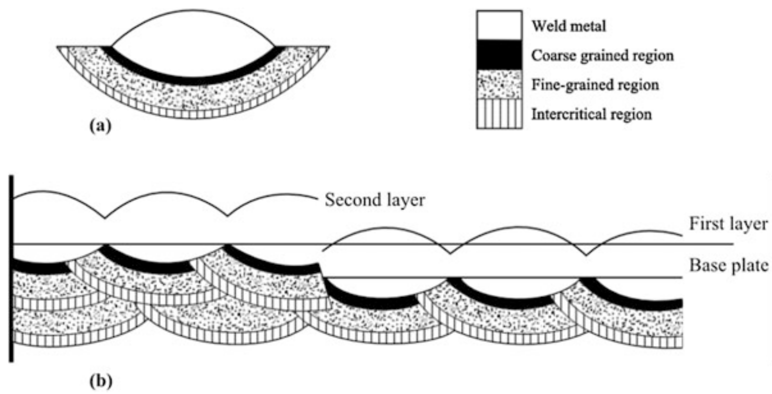


Figure 4.34 Schematic showing a two-layer repair welding. (**a**) HAZ of a single weld bead. (**b**) First layer causes coarse-grained regions to form in the HAZ of the base metal. (Source: ASM Metal H/B, Vol.6)

Figure 4.34 shows the heat from second layer is used to refine the coarse-grained region in the HAZ of the base metal due to the first layer. The deposition of the second layer refines these initial coarse-grained regions. Temper bead technique should utilize minimum 93 °C (200 °F) to 177 °C (350 °F) preheat; maximum 232 °C (450 °F) interpass temperature; and bake-out at least 260 °C (500 °F) for 2 hours.

Meanwhile the buttering is built up by a buffering welding material in metallurgical and physical properties, on one or both faces of a dissimilar weld joint, prior to the preparation of the joint for final welding, for the purpose of providing a suitable transition weld deposit for the subsequent completion of the joint. This can be done in order to make up for poor joint preparation as indicated previously, but also is done to minimize the effect of PWHT on a sensitive material or eliminate subsequent PWHT.

The common goal of both welding techniques of CDW and buttering welding is to minimize or eliminate the final PWHT.

4.5.1 Temper Bead Welding Technique

1. Purpose; It is as an alternative to PWHT when PWHT is impractical. This technique is permitted mostly for the maintenance and repair applications.
   Table 4.43 shows welding variables for temper bead procedure qualification in ASME Sec. IX, QW-290.4).
2. Technique; The HAZ of the bottom bead of each pass due to the top bead applied with lower size electrode leaves less than 20–30% of the weld metal cross-sectional area as "typical columnar grains," and the balanced area is a normalized structure. The top layer of the reinforcement mainly consisting of columnar grains is required to be ground, to match the surface contour. Temper bead welding technique is done when the final beads of welding are made over-flush, deposited only on previous beads of welding for tempering purposes without making contact with the base metal, and then removing these final beads [ASME Sec VIII, Div. 1, ULW-32].

Codes and Standards for Temper Bead and Half Bead Welding Techniques

- ASME Sec. I, PW-40.3.4 and PW-40.3.6
- ASME Sec. VIII, Div. 1, UCS-56, ULW-26
- ASME Sec. IX, QW-290, Table QW-290.4, QW-403.25/29, QW-410.61/62, Fig. QW-462.12/13, and K-303
- ASME STP-PT-058 Temper Bead Qualification Hardness Acceptance Criteria (P No. 4-1 and 5A-1)
- ASME PCC-2, Article 2.8
- API 510 Pressure Vessel Inspection Code
- API RP570 Piping Inspection Code
- API 653 Tank Inspection, Repair, Alteration, and Reconstruction
- API RP577, 11.2.4.2 Temper Bead Welding Technique During Hot Tapping
- API 1104 Welding of Pipelines and Related Facilities
- NBIC, ANSI/NB-23
- AS 3992/4458
- AS/NZS 1200/3788
- WRC 412, 499 & 506

Table 4.43 Welding variables for temper bead procedure qualification (ASME Sec. IX, QW-290.4)

Paragraph of ASME Sec. IX		Brief of variables	Hardness test essential variables	Impact test essential variables	Nonessential variables
QW-402	.23	+ Fluid backing	x		
	.24	+ Fluid backing		x	
QW-403	.25	Ø P-No. or Gr. No.		x	
	.26	> Carbon equivalent	x		
	.27	> Thickness	x		
QW-404	.51	Storage			x
	.52	Diffusible hydrogen			x
QW-406	.8	> Interpass temperature		x	
	.9	< Preheat temperature	x		
	.10	Preheat soak time			x
	.11	Postweld bake-out			x
QW-408	.24	Gas moisture			x
QW-409	.29	Ø Heat input ratio	x	x	
QW-410	.10	Ø Single to multiple electrode	x	x	
	.58	− Surface temper beads	x	x	
	.59	Ø Type of welding	x	x	
	.60	+ Thermal preparation	x	x	
	.61	Surface bead placement	x	x	
	.62	Surface bead removal method			x
	.63	Bead overlap	x	x	
	.65	± Grinding	x	x	

Legend: + addition, − deletion, > increase/greater than, < decrease/less than, Ø change
Note: See Sect. 4.9.1 for essential and nonessential variables

4.5.2 *Half Bead Welding Technique*

1. Purpose
   It is the same purpose as temper bead technique. This technique is also permitted mostly for the maintenance and repair applications. ASME Section III, XI, and API 510 have developed the rules recently.
2. Technique
   After every layer, the top half of the weld bead is ground off before applying the next layer.
   The consumption of welding electrodes can shoot up (Fig. 4.35).

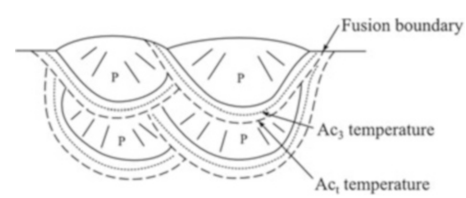


Figure 4.35 Primary (P) and reaustenitized regions (columnar structure is not clearly detected) in the weld metal region of multipass weld. (Source: ASM Metal H/B, Vol. 6)

4.5.3 *Buttering Welding*

1. Definition and Purpose
   ASME Sec. IX and AWS A3.0 define that the buttering is the addition of material, by welding, on one or both faces of a joint, prior to the preparation of the joint for final welding, for the purpose of providing a suitable transition weld deposit for the subsequent completion of the joint. Therefore, the definition of buttering welding should be separated from the terms of weld buildup or weld overlay which is for thickness reinforcing or corrosion/erosion resistance layer.
   As a result of buttering, the PWHT requirement and/or deformation can be minimized and eliminated by buffering weld buildup of (one or both) base metal(s) before beginning to weld the dissimilar weld joint itself. The buttered member is heat treated and the completed weld is not heat treated after welding.
   An example of this is the buttering of an alloy steel weld preparation with a nickel-based weld metal and postweld heat treating this part before making the joining weld between the buttering and a steel, which would be degraded by heat treatment. Figure 4.36 shows a typical process of buttering welding. The filler metal used for buttering has a different F-number from that used for the subsequent completion of the weld.
   Normally the buttering welding should have three layers 5 mm (0.188 in.) thick after being ground or machined as a minimum unless the undiluted layer is proved by the PQR. ASME Sec. IX, QW-283 states the requirements for the buttering welding and the PQR.

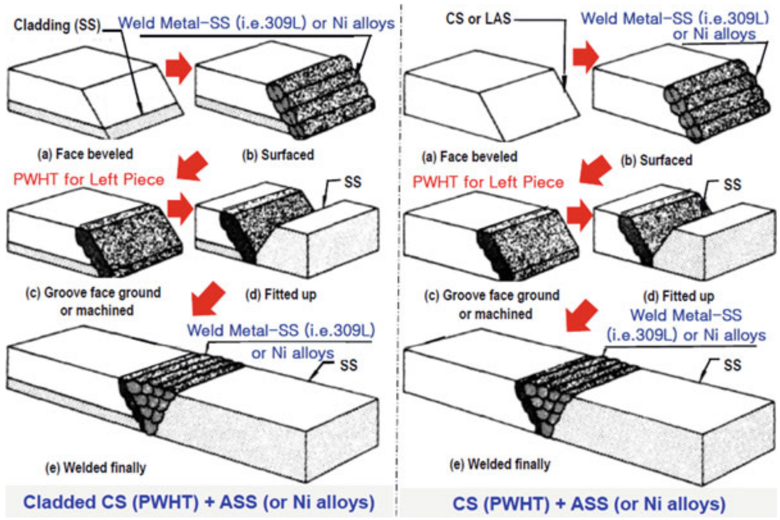
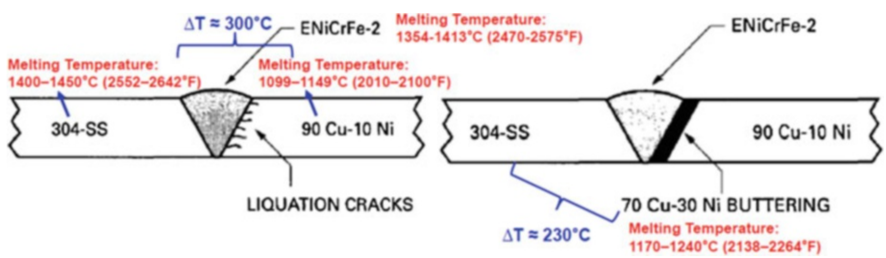


Figure 4.36 Typical sequence of buttering welding. (Source: ASM SS H/B)



(a) (b)

Figure 4.37 Buttering Welding Technique 1 to avoid liquation cracking. (**a**) Liquation cracking. (**b**) Use of buttering to avoid liquation cracking. (Source: AWS clad and dissimilar metals, Chapter 6, 1998)

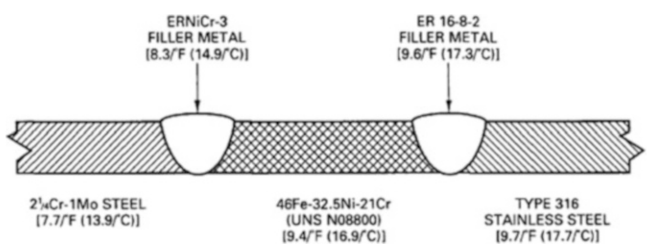


Figure 4.38 Buttering Welding Technique 2 to avoid liquation cracking. (Source: AWS clad and dissimilar metals, Chapter 6, 1998)

Buttering welding is also applicable for hot tap welding to avoid distortion and/or burn-through of the pipe after welding. See Sect. 4.6.5 for buttering welding on hot tapping.

2. Techniques
Buttering or weld buildup on the prepared surfaces should not exceed the lesser of 1/3 of the base metal thickness of 10 mm. MT or PT inspection should be performed on the completed buttering layers prior to/after deposition of further weld metal. Some dissimilar metals welding can be susceptible to liquation cracking due to greatly different melting temperatures between both materials. Liquation cracking may be avoided by buttering with an intermediate melting temperature weld metal. For instance, as seen in Fig. 4.37, a groove weld between 304 SS and 90Cu-10Ni plates using ENiCrFe-2 can result in HAZ liquation cracking in the 90Cu-10Ni groove face due to the large melting temperature differential. By applying a weld overlay, or buttering layer, of 70Cu-30Ni weld metal to the 90Cu-10Ni plate, as shown below, liquation cracking can be avoided.
Figure 4.38 shows another case. The liquation cracking may be also avoided by buttering welding with an intermediate thermal expansion coefficient weld metal. The mean coefficient of thermal expansion from 21–538 °C (70–1000 °F) is noted for each material in units of length $\times$ 10^{-6}/(length•degree of temperature).

Codes and standards
– ASME Section IX, QW-283
– API 510
– NBIC, ANSI/NB-23
– WRC 412/499/506

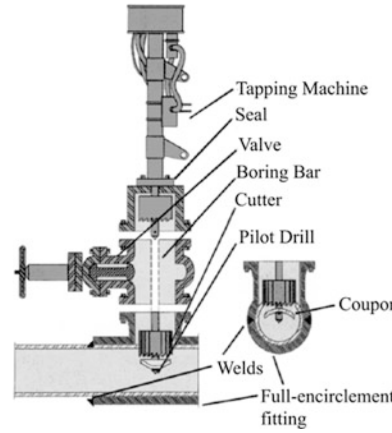


Figure 4.39 Typical tapping setup for plugging operation. (Source: IPSCO brochure, 2012)

4.6 Hot Tap Welding

4.6.1 Characteristics of Hot Tapping

During operation, there are some needs to install the new line for the existing pipeline, piping, and equipment. Figures 4.39 and 4.40 show the typical procedure of hot tapping on piping and storage tanks. It is also applicable to storage tanks and low pressure vessels.

1. Advantages
   – Zero transportation impacts (in most cases).
   – Zero emissions – Potential for greenhouse gas emission credits.
   – Improved safety – Reduced risk.
   – Less equipment required.
   – Cost is 90% lower than a cold tee.
2. Benefits
   – The technology is safe.
   – Hot taps can minimize or eliminate transportation interruptions.
   – Hot tapping is a proven technology.
   – Hot taps make economic sense.
   – Hot tapping qualifies for GHG (greenhouse gas) emissions avoidance credits.
3. Hot Tapping/In-Service Welding Hazards Associated with Some Particular Substances: See API RP577 (third Edition)

4.6.2 General Consideration

There are two primary concerns with welding onto in-service pipeline/piping/equipment. The first is for welder safety during welding, since there is a risk of the welding arc causing the pipe/shell wall to be penetrated allowing the contents to escape. The second concern is for the integrity of the following welding, since welds made in-service cool at an accelerated rate as the result of the ability of the flowing contents to remove heat from the pipe/shell wall. These welds, therefore, are likely to have hard HAZ and a subsequent susceptibility to hydrogen cracking. The welding skill for all positions is generally required. The hot tapping may be prohibited for the following conditions unless otherwise the approved Hot Tap Simulation Model or the end-user requires:

(a) Combustible or explosive mixtures that could react with addition of heat.
(b) Compressed air lines, which contain lubricating oil when the inside temperature is above that to cause ignition.
(c) Flare lines that contain explosive mixtures, unless there is a positive flow during welding.
(d) Hydrogen and hydrogen mixtures lines, over than 100 °C (212 °F) service temperature.
(e) Operating temperature greater than 232 °C (450 °F).
(f) Caustics or amine services (susceptible to SCC).
(g) Wet H_2S (sour) or HF services (due to difficult hardness control).
(h) Oxygen or oxygen-enriched service (flammable).
(i) Peroxides, chlorine, ethylene oxide, propylene oxide, or other chemicals which can violently decompose and/or become hazardous from the heat of welding. See API RP577, Table 13, for more information.
(j) PWHT-required pressure vessels or no-PWHT-required pressure vessels with design pressure >10 barg (or 150 psig).
(k) Not recommended for thin wall less than 6.4 mm (1/4 in.) thick.
(l) Impact tested materials or impact test exempted materials per code.
(m) Internally metallic-lined (lining, clad, weld overlay, or metallizing), insulated or refractory lined, coated condition.
(n) Internally interrupted condition between inserted hot tap tool and the functional internal components.
(o) Any metals other than carbon steel unless otherwise approved by the responsible metallurgist.
(p) API 653 indicates the limitation for hot tap connection nozzle sizes and shell plate thickness (see Table 4.44). See API 653, 9.14 for more details of the limitations of hot taps for storage tanks.

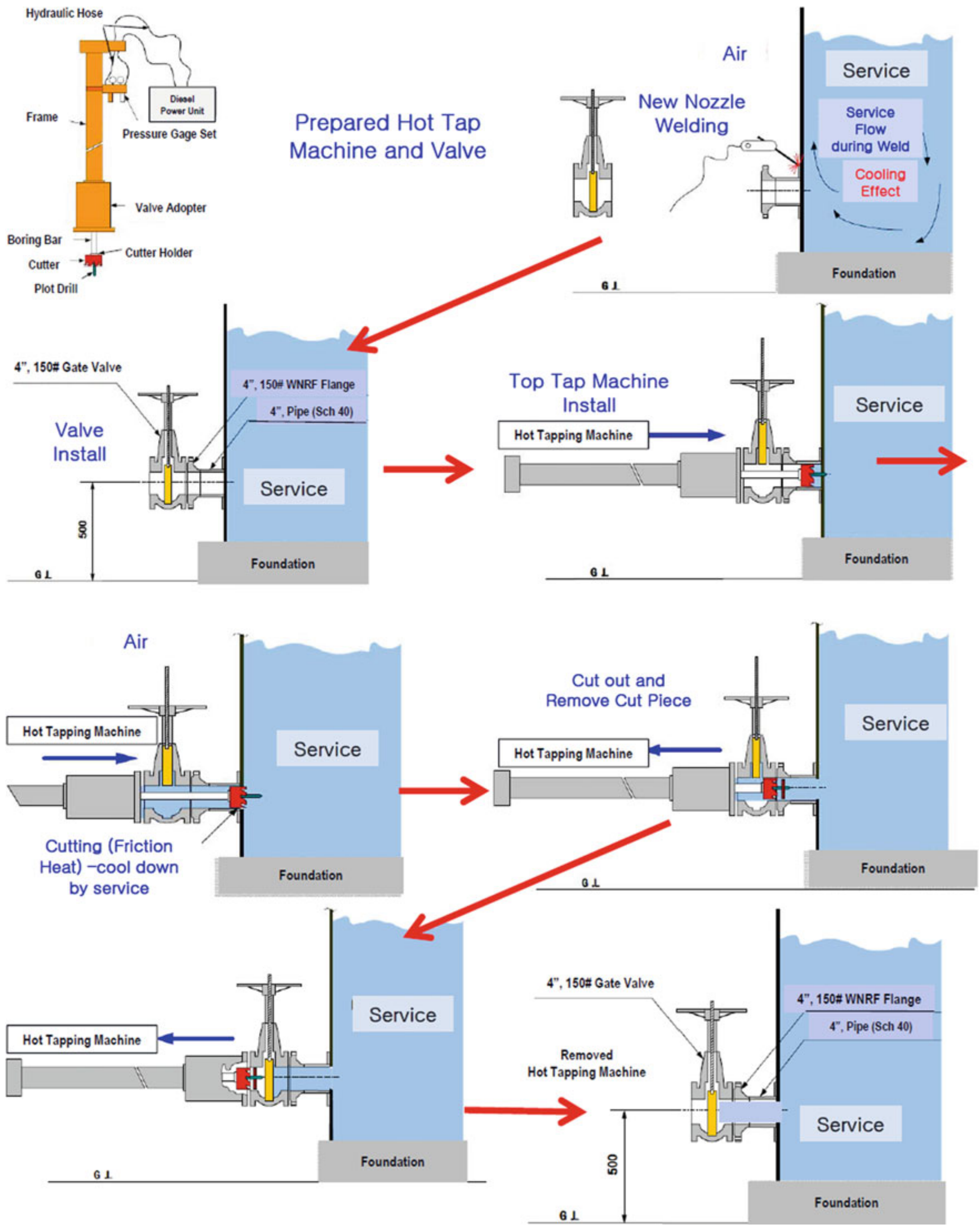


Figure 4.40 Hot tapping procedure on the storage tank. (Source: Williamson and CVP reports, 2010 – modified)

Table 4.44 Limitation for hot tap connection sizes and shell plate thickness (API 653, Table 9.1)

Connected nozzle size, NPS (in.)	Minimum shell plate thickness (in.)[(a)]
≤6	3/16
≤8	1/4
≤10	5/16
≤14	3/8
≤16	7/16
≤18	1/2

Commentary Note: [(a)]Minimum thickness is required to prevent burn-through

4.6.3 Consideration of Welding Electrodes

Hot tap and in-service welding operations should be carried out only with low-hydrogen consumables and electrodes (e.g., E7016, E7018, and E7048). Extra-low-hydrogen consumables such as Exxxx-H4 should be used for welding carbon steels with CE greater than 0.42% or where there is potential for delayed hydrogen-induced cracking (DHIC) such as cold worked pieces, high strength, and highly constrained areas.

Cellulosic type electrodes (e.g., E6010, E6011, or E7010) may be used only for root and hot passes. Although low-hydrogen electrodes are preferred, some refining locations and the pipeline industry prefer to use cellulosic electrodes frequently because they are easy to operate and provide improved control over the welding arc. Root pass with low-hydrogen electrodes reduces risk of DHIC. It also reduces risk of burn-through because the amount of heat directed to the base metal is less than when using cellulosic type electrodes. However, manipulation of low-hydrogen electrode for root pass is not as easy, but it can be done by training and practice. It should be noted that cellulosic electrodes have the following adverse effects on the integrity of the weldment:

(a) Deep penetration, therefore higher risk of burn-through than low-hydrogen electrodes
(b) High diffusible hydrogen (DH), therefore higher risk of hydrogen-assisted cracking

4.6.4 Consideration of Service Flow Rates

In order to reduce the risk from burn-through, appropriate minimum flow rates, about 0.4 m/second (1.3 fps) for liquid stream, should be considered in piping system. Faster (high) liquid flow rates, because normally the liquid temperature is greatly lower than welding temperature, may cool down the weld area quickly (effective to avoid the burn-through); however, it can cause hard zones that are susceptible to weld cracking or low toughness properties in the weldment, so that the metal properties may be degraded. If the normal flow of liquids exceeds 1.2 m/second (4.0 fps) or if the flow cools the metal to below dew point, at least 20 °C (70 °F) preheating is recommended until the weld has been completed. Under high liquid flow rate, the minimum interpass temperatures during welding may not be attainable, resulting in undesirable material properties, especially decreased toughness. Therefore, during hot tap welding, the service velocity should be between 0.4 m/second and 1.3 m/second (1.2 fps and 4.0 fps) in liquid handling piping.

For making attachment welds to storage tanks or pressure vessels containing a large quantity of liquid at least 0.9 m (3 ft) below the liquid/vapor line, normal circulation will effectively cool the weld area.

Meanwhile, welding on a line under noncontinuous flow conditions, e.g., a flare line, a standby line, or an emergency line, should not be attempted unless it has been confirmed that no explosive or flammable mixture will be generated during hot tap welding. In cases where this requirement cannot be met, inert gas or nitrogen purging is recommended.

4.6.5 Welding Crack and Burn-Through

Welding on in-service pipelines requires weld procedure development and qualification, as well as a highly trained workforce to ensure integrity of welds when pipelines are operating at full pressure and under full-flow conditions. Low-hydrogen welding procedures are used exclusively to perform all welding associated with hot tapping, which greatly reduces the potential for DHIC. Low-hydrogen welding procedures also substantially reduce the risk of burn-through. Extensive testing is performed to evaluate a welder's skill level and for weld procedure qualification to applicable national and international standards.

During actual welding, the branch to carrier pipe fillet welds are examined using the dry magnetic powder process following the root pass, hot pass, and cap. Subsequent to the completion of the weld, a wet contrast magnetic particle inspection is carried out 12 hours after to check for DHIC indications.

In order to avoid overheating and burn-through (Fig. 4.41), the WPS should be based on experience in performing welding operations on similar piping or equipment and/or be based on heat transfer analysis. Many users establish procedures detailing the minimum wall thickness that can be hot tapped or welded in-service for a given set of conditions like pressure, temperature, and flow rate. Some users include in their procedures the use of mock-up weld coupons when the actual thickness of the material to be welded is less than 6.4 mm (0.25 in.).

The mock-up coupon represents the actual material and thickness, the welding parameters are recorded, and the weld penetration is verified by etching. This information becomes the supplement to the repair package. To minimize burn-through, (i) the first weld pass to equipment or piping less than 6.4 mm (1/4 in.) thick should be made with 2.4 mm (3/32 in.) or smaller diameter welding electrode to limit heat input and (ii) maximum wall temperature of the base metal on welding should be 982 °C (1800 °F) for low-hydrogen electrodes and 760 °C (1400 °F) for cellulosic electrodes, but cellulosic is not recommended for hot tap welding. For equipment and piping wall thicknesses where burn-through is not a primary concern, a larger-diameter electrode can be used. Weaving the bead should also be avoided as this increases the heat input. The following guidelines are recommended as common practices unless the approved Simulation Model (see references below) and/or the end-user provides different requirements and limitations:

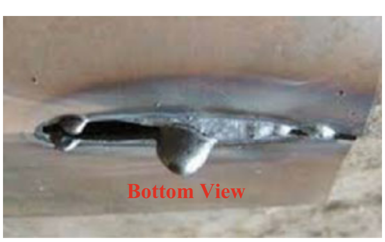


Figure 4.41 Burn-through on welding

1. Service and Design Conditions to Perform Hot Tapping
   (a) Recommended Flow Rates (FR) during welding when the metal thickness is less than 12.7 mm (½ in.) to prevent burn-through and rapid cooling):

1. Liquid: 0.40–1.22 m/second (1.2–4.0 fps)
2. Gas: min. 0.40 m/second (1.3 fps), no limit for maximum

(b) Operating Pressure (OP): The MAWP (maximum allowable working pressure) during hot tap welding shall be calculated based on the allowable stress at the welding temperature. For short-term welding, 33% increase over the allowable stress value per ASME B31.3 or API 620 and 650 may be allowed. The width of HAZ which is degraded the stress value may be 3.2 mm (1/8 in.).

(c) Normally it is not applicable for the metals which were required PWHT (or hardness control or CS, ≤225 BHN, but ≤200 BHN preferable) or on service at vacuum condition.

2. Hot Tap Welding Requirements
   (a) Ceq (CE) of the formula in BS 2642, AWS D1.1, and IIW (see Sect. 4.4.1(2)(b), Eq. 1)
   Ceq tolerance permitted: ± 0.20%
   Ceq ≤ 0.38% (preferable), 0.45% (maximum)
   Ceq = max. 0.40–0.43% (several company standards)
   (b) Preheating:
   1. Minimum preheat 125–150 °C (250–300 °F) for CE ≥ 0.38% and weld size >19 mm (0.75 in.) unless an extra-low-hydrogen electrode (e.g., E7016, 7018, or 7048 with H4) is used.
   2. API 510 (pressure vessel inspection for maintenance) and API 570 (piping inspection for maintenance) indicate a 150 °C (300 °F) minimum preheat.
   3. 200 °C (392 °F) maximum interpass temperature.
   (c) Recommended heat input: 0.6 to 1.6 kJ/mm (15–40 kJ/in.), but max. 2.1 kJ/mm (53 kJ/in.) may be applicable for medium or thick wall welding.
   (d) Recommended welding processes: GTAW, FCAW (impact tested and low hydrogen preferable), SMAW, GMAW (but short-circuit mode is avoided).
   (e) Controlled deposition welding techniques (temper bead or half bead) may be applicable when the weld hardness exceeds 350Hv or if required by end-user.
   (f) A minimum 175 °C (350 °F) preheat is required for the following conditions.
   1. 3.2 mm (0.125 in.) initial buttering layer in case of Weldolet type fitting. The buttering should not project inside the fitting to run pipe contact location, to avoid any fit-up (tack welding) problems.
   2. When half bead welding technique (a half of thickness of each pass is removed by grinding prior to applying subsequent weld layers) is applied.
   (g) Thin thickness: Use current control methods for pipe wall thickness, less than 5.0 mm (0.20 in.) to avoid burn-through.
   (h) Travel speed: Slow [≤76 mm (3 in.) /min.]
   (i) Cooling rates (CR): Maximize the cooling rate. The following procedures are normally applied.
   1. Permanent test flow loop, with actual media pressures and flow rates
   2. Temporary test low loops, with a representative fluid
   3. Water-filled pipe with flowing at atmospheric temperature in a test rig similar to that shown in API 1104 (welding of pipelines and related facilities), Appendix B (simple, basic – but the worst case)
   (j) Weld deposit technique: Use stringer beads with slight osculation/avoid weave beads if possible.
   (k) Split sleeve welding sequence: The longitudinal weld joint should be first welded (see Fig. 4.42).

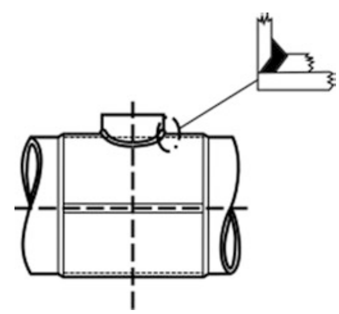


Figure 4.42 Split sleeve welding

   (l) Welding electrodes:
   1. Low hydrogen
   2. Diffusible hydrogen (DH) content ≤ H8 (8 ml/100 g of deposited metal), min. 2 hours
   3. Electrode diameter for SMAW: small; 2.4 mm (3/32 in.) for root pass (E6010 preferable)/3.2 mm (1/8 in.) for fill/2.0 mm (5/64 in.) for buttering or thin walls
   (m) Longitudinal weld: Where a full penetration longitudinal weld is desired, then use of a backup strip is suggested, which again should be specified when ordering the fitting.

3. Inspection for Hot Tap Welding
   (a) Weld area plus 75 mm (3 in.) on either side should be fully magnetic particle and ultrasonic examination tested to determine defects and laminations (if any) existing prior to welding.
   (b) Visual inspection of all attachment welds after welding and before attaching the hot tap machine. Ensure that weld root is not excessive as shown on the hot tap engineering drawing. Visual inspection should be performed on 100% of between pass welds for discontinuities such as cracking, porosity, and slag removal.
   (c) (c) Magnetic particle inspection (liquid penetrant inspection for nonmagnetic materials) should be performed on 100% of root and cap welds.

(d) Ultrasonic inspection should be performed on 100% of the finished welds, 72 hours after the completion of welds. Alternatively, MT or PT should be performed on the root pass and MT or PT should also be performed on the weld, 72 hours after completion of the weld.
(e) The valve to be installed at the hot tap location should be leak tested in accordance with API 598 (valve inspection for maintenance) or as shown on engineered drawing prior to installation in the field.
(f) Valve to be inspected for sufficient clearance of cutter prior to tapping. Valves must have clear, full-round openings at least 3.2 mm (0.125 in.) greater in diameter than the specified drill or cutter OD.
(g) The branch connection should be hydrostatically or pneumatically tested. Hydrotest is limited to a skin temperature of 93 °C (200 °F). For temperatures above 93 °C (200 °F), pneumatic test must be performed with the use of inert gas (nitrogen) or helium. The certified inspector must completely verify the full test process. Caution should be exercised during the pneumatic testing of the branch connection. It is the responsibility of the design engineer to develop the safe pneumatic test procedure that will be included in the design package.
(h) The test pressure should be as follows:
   1. The maximum value of the test pressure should be calculated in accordance with the particular design code. However, the following should be also taken into account in determining the test pressures:
   2. Test pressure for preformed split tees and full encirclement sleeves should be summation of actual operating pressure in the run pipe and maximum allowable pressure differential with respect to buckling of the run pipe calculated as defined in ASME Section VIII, Division 1, UG-28.
   Note: Design Engineer may use Williamson Industries' published guide titled "Approximate Guide for Maximum External Testing Pressure on Run Piping" to determine the maximum differential pressure and test pressures. However, in no case should the test pressure exceed the design code test pressure of the branch pipe.
(i) The general testing procedure to be followed should be:
   1. Shop leak testing of the hot tap valve, preferably with the valve not installed on the branch, for duration of at least 5 minutes.
   2. Testing of the branch connection, with the valve installed and in the open position, to demonstrate leak tightness and strength. Duration should be at least 30 minutes.
   3. Leak testing of the drilling machine mounted on the valve (with valve closed), for a duration of at least 5 minutes. Leak test pressure should be equal to the highest operating pressure in the run pipe during the hot tap operation.
   Note: Testing sequence and testing combinations may be modified depending upon the field or contractor's practice. However, any modified procedure should be reviewed by field engineer.
(j) The saddle or reinforcing pad should be pneumatic tested at 1 barg (15 psig). The inspector should verify this test.

Code and Regulatory Requirements for Hot Tapping

– API 510 (Pressure Vessel Maintaining Repair/Inspection)
– API 570 (Piping Maintaining Repair/Inspection)
– API 653 (Storage Tanks Maintaining Repair/Inspection)
– API 1104 (Welding of Pipelines and Related Facilities)
– API RP1107 (Pipeline Maintenance Welding)
– API RP2201 (Hot Tapping Practice)
– API RP577 (Welding Inspection and Metallurgy)
– ASME B31.4 (Pipeline Transportation Systems for Liquids and Slurries)
– ASME B31.8 (Gas Transmission and Distribution Piping Systems)
– ASME B31.12 (Hydrogen Piping and Pipelines)
– ASME PCC-2 (Repair of Pressure Equipment and Piping)
– NBIC NB23 (Repair and Alteration)
– US DOT 49CFR parts 192 and 195 (Pipeline and Hazardous Materials Safety Administration)
– PRCI PR-185-617 (Criteria for Hot Tap Welding)
– PRCI PR-185-816 (Review of procedures for Welding unto Pressurized Pipelines)
– PRCI NG-18 Report #175 (proof testing of the pre-hot tap branch connection)
– BS 4515 (welding of steel pipelines on land and offshore. Carbon and carbon manganese steel pipelines)
– BS 6990 (Code of practice for welding on steel pipes containing process fluids or their residuals)
– CSA Z662 (Oil and Gas Pipeline Systems)

References and Simulation Model for Hot Tapping

– Williamson Industries' Manuals
– Battelle Institute's Manuals and Simulation Model
– Pipeline Research Council International (PRCI) Model
– Edison Welding Institute's Manual
– E2G Hot Tap Simulation Model

4.7 Welding Processes

4.7.1 Master Chart of Welding Processes (Fig. 4.43)

4.7.2 Application of Arc Welding Processes

Table 4.45 shows the general characteristics (nonmandatory) for selection of arc welding processes.

Table 4.46 shows the general characteristics (nonmandatory) for selection of arc welding processes.

Table 4.47 shows the acceptable welding process and limitations in ASME Sec. VIII, Div. 2.

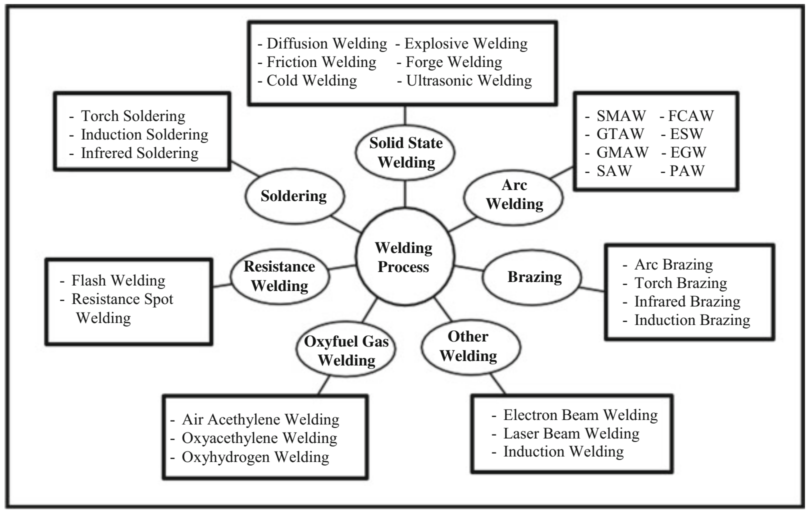


Figure 4.43 Master chart of welding processes

Table 4.45 (1/3) Comparison of general characteristics (nonmandatory) for selection of arc welding processes

Welding processes	Advantages	Disadvantages
SMAW (Shield Metal Arc Welding)	– The simplest and most versatile of the arc welding processes with any positions and most metals for all industries.	– Lower deposition rate and higher loose time (to change the electrode frequently and to remove the slug before subsequent passes) and higher stub loss than semiautomatic or automatic processes. – Ventilation is required in confined spaces because of high smoke and fumes. – Extra welder skill is needed for radiograph-quality welds when welded from one side.
GTAW (Gas Tungsten Arc Welding)	– Produces high-quality welds (especially root pass and clean weld bead) without slag in most materials. For example, on thin walled (<5 mm), the current can be adjusted low enough to control penetration and prevent burn-through. – The contaminants can be effectively excluded on welds by the backside charging gas. – The lower speed of travel provides better visibility and makes it easier to control the weld metal during deposition and fusion than other welding processes.	– Lower deposition rate compared with other processes. – Normally requires closer control of joint fit-up to produce high-quality welds from one side. – Very sensitive the cleaned condition on the weld bevels. So, better cleaning to remove oil, grease, rust, and other contaminants on weld bevels and the neighbors is required in order to avoid porosity and other weld defects. – More careful shielding from air movements above about 5 mph is required in order to maintain the inert gas shield over the molten puddle. Additional shielding tool may be required.
FCAW (Flux Core Arc Welding) <two types> ; FCAW-G (Gas Shielded) ; FCAW-S (Self-Shielded)	*FCAW-G process* – Deeper penetration and higher deposition rates than the SMAW process – more economical in many shop applications. – Alloying elements can be added to the flux core to provide a wide variety of compositions, including many LAS or SS. – The flux provides good protection of the molten puddle by generating both a protective gas blanket and a slag covering. However, the process will not tolerate wind velocity (> 2.2 m/s or >5 miles/hr) due to excessive porosity. – Suitable for all positions without the problems of lack of fusion associated with GMAW short-circuiting welding.	<Both FCAW-G and FCAW-S> – Produce a slag that has to be removed from the weld between passes. – Both are to be with low-hydrogen processes. – Welds made with these processes can have poor notch toughness. Impact test for the PQR and filler metal (e.g., T-1, T-5, and T-8 electrodes) may be required for the MDMT < −10 °C (14 °F). – The fume rate for SS welding is about the same as for SMAW electrodes and is less than for CS self-shielded wires. *FCAW-G process* – Not to be used where the wind velocity is >2.2 m/s or >5 miles/hr because of the risk of excessive porosity. Increasing gas flow to overcome excessive wind is not a solution, as it may make conditions worse by creating turbulence that draws in additional air. – Produces more smoke than solid wire GMAW.

Sources: AWS, ASM Metal H/B Vol. 6 & 6A, ASM Welding H/B, Suppliers' Manuals, and Users' Specifications

Table 4.45 (2/3) Comparison of general characteristics (nonmandatory) for selection of arc welding processes

Welding processes	Advantages	Disadvantages
FCAW (Flux Core Arc Welding) <two types> ; FCAW-G (Gas Shielded) ; FCAW-S (Self-Shielded)	*FCAW-S process* – Filler metals eliminate the need for external shielding gas and tolerate more severe wind conditions without excessive porosity. – The process is considered to be equal to coated electrode processes in tolerance to wind. – Used for single-sided T-Y-K joints with all-position fill passes on butt or fillet welds on offshore structures in lieu of coated electrodes (SMAW). – Welders need training in special procedures, but the process is easy to use. – Applications may include heavy wall sections, pipelines, and weld overlay.	*FCAW-S process* – Produce even larger amounts of smoke, so for shop applications it requires good ventilation and sometimes special smoke removal equipment at the welding gun. – Welds made with self-shield wires require strict control of bead thickness and width and of electrode stick-out to obtain high toughness properties.
GMAW (Gas Metal Arc Welding) <four types per transfer mode> – S (short circuit transfer) P (pulse) – Sp (spray) – G (globular)	<All Transfer Modes> – Used semiautomatically or machine guided for automatic welding. – Produces higher deposition rates on most metals. – Suitable for both groove welds and CRA overlay welding on CA or LAS. – Welding speeds and deposition rates are equal to or greater than with SMAW. – Weld dilution is generally lower because of less penetration. – Because there is no flux and relatively small amounts of deoxidizers are added to the wire, there is very little cleaning needed after welding (as opposed to coated electrode welding). No slag to clean after welding. – Uniform arc length is maintained by the constant voltage power supply. <Individual Transfer Modes> – Less smoke and spatter with GMAW-S than SMAW. – With the low heat input and penetration, thin sections are easily joined and wider root gaps (GMAW-S) are more easily welded. – For shop fabrication of piping (GMAW-S), high quality root passes can be made faster in any position and generally at lower cost. – Spray transfer and globular transfer modes produce a highly visible weld puddle, similar to the puddle of short-circuiting but without a slag covering.	<All Transfer Modes> – Welding equipment is more expensive and complicated to set up and maintain than the equipment for SMAW. The cost of wire and shielding gas can be greater than the cost of coated electrodes (SMAW), but this is offset by higher productivity and less wastage. – Gas shielding can be disrupted by external air currents, so precautions must be taken to avoid wind velocities of >2.2 m/s or >5 miles/hr – Wind shields or enclosures may be required to block air currents or reduce them to velocities low enough to maintain adequate gas shielding. Increasing gas flow rates to compensate for excessive wind may make the problem worse by creating turbulence around the arc and drawing in air. – GMAW requires greater access to the work because of the size of the welding gun and nozzle. Generally, the wire feeder must be positioned close to the work. – Short-circuiting welding can be used without restriction for root passes in butt welds or branch connections but should be strictly controlled if used for fill passes because of the risk of nonfusion or cold laps. – For fill passes in piping butt welds, it should only be used where welding progression is uphill between 10 o'clock and 2 o'clock, whether the pipe is in the fixed position (5G) or rotated (1G). – It is not suitable for fillet welds where material thickness exceeds 1/4 in. and is generally not used in the fabrication of pressure vessels, tanks, or structural members. – Lack of fusion between weld layers is difficult to detect by radiography, and where there has been poor control of the short-circuiting process, the problem of lack of fusion has been severe enough on occasion to cause some fabricators to abandon using the short-circuiting process. – Compared to coated electrode welding, short-circuiting welding requires better joint cleaning, fit-up, and grinding of the tack welds to obtain good root pass quality. – Lack of fusion is not a problem with higher heat input spray transfer or globular transfer GMAW. – For spray transfer GMAW, there is more arc radiation. This is more uncomfortable for the welder and makes the process more suited to automatic welding for some applications. – Spray transfer GMAW welding is limited to flat and horizontal position welding because of the larger weld puddle.

Table 4.45 (3/3) Comparison of general characteristics (nonmandatory) for selection of arc welding processes

Welding processes	Advantages	Disadvantages
SAW	– Applicable for most metal welding. – Very high welding deposition rate – higher welding currents and multiple electrodes can be used with the process to achieve deposition rates from two to ten times that of SMAW. – Can be reduced the number of passes because of deep penetration characteristics. – Extensively used for making corrosion-resistant overlays using strip electrodes (e.g., 0.4–0.5 mm thick by 30, 60∗, 90, 120, 150 mm wide). *most common width – The slag covering the weld provides excellent protection of the molten weld metal, resulting in high-quality weld deposits and clean bead. – No intense radiation of an open arc process, and this gives safety to welder. – Low-hydrogen welding process, but the hydrogen level depends on the type of flux selected and its dryness. – Lower hardness at HAZ because of higher heat input-slower cooling rates.	– For most applications, SAW requires additional handling and setup time to position work so welding can be done in the flat position. – The lack of visibility of the arc and molten puddle during welding makes it harder to keep the weld positioned in the joint, although this is generally not a problem. – Setup time for welding is usually greater for SAW than for SMAW and GMAW, so the process is not as cost-effective on smaller jobs. – Where higher heat input is used, grain coarsening can occur in the HAZ. This can cause a loss of impact properties, which may not be acceptable in some applications. – For multipass welds, wire/flux combinations have to be selected that will avoid manganese and silicon buildup in the weld, since buildup of these elements increases hardness, lowers toughness, and can cause cracking problems in sour service. – Common welding defects include: • Porosity due to weld contamination. This results from inadequate cleaning of rust and mill scale from the joint. • Slag entrapment due to excessive convexity or undercut. This happens when slag is trapped along the edge of the weld and is not removed during normal cleaning. • Centerbead weld cracks due to improper bead shape. This occurs in welds that are deeper than they are wide. **Considerations for Choosing Wire/Flux Combinations** – Alloying elements may be added to either the electrode wire or the flux, but better chemistry control is obtained when alloys are added to the wire and a neutral flux is used. – Base metal dilution is greater with SAW than with most other welding processes because of increased penetration. Base metal dilution can have a significant effect on weld metal chemistry and should be considered when selecting wire/flux combinations, particularly for thinner materials. – PWHT reduces weld metal hardness but also lowers tensile strength. PWHT is particularly significant for higher temperatures and longer holding times. The effect of PWHT on tensile strength must be considered in choosing wire/flux combinations. – As a result, careful attention has to be paid to selecting wire/flux combinations that will produce weld metal compositions with both proper chemistry and strength.
ESW/EGW (Electroslag Welding/ Electrogas Welding)	– Both processes are available vertical welds of various thicknesses (mostly for heavy wall) in less time than is required for other welding processes. – ESW: Extensively used for making corrosion-resistant overlays using strip electrodes (e.g., 0.4–0.5 mm thick by 30, 60∗, 90, 120, 150 mm wide). *Most common width – ESW is primarily used in the shop, while EGW can be used either in the shop or in the field. – Simple joint preparation and less distortion on welds & HAZs for both processes than with other welding processes.	– Both processes are limited to joining CS and LAS in the vertical position. – Setup time for these processes is very high but is offset by higher deposition rates. – The significance of setup time decreases with increasing thickness of the weld. Electroslag welds are sensitive to bead shape control. – Centerline cracking can occur when the form factor (weld pool width divided by weld pool depth) is low. An example of a low form factor that is crack sensitive (i.e., unity) is a weld pool as deep as it is wide. – Both processes require very high heat input. ESW has the highest heat input, producing large coarse-grained welds and a HAZ low in notch toughness. The heat input with EGW is not as great as with ESW, but there is some degradation of properties in the HAZ. This limits application of EGW to materials with poorer notch toughness. – ESW welds require a grain refinement heat treatment after welding (such as normalizing) to restore notch toughness. The need for normalizing after welding usually prevents the use of ESW for field welding. – This limitation has led one contractor to restrict the use of EGW on field storage tanks to those that have minimum service temperatures of 0 °C (32 °F) or above.
PAW (Plasma Arc Welding)	– PAW which was advanced process from the GTAW has a greater energy concentration as compared to GTAW. – A deep, narrow penetration is achievable; reducing distortion and allowing square-butt joints in material up to 12.7 mm (0.5 in.) thick. – Greater arc stability allows a much longer arc length (standoff) and much greater tolerance to arc length changes.	– PAW requires relatively expensive and complex equipment as compared to GTAW; proper torch maintenance is critical. – Welding procedures tend to be more complex and less tolerant to variations in fit-up, etc.

General Note: See AWS A5.32 for comparison and selection of shielding gases used in fusion welding

Table 4.46 General characteristics (nonmandatory) for selection of arc welding processes

Welding processes	Limitation	Positions	Deposition rate, kg/hr [consumable diameter, mm]	Typical dilution, %	Remark (see Fig. 4.44)
SMAW	1. General 2. Overlay welding (1G & 2G)	All	1.5 [3.2] 3.0 [Φ5.0]	30 35	
SAW	1. Long seams (all dia.) and girth seams (≥356 mm) 2. Overlay welding (1G & 2G)	F & H	4–8 [wire Φ3.2] 15–17 [strip 0.5 × 60]	35 15	See Fig. 4.65 for overlay
ESW	1. Overlay welding (1G & 2G)	F & H	20–22 [strip 0.5 × 60]	10	
GTAW	1. Root (one or two) passes without back-gouged and back-welded 2. Overlay welding (inside of small bore pipe)	All	1–2 [Φ1.2]	20	
GMAW-short circuit transfer	1. Root (one or two) passes on Category A & B and nozzle-to-shell welds only if back-gouged and back-welded 2. Root passes on circumferential piping welds for fabricated nozzles or internal piping 3. Root passes on pressure-containing internals of vessels	All in short & pulsed Limit outdoor	2–5 [Φ1.2] – spray arc 3–7 [Φ1.6] – spray arc	30 30	
FCAW	1. Some prohibition (a) for pressure-retaining parts, (b) minimum design temperature of −40 °C (−40 °F), (c) for Category D nozzles 2. Widely used for non-pressure parts 3. May be used for pressure parts (low pressure)	All Limit outdoor except self-shielded	3–6 [Φ1.2]	25	

Table 4.47 Acceptable welding process and limitations in ASME Sec. VIII, Div. 2 (The paragraphs and table specified in this table come from ASME Sec. VIII, Div. 2)

Welding process	Application/limitation	Special heat treatment requirement
• GMAW, GTAW, PAW, LBW	All material	None
• EBW	All material	Exceptions for postweld heat treatment as provided in paragraph 6.4.2 are not permitted for welding of ferritic materials greater than 3 mm (0.125 in.) in thickness
• SMAW, SAW, EW, induction	All material except titanium	None
• Electrogas, ESG	Butt weld only in ferritic steel and the following ASS: • SA-240-TP304, TP304L, TP316, TP316L • SA-182-F304, F304L, TP316, TP316L • SA-351-CF3, CF3A, CF3M, CF8, CF8A, CF8M	For electroslag welding in ferritic materials over 38 mm (1.5 in.) in thickness at the joint or electrogas welding with a single pass greater than 38 mm (1.5 in.), the joint shall be given a grain refining (austenitizing) heat treatment
• Inertia • Continuous drive friction	• Materials assigned a P-Number in Section IX excluding rimmed, semi-killed steel, or titanium	Exceptions for postweld heat treatment as provided in paragraph 6.4.2 are not permitted for welding P-No. 3, 4, 5A, 5B, 5C, 6, 7 (except TP450 and TP410S) and P-No.10
• Arc stud • Resistance stud (for attachments as non-pressure parts)	• Non-pressure parts having a load- or non-load-carrying function except for quenched and tempered high strength steels (see Table 3-A.4), provided that, in the case of ferrous materials, heat treatment requirements of paragraph 6.4.2 for the materials used in the vessel are complied • Stud shall be limited to 25 mm (1 in.) diameter for round studs and an equivalent cross-sectional area for studs with other shapes	In the case of ferrous material, heat treatment requirements of paragraphs 6.4.3.6 and 6.6.6.3 for the materials used in the vessel shall be complied

General Notes
(1)ASME Sec. VIII, Div. 1 UHT (ferritic steel with tensile properties enhanced by heat treatment) states that filler metal containing $V > 0.06\%$ shall not be used for weldments subjected to PWHT

Figure 4.44 shows the comparison of deposit rates in kg/hr for different welding processes. ESW and SAW shows the highest deposition rate.

See Sect. 2.1.4.2 for all welding requirements of Cr-Mo steel pressure vessels. The following are the summary for typical application requirements and cautions for each welding process.

4.7.2.1 SMAW (Shield Metal Arc Welding)

(a) Application of SMAW

1. SMAW processes may be used for hot pass for CS root (if approved by end-user) and fill passes of butt welds, attachment welds, and overlay welding on accessible surfaces such as flange faces.

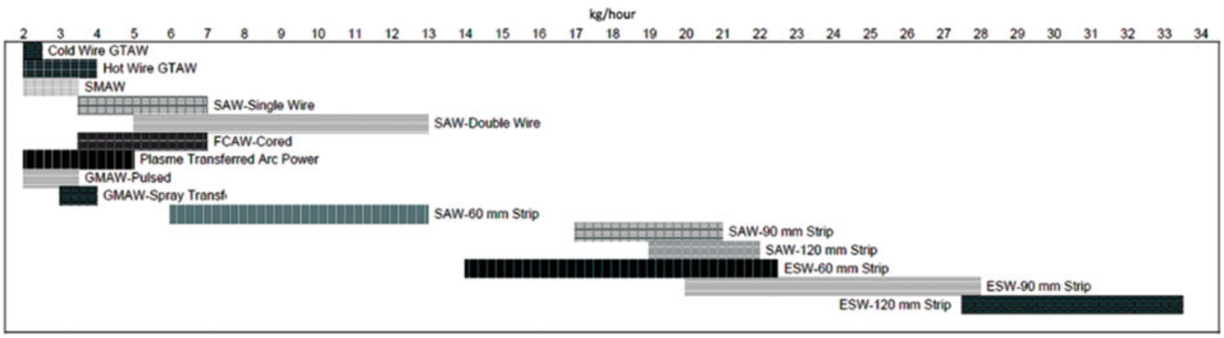


Figure 4.44 Comparison of deposit rates in kg/hr for different welding processes. (Source: ASM SS H/B & NiDI Publ. 10,064)

2. SMAW should not be used for CS welding open roots (butt and groove welds) unless the backside of the root is ground or back-gouged to sound metal and back welded or backing strips at the backside of the root are used or approved by the end-user.
3. SMAW processes should not be used for root passes in single-sided weld joint of LAS, SS, and all alloy materials.
4. When impact tests are required for the base metal of CS and LAS and when the AWS/ASME filler metal specification does not require impact tests for the classification at or below the MDMT, the impact test for the procedure may be required for each manufacturer and brand to be used.

(b) Welding Electrodes
1. All SMAW processes for CS and LAS pressure-containing welds should be made using low-hydrogen-type electrodes (H16 or lower).
2. Cellulosic electrodes (E6010/E4310 or E6011/E4311) for CS may be acceptable only for the following conditions.
   – Root pass of single-welded joints.
   – Welding galvanized structural attachments to CS pressure-containing components.
3. E6013 may be used for shoe, clip, and pipe support attachments to minimize undercutting.
4. See Sects. 4.8.1.1 and 4.8.1.2 for welding electrode standard description of SMAW for CS and LAS.

4.7.2.2 GTAW (Gas Tungsten Arc Welding)

(a) Application of GTAW
1. GTAW is excellent for thin wall and/or small diameter piping and tubing including orbital welding of SS, Ni alloys, Cu alloys, and Al alloys. On thin wall pipe, 3.2 mm (0.125 in.) and less, a square edge preparation that is butted tight can be used. The root pass is made without filler metal addition (called autogenous weld).
2. On heavier wall piping, it is frequently used for the root pass on welds requiring high quality, such as for high pressure, high temperature hydrogen piping and return bends in furnace/boiler coils. On thicker pipe, the joint edges are beveled and fitted up with a gap (called open root), and filler metal is added during welding of the root pass. In lieu of adding filler metal, consumable insert rings under the careful control of fit-up can be fitted into the joint and fused into the root to compensate the filler metal addition if the client approves.
3. GTAW is also used for root passes where a smooth inside diameter surface is required, such as on piping in EAC, fatigue, and acidic environments. Because of the inert gas protection of the weld and excellent process control, GTAW is frequently used on reactive/oxidizable metals such as titanium (Ti) and magnesium (Mg).
4. GTAW may be used for any material and thickness and in any position with the following restriction unless approved by the client: Other than producing mill products (EFW welded pipe without filler metal), welding without filler metal (autogenous welding) should not be used.
5. When the automatic pulsed gas tungsten arc welding (GTAW-P) is used for root pass welding of single-welded joints, the welding machine manufacturer and the machine model number shall be considered as an essential variable in qualifying PQR.
6. When a dual-process WPS is used (i.e., GTAW/SMAW), the initial GTAW process should have a minimum of two passes.

(b) Welding Fillers
1. All strength welds made with GTAW must be done using solid filler metal and high-frequency starting. Starting by touching the tungsten electrode to the base metal is not allowed.
2. Filler wire type shall be identified by a tag attached to or direct marking on the surface of each length of wire.
3. See Sects. 4.8.1.3 and 4.8.1.4 for filler metal (wire) standard description of GTAW.

(c) Shielding Gases
1. A backup gas purge is used for materials that are sensitive to contamination from air on single-welded joints that are not back-gouged (e.g., piping and closing seams).
2. An inert gas backing purge shall be used during the welding of the root and second pass of open butt welds containing alloy contents of LAS (Cr $\geq$2.25%), SS, Ni alloys, Cu alloys, and Al alloys. Typically, inert gas purge is not necessary for welding CS or LAS (Cr $<$ 2.25%).

3. Either argon (Ar) or helium (He) can be used for purge gas. As an alternate, nitrogen may be used for the purge gas for welding ASS and Cu alloys. Nitrogen (N_2) is not suitable for most other materials because it acts as a contaminant except only for the backing gas for SS.
4. The best results for SS and high Ni alloys are obtained when they are purged to oxygen levels of less than 1%. Purging with 4–10 times the required volume is needed to obtain the relatively inert atmosphere. Where uncertainty exists regarding the adequacy of the purge, a mine safety oxygen analyzer can be used to check the oxygen level in the purge gas being exhausted from the weld area.
5. Initial gas purging is usually done at a high flow rate ($\geq$30 ft^3/hr) to flush the system and then reduced to a low flow rate ($\leq$8 ft^3/hr) for welding. Particular care should be taken to ensure that the backup gas pressure is not excessive when welding the root pass; otherwise weld blowout or root concavity can occur.
6. WPS/PQR should specify the type, style, and concentration of the insert gases.
7. Adequate venting or exhaust is important to prevent excessive pressure buildup during welding. The area of the vents for exhausting backup gas should be at least equal the area of the opening used to admit the backup gas to the system. After completion of the root and several fill layers, the backup gas purge can be discontinued.

4.7.2.3 GMAW (Gas Metal Arc Welding)

(a) General Application

The GMAW process is known by MIG (metal inert gas). However, MIG is no longer descriptive of GMAW because not all of the shield gases used with the process are inert. One of the GMAW is MAG (metal active gas) process. The electrode is generally solid and all of the shielding gas is supplied by an external source.

It can be used not only semiautomatically. It is mainly applied to not only root pass because of the low heat input and deep penetration but also weld overlay because of the high deposition rates.

The properties of GMAW depend on the arc transfer modes. Figures 4.45 and 4.46 and Table 4.48 show the comparison of characteristics of several transfer modes of GMAW.

See Sects. 4.8.1.3 and 4.8.1.4 for filler metal (wire) standard description of GMAW.

Figure 4.46 shows optimum voltage and current range of several transfer modes of GMAW.

(b) Requirements and Limitation (Additional or Alternative Requirements in Table 4.48)

1. GMAW-S (Short-Circuiting Transfer Mode)

It is of particular significance to inspectors in that many specifications, codes, and standards impose limitations or special conditions on its use. The technique can suffer from incomplete fusion particularly in the sidewall of steep or narrow weld preparations. This occurs as transfer of small fast freezing droplets only occurs while the electrode is short-circuited by contact with the workpiece. Intermittent loss of contact can leave areas of lack of fusion. In shallow weld preparations, these are also very difficult to detect with conventional radiographic techniques. Consequently, a higher standard of NDE inspection is required. In pipeline welding, automated ultrasonic has been used to overcome this problem. The risk of lack of fusion (LF) associated with GMAW-S means restrictions on qualification of welders using radiography only and welding inspectors should make the following notes for prevention of these potential problems.

– GMAW-S may be used only for root pass welding on piping. Root pass welding with GMAW-S for other applications is permitted, provided the root pass is completely removed from the backside. For example, GMAW-S may be permitted for root and hot pass of one-sided welding if the total deposited thickness is less than 25% of the total thickness of the weld and the base material is a P-1 material with maximum thickness of 10 mm (3/8 in.).
– For root pass applications in single-welded butt joints, internal gas purging with inert gas is required for materials having over 2% total alloy content.
– For vertical welding, the root pass and second pass progression for a material of any thickness may be either uphill or downhill.

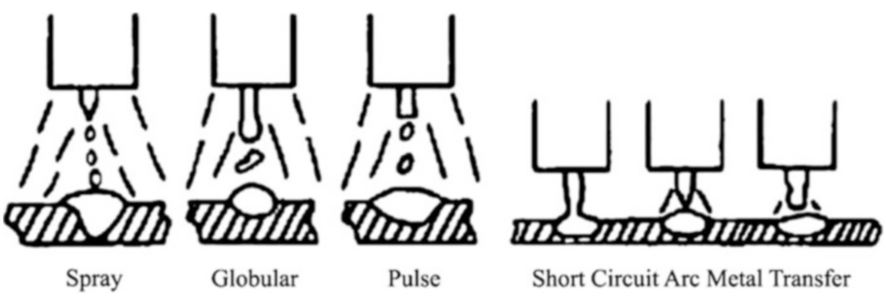


Figure 4.45 Several transfer modes of GMAW

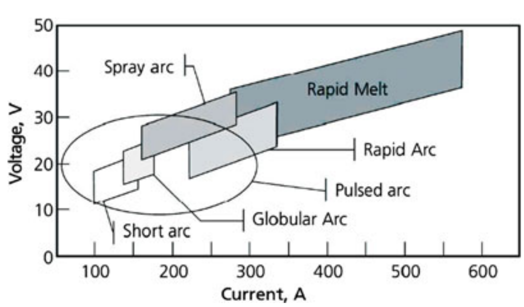


Figure 4.46 Optimum voltage and current range of several transfer modes of GMAW. (Source: WelderDestiny Report, 2005 – modified)

Table 4.48 Comparison of characteristics of several transfer modes of GMAW

GMAW-S (short circuits)	GMAW-P (pulsed)	GMAW-Sp (spray) or G (globular)
1. Smoke and spatter are less than with SMAW. 2. Permitted for root and hot pass of one-sided welding if the total deposited thickness is less than 25% of the total thickness of the weld and P-1 material, $\leq$10 mm (3/8″) thick. 3. Permitted for welding root passes in double-sided joints; the root passes shall be ground or back-gouged to sound weld metal and back welded. But not permitted for branch connections, socket welds, slip-on flanges, or couplings. 4. For vertical welding, the root pass and second pass progression for a material of any thickness may be either uphill or downhill. 5. Use the fill and cap pass for butt or fillet weld provided any member <3/8″ thick and vertical welding is performed with uphill.	1. Whenever the welding system is changed or the settings on existing equipment are significantly altered, the fabricator should verify weld properties. 2. Because of constant voltage power supply, the amperage automatically towards the work. If the arc length shortens or lengthens, the power source changes the current output to increase or decrease the electrode burn-off and maintain constant arc length and voltage. 3. Used for any material thickness in any position (most welding). 4. Not permitted for root pass welding of single-sided joints. 5. When used for root passes in double-sided joints, the root passes shall be ground or back-gouged to sound weld metal and back welded.	1. 100% CO_2 or argon-CO_2 mixtures for globular mode. 2. Binary blends containing Ar + 1–5% O_2 or Ar + CO_2, where the C \\O_2 levels are 18% or less for spray mode. 3. Produce a highly visible weld puddle, similar to the puddle of short-circuiting arc but without a slag covering. 4. No flux – very little cleaning after welding. 5. Limited flat and horizontal welds. 6. Not permitted for root pass welding of single-sided joints. 7. When used for root passes in double-sided joints, the root passes shall be ground or back-gouged to sound weld metal and back welded.

- The fill and cap passes for butt or fillet welds may be welded with this process, provided the thickness of any member does not exceed 10 mm (3/8 in.) and vertical welding is performed with uphill progression.
- Application of GMAW-S may be acceptable for all standard shop fabrications.
- Welding may be done in any position except vertical-down, and the current is not less than 170 A.
- Welding may be done in the vertical-up position (3G), and the heat input is not less than 14,000 Joules/cm (35,000 Joules/in.).
- Welders who are performing GTAW-S on production welds should be qualified by mechanical testing using side bend specimens. Also, API RP582 requires the following limitations for GMAW-S.
- The process shall not be used for branch connections, nozzle-to-shell welds, or socket welds.
- Variations of GMAW-S shall have the same limitations as outlined above. Proposals to use GMAW-S variations without back purging shall be approved by the owner's engineer.

2. GMAW-Sp (Spray Transfer) and GMAW-G (Globular)
   - The spray and globular arc processes are acceptable for all standard shop fabrication other than below.
   - Not permitted for root pass welding of single-sided joints.
   - When used for root pass in double-sided joints, the root should be back-gouged, back-chipped or ground, and back-welded.
   - Maximum base metal thickness 10 mm (3/8 in.): restricted to carbon steel materials.
   - These transfers for thicknesses over 10 mm (3/8 in.) require special qualification and acceptance on a shop-by-shop basis.
   - The fill and cap passes for butt and fillet welds may be used with this process provided the thickness of any member does not exceed 12.7 mm (1/2 in.) and vertical welding is permitted with the uphill progression.
   - Both spray and globular transfer GMAW are used for corrosion-resistant overlays.
   - GMAW-Sp is used on butt welds of stainless steels, nickel alloys, and copper alloys. Pulsed arc welding can be used in similar applications but has the advantage of all-position welding capability.
   - GMAW-Sp is not preferred on carbon steel if submerged arc welding (SAW) can be used, but is used on copper and nickel alloys.
   - GMAW-Sp and GMAW-G should only be used at the flat position unless otherwise approved by the owner's engineer with the approved WPS/PQR.
3. GMAW-P (Pulsed)
   - Not permitted for root pass welding of single-sided joints.
   - When used for root pass in double-sided joints, the root should be back-gouged, back-chipped or ground, and back-welded.
   - The fill and cap passes for butt and fillet welds may be welded with this process provided the thickness of any member does not exceed 12.7 mm (0.5 in.) and vertical welding is permitted with the uphill progression.
   - The WPS and PQR for this process should address all variables applicable to the welding system and machine settings. These variables should be considered essential, and any change will require requalification.
4. Surface Tension Transfer (STT™) – STT instead of GMAW-S may be accepted if the end-user accepted. Supplier shall submit prior experience and reference list, with contacts, prior to consideration. See Sect. 4.7.3.1 for more details.

4.7.2.4 FCAW (Flux Core Arc Welding)

FCAW uses a flux-containing electrode rather than a solid or fabricated electrode (metal powders in a sheath). The core ingredients may supply some or all of the shielding gas needed, while the shielding gas for GMAW comes from an external source. Two types of shielding methods are used for FCAW.

The gas-shielded process (FCAW-G) requires an external shielding gas (usually CO_2 or argon-CO_2), while the self-shielded process (FCAW-S) generates its own shielding gas.

FCAW can be used as either a semiautomatic or automatic welding process but has widest application as a semiautomatic process. Traditionally FCAW process has been restricted to apply for pressure-containing facilities or low temperature services. However, the use of FCAW process has been extending to pressure-containing parts as well according to the technical development of FCAW since 2000. Here is a general background and guideline for the application of oil and gas industries.

(a) General Limitations

1. FCAW welds can be more prone to slag inclusions than other welding processes. Therefore, FCAW is restricted to the welds exposed to moderate/severe wet H_2S or hydrofluoric (HF) acid services.
2. There are some reports for localized hard spots due to nitrides in welds made by FCAW process. Nitrogen is absorbed into the weld due to pickup from the atmosphere into the weld arc. Hard spots which make the weld more susceptible to sulfide stress cracking (SSC) are most likely to occur when there is a high crosswind.
3. FCAW welds are also prone to have variable toughness through the weld if heat input variables are not followed. This is why impact testing is recommended even when the service does not require the test per code. The electrodes shall meet impact test requirements in the codes, but should not be used the exemption conditions (e.g., PWHT effect, stress ratio effect, and yield strength effect) in the codes.
4. The use of electrodes with a diameter in excess of 1.6 mm (0.063 in.) may not be permitted.
5. The selection of external shielding gas, welding position, and polarity should be considered as essential variables and should meet the electrode manufacturer's recommendations, as well as the classification requirements pertaining to these variables. Changes in the variables, as recorded on the PQR, or variations from ASME Code Section II, Part C, shall require requalification.
6. For procedures requiring either impact or hardness testing, it is advisable to review weld metal properties with the consumable manufacturer to ensure the original qualified properties continue to be met. When rutile-type (i.e., E71T-1 type) consumables are used in as-welded or in the PWHT'd condition with impact testing required, the specific brand and trade name of the consumable used in production must be qualified on supporting PQRs with impact test results meeting the minimum design code requirements.

   Welding consumables, including those for FCAW, are routinely used in situations not addressed by the testing requirements in AWS/ASME welding specifications. A periodic review with the manufacturer is good practice to ensure minor variations that occur over time with FCAW consumable formulations (e.g., raw material and microalloying changes) do not adversely affect the ability of these products to perform as intended. Small changes in microalloying additions can have significant effects on properties.
7. There is a possibility for hydrogen-type cracking due to the inability to control the hydrogen diffusion in the welding wire. For welding pressure-containing equipment wall thickness in excess of 9.5 mm (0.375 in.), the diffusible hydrogen (DH) limit for FCAW consumables (as manufactured) shall meet the specifications in Table 4.49.

Table 4.49 Diffusible hydrogen (DH) limits for FCAW consumables of CS and LAS

SMTS for the base metal	Maximum DH designation (per ASME/AWS SFA/A5.20 or SFA/A5.29)
≤70 ksi (483 MPa)	H16
>70 ksi (483 MPa) and ≤85 ksi (587 MPa)	H8
>85 ksi (587 MPa)	H4

Source: API RP582, Table 1

8. For pressure-containing applications, the following requirements may apply:
   (a) The process is not acceptable for root pass welds without backing.
   (b) The process is limited to the gas-shielded method.
   (c) Procedures submitted for approval shall include vendor trade names for all electrode consumables as well as weld metal CVN impact tests for all procedures that are postweld heat-treated fabrications. CVN impact tests shall meet ≥27 J (20 ft-lbs) average and ≥20 J (15 ft-lbs) minimum at −29 °C (−20 °F).
   (d) CS fabrication shall use gas-shielded electrodes that meet the requirements of E7XT-1, E7XT-5, or E7XT-12.
   (e) Cr-Mo steels or SS fabrication must have prior approval from the owner's engineer. If approved, the process shall use EXXT-1 or EXXT-5 gas-shielded electrodes.
   (f) ASS FCAW electrodes used for welds that will be PWHT or in service at equal to or greater than 538 °C (1000 °F) shall be designated as bismuth (Bi) free. The PQR shall show that the deposited weld metal has a bismuth concentration less than or equal to 0.002 wt%. Weld deposit should have a max ferrite number of 9FN due to bad toughness.
9. For structural applications, including non-pressure-containing attachments such as insulation clips, tray supports, and nameplates, the following requirements may apply:
   (a) Structural attachments welded directly to pressure-containing equipment shall use the gas-shielded process.
   (b) All other structural welding may use the gas-shielded or self-shielded wires.
10. When opened filler metal coil is uploaded onto the welding machine, the first 150 mm (6 in.) of the filler shall be removed.
11. See Sects. 4.8.1.5, 4.8.1.6, 4.8.1.7, and 4.8.1.8 for filler metal (wire) standard description of FCAW.

(b) Limitations per Shielding Types

1. Self-Shielded FCAW (FCAW-S)

   Self-shielding FCAW (FCAW-S) is normally used only for welding of CS structural structures so that may not be permitted for pressure boundary welds, lifting lugs, skirts, or base ring welds. When it is permitted, the following guidelines and restrictions should apply:
   (a) Electrode types identified by the consumable manufacturer for multipass application should be used.

(b) Only electrode classifications which have specified minimum impact test requirements should be used.
(c) FCAW-S shall not be used with other welding processes without qualifying the specific combination.
(d) E71T-8 electrode is a FCAW-S electrode for welding CS and LAS that are of greatest interest for industry applications. These can be used in all positions, have good notch toughness, and are generally low in hydrogen (less than 10 ml/100 g weld metal). These electrodes are used in sizes from 0.068 to 3/32-in. diameter. All-position welding is done with 5/64-in. diameter or smaller electrodes, while the larger-diameter wires are used only for flat or horizontal welding. Downhill welding is generally not done except when using electrodes that are specially formulated for pipeline welding. Self-shielded electrodes have denitrifiers added to them to prevent porosity caused by nitrogen picked up during welding. Aluminum is generally used for denitrifying the weld; a weld deposit of up to 1% aluminum is not considered harmful.
(e) Welds made with the FCAW-S process in critical applications, such as T-Y-K joints (T-, Y-, and K-shaped joints and their combinations) for offshore platforms, require special welder training and strict adherence to established welding procedures, as well as attention to electrode stick-out, weave width, pass thickness, and preheat.

2. Externally gas-shielded FCAW (FCAW-G)

FCAW-G may have the following restrictions.

– It is permitted for groove and fillet welds for P-No. 1 through 5B and P-No. 8 pressure boundaries in other than cracking environments (wet H_2S service category 2 and 3 in NACE publ. 8X194, HF, amine, caustic, and hydrogen service at 232 °C (450 °F) and above, etc.).
– It should not be used for ASS operating at 510 °C (950 °F) and above.
– It is permitted for CS structural welds.
– FCAW-G using short arc transfer mode is not permitted.
– Generally FCAW-G for pressure welds is limited to flat or horizontal position welding only, unless shop can especially demonstrate out-of-position capability on the PQR.
– It is not permitted for use on the root pass of groove welds welded from one side only.
– It is permitted for the root pass if it will be back-gouged out.
– Field/outdoor welds using FCAW-S should not be attempted when the wind speed is at 5 mile/hr and above. If the winds are higher, suitable wind shielding under end-user's approval may be used.
– More strict NDE should be performed in accordance with the end-user's specification.
– For CS and LAS, T-1 (acid slag), T-2 (single-pass welding), and T-5 (basic slag) type flux-cored electrodes are generally used. T-1 type electrodes have good welding characteristics, but the acid slag does not help keep weld metal low in hydrogen unless specially formulated. Only a limited number of flux-cored electrodes meet low-hydrogen requirements (i.e., < 10 ml/100 g weld metal), and these are most commonly available in the T-1 type. The T-1 type can be used with either CO_2 or argon-CO_2 shielding gas. T-1 electrodes have a smoother arc and less spatter with argon-CO_2, although the weld is slightly higher in manganese and silicon. EX0T-1 electrodes are designed for flat and horizontal position welding only. All-position welding can be performed with EX1T-1 electrodes in diameters up to 1.6 mm (1/16 in.). Vertical welding is generally done in the uphill direction.

  The T-2 type electrodes are designed for single-pass welding on rusty materials and are higher in the deoxidizers manganese and silicon. T-2 type electrodes should never be used for multipass welds because the additional manganese and silicon cause the undiluted weld tensile strength to increase sufficiently (to above 689.5 MPa (100 ksi)) to cause cracking problems either during welding or in sour service.

4.7.2.5 SAW (Submerged Arc Welding)

Most companies' welding machines do not use automatic SAW because there is not enough welding demand to justify the equipment. Even where equipment is available for handheld semiautomatic welding, the SAW process is less favored than GMAW because GMAW is more versatile. Most SAW for new construction and revamping is used on the customized equipment and for field welding of storage tanks and spheres. Also, SAW is used extensively by most manufacturers for large structures such as tanks, pressure vessels, ships, and offshore platforms/structures, subsea drilling equipment, and weld overlay cladding (for such applications as tubesheets) with either a strip or wire electrodes.

The combination of wire and flux is very important in SAW process because the molten weld and the arc zone are protected from atmospheric contamination under a blanket (submerged) of flux which is granular and fusible mineral compounds and becomes conductive and provides a current path between the electrode and the work during melting.

Therefore, API RP582 states that SAW procedures should be requalified whenever the welding flux is changed from one manufacturer's trade name to another. Equivalence under ASME Sec. II, Part C, or AWS filler metal specifications should not be considered adequate for substitution without requalification. It is recognized that fluxes having the same classification can be very different in their composition. However, nominal flux composition is not included in AWS or ASME specifications/codes, and flux suppliers do not normally provide this information. Differences among fluxes of the same classification can result in different and unanticipated weld properties when these fluxes are used interchangeably over the range of variables typically stated in weld procedure specifications. Manually held (semiautomatic) SAW is not permitted for welding pressure-containing parts, unless approved by the purchaser. A separate qualification is required for SAW welds in which any pass thickness is greater than 13 mm (0.5 in.).

See Sect. 4.8.1.9 for welding electrodes (wire) standard description of SAW.

(a) Typically, the use of SAW shall be limited to the following conditions:

1. The welding electrode and flux should either be from the same manufacturer or, if from different manufacturer, should have the manufacturer written certification for use as a combination.
2. For single-wire SAW, DCEN (direct current electrode negative or straight polarity) is not permitted.
3. For tandem or multiple arc SAW, the wire feed speed, travel speed, polarity, and maximum heat input should be provided for each electrode.
4. Each SAW pass should be limited to 13 mm (0.5 in.) maximum thickness.
5. Handheld SAW should not be used on pressure-containing welds unless the completed weld is radiographed 100%.
6. PQR for P1 steels should include hardness test results even if PWHT is not required.

(b) Typically SAW wires/fluxes and the combinations should have the following characteristics.

1. To improve the electrical conductivity (arc stability) and ionization of the slag and arc plasma.
2. To produce gases and vapors which can assist proper droplets formation at the electrode tip and their transfer through the arc stage.
3. To be viscous but dense liquid slag for protection of the welds against atmosphere and for forming of smooth weld bead surfaces and toes.
4. To be improved the weld metal metallurgy by burn-out or pickup of flux elements during the arc stags.
5. To have good weldability such as self-detaching slags and excellent weld bead shaping.
6. To be applicable for various welding problems and processes in combination with standard wire electrodes.
7. Acid type (active) or alloying fluxes except manganese (Mn) are prohibited, so that only neutral type fluxes should be used unless otherwise approved.
8. Alloy welding should be done with an alloy filler wire and a neutral flux. Alloy elements should not be added to the flux.
9. Flux used for 300 series ASS welding, excluding weld overlay, may contain an alloy addition of 1% to 2% Cr to compensate for alloy burn-out during welding.
10. The use of recrushed SAW slag as a flux or as a flux addition is not permitted.
11. Flux and wire combinations for production welds should be of the same brands (manufacturer) and grades as those used in procedure qualifications.
12. Minimum voltage should be qualified with the same flux and electrode combination as proposed for production welding. Flux/electrode welding combinations are to comply with AWS A5.17 and A5.23.
13. EL8, EL8K, EL12, or EM12 filler metals should not be used when welding of 485 MPa (70 ksi) of SMTS base materials which receive a PWHT and/or a postweld normalizing heat treatment.
14. All filler wire and flux combinations must be certified by the manufacturer in the PWHT'd conditions if the welded components are to be PWHT'd.

(c) Classes of SAW fluxes in ASME/AWS A5.17/5.23

1. ASME/AWS A5.17(M)/5.23(M) classify the fluxes on the basis of the chemical composition and the mechanical properties of the weld metal as produced with certain wire electrodes. So, a particular flux can have many classifications due to the different electrodes and the heat treatments used. The flux/wire combinations can be classified:
   (a) According to the US customary system (U), representing the tension test results in psi and the impact test results in digits depending on °F temperature and energy level of 27 J (20 ft-lbf), in condition "A" = as welded or "P" = postweld heat treated in dependency of the desired application and wire classification.
   (b) According to the International System of Units (SI or M), representing the results of the tension test in MPa and the impact test results in digits depending on °C temperature and energy level of ISO-V 27 J (20 ft-lbf).
2. It produces an all-weld metal of somewhat different composition than that of the wire electrode due to chemical reactions and interactions in the arc, to the welding parameters (mainly voltage), and to the presence of metallic ingredients in the individual flux. So AWS specifications are subdividing the fluxes according to their metallurgical reactions.
3. Neutral fluxes are not significantly changing the Mn and Si content in the weld metal as a result of changes in arc voltages and arc length. They do not contain many deoxidizers and rely on metallic deoxidation via elements of the wire or plate metal.
4. Active fluxes contain deoxidizing constituents such as Fe-Mn and Fe-Si to provide improved resistance to porosity and cracking susceptibility, mainly in single/two-run technique. Metallurgical reactions Si + Mn take place depending on the welding parameters, mainly arc voltage.
5. Alloy fluxes are used to make alloy weld metal in combination with C-steel wire electrodes. The alloys for the weld metal are added as ingredients in the flux (ferro-alloys, e.g., Cr). Alloy flux should be mainly used for hardfacing.
6. There is no classification for fluxes for stainless steel or Ni-based alloys. ASME/AWS A5.9 gives information of the existence of various fluxes – neutral or alloyed ones – and shows significant changes between the chemical composition of the wire and the weld deposit. This variation of alloying elements is similar.

(d) Classes of SAW fluxes in European Standard EN 760

Flux class 1: to be used for SAW of non-alloyed and low alloy structural steels, fine-grained steels, and creep-resisting steels. There are no alloys other than Mn and Si. Thus the weld metal analysis is predominantly influenced by the composition of the wire electrode and the metallurgical reactions from the flux.

Flux class 2: for welding and surfacing of stainless and heat-resisting Cr (-Ni-Mo) steels and Ni alloys.

Flux class 3: for hardfacing operations. Alloying elements such as C, Cr, Ni, and Mo are transferred from the flux.

Additionally, the metallurgical behavior in combination with the wire electrode S2 and specified welding conditions, the type of current (AC for AC/DC or DC only), and the diffusible hydrogen (DH) level achieved in the deposited metal should be indicated when classifying fluxes according to BS EN 760.

Meanwhile special fluxes are classified according to EN760, class 2 for the welding or cladding in combination with stainless Cr-Ni (-Mo)- or Ni-based alloyed wires or strips. Independently their basicity index (BI), class 2 fluxes should not add any alloying element besides Si and Mn.

Alloy fluxes do add alloys such as Cr, Mo, Nb, or others and are classified as BS EN 760, class 3 types. They are designed mainly for hardfacing and should be "tailored" to the user's requirements.

(e) Basicity index (BI) of SAW fluxes

Basicity has great influence on impact toughness of the weld metal. Increasing basicity brings down the oxygen content and hence the inclusion level in the weld metal. Consequently, the impact toughness will increase and also, to a limited extent, the ductility of the weld metal. The relation between basicity and impact toughness is particularly important for high alloyed grades, such as duplex stainless steels.

There are various formulas for the calculation of the flux's basicity. The BI formula according to T. Boniczewski is presently commonly used, but still in discussion regarding the effectiveness for the practical application on the actual reactions of the gases during the welding process. Normally high BI shows high toughness, a quality of great interest to the engineer, while lower BI (acidic) flux shows excellent slug behavior, a characteristic of interest to the welder attempting to improve weld bead morphology and deposit rate. BI of a flux according to T. Boniczewski (in weight %) in 1972: Basing on the calculations according to this formula, SAW fluxes can be classified into several chemical groups (similar to the manual cover of stick electrodes) with different application attitudes. Table 4.50 shows basicity and their characteristics of fluxes in SAW process.

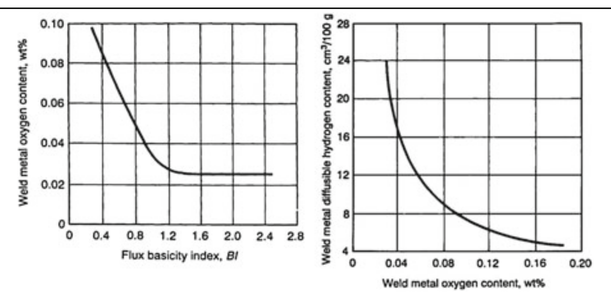
$$BI = \frac{\%CaO + \%MgO + \%BaO + \%CaF_2 + \%Na_2O + \%K_2O + 0.5(\%MnO + \%FeO)}{\%SiO_2 + 0.5(\%Al_2O_3 + \%TiO_2 + \%ZrO_2)}$$

References for Flux

- ANSI/AWS A5.17(M) and S5.23(M) Electrodes and Fluxes for SAW of CS and LAS
- BS EN 760 Welding Consumables Fluxes for SAW
- ISO 14171 Welding Consumables

Table 4.50 Basicity and characteristics of fluxes for SAW including relation of DH-O2-BI (ASM welding H/B)

Basicity index (BI)	Type of flux
≤ 0.8	Acid (1)
0.8 < BI ≤ 1.2	Neutral (1)
1.2 < BI ≤ 2.5	Semi-basic or Basic (2)
> 2.5	High Basic (3)



Notes:

(1)*Acid and neutral fluxes* produce slag with low melting range. This is advantageous for good deslagging capability. The electrical conductivity of the liquid flux-slag is high enough to form very good surface and wetting performance of the welds. Acid/neutral fluxes show excellent weldability so that they are generally used for SAW in two-run technique of thin-walled metals, e.g., fillet welding of steel constructions or finned tube walls of power plants or LP gas cylinders as well as where high-impact toughness is not a requirement

(2)*Semi-basic/basic fluxes* are starting to solidify at high temperature similar with many gas/metal and flux/metal reactions in the arc stage and in the weld metal. Finely dispersed micro-slag inclusions remain as micro-constituents and can act as nuclei during the formation of the weld metal structure. The oxides swept into the weld pool are drifted to the top of the weld metal at rather early stages and, so, effecting good deoxidizing and fine-grained structure in the weld. Semi-basic/basic SAW fluxes show rather constant metallurgical behavior when single and multi-wire welding. In combination with compatible wires, mechanical properties with low temperature impact toughness (−40 °C (−40 °F) and colder) are achieved when SA welding multilayers of thick wall boilers and vessels as well as when welding longitudinal or helical pipes in two-run technique. These fluxes provide good weldability with fine weld bead performance and self-detaching slag. All fluxes own low diffusible hydrogen (DH) potential; H_2 diffusivity <5 ml/100 g deposit metal according to ISO 3690 can be achieved also with AC welding

(3)*High basic fluxes* possess low slag viscosity and low current-carrying capacity. Finely dispersed micro-slag inclusions and oxides have beneficial influence for the formation of a ductile weld structure, which grant good cryogenic impact properties. High basic fluxes are commonly used with single-wire/tandem processes for welding low alloy steels with requirements of resistance to embrittlement at high temperatures (e.g., Cr-Mo low alloy steels) or to reach the required impact strength with suitable wire electrodes and HSLA (high strength low alloy) steels. Low diffusible hydrogen (DH) levels can be achieved.

Table 4.51 Classification according to ASME Sec. D, Part C – A5.17 and A5.23, Tables 6U/6M and 7U/7M

(a) Mechanical properties

*F*lux-*E*lectrodes (typical)		Mechanical properties[a]				
		UTS, min/max.		YS (0.2%)		Elong.
US customary	Metric	ksi	MPa	min. ksi	min. MPa	min. %
F6xxx-Eyyy	F43xx-Eyyy	60/80	430/560	48	330	22
F7xxx-Eyyy	F48xx-Eyyy	70/95	480/660	58	400	22
F8xxx-Eyyy	F55xx-Eyyy	80/100	550/700	68	470	20
F9xxx-Eyyy	F62xx-Eyyy	90/110	620/760	78	540	17
F10xx-Eyyy	F69xx-Eyyy	100/120	690/830	88	610	16
F11xx-Eyyy	F76xx-Eyyy	110/130	760/900	98	680	15
F12xx-Eyyy	F83xx-Eyyy	120/140	830/970	108	750	14

Commentary Notes:
[a]The mechanical test data and impact test requirements are for welded joint
[b]The designators for CVN test are used with the same values of °C or °F. So, the unit of US customary or SI shall be described for all related documents (as A5.17/A5.23-US customary unit or A5.17M.A5.23M-SI unit)
[c]See Sect. 4.8.1.9 for more details of the coding system of flux-electrodes

(b) Standard digits for V-notch impact test

Digit	V-notch impact test, 27 J min (20 ft.lbf min.)	
	at °C	at °F
Z	Not required	
0	–	32
2	−20	−20
3	−30	−30
4	−40	−40
5	−50	−50
6	−60	−60
8	−80	−80
10	−100	−100
15	−150	−150
Z	No CVN test	

Table 4.52 Variations of alloying elements for SAW using SS wires(1)

Element	Typical change from wire to deposit	Typical alloy variations using WP380 (420 A, 29 V, 55 cm/min.)
C	On "L" grade: usually gain +0.01% to +0.02% None on "L" grade: usually loss up to −0.02%	+0.05% to +0.01%
Si	Gain +0.3% to +0.6%	+0.3% to +0.5%
Mn	Varies −0.5% / +0.5%	−0.3% to −0.6%
Cr	Usually a loss, unless a deliberate addition is made to the flux: −0.5% to −3.0%	−0.5% to −1.2%
Ni	Little change, unless a deliberate addition is made to the flux:	± 0%
Mo	Little change, unless a deliberate addition is made to the flux:	± 0%
Nb (Cb)	Usually a loss, unless a deliberate addition is made to the flux: −0.1% to −0.5%	−0.15% to −0.35%

Sources: AWS A5.9-Table A1 and ASME Sec. II-Part C, SFA-5.9, Table A.2
Note: (1)The effects of a particular flux/electrode combination should be evaluated by PQR

Table 4.51 shows the classification according to ANSI/AWS A5.17M and A5.23M, Tables 6U/6M and 7U/7M.

Table 4.52 shows the variations of alloying elements for SAW using SS wires.

4.7.2.6 ESW (Electroslag Welding)

The most common application of ESW has been for the longitudinal seams in shell rings for heavy wall carbon steel and low alloy pressure vessels. EGW has been used for the vertical seams of oil storage tanks.

ESW may be also used for corrosion-resistant weld overlay if approved by the purchaser. Welding procedures for ESW should be requalified whenever the welding flux or wire is changed from one manufacturer to another or from one manufacturer's grade to another grade from the same manufacturer. Equivalency under ASME Code Section II, Part C shall not be considered adequate for substitution without qualification.

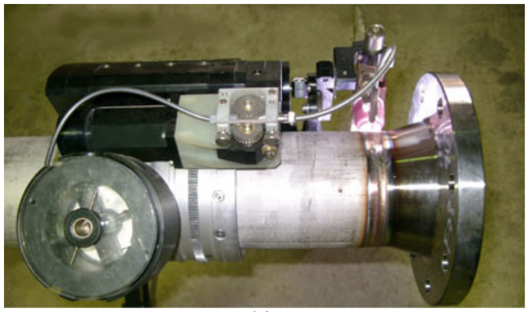
The use of ESW shall meet the following requirements:

(a) ESW should not be used for pressure-retaining welds unless approved by the purchaser.
(b) ESW process should be subject to the following conditions.
  – CS welds are to be normalized unless otherwise approved by purchaser.
  – CVN impact toughness tests are required in accordance with ASME Section VIII, Division 1, UG-84.
  – Ultrasonic inspection of welds shall be performed in accordance with ASME, Section VIII, Division 1, Appendix XII after PWHT and 100% RT.
  – WPS should include procedures for the repair of defects.

4.7.2.7 EGW (Electrogas Welding)

The use of EGW should be limited by the following conditions.

(a) EGW should be used only with filler materials specifically intended for the EGW process (ASME/AWS SFA/A5.26/SFA/A5.26M).
(b) Welding consumables should be limited to the classification and the manufacturer's trade name used in the PQR.
(c) Only filler materials having classifications with specified minimum impact test requirements should be used.
(d) EGW process should be subject to the following conditions.
  – CS welds are to be normalized unless otherwise approved by purchaser.
  – CVN impact toughness tests are required in accordance with ASME Section VIII, Division 1, UG-84.
  – Ultrasonic inspection of welds shall be performed in accordance with ASME, Section VIII, Division 1, Appendix XII after PWHT and 100% RT.
  – WPS should include procedures for the repair of defects.



(a)

(b)

Figure 4.47 Orbital welding. (**a**) Typical orbital welding (for large diameter). (**b**) Typical orbital welding (for small bore)

4.7.2.8 PAW (Plasma Arc Welding)

Recently PAW process has been widely used for the welding of LNG carrier membrane sheets (e.g., 304L SS) because of lower deformation and higher productivity compared to SMAW or GTAW.

However, use of PAW should be limited to the following:

(a) The WPS/PQR should state whether the "Transferred Arc" or "Non-transferred Arc" mode is to be utilized.
(b) The WPS/PQR should state whether the "Key-Hole" or "Melt-In" technique is to be utilized.
(c) The shielding or plasma gases, any backing or trailing gases should be recorded on the WPS, including flow rates, and shall be the same as utilized in qualifying the PQR.
(d) The WPS and PQR for this PAW should address all variables applicable to the welding system and machine settings. These variables should be considered essential, and any change will require requalification.

See Sect. 4.8.1.4 for welding electrode standard description of PAW.

4.7.3 Advanced Welding Techniques

4.7.3.1 Orbital Welding

An automatic or machine welding in which the electrode rotates (orbits) around the circumference of a stationary pipe or tube. Orbital welding (Fig. 4.47) was first used in the 1960s when the aerospace industry recognized the need for a superior joining technique for aerospace hydraulic lines. A mechanism was developed in which the arc from a tungsten electrode was rotated around the tubing weld joint. The arc welding current was regulated with a control system, thus automating the entire process. The result was a more precise and reliable method than the manual welding method it replaced.

Standard enclosed orbital weld heads are practical in welding tube sizes from OD 1.6 mm (0.063 in.) to OD 152 mm (6 in.) with wall thickness of up to 3.9 mm (0.154 in.). Larger diameters and wall thickness can be accommodated with open style weld head. GTAW is a most common welding process for orbital welding; GMAW and FCAW may be applied if the purchaser agrees.

4.7.3.2 Surface Tension Transfer (STT) Welding: Modified GMAW Process (as Short Arc Transfer Mode or Short Arc Welding)

(a) What is STT™?
 – STT is a GMAW, controlled short-circuit transfer process developed by a welding electric company.
 – Unlike standard constant voltage GMAW machines, the STT machine has no voltage control knob.
 – STT uses current controls to adjust the heat independent of wire feed speed, so changes in electrode extension do not affect heat.
 – STT process makes welds that require low heat input much easier without overheating or burning through, and distortion is minimized.
 – Spatter and fumes are reduced because the electrode is not overheated – even with larger-diameter wires and 100% CO_2 shielding gas.
 – This gas and wire combination lowers consumable costs. It has high productivity because the process will work in all positions and only requires average operator skill. Therefore, STT process could be called an intelligent TIG welding process for short arc welding.
(b) Advantages of STT replacing SMAW
 – Reduces lack of fusion
 – Good puddle control
 – Consistent X-ray quality welds
 – Shorter training time
 – Lower fume generation and spatter
 – Can use various compositions of shielding gas
 – 100% CO_2 on mild steel

(c) Advantages of STT replacing GTAW
- – Four times faster
- – Vertical down welding
- – Shorter training time
- – 100% CO_2 (on mild steel)
- – Improved quality welds on stainless steels, nickel alloys, and mild steel
- – Consistent X-ray quality welds

(d) Ideal Application of STT
- – Open root (normally up to 5 mm) – pipe and plate
- – Stainless steels and nickel alloys – oil and gas and petrochemical industries
- – Utility and food industry
- – Thin-gauge material – automotive
- – Silicon bronze – automotive
- – Galvanized steel – such as furnace ducts
- – Semiautomatic and robotic applications

4.7.3.3 New Regulated Metal Deposition (RMD™) MIG Welding Process Improves Stainless Steel Pipe Fabrication: Modified GMAW Process

(a) Characteristics of RMD
1. The RMD process is a modified short-circuit MIG welding process which is developed for better quality and productivity of stainless steel pipe fabrication by a welding electric company.
2. It is easy to learn and addresses the welder shortage by providing an easier process that gets more work done faster and at a higher quality.
3. Precisely controlled metal transfer provides uniform droplet deposition, making it easier for the welder to control the puddle.
4. Shielding gas comes out of the gun relatively undisturbed, pushing through the root opening and preventing sugaring on the backside of the weld. This allows certain 300 series SS to be welded without a backing gas, which can improve productivity by as much as 4 times.
5. The RMD maintains a consistent arc length regardless of stick-out.
6. The amount of the root pass metal deposited will be sufficient to supply the heat input requirements of the first pulsed MIG or flux-cored fill pass, possibly eliminating the need for a TIG hot pass.
7. Same wire and shielding gas can be used for the fill and cap passes using a next-generation pulsed MIG process (Pro-Pulse™), which improves travel speeds and deposition rates while lowering heat input.
8. Note that using the RMD process without a backing gas does produce a small amount of oxide scale on the backside of the weld, which usually flakes off as the weld cools. While within the standards for oil and petrochemical applications, it does not meet the "high purity" standard found in the pharmaceutical, semiconductor, or food industries.
9. Pipe fabricators have long memories. Chances are most have tried, and many have rejected, the other GMAW procedures for root pass welding. However, GMAW technology advances in recent years now provide dramatically better results. It sounds cliché, but you actually have to experience the new modified short-circuit transfer to believe how easily an operator can learn it and how easily it creates a quality root bead. Hopefully, the 100% to 400% productivity improvements will be enough of an incentive for stainless pipe fabricators to reexamine the GMAW process.

(b) Advantages of RMD

It reduces available welding current to create a consistent metal transfer. Precisely controlled metal transfer provides uniform droplet deposition, making it easier for the welder to control the puddle.
1. The smooth metal transfer compensates for a high-low misalignment between pipe sections. It easily bridges gaps of up to 5 mm.
2. Smooth metal transfer creates more consistent root reinforcement on the inside of the pipe.
3. The shielding gas coming out of the gun remains relatively undisturbed by the controlled transfer. As a result, enough shielding gas gets pushed through the root opening to prevent sugaring (oxidation) on the backside of the weld. Some fabricators have qualified procedures to weld some of the 300 series SS without a backing gas, improving productivity by up to 400% (large diameter pipes take a long time to purge, and the gas is costly).
4. The RMD process maintains a consistent arc length regardless of electrode stick-out. It compensates for operators that have problems holding a constant stick-out, and it enables a better view of the weld puddle.
5. The RMD creates a root pass weld with a 3.2–6.4 mm (0.125–0.25 in.) throat. In many instances, the amount of root pass metal deposited will be sufficient to support the heat input requirements of the first pulsed GMAW or FCAW fill pass. Fabricators can eliminate the GTAW hot pass, saving the welding cost.
6. The same wire and shielding gas can be used for the fill and cap passes using a next-generation pulsed GMAW process called Pro-Pulse. This process improves performance and operator acceptance compared to traditional pulsed welding, and it improves both travel speeds and deposition rates while lowering overall heat input.

(c) Five Critical Considerations

The techniques for welding CS pipe are the same as those described here for welding stainless; however, to qualify procedures for welding 300 series SS pipe without backing gas, fabricators must do the following:

1. Ensure a minimum 3.2 mm (1/8 in.) gap around the entire circumference of the joint. This gap allows the shielding gas to flow through to protect the backside of the joint from oxidation.
2. Clean the pipe both inside and out to remove any contaminates or unwanted substances. Use a wire brush to clean at least 25 mm (1 in.) back from the edge of the joint.
3. Use only a stainless steel wire with a high silicon content, such as a 316LSi SS or 308LSi SS. Higher silicon content helps the puddle wet out and acts as a deoxidizer.
4. For optimum performance, use a "Tri-H" gas that is 90% He, 7.5% Ar, and 2.5% CO_2 (alternatively 98% Ar and 2% CO_2).
5. For best results, use a tapered nozzle for the root pass because it localizes the gas coverage. Tapered nozzles with built-in gas diffusers provide exceptional coverage.

4.8 Designations of Welding Metals

4.8.1 ASME Section II, Part C/AWS: Designations of Welding Consumable Materials

The classes and application of SFA numbers are shown in Tables 2.104 and 2.105.

4.8.1.1 ASME Section II, Part C, SFA-5.1: CS Electrodes for SMAW

E XX YY(M) - 1 HZ R

R= To meet the moisture content limits, time and test (See SFA-5.1, Table 10)

Diffusible hydrogen requirement, H16, H8, H4 (Detail: See SFA-5.1, Table 11)
See para. 4.3.2 in this book for more detail of diffusible hydrogen.

Impact toughness requirements (See SFA-5.1, Table 3 for detail)- See Note (b) below.

Military requirements (grater toughness, lower moisture content, mandatory diffusible hydrogen limits

Welding position, Covering type, and Current type - See Note (a) below.

Required min. tensile strength of weld metal, ksi.(See A5.1M in ASME Sec.II-C for SI Unit)

Electrode

Class designations[(b), (c)]

YY[(a)]	Type of covering	Welding position	Type of current
10	High cellulose sodium	F, V, OH, H	DCEP
11	High cellulose potassium	F, V, OH, H	AC or DCEP
12	High titania sodium	F, V, OH, H	AC or DCEN
13	Iron oxide titania potassium	F, V, OH, H	AC, DCEP, or DCEN
14	Iron powder, titania	F, V, OH, H	AC, DCEP, or R DCEN
15	Low-hydrogen sodium	F, V, OH, H	DCEP
16	Low-hydrogen potassium	F, V, OH, H	AC or DCEP
18	Low-hydrogen potassium, iron powder	F, V, OH, H	AC or DCEP
18M	Low-hydrogen iron powder	F, V, OH, H	DCEP
19	Iron oxide titania potassium	F, V, OH, H	AC, DCEP, or DCEN
20	High iron oxide	H-fillet F	AC or DCEN AC, DCEP, or DCEN
22	High iron oxide	F, H	AC or DCEN
24	Iron powder, titania	H-fillet, F	AC, DCEP, or DCEN
27	High iron oxide, iron powder	H-fillet F	AC or DCEN AC, DCEP, or DCEN
28	Low-hydrogen potassium, iron powder	H-fillet, F	AC or DCEP
48	Low-hydrogen potassium, iron powder	F, V, OH, H, V-down	AC or DCEP

Abbreviation: *AC* alternative current, *DC* direct current, *EP* electrode positive, *EN* electrode negative, *F* flat, *H* horizontal, *V* vertical, *OH* overhead
Notes:
[(a)]The first digit: 1 = all position (F, V, OH, H), 2 = H, H-fillet, F, 4 = F, V, OH, H, V-down
[(b)]The improved toughness is required for E7016, E7018, E7028, and E7048 (unit: US customary)
[(c)]Sample description: E7016-1M8R (unit: US customary)

4.8.1.2 ASME Section II, Part C, SFA-5.5: LAS Electrodes for SMAW

Mandatory Classification Designators

E (X)XX YY - M* HZ R

E (X)XX YY - X HZ R**

R= To meet the moisture content limits, time and test (See SFA-5.5, Table 11)

Diffusible hydrogen requirement, H16, H8, H4 (Detail: See SFA-5.5, Table 12)
See para. 4.3.2 in this book for more detail of diffusible hydrogen.

*M, M1, M1 HZ, or M1 HZ: Military requirements

**: mandatory up to X. X = Chemical composition undiluted weld metal-See Note (2).

Welding position, Covering type, and Current type - See Note (1)

Required min. tensile strength of weld metal, ksi (See A5.5M in ASME Sec.II-C for SI Unit)

Electrode

Class designations[(2),(3)]

YY[(1)]	Type of covering	Welding position	Type of current
10	High cellulose sodium	F, V, OH, H	DCEP
11	High cellulose potassium	F, V, OH, H	AC or DCEP
13	Iron oxide titania potassium	F, V, OH, H	AC, DCEP, or DCEN
15	Low-hydrogen sodium	F, V, OH, H	DCEP
16	Low-hydrogen potassium	F, V, OH, H	AC or DCEP
18	Low-hydrogen potassium, iron powder	F, V, OH, H	AC or DCEP
18M	Low-hydrogen iron powder	F, V, OH, H	DCEP
18M1	Iron oxide titania potassium	F, V, OH, H	AC, DCEP, or DCEN
20	High iron oxide	H-fillet F	AC or DCEN AC, DCEP, or DCEN
27	High iron oxide, iron powder	H-fillet F	AC or DCEN AC, DCEP, or DCEN

Abbreviation: *AC* alternative current, *DC* direct current, *EP* electrode positive, *EN* = electrode negative, *F* flat, *H* horizontal, *V* vertical, *OH* overhead

Notes:

(1)The first digit: 1 = all position (F, V, OH, H), 2 = H, H-fillet, F

(2)Chemical composition group – see ASME Sec. II-C, SFA-5.5, Table 2 for more details
C-Mo steel: A1
Cr-Mo steel: B1, B2, B2L, B3, B3L, B4L, B5, B6, B6L, B7, B7L, B8, B8L, B9, B23
Ni steel: C1, C1L, C2, C2L, C3, C3L, C4, C5L
Ni-Mo steel: NM1, NM2
Mn-Mo: D1, D2, D3
Other LAS: G
Pipeline: P1
Weathering Steel: It is a common term for the steel to be exposed to atmosphere without coating.

(3)Sample description for mandatory description: E8018-B2 (Unit: US customary)

4.8.1.3 ASME Section II, Part C, SFA-5.18: CS Solid Wire for GMAW and GTAW; ASME Section II, Part C, SFA-5.28: LAS Solid Wire for GMAW and GTAW

E R 70 S - X

Specific chemical composition, as manufactured. (See Note 1, 2, and 3)

Wire form: **S**=solid, T=tubular, C=composite

Required min. tensile strength of weld metal, ksi (See A5.18M and A5.28M in ASME Sec.II-C for SI Unit)

Wire may be used as a filler rod

Electrode

*Notes: (Unit: US customary)

1. Suffix G indicates (e.g., ER80S-**G**): no specified requirement, a proprietary or provisional grade
2. Suffix **N** indicates (e.g., ER80S-**N**): The weld metal is intended for the core belt region of nuclear reactor vessels with $P \leq 0.012\%$ and Cu 0.08%
3. Suffix **Number** indicates (e.g., ER80S-**2,3,4,6,7, A1, B2, B2L, B3, B3L, B6, B8, B9, Ni1, Ni2, Ni3, D2, 1**): different chemical composition
   CS: 2, 3, 4, 6, and 7
   LAS: C-Mo steel: A1
   Cr-Mo steel: B2, B2L, B3, B3L, B6, B8, B9
   Ni steel: Ni1, Ni2, Ni3
   Mn-Mo steel: D2
   Other LAS: 1

4.8.1.4 ASME Section II, Part C, SFA-5.18: CS Composite Electrodes for GMAW, GTAW, PAW; ASME Section II, Part C, SFA-5.28: LAS Composite Electrodes for GMAW, GTAW, PAW

E 70 C - X Y

- Y: Specific chemical composition, as manufactured *only for CS.* (See Note 3 & 4)
- X: Specific chemical composition, as manufactured. (See Note 1 & 2)
- C: Wire form: **C**=composite, **S**=solid, **T**=tubular
- 70: Required min. tensile strength of weld metal, ksi. (See A5.18M and A5.28M in ASME Sec.II-C for SI Unit)
- E: Electrode

*Notes: (see A5.18M and A5.28M in ASME Sec. II-C for SI unit)

1. The first Suffix **G** indicates (e.g., E70C-**G**): no specified requirement, a proprietary or provisional grade/the second suffix may be omitted if these gases are not used for classification.
2. The first Suffix **Number** indicates (e.g., E70C-**3, 6, D2, B2L, B2, B3L, B3, Ni1, Ni2, Ni3**): different chemical composition
   CS: 3, 6
   LAS: Cr-Mo: B2, B2L, B3, B3L
   Ni: Ni1, Ni2, Ni3
   Mn-Mo: D2
3. The second Suffix **C** indicates (e.g., E70C-3**C**): 100% CO_2 shielding (AWS A5.32 Class SG-C)
4. The second Suffix **M** indicates (e.g., E70C-3**M**): 75~80% Ar/balance CO_2 shielding (AWS A5.32 Class SG-AC-Y, where Y is 20 to 50)

4.8.1.5 ASME Section II, Part C, SFA-5.20: CS Flux-Cored Wire for FCAW

E 7 1 T - 5

- 5: Usability, performance characteristics
- T: Flux cored (tubular) electrode
- 1: Welding Position: 0 = F & H, 1 = all position
- 7: Required min. tensile strength of weld metal, × 10ksi. (See A5.20M in ASME Sec.II-C for SI Unit))
- E: Electrode

4.8.1.6 ASME Section II, Part C, SFA-5.29: Flux-Cored Wire (FCAW) for LAS

E 8 1 T 1 - B2

- **B2**: Composition of deposited weld metal
- **1**: Usability, performance characteristics
- **T**: Flux cored (tubular) electrode
- **1**: Welding Position: 0 = F & H, 1 = all position
- **8**: Required min. tensile strength of weld metal, × 10ksi. (See A5.29M in ASME Sec.II-C for SI Unit)
- **E**: Electrode

4.8.1.7 ASME Section II, Part C, SFA-5.22: SS Flux-Cored Stainless Steel Electrode/Rods for FCAW

E 310 T - 1

- **1**: External shielding gas: **1** = CO_2, **2** = Ar-$2O_2$, **3** = self shielded
- **T**: Flux cored (tubular) electrode
- **310**: AISI stainless steel designation
- **E**: Electrode

4.8.1.8 ASME Section II, Part C, SFA-5.9: SS Rods, Electrodes, and Filler Metal Stainless Steel for FCAW/Strip/Composite Cored

E X 308 X

- **X**: Contains extra element: **Si** = silicon, **L** = low carbon, ≤0.03%, **H**=high carbon=0.04~0.10%, **Mo**=molybdenum 2~3%, **Cb**=columbium,
- **308**: AISI stainless steel designation (Note: suffix **LR** = low residuals e.g., ER320LR)
- **X**: Wire type: **R** = Solid wire as a filler rod, **Q** = Strip electrode, **C** = Composite metal cored or stranded electrode
- **E**: Electrode

4.8.1.9 ASME Section II, Part C, SFA-5.17: CS Electrodes for SAW; ASME Section II, Part C, SFA-5.23: LAS Electrodes for SAW

F S X X X - ECX'X'X' X - X'X'X' X HX

- **HX**: Diffusible hydrogen requirement, H16, H8, H4 (See SFA-5.17, Table 7, SFA-5.23, Table 8, and para. 4.3.2 in this book)
- **X**: **N** – Only for Nuclear application-repeated
- **X'X'X'**: X'X'X'=chemical composition of electrode, repeated X'X'X- 1 to 4 digits only for LAS
- **X**: **N** – Only for Nuclear application
- **ECX'X'X'**: **Electrode**: EC=composited electrode (See Note 3 & 4), E=solid electrode (See Note 5 & 6)
- **X**: A temperature (°F) at or above which the impact strength of the weld metal referred to above meets or exceeds 20ft-lbf. Two digits are used of test temperature of -73°C (-100°F) or lower (See Note 2)
- **X**: PWHT yes or no: A=as welded, P=PWHT
- **X**: Required min. tensile strength of weld metal, × 10^4 psi (See SFA-5.17, Table 5U in and SFA-5.23, Table 6U), Note 1.
- **S**: Welding flux being classified is made solely from crushed slag or a blend of crushed slag with unused flux. Omission of S that the flux being classified is unused (virgin) flux. [most cases]
- **F**: **Flux**

*Notes: (see A5.17M and A5.23M in ASME Sec. II-C for SI unit)

1. For example, 7 is for 70 to 95 ksi, 8 is for 80–100 ksi, and 11 is 110–130 ksi
2. Impact test requirements

Digit	Max. test temperature, °C (°F)	Min. average energy level	Materials
0	−18 (0)	27 J (20 ft-lbf)	
2	−29 (−20)		
4	−40 (−40)		CS & LAS
5	−46 (−50)		
6	−51 (−60)		
8	−62 (−80)		
10	−73 (−100)		LAS
15	−101 (−150)		
Z	No impact requirements		
N	Min. 102 J (75 ft-lbf) @ room temperature		

3. Table 1 in SFA-5.17 (CS-solid wire); G = no specified requirement

Low Mn steel	0.25–0.60% Mn	EL8, EL8K, EL12
Medium Mn steel	0.60–1.35% Mn	EM11K, EM12, EM12K, EM13K, EM14K, EM15K
High Mn steel	1.00–1.40% Mn	EH10k, EH11K, EH12K, EH14, EG

4. Table 1 in SFA-5.23 (LAS-solid wire); G = no specified requirement

C-Cu steel	EL12, EM12K
C-Mo-Cu steel	EA1, EA2, EA3, EA3K, EA4
C-Cr-Mo-Cu steel	EB1, EB2, EB2H, EB3, EB5, EB6, EB6H, EB8
C-Cr-Mo-Ni-Cu steel	EB9
C-Ni-Cu steel	ENi1K, ENi2, ENi3
C-Ni-Mo-Cu steel	ENi1, ENi4, ENi5, EF1, EF2, EF3
C-Ni-Cr-Mo-Cu steel	EF4, EF5, EF6, EM2, EM3, EM4
C-Ni-Cr-Cu steel	EW

5. Table 2 in SFA-5.17 (CS-composite wire); G = no specified requirement
   EC1 and ECG
6. Table 2 in SFA-5.23 (LAS-composite wire); G = no specified requirement

C-Cu steel	EL12, EM12K
C-Mo-Cu steel	A1, A2, A3, A4
C-Cr-Mo-Cu steel	B1, B2, B2H, B3, B4, B5, B6, B6H, B8
C-Cr-Mo-Ni-Cu steel	B9
C-Ni-Cu steel	Ni2, Ni3
C-Ni-Mo-Cu steel	Ni1, Ni4, Ni5, F1, F2, F3
C-Ni-Cr-Mo-Cu steel	F4, F5, F6, M1, M2, M3, M4, M5, M6
C-Ni-Cr-Cu steel	W

7. Sample description:
   CS: F7A6-EM12K/F7P4-EC1
   LAS: F9P0-EB3-B3/F9A2-ECM1-M1

4.8.2 Designation of Chemical Composition and Tensile Strength

All requirements are based on the electrodes/filler materials in ASME Section II, Part C/ AWS, while the electrodes/filler materials manufacturers' data are based on the weldments (undiluted area) unless otherwise specified. The designation is normally rounded off by 1000 psi for SMAW, GMAW, GTAW, and PAW and 10,000 psi for SAW and FCAW.

4.9 Welding Procedure Specification (WPS) and Procedure Qualification Record (PQR)

4.9.1 Variables for Welding

The welding variables are classified as essential, supplementary essential, and nonessential. The variables involved in most specifications are considered to be essential variables. In some codes the term nonessential variables may also be used.

4.9.1.1 Essential Variables in ASME Sec. IX

(a) ASME Sec. IX (for ASME BPVC and Piping) – ASME Sec. IX, QG-105.1 (procedure) and QG-105.2 (performance) and QW-400 to QW-492
They are those factors which must be recorded, and if they are changed in any way, the procedure must be retested and requalified. The essential list of welding variables has a direct impact on qualification of the WPS and are commonly used in WPS qualification where impact testing or notch toughness fracture behavior of base materials is not a concern after welding. Any change in the list of essential welding variables would require requalification of a WPS (Table 4.53).
1. Essential variables involved in the procedure usually include the following:
   - The welding process and its variation
   - The method of applying the process
   - The base metal type, specification, or composition
   - The base metal geometry, normally thickness
   - The base metal need for preheat or post-heat
   - The welding position
   - The filler metal and other materials consumed in making the weld
   - The weld joint, that is, the joint type and the weld
   - Electrical or operational parameters involved
   - Welding technique
2. Materials Group for Essential Variables
   (a) Note P-No.5, No.9 & No.10 are divided into sub groups e.g., P-No.5A, No.5B, etc., treat each sub group like a separate P Numbers (P-No.).
   (b) Dissimilar materials are acceptable providing they are compatible. For example, P-No.1 to P-No.8, but this does not cover P-No.1 to P-No.1 or P-No.8 to P-No.8.
   (c) Note S numbers are for pipework to B31, a P Number (P-No.) covers S number (S-No.) but not the converse.
3. Welding Consumables
   A change in consumable is only permissible provided it has the same F number and A number as the PQR.

Table 4.53 Essential variables in ASME Sec. IX, QW400 to 451 and 150 to 190 (entire or partial per welding process)

Variables	Contents	
Joints (QW-402)	WPS qualified on groove welds qualify for fillet welds, but not vice versa. Test welds made with either plate or pipe coupons qualify welding for both plate and pipe. Groove is not an essential variable but the types must be shown in WPS.	
Base metal (QW-403)	A change in base metal from one P-No in Table QW-422 to another P-No, or to a metal not listed, requires requalification. Dissimilar metal (different P-No.) welding is required requalification even though both metals have been independently qualified using the same procedure (except P-No 1,3, 4, and 5 joint when P-No metal welded to each of the lower P-No metals, but not vice versa).	
Filler metal (QW-404)	A change in filler metal F No or A No requires requalification. Qualification with A No 1 (mild steel) also qualifies A No 2 (C-Mo steel) and vice versa. Change of cross section area of filler weldment, wire speed: Over than ±10%.	
Position (QW-405)	A change from any position to the vertical position uphill progression. Vertical uphill progression (e.g., 3G, 5G, or 6G) qualifies for all position. In uphill progression, a change from stringer bead to weave bead.	
Preheat (QW-406)	A decrease in preheat temperature of 55 °C (100 °F) or more requires requalification. And others.	
PWHT (QW-407)	The addition or deletion of PWHT requires requalification. Increasing the holding time for PWHT does not require requalification except where impact test is required (test coupon must have at least 80% of the aggregate time of the production weld).	
Shield gas (QW-408)	In gas-shielded welding, a change of the gas composition or omission of the gas requires requalification.	
Electrical (QW-409)	Current, polarity, heat input, etc.	
Techniques (QW-410)	Layers, string, cup, oscillation, peening, electrode spacing, etc.	
Mechanical tests	– Tensile test (QW-150) – Guided bend tests (QW-160) – Toughness tests (QW-170)	– Fillet-weld test (QW-180) – Other tests and examinations (QW-190)
Thickness (QW-451)	See Table 4.57 in this book.	
Number of passes	A change of multiple passes per side to single pass per side does not require requalification except when impact test is not required.	

4. Thickness Limits
   (a) Thickness limits groove welds. See Table 4.57 Qualified thickness for WPS from the tested thickness in PQR for butt groove weld in this book.
      - Dissimilar thickness: See ASME Sec. IX, QW-202.4 – The thickness of thinner part must be within the range permitted in ASME Sec. IX, QW-451 (See Table 4.57 in this book). The thickness of the thicker part shall be (i) no limitation for ASS, Ni based alloys, Ti based alloys, and Zr based alloys if $t > 6$ mm (1/4 in.), (ii) within the range permitted in ASME Sec. IX, QW-451 (See Table 4.57 in this book) for all other metals.
      - Minimum base metal thickness. See ASME Sec. IX, QW403.6.
   (b) The thickness little 't' of deposited weld metal for each process involved is approved from 0 to $2 \times t$ except:
      - MIG/MAG (GMAW/FCAW) dip transfer weld of deposited thickness less than 12.7 mm (0.5 in.) approves maximum thickness of $1.1 \times t$ only. See ASME Sec. IX, QW403.9, 403.10, and 403.32.
      - If any pass in a single or multipass weld is >12.7 mm (0.5 in.), then the thickness approval equals $1.1 \times t$.
   (c) Thickness limits for fillet welds as per ASME Sec. IX, QW462.4(a) or QW462.4(d) qualify all fillet weld sizes on all base material thicknesses and all diameters in one test.

(b) AWS D1.1 (for Steel Structures)
Variables that affect the mechanical or chemical composition of material properties or soundness of the weldment are not allowed without requalification per AWS. Each welding process has different variables for essential and supplemental essential. See Table 4.58 Qualified thickness for WPS from the tested thickness in PQR for CJP groove weld in this book.

See the following parts and tables in AWS D1.1 for more details.

AWS D1.1, Table 4.5 for PQR Essential Variable changes requiring WPS requalification for SMAW, SAW, GMAW, FCAW, and GTAW (see AWS D1.1, 4.8.1 as well)

AWS D1.1, Table 4.7 for PQR Essential Variable changes requiring WPS requalification for ESW or EGW (see AWS D1.1, 4.8.2 as well)

AWS D1.1, Part 4.8 for WPS Qualification (general)

AWS D1.1, Part 4.19 and AWS D1.1, Table 4.12 for Performance Qualification

AWS D1.1, Part C-4.8 and C-4.19 for Qualification Responsibility

4.9.1.2 Supplemental Essential Variables in ASME Sec. IX

(a) ASME Sec. IX (for ASME BPVC and Piping) – ASME Sec. IX, QG-105.3 and QW-401.1
A change in a welding condition which will affect the notch toughness properties of a weldment (i.e., change in welding process, uphill or down vertical welding, heat input, preheating, or PWHT, etc). When a procedure has been previously qualified to satisfy all requirements other than notch toughness, it is then necessary only to prepare an additional test coupon using the same procedure with the same essential variables, but additionally with all of the required supplementary essential variables, with the coupon long enough to provide the necessary notch toughness specimens.

(b) AWS D1.1 (for Steel Structures)
See AWS D1.1, Table 4.6 for PQR supplementary essential variable changes for CVN impact test application requiring WPS requalification for SMAW, SAW, GMAW, FCAW, and GTAW.

4.9.1.3 Nonessential Variables in ASME Sec. IX

(a) ASME Sec. IX (for ASME BPVC and Piping) – ASME Sec. IX, QG-105.4 and other than essential and supplemental essential variables
They are usually of less importance and may be changed within prescribed limits and the procedure need not be requalified. They are classed as Nonessential if impact testing is not required. Some specifications also include nonessential variables, and these are usually the following:
- The travel progression (uphill or downhill)
- The size of the electrode or filler wire
- Certain details of the weld joint design
- The use and type of weld backing
- The polarity of the welding current

(b) AWS D1.1 (for Steel Structures)
Other than essential and supplemental essential variables.

4.9.1.4 Check Sheets for WPS and PQR

Table 4.54 shows a sample check sheet of WPS and PQR for ASME BPVC and Piping. It may be very useful for welding engineers who are involved in the project execution. See API RP577 (Welding Processes, Inspection, and Metallurgy) for detailed summary for Essential, Supplementary Essential, and Nonessential of WPS and PQR per each paragraph of ASME Sec. IX.

Table 4.54 (1/2) Sample check sheet of WPS and PQR for ASME BPVC and piping (only for reference)

Paragraph	SMAW			SAW			GMAW/FCAW			GTAW		
QW-402 Joints												
0.1 φ in groove design			N			N			N			N
0.4 – of backing in single-sided weld			N			N			N			N
0.5 + of backing and chemical composition												N
0.10 φ in root spacing			N			N			N			N
0.11 ± nonfusing retainers			N			N			N			N
QW-403 base metal												
0.5 φ in group number QW-422		S			S			S			S	
0.6 T limits impact		S			S			S			S	
.7 T/t limits >8 in. (203 mm)	E			E			E			E		
0.8 φ ⊤ qualified	E			E			E			E		
0.9 tpass > ½ in. (13 mm)	E			E			E					
0.10 ⊤ limits qualified (short circuit arc)							E					
0.11 φ P-N° qualified	E			E			E			E		
0.13 φ P-N° 5/9/10	E			E			E			E		
QW- 404 filler metals												
0.3 φ size												N
0.4 φ F-N°	E			E			E			E		
0.5 φ A-N°	E			E			E			E		
0.6 φ diameter			N			N			N			
0.7 φ diameter > ¼ in. (6 mm)		S										
0.9 φ flux/wire classification				E								
0.10 φ alloy flux				E								
0.12 φ AWS classification		S						S			S	
0.14 ± filler										E		
0.22 ± consumable insert												N
0.23 φ filler metal product form (solid/metal of flux-cored)												
0.24 ± φ supplemental filler metal				E			E					
0.25 ± supplemental powder filler metal				E			E					
0.26 > supplemental powder filler metal				E			E					
0.27 φ alloy elements				E			E					
0.29 φ flux designation						N						
0.30 φ *t*	E			E			E			E		
0.32 *t* limits (short-circuit arc)							E					
0.33 φ AWS classification			N			N			N			N
0.34 φ flux type				E								
0.35 φ flux/wire classification					S	N						
0.36 recrushed slag				E								
0.50 ± flux												N
QW-405 positions												
0.1 + position			N			N			N			N
0.2 φ position		S						S			S	
0.3 φ ↑↓ vertical welding			N						N			N
QW – 406 preheat												
0.1 decrease >56 °C (100 °F)	E			E			E			E		
0.2 φ preheat maintenance			N			N			N			
0.3 increase >56 °C (100 °F) (IP)		S			S			S			S	
QW-407 PWHT												
0.1 φ PWHT	E			E			E			E		
0.2 φ PWHT (time & temperature range)		S			S			S			S	
0.4 T limits	E			E			E			E		

Table 4.54 (2/2) Sample check sheet of WPS and PQR for ASME BPVC and piping (only for reference)

Paragraph												
	SMAW			SAW			GMAW/FCAW			GTAW		
QW – 408 gas												
0.1 ± trailing or φ composition									N			N
0.2 φ single, mixture or %							E			E		
0.3 φ flow rate									N			N
0.5 ± or φ backing flow									N			N
0.9 – Backing or φ composition							E			E		
0.10 φ shielding or trailing							E			E		
QW – 409 electrical characteristics												
0.1 > heat input		S			S			S			S	
0.2 φ transfer mode							E					
0.3 ± pulsing I												N
0.4 φ current or polarity		S	N		S	N		S	N		S	N
0.8 φ I & E range			N			N			N			N
0.12 φ tungsten electrode												N
QW – 410 technique												
0.1 φ string/weave			N			N			N			N
0.3 φ orifice cup, or nozzle size												N
0.5 φ method of cleaning			N			N			N			N
0.6 φ method of back-gouge			N			N			N			N
0.7 φ oscillation						N			N			N
0.8 φ tube to work distance						N			N			
0.9 φ multi to single pass per side			N		S	N		S	N		S	N
0.10 φ single to multi electrodes					S	N		S	N		S	N
0.11 φ closed to out-of-chamber welding										E		
0.15 φ electrode spacing						N			N			N
0.25 φ manual or automatic			N			N			N			N
0.26 ± peening			N			N			N			N

Legend
+ Addition, > Increase/greater than, ↑Uphill, ← Forehand, φ Change
− Deletion, < Decrease/less than, ↓ Downhill, → Backhand
E essential variables which must be indicated on both the WPS and recorded on the PQR. Any changes to these variables require requalification of WPS
S supplementary essential variables must be indicated on the WPS and Recorded on the PQR when impact testing is required. Changes to these variables when impact testing is performed require requalification of WPS
*N N*onessential variables must be indicated on the WPS but when changed do not require requalification of WPS
Note: WPSs are to indicate all essential, nonessential, and supplementary essential variables. Do not indicate variables which are not used as NA; they are applicable and should be entered on the WPS as None or Not used.

4.9.2 WPS (Welding Procedure Specification): See Tables 4.55 and 4.56 for Sample WPSs of Pressure Vessels and Piping Components (ASME Section IX) and AWS D1.1, Form M-2 for Structural Steels

4.9.2.1 Role and Definition of WPS

This document details the practical application of the Procedure Qualification Record (PQR). It should contain enough information to give direction to the welder and should address all variables associated with the welding process defined in QW250 including nonessential and supplementary.

As welding becomes a modern engineering technology, it requires that the various elements involved be identified in a standardized way. This is accomplished by writing a procedure which is simply a “manner of doing” or “the detailed elements (with prescribed values or range of values) of a process or method used to produce a specific result.” The AWS definition for a welding procedure is “the detailed methods and practices including all joint welding procedures involved in the production of a weldment.” The joint welding procedure mentioned includes “the materials, detailed methods and practices employed in the welding of a particular joint.”

A WPS can combine welding processes from other PQRs, but all the relevant variables must be addressed including parent metal thickness. There is an exception to this rule for root runs from PQRs that are greater than 1.5 in. thick (38.1 mm); see code for details.

A welding procedure is used to make a record of all of the different elements, variables, and factors that are involved in producing a specific weld or weldment. Welding procedures should be written whenever it is necessary to:

Table 4.55 Sample WPS for SMAW

SHOP/FIELD TEST & INSPECTION REPORT - sample
WELDING PROCEDURE SPECIFICATION (WPS) - SMAW

XXXX JOB NO.__________ REPORT NO. __________

COMPANY NAME XXXXXXXX

WELDING PROCEDURE SPECIFICATION NO. SM-1.1-04 DATE : April 6, 20xx

SUPPORTING PQR NO.(S) QLG-SM-1.1-12 REVISION NO. 0 DATE : March 10, 20xx

WELDING PROCESS(ES) SMAW TYPE(S) Manual

SCOPE Groove, Fillet, CVN Test, PWHT

JOINTS(QW-402)
GROOVE DESIGN Single V
BACKING : YES NO V
BACKING MATERIAL(TYPE) __________
OTHER __________

BASE METALS (QW-403)
P-No. 1 TO P-No. 1
THICKNESS RANGE* 4.8mm ~ 38mm
PIPE DIA. RANGE All
OTHER * CVN Tested, with PWHT

FILLER METALS (QW-404)
F. NO. 3 / 4 OTHER
A. NO. 1 OTHER
SPEC. NO.(SFA) 5.1
AWS NO. (CLASS) E 6010(root) & E 7016(rest)
SIZE OF ELECTRODE Φ3.2mm, Φ4.0mm, Φ5.0mm
SIZE OF FILLER -
ELECTRODE-FLUX(CLASS) -
CONSUMABLE INSERT -
OTHER

POSITION (QW-405)
POSITION OF GROOVE All
WELDING PROGRESSION : UP V DOWN
OTHER

PREHEAT (QW-406)
PREHEAT TEMP. Min. 10°C(t≤19 mm),Min. 5°C(t>19 mm)
INTERPASS TEMP. Max. 427°C
PREHEAT MAINTENANCE by touch flame
OTHER

POSTWELD HEAT TREATMENT (QW-407)
TEMPERATURE 620-650°C
TIME RANGE Per Code
OTHER See Project Specification.

GAS (QW-408)
SHIELDING GAS(ES)
PERCENT COMPOSITION(MIXTURES)
FLOW RATE
GAS BACKING
TRAILING SHIELDING GAS COMPOSITION
OTHER

ELECTRICAL CHARACTERISTIC (QW-409)
CURRENT AC OR DC AC POLARITY -
AMPS(RANGE) 90 ~ 180A VOLTS(RANGE) 20 ~ 30V
OTHERS

TECHNIQUE (QW-410)
STRING OR WEAVE BEAD Both
ORIFICE OR GAS CUP SIZE Φ10 ~ 12 mm
Initial & Interpass Cleaning (Brushing, Grinding, etc.)
Grinding or Wire rushing
METHOD OF BACK GOUGING Grinding
OSCILLATION N.A
CONTACT TUBE TO WORK DISTANCE -
MULTIPLE OR SINGLE PASS(PER SIDE) Multiple
MULTIPLE OR SINGLE ELECTRODES Single
TRAVEL SPEED(RANGE) 1.0 ~ 3.5 mm/sec
OTHER

WELD LAYER (S)	PROCESS	FILLER METAL		CURRENT		VOLT RANGE	TRAVEL SPEED RANGE(mm/sec)	OTHER
		CLASS	DIAMETER	POLARITY	A-RANGE(A)			
1	SMAW	E 6010	Φ3.2	AC	90 ~ 150	20 ~ 25	1.0 ~ 2.5	
2	SMAW	E 7016	Φ4.0	AC	130 ~ 180	23 ~ 30	1.0 ~ 3.5	
Rest	SMAW	E 7016	Φ5.0	AC	180 ~ 240	25 ~ 30	1.0 ~ 3.5	

- Maintain dimensions by controlling distortion
- Reduce residual or locked-up stresses
- Minimize detrimental metallurgical changes
- Consistently build a weldment the same way
- Comply with certain specifications and codes

Table 4.56 Sample WPS for GTAW + SMAW

SHEET NO. 1 of 1

SHOP/FIELD TEST & INSPECTION REPORT - sample
WELDING PROCEDURE SPECIFICATION (WPS) - GTAW + SMAW

XXXXX JOB NO. ______ REPORT NO. ______

COMPANY NAME XXXXXX

WELDING PROCEDURE SPECIFICATION NO. GT.SM-4.4-01 DATE : April 6, 20xx

SUPPORTING PQR NO.(S) QLG-GT.SM-4.4-38 REVISION NO. 0 DATE : March 17, 20xx

WELDING PROCESS(ES) GTAW + SMAW

SCOPE Groove, Fillet, CVN Test, PWHT TYPE(S) Manual

~~See Attached Reports for CVN/PWHT~~

JOINTS(QW-402)
GROOVE DESIGN Single V
BACKING : YES NO V
BACKING MATERIAL(TYPE)
OTHER

BASE METALS (QW-403)
P-No. 4 TO P-No. 4
THICKNESS RANGE 1.6mm ~ 13mm
PIPE DIA. RANGE ≤ NPS 4 in.
OTHER Carbon content ≤ 0.15%

FILLER METALS (QW-404)
F. NO. 6 / 6 OTHER
A. NO. 3 / 3 OTHER
SPEC. NO.(SFA) 5.28 / 5.5
AWS NO. (CLASS) ER 80S-B2 / E 8016-B2
SIZE OF ELECTRODE Φ3.2mm, Φ4.0mm
SIZE OF FILLER Φ2.4mm
ELECTRODE-FLUX(CLASS) N.A
CONSUMABLE INSERT -
OTHER

POSITION (QW-405)
POSITION OF GROOVE All
WELDING PROGRESSION : UP V DOWN
OTHER

PREHEAT (QW-406)
PREHEAT TEMP. Min. 120°C
INTERPASS TEMP. Max. 260°C
PREHEAT MAINTENANCE by touch flame
OTHER

POSTWELD HEAT TREATMENT (QW-407)
TEMPERATURE N/A
TIME RANGE N/A
OTHER

GAS (QW-408)
SHIELDING GAS(ES) Ar
PERCENT COMPOSITION(MIXTURES) 99.9%
FLOW RATE 8 ~ 15ℓ/min
GAS BACKING Ar 2 ~ 4 ℓ/min
TRAILING SHIELDING GAS COMPOSITION -
OTHER

ELECTRICAL CHARACTERISTIC (QW-409)
CURRENT AC OR DC DC / AC POLARITY SP / -
AMPS(RANGE) 90 ~ 180A VOLTS(RANGE) 12 ~ 28V
OTHERS

TECHNIQUE (QW-410)
STRING OR WEAVE BEAD
Both
ORIFICE OR GAS CUP SIZE Φ10 ~ 12 mm
Initial & Interpass Cleaning (Brushing, Grinding, etc.)
Grinding or Wire brushing
METHOD OF BACK GOUGING N.A
OSCILLATION N.A
CONTACT TUBE TO WORK DISTANCE -
MULTIPLE OR SINGLE PASS(PER SIDE)
Multiple
MULTIPLE OR SINGLE ELECTRODES Single
TRAVEL SPEED(RANGE) 0.8 ~ 3.5 mm/sec
OTHER

WELD LAYER (S)	PROCESS	FILLER METAL		CURRENT		VOLT RANGE	TRAVEL SPEED RANGE(mm/sec)	OTHER
		CLASS	DIAMETER	POLARITY	A-RANGE(A)			
1	GTAW	ER 80S-B2	Φ2.4	DC - SP	90 ~ 150	12 ~ 17	0.8 ~ 3.0	
2	SMAW	E 8016-B2	Φ3.2	AC	90 ~ 130	20 ~ 25	1.0 ~ 2.5	
Rest	SMAW	E 8016-B2	Φ4.0	AC	130 ~ 180	23 ~ 28	1.0 ~ 3.5	

4.9.2.2 Test and Qualification

Welding procedures must be tested or qualified, and they must be communicated to those who need to know. This includes the designer, the welding inspector, the welding supervisor, and, last but not least, the welder.

When welding codes or high-quality work is involved, this can become a WPS, which lists in detail the various factors or variables involved. Different codes and specifications have somewhat different requirements for a welding procedure, but in general a welding procedure consists of three parts as follows:

- A detailed written explanation of how the weld is to be made
- A drawing or sketch showing the weld joint design and the conditions for making each pass or bead
- A record of the test results of the resulting weld

4.9.2.3 Qualified Welding Procedure and Specification

If the weld meets the requirements of the code or specification and if the written procedure is properly executed and signed, it becomes a qualified welding procedure.

The procedure write-up must include each of the listed variables and describe in detail how it is to be done. The second portion of the welding procedure is the joint detail sketch and table or schedule of welding conditions.

Tests are performed to determine if the weld made to the procedure specification meets certain standards as established by the code or specification. If the destructive tests meet the minimum requirements, the procedure then becomes a qualified procedure specification. The writing, testing, and qualifying procedures become quite involved and are different for different specifications.

In certain codes, welding procedures are prequalified. By using data provided in the code, individual qualified procedure specifications are not required, for the standard joints on common base materials using the shielded metal arc welding process.

4.9.2.4 Factors in Welding Procedure

The factors included in a procedure should be considered in approaching any new welding job. By means of knowledge and experience, establish the optimum factors or variables in order to make the best and most economical weld on the material to be welded and in the position that must be welded.

Welding procedures take on added significance based on the quality requirements that can be involved. When exact reproducibility and perfect quality are required, the procedures will become much more technical with added requirements, particularly in testing. Tests will become more complex to determine that the weld joint has the necessary properties to withstand the service for which the weld is designed.

Procedures are written to produce the highest-quality weld required for the service involved, but at the least possible cost, and to provide weld consistency. It may be necessary to try different processes, different joint details, and so on, to arrive at the lowest-cost weld which will satisfy the service requirements of the weldment.

4.9.2.5 Tested Thickness in PQR and Qualified Thickness for WPS: ASME Sec. IX, Table QW 451.1

Table 4.57 and 4.58 show the qualified thickness for WPS from the tested thickness in PQR for butt groove weld in ASME Sec. IX, Table QW 451.1 and for CJP groove weld of structures in AWS D1.1 respectively. This table covers full penetration (fullpen) and partial welding of butt joint. "*t*" is for actually weld-deposited thickness in PQR, while "*T*" is for nominal thickness of test coupon in PQR. In full penetration weld for the same thickness butt joint, $t = T$.

Table 4.57 Qualified thickness for WPS from the tested thickness in PQR for butt groove weld

Thickness T of test coupon, welded, in. (mm)	Range of thickness T of base metal, qualified, in. (mm)[(a), (b)] Minimum	Maximum	Maximum thickness t of deposited weld metal, qualified, in. (mm)[(a), (b)]
$T \le 1/16$ (1.5)	T	$2T$	$2t$
1/16 (1.5) $< T \le 3/8$ (10)	1/16 (1.5)	$2T$	$2t$
3/8 (10) $< T \le 3/4$ (19)	3/16 (5)	$2T$	$2t$
3/4 (19) $< T \le 1\ 1/2$ (38)	3/16 (5)	$2T$	$2t$ when $t < 3/4$ (19)
3/4 (19) $< T \le 1\ 1/2$ (38)	3/16 (5)	$2T$	$2t$ when $t \ge 3/4$ (19)
1 1/2 (38) $< T \le 6$ (150)	3/16 (5)	8 (200)[(c)]	$2t$ when $t < 3/4$ (19)
1 1/2 (38) $< T \le 6$ (150)	3/16 (5)	8 (200)[(c)]	8 (200)[(c)] when $t \ge 3/4$ (19)
$T > 6$ (150)[(d)]	3/16 (5)	$1.33T$	$2t$ when $t < 3/4$ (19)
$T > 6$ (150)[(d)]	3/16 (5)	$1.33T$	$1.33T$ when $t \ge 3/4$ (19)

Source: ASME Sec. IX, Table QW 451.1

Notes: T nominal thickness of test coupon, t = thickness of actually deposited weld metal, all "QW-" from ASME Sec. IX

[(a)]The following variables further restrict the limits shown in this table when they are referenced in QW-250 for the process under consideration: QW-403.9, QW-403.10, and QW-404.32. Also, QW-202.2, QW-202.3, and QW-202.4 provide exemptions that supersede the limits of this table

[(b)]For combination of welding procedures, see QW-200.4

[(c)]For the SMAW, SAW, GMAW, PAW, LLBW, and GTAW welding processes only; otherwise per Note (1) or $2T$, or $2t$, whichever is applicable

[(d)]For test coupons over 150 mm (6 in.) thick, the full thickness of the test coupon shall be welded

Table 4.58 Qualified thickness for WPS from the tested thickness in PQR for CJP groove weld of structures

Tests	Nominal plate thickness (T) tested, in.	Nominal plate, pipe, or tube thickness[c,d] qualified, in.	
		Minimum	Maximum
Tests on plate[a, b]	$1/8 \leq T \leq 3/8$	1/8	$2T$
	$3/8 < T < 1$	1/8	$2T$
	$T \geq 1$	1/8	Unlimited
Tests on ESW and EGW[a, f]	T	$0.5T$	$1.1T$

Source: AWS D1.1, Table 4.2
Notes: *CJP* complete joint penetration
[a]All test plate welds shall be visually inspected (see AWS D1.1, 4.9.1) and subject to NDT (see AWS D1.1, 4.9.2)
[b]See AWS D1.1, Figures 4.6 and 4.7 for test plate requirements
[c]For square groove welds that are qualified without back-gouging, the maximum thickness qualified shall be limited to the test thickness
[d]CJP groove weld qualification on any thickness shall qualify any size of fillet or PJP groove weld for any thickness (see AWS D1.1, 4.11.3)
[f]See AWS D1.1, Figure 4.5 for plate requirements

4.9.3 PQR (Procedure Qualification Record): See Tables 4.59 and 4.60 for Sample PQR

The Procedure Qualification Record (PQR) is a record of the welding variables (Essential or Supplementary Essential or Nonessential) [See ASME Sec. IX, Table QW-250 to QW-265 for ASME BPVC and Piping] for each process involved and all the destructive test results of the test welded coupon. PQR's are not required if Standard Welding Procedures are used; see below for details. The testing requirements are as follows:

(a) Tensile tests for butt welds: specimens from plate, pipe, etc./test procedure/acceptance categories (see ASME Sec. IX, QW-150 for ASME BPVC and Piping).
(b) Guided bend tests: test jigs, test specimens from plate, pipe, etc./test procedure/acceptance categories (see ASME Sec. IX, QW-160 for ASME BPVC and Piping).
(c) Toughness tests when required by referencing codes – CVN impact test (ASTM A380) and drop weight test (ASTM E208), from plate, pipe, etc./test procedure/acceptance categories (see ASME Sec. IX, QW-170 for ASME BPVC and Piping).
(d) Fillet weld tests: specimens with production assembly mock-ups, fracture specimens, macro-examination performance specimens, and diffusion welding/test procedure/acceptance categories (see ASME Sec. IX, QW-180 for ASME BPVC and Piping).
(e) Other tests and examinations: NDE (RT, UT, VT, PT)/stud-weld tests/tube-to-tubesheet tests including mock-ups/resistance weld tests/laser beam lap joint tests/flash weld tests/specimens/test procedure/acceptance categories (see ASME Sec. IX, QW-190 for ASME BPVC and Piping).
(f) Addition tests, examination, and consideration per end-user's request: hot tension test, heat treatment (including multi-cycle), creep rupture, K1c, J1c, step cooling test, specific corrosion test, microstructure examination, fatigue (corrosion) test with S-N curve, K-R curve determination test, J-R curve test, Izod test (ASTM E23) specimens, bend test, grain size, disbanding (shear stress) test, through-thickness test, specific NDE, etc. See Sects. 5.2.1 and 5.2.2 for several test methods and procedures.
(g) See AWS D1.1, Form M-1 for PQR form of structural steels.

4.10 Production Tests and Acceptance Criteria for Welds

4.10.1 Production Tests for Welds

1. ASME Sec. VIII, Div. 1: See UG-84, (e) through (j) for impact production tests and UNF-95 for welding production test plates of nonferrous metals.
2. ASME Sec. VIII, Div. 2: Heat treatment requirements of ASME Sec. VIII, Div. 2, 6.4.2 (requirements for PWHT), 3.10.2 (requirements for sample test coupons), and 3.10.4 (procedure for obtaining test specimens and coupons) shall apply to test plates, except that the provisions of ASME Sec. VIII, Div. 2, 3.10.3.2 (exemptions from requirement of sample test coupons) are not applicable to test plates for welds joining P-No. 3, Gr. 1 and 2 materials. For P-No. 1, Gr. 1, 2, and 3 materials, impact testing of the welds and HAZs of the PQR and production test plates need not be repeated when the fabrication heat treatment differs from the heat treatment applied to the test plates, provided the PWHT or simulated heat treatment cycles applied to the test plates and the production welds were applied observing the holding temperatures and times specified in ASME Sec. VIII, Div. 2, Table 6.8 (see Table 4.124 in this book) or the holding temperatures and times permitted in ASME Sec. VIII, Div. 2, Table 6.16 (see Table 4.124d in this book).
3. ASME B31.3: Impact tests that meet the requirements of Table 323.3.1 (Impact Testing Requirements for Metals – base metal and production), which are performed as part of the weld procedure qualification, will satisfy all requirements of para. 323.2.2 (Low Temperature Limits, listed materials) and need not be repeated for production welds.

Table 4.59 (1/2) Sample PQR for SMAW

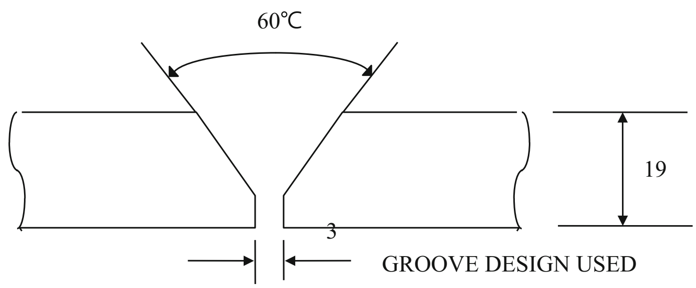
SHEET NO . 1 of 2

FIELD TEST/INSPECTION REPORT - sample
PROCEDURE QUALIFICATION RECORD (PQR) - SMAW

XXXX JOB NO. ______ REPORT NO. ______

COMPANY NAME XXXXX
PROCEDURE QUALIFICATION RECORD NO. QLG-.SM-1.1-12 DATE March 10, 20xx
WPS NO. SM-1.1-04
WELDING PROCESS(ES) SMAW
TYPE(MANUAL AUTOMATIC, SEMI-AUTO Manual
SCOPE Groove, CVN Test, PWHT

JOINT (QW-402)



GROOVE DESIGN USED

BASE METALS (QW-403)
MATERIAL SPEC. SA 516
TYPE OR GRADE 70
P-No. 1 TO P-No. 1
THICKNESS 19 mm
DIAMETER N.A
OTHER

FILLER METALS (QW-404)
WELD METAL ANALYSIS A NO. 1
SIZE OF ELECTRODE Φ3.2mm, Φ4.0mm
FILTER METAL F NO. 4
SFA SPECIFICATION 5.1
AWS CLASSIFICATION E 7016
OTHER

POSITION (QW-405)
POSITION OF GROOVE 1G
WELD PROGRESSION (UPHILL, DOWNHILL) -
OTHER

PREHEAT (QW-406)
PREHEAT TEMP. 20°C
INTERPASS TEMP. 400 ~ 425°C
OTHER

POSTWELD HEAT TREATMENT (QW-407)
TEMPERATURE 620-650°C
TIME RANGE 1 hour
OTHER See Attached Report

GAS (QW-408)
TYPE OF GAS (ES)
COMPOSITION OF GAS. MIXTURE
OTHER

ELECTRICAL CHARACTERISTICS (QW-409)
CURRENT AC
POLARITY -
AMPS 110 ~ 230A VOLTS 20 ~ 28V
OTHER

TECHNIQUE(QW-410)
TRAVEL SPEED 1.7 ~ 3.0mm/sec
STRING OR WEAVE BEAD Both
OSCILLATION -
MULTIPASS OR SINGLE PASS(PER SIDE) Multiple
MULTIPLE OR SINGLE ELECTRODES Single
OTHER

NOTE :

Table 4.59 (2/2) Sample PQR for SMAW

SHEET NO . 2 of 2

SHOP/FIELD TEST & INSPECTION REPORT - sample
PROCEDURE QUALIFICATION RECORD (PQR)

XXXX JOB NO.________ PQR NO. QLG-SM-1.1-12

TENSILE TEST (QW-150)

SPECIMEN NO	WIDTH mm	THICKNESS mm	AREA mm^2	ULTIMATE TOTAL LOAD kg	ULTIMATE UNIT STRESS kg/mm^2	CHARACTER OF FAILURE & LOCATION
1	19.1	18.9	361.0	19,061	52.8	Ductile / B.M
2	19.1	19.0	362.9	19,451	53.6	ditto

GUIDED BENDED TESTS (QW-160)

TYPE AND FIGURE NO.	RESULT
Side Bend (QW 462.2(a))	Accept
Side Bend (QW 462.2(a))	Accept
Side Bend (QW 462.2(a))	Accept
Side Bend (QW 462.2(a))	Accept

TOUGHNESS TESTS (QW-170)

SPECIMEN	NOTCH LOCATION	NOTCH TYPE	TEST. TEMP.	IMPACT VALUES	LATERAL EXP.		DROP WEIGHT	
					% SHEAR	MILS	BREAK	NO BREAK
See Attached Reports								

FILLET WELD TEST (QW-180)

RESULT-SATISFACTORY: YES______NO______PENETRATION INTO PARENT METAL: YES________NO ________

TYPE AND CHARACTER OF FAILURE________MACRO-RESULTS________

OTHER TESTS

TYPE OF TEST______ Radiographic Test : OK
DEPOSIT ANALYSIS________
OTHER______ Macro Test : Good

CERTIFICATE OF COMPLIANCE

WELDER'S NAME XXXXX CLOCK NO.________STAMP NO.________
TESTS CONDUCTED BY XXXXX LABORATORY TEST NO.________
WE CERTIFY THAT THE STATEMENTS IN THIS RECORD ARE CORRECT AND THAT THE TEST WELDS WERE PREPARED WELDED AND TESTED IN ACCORDANCE WITH THE REQUIREMENTS OF SECTION IX OF THE ASME CODE.

CONTRACTOR XXXXX
DATE March 1, 20xx BY XXXXX
CHIEF OF FIELD QC SECTION/XXX Project
(DETAIL OF RECORD OF TESTS ARE ILLUSTRATIVE ONLY AND MAY BE MODIFIED TO CONFORM TO THE TYPE AND NUMBER OF TESTS REQUIRED BY THE CODE.)

Table 4.60 (1/2) Sample PQR for GTAW + SMAW

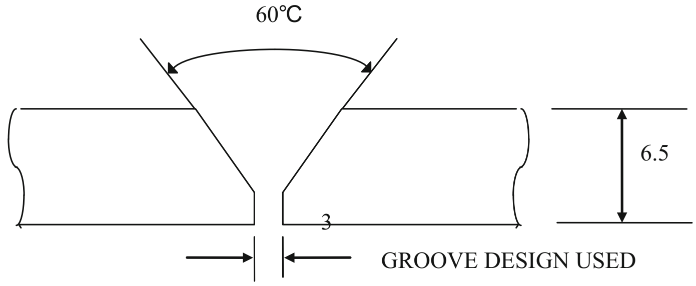
SHEET NO . 1 of 2

SHOP/FIELD TEST & INSPECTION REPORT - sample
PROCEDURE QUALIFICATION RECORD (PQR) – GTAW + SMAW

XXXX JOB NO. ______ REPORT NO. ______

COMPANY NAME XXXXXX
PROCEDURE QUALIFICATION RECORD NO. QLG-GT.SM-4.4-38 DATE March 17, 20xx
WPS NO. GT.SM-4.4-01
WELDING PROCESS(ES) GTAW + SMAW
TYPE(MANUAL AUTOMATIC, SEMI-AUTO Manual
SCOPE Groove, No CVN Test, No PWHT

JOINT (QW-402)



BASE METALS (QW-403) MATERIAL SPEC. A 335 TYPE OR GRADE P 11 P-No. 4 TO P-No. 4 THICKNESS 6.5 mm DIAMETER NPS 4 in. OTHER	**POSTWELD HEAT TREATMENT (QW-407)** TEMPERATURE N.A TIME OTHER
FILLER METALS (QW-404) WELD METAL ANALYSIS A NO. 3 / 3 SIZE OF ELECTRODE Φ 2.4mm, Φ3.2mm, Φ4.0mm FILTER METAL F NO. 6 / 6 SFA SPECIFICATION 5.28 / 5.5 AWS CLASSIFICATION ER 80S-B2 / E 8016-B2 OTHER	**GAS (QW-408)** TYPE OF GAS (ES) Ar COMPOSITION OF GAS. MIXTURE 99.9 % OTHER **ELECTRICAL CHARACTERISTICS (QW-409)** CURRENT DC / AC POLARITY SP / - AMPS 95 ~ 170A VOLTS 14 ~ 28V OTHER
POSITION (QW-405) POSITION OF GROOVE 1G WELD PROGRESSION (UPHILL, DOWNHILL) - OTHER	
PREHEAT (QW-406) PREHEAT TEMP. 133°C INTERPASS TEMP. 235 ~ 254°C OTHER	**TECHNIQUE(QW-410)** TRAVEL SPEED 0.8 ~ 3.2 mm/sec. STRING OR WEAVE BEAD Both OSCILLATION - MULTIPASS OR SINGLE PASS(PER SIDE) Multiple MULTIPLE OR SINGLE ELECTRODES Single OTHER

Table 4.60 (2/2) Sample PQR for GTAW + SMAW

SHEET NO . 2 of 2

FIELD TEST/INSPECTION REPORT - sample
PROCEDURE QUALIFICATION RECORD (PQR)

XXX JOB NO.______ PQR NO. QLG-GT.SM-4.4-38

TENSILE TEST (QW-150)

SPECIMEN NO	WIDTH mm	THICKNESS mm	AREA mm^2	ULTIMATE TOTAL LOAD kg	ULTIMATE UNIT STRESS kg/mm^2	CHARACTER OF FAILURE & LOCATION
1	19.0	6.2	117.8	5,690	48.3	Ductile / B.M
2	19.1	6.1	116.5	5,418	46.5	ditto

GUIDED BENDED TESTS (QW-160)

TYPE AND FIGURE NO.	RESULT
Root Bend (QW 462.3(a))	Accept
Root Bend (QW 462.3(a))	Accept
Face Bend (QW 462.3(a))	Accept
Face Bend (QW 462.3(a))	Accept

TOUGHNESS TESTS (QW-170)

SPECIMEN	NOTCH LOCATION	NOTCH TYPE	TEST. TEMP.	IMPACT VALUES	LATERAL EXP.		DROP WEIGHT	
					% SHEAR	MILS	BREAK	NO BREAK
				N.A				

FILLET WELD TEST (QW-180)

RESULT-SATISFACTORY: YES______NO______PENETRATION INTO PARENT METAL: YES______NO______

TYPE AND CHARACTER OF FAILURE______MACRO-RESULTS______

OTHER TESTS

TYPE OF TEST Radiographic Test : OK
DEPOSIT ANALYSIS______
OTHER Macro Test : Good

CERTIFICATE OF COMPLIANCE

WELDER'S NAME XXXX CLOCK NO.______STAMP NO.______
TESTS CONDUCTED BY XXXX LABORATORY TEST NO.______
WE CERTIFY THAT THE STATEMENTS IN THIS RECORD ARE CORRECT AND THAT THE TEST WELDS WERE PREPARED WELDED AND TESTED IN ACCORDANCE WITH THE REQUIREMENTS OF SECTION IX OF THE ASME CODE.

CONTRACTOR XXXX
DATE March 1, 20xx BY XXXXXX
CHIEF OF FIELD QC SECTION/XXXX Project
(DETAIL OF RECORD OF TESTS ARE ILLUSTRATIVE ONLY AND MAY BE MODIFIED TO CONFORM TO THE TYPE AND NUMBER OF TESTS REQUIRED BY THE CODE.)

4.10.2 Acceptance Criteria for Welds

ASME Section VIII and IX and AWS D.1.1 have several acceptance categories for base metal, WPS/PQR, tolerances, test and inspection (including DE and NDE), welders' tests, etc. Table 4.61 and 4.61a show the acceptance criteria for welds and examination methods for evaluating weld imperfections (ASME B31.3).

Table 4.61 Acceptance criteria for welds and examination methods for evaluating weld imperfections (ASME B31.3, Table 341.3.2)

Criteria (A–M) for types of welds and for service conditions [Note (1)]											Examination on methods			
Normal and category M fluid service			Severe cyclic conditions			Category D fluid service								
Type of weld			Type of weld			Type of weld								
Girth, miter groove & branch connection [Note (2)]	Longitudinal groove [Note (3)]	Fillet [Note (4)]	Girth, miter groove & branch connection [Note (2)]	Longitudinal groove [Note (3)]	Fillet [Note (4)]	Girth and miter groove	Longitudinal groove [Note(3)]	Fillet [Note (4)]	Branch connection [Note (2)]	Weld imperfection	Visual (VT)	RT	MT	PT
A	A	A	A	A	A	A	A	A	A	Crack	✓	✓	✓	✓
A	A	A	A	A	A	C	A	N/A	A	Lack of fusion	✓	✓	. . .	. . .
B	A	N/A	A	A	N/A	C	A	N/A	B	Incomplete penetration	✓	✓	. . .	. . .
E	E	N/A	D	D	N/A	N/A	N/A	N/A	N/A	Internal porosity	. . .	✓	. . .	. . .
G	G	N/A	F	F	N/A	N/A	N/A	N/A	N/A	Internal slag inclusion, tungsten inclusion, or elongated indication	. . .	✓	. . .	. . .
H	A	H	A	A	A	I	A	H	H	Undercutting	✓	✓	. . .	. . .
A	A	A	A	A	A	A	A	A	A	Surface porosity or exposed slag inclusion [Note (5)]	✓	. . .	. . .	. . .
N/A	N/A	N/A	I	J	J	N/A	N/A	N/A	N/A	Surface finish	✓	. . .	. . .	. . .
K	K	N/A	K	K	N/A	K	K	N/A	K	Concave root surface (suck up)	✓	✓	. . .	. . .
L	L	L	L	L	L	M	M	M	M	Weld reinforcement or internal protrusion	✓	. . .	. . .	. . .

General Notes:
[(a)]Weld imperfections are evaluated by one or more of the types of examination methods given, as specified in paras. 341.4.1, 341.4.2, and 341.4.3 and M341.4 in ASME B31.3, or by the engineering design
[(b)]"N/A" indicates the Code does not establish acceptance criteria or does not require evaluation of this kind of imperfection for this type of weld
[(c)]Check (✓) indicates examination method generally used for evaluating this kind of weld imperfection
[(d)]Ellipsis (. . .) indicates examination method not generally used for evaluating this kind of weld imperfection

Table 4.61a Criterion value notes for Table 4.61 (ASME B31.3, Table 341.3.2)

Criterion		
Symbol	Measure	Acceptable value limits [Note (6)]
A	Extent of imperfection	Zero (no evident imperfection)
B	Depth of incomplete penetration Cumulative length of incomplete penetration	$\leq$1 mm (0.03 in.) and $\leq$0/2 T_w $\leq$38 mm (1.5 in.) in any 150 mm (6 in.) weld length
C	Depth of lack of fusion and incomplete penetration Cumulative length of lack of fusion and incomplete penetration [Note (7)]	$\leq$0.2 T_w $\leq$38 mm (1.5 in.) in any 150 mm (6 in.) weld length
D	Size and distribution of internal porosity	See ASME Section VIII, Division 1, Appendix 4
E	Size and distribution of internal porosity	For $T_w \leq$ 6 mm (0.25 in.), limit is same as D For $T_w >$ 6 mm (0.25 in.), limit is 1.5 × D
F	Slag inclusion, tungsten inclusion, or elongated indication	
	Individual length	$\leq T_w$ /3
	Individual width	$\leq$2.5 mm (0.1 in.) and $\leq T_w$ /3
	Cumulative length	$\leq T_w$ in any 12 T_w weld length
G	Slag inclusion, tungsten inclusion, or elongated indication	
	Individual length	$\leq$2 T_w
	Individual width	$\leq$3 mm (0.125 in.) and $\leq T_w$ /2
	Cumulative length	$\leq$4 T_w in any 150 mm (6 in.) weld length
H	Depth of undercut	$\leq$1 mm (0.03 in.) and $\leq T_w$ /4
I	Depth of undercut	$\leq$1.5 mm (0.063 in.) and $\leq$[T_w /4 or 1 mm (0.03 in.)]
I	Surface roughness	$\leq$500 min. Ra per ASME B46.1
K	Depth of root surface concavity	Total joint thickness. Incl. weld reinforcement, $\geq T_w$
L	Height of reinforcement or internal protrusion [Note (8)] in any plane through the weld shall be within limits of the applicable height value in the tabulation at right, except as provided in Note (9). Weld metal shall merge smoothly into the component surfaces	*For T_w, mm (in.)* — *Height, mm (in.)* $\leq$6 (0.25 in.) — $\leq$1.5 (0.063 in.) >6 (0.25 in.), $\leq$13 (0.5 in.) — $\leq$3 (0.125 in.) >13 (0.5 in.), $\leq$25 (1 in.) — $\leq$4 (0.156 in/) >25 (1 in.) — $\leq$5 (0.188 in.)
M	Height of reinforcement or internal protrusion [Note (8)] as described in L, Note (9) does not apply	Limit is twice the value applicable for L above

Abbreviation
T_w wall thickness
Ra (Roughness Average in microinches): 500 Ra = 550 RMS (root mean square in microinches)
Category M Fluid: See Sect. 1.1.11.2
Category D Fluid: See Sect. 1.1.11.1
Notes
(1) Criteria given are for required examination. More stringent criteria may be specified in the engineering design. See also paras. 341.5 and 341.5.3 in ASME B31.3
(2) Branch connection weld includes pressure-containing welds in branches and fabricated laps
(3) Longitudinal groove weld includes straight and spiral seam. Criteria are not intended to apply to welds made in accordance with a standard listed in Table A-1 or Table 326.1 in ASME B31.3. Alternative Leak Test requires examination of these welds; see para. 345.9 in ASME B31.3
(4) Fillet weld includes socket and seal welds and attachment welds for slip-on flanges, branch reinforcement, and supports
(5) These imperfections are evaluated only for welds $\leq$5 mm (3/16 in.) in nominal thickness
(6) Where two limiting values are separated by "and," the lesser of the values determines acceptance. Where two sets of values are separated by "or," the larger value is acceptable. *Tw* is the nominal wall thickness of the thinner of two components joined by a butt weld
(7) Tightly butted unfused root faces are unacceptable
(8) For groove welds, height is the lesser of the measurements made from the surfaces of the adjacent components; both reinforcement and internal protrusion are permitted in a weld. For fillet welds, height is measured from the theoretical throat, Fig. 328.5.2A in ASME B31.3; internal protrusion does not apply
(9) For welds in aluminum alloy only, internal protrusion shall not exceed the following values:
(a) 1.5 mm (0.063 in.) for thickness $\leq$2 mm (0.08 in.)
(b) 2.5 mm (0.1 in.) for thickness >2 mm (0.08 in.) and $\leq$6 mm (0.25 in)
For external reinforcement and for greater thicknesses, see the tabulation for symbol L.

4.11 Welding of Several Metals and Special Types

The weldability of metals greatly depends on the combination of the base metals. Normally the welding between similar metals (same P. number) is easily available for most metals. ASME Sec. VIII, Div. 2 does not allow the welding of TMCP steel (i.e., SA-841) by the ESW or EGW process. Welding for heavy wall Q-T steels should be carefully applied under the qualified WPS/PQR. Table 4.62 shows the most common SMAW electrodes for the welding between similar metals (CS and LAS). However, the dissimilar metal welding should be carefully applied because they have different metallic structures, physical properties, and different mechanical properties which caused the dissimilar metal weld crack, undesirable metallic compounds, and deformation.

See Sect. 2.1.7.7 for the welding for hardfacing.

Table 4.62 Similar welding electrodes selection for carbon steels and low alloy steels (SMAW)

ASTM No.	Grades	Electrodes	ASTM No.	Grades	Electrodes
A36	–	[b]	A441	All	E7018 or E7028
A113	All	[b]			[c]
A131	A, B, C. CS, D, E	[b]	A442	All	E7018 or E7028
	AH, DH, EH	E7018	A444	A, B, C	[b, d]
A148	80-40. 50	E8018-C3	A446	D, F	E7010-A1
	90-60	E9018-G	A455	All	E8018-C3
	105-85. 120-95	E11018-M	A486	70	E7018 or E7028
A202	A, B	E9018-G		90	E9018-G
A203	A, B	E8018-C1	A484	8N, 9N	E8018-B3
	D, E	E8018-C2		A, AN, AQ, B,	[b]
	A, B	E7010-A1 or E7018-A1		N, C, CN	
	C	E8018-B2		BQ, CQ	E8018-C3
A205	A, B	E8018-C3	A514	All	E11018-M
A225	A, B	E8018-C3			[c]
A236	A, B	E7018 or E7028	A515	All	E7018 or E7028
	C, D, F	E8018-C3	A516	55, 60	E8018 or E7028
	F, G	E9018-G		65, 70	E7018 or E7018-1
	H	E11018-M			E6010 for root pass
A238	A	E8018-C3	A517	All	E11018-M
	B	E9018-G			[c]
	C, D, E	E11018-M	A526		[b, d]
A242	All	E7018 or E7028	A528		[b, d]
A266	1	[b]	A529		[b]
	2	E7018	A533	Class 1	E8018-C3
	3	E8018-C3		Class 2, 3	E11018-M
A283	All	[b]	A537	Class 1	E7018 or E7028
A284	All	[b]		Class 2	E8018-C3
A285	All	[b]	A541	Class 1	E7018 or E7028
A299	All	E8018-C3		Class 2, 3, 4	E8018-C3
A302	All	E8018-C3		Class 5	E8018-B2
A328	All	E7018-or E7028		Class 6	E9018-B3
A333-6	All	E7018	A543	1, 2, 3	E11018-M
A352	LCA, LCB, LCC	E7018			[c]
	LC1	E7018-A1	A570	All	[b]
	LC2	E8018-C1	A572	42, 45	[b]
	LC3	E8018-C2		50, 55	E7018 or E7028
A356	5	E8018-B1		60, 65	E8018-C3
	6	E8018-B2	E573	65, 70	E7018 or E7028
	8, 10	E9018-B3	E588	All	E7018 or E7028
A361		[b, d]			[c]
A366		[b]	E606	All	[b]
A372	Class I	E7018 or E7028	E607	45, 50, 55	[b]
	Class II	E8018-C3		60, 65	E8018-C3
	Class III	E9018-G		70	E9018-G
	Class IV	E11018-M	E611	A, B, C, D	[b]
A387	A, B, C	E8018-B2	A615	40	[b]
	D	E9018-B3		60	E9018-G
A389	C23	E8018-B2		75	E11018-M
	C24	E9018-B3	A616	50	E8018-C3
A410		E8018-C2		60	E9018-G
A414	A, B, C, D		A617	40	[b]
	E, F	E7018 or E7028		60	E9018-G
	G	E8018-C3	A706	60	E9018-G
A424		E7018			

Note: Recommendations are based on matching tensile properties of weld deposit and plate and also on chemical compositions of weld deposit and plate where composition is important. Since it is impossible to foresee all conditions of every application, electrodes other than those listed may also be satisfactory

[a] Plates, sheets, forgings, shapes, and castings

[b] Unless restricted by specifications, use any E60XX or E70XX electrode for grades with 60 ksi or less tensile strength: use E70XX electrodes for grades with 60 to 70 ksi tensile strength

[c] Use E8018-C1 or E8018-B2 for best color match on unpainted steels with enhanced atmospheric corrosion resistance; consult steel supplier

[d] Usually E6010 is the most satisfactory electrode for galvanized sheet

[e] E7018 and E8018 are frequently used for fillet welds

4.11.1 Dissimilar Metal Welding (DMW)

4.11.1.1 Check Points of DMW Joints

The following check points may be typically considered to avoid the metal damage for the DMW joints.

(a) Due to the difficulty of controlling welding parameters in the field, shop welding of dissimilar metals is preferred.
(b) The chemical analysis of the dissimilar metal welds and the ferrite number measurement for stainless steel should be performed and complied with the purchaser's requirements.
(c) The welding electrode should be selected after sufficient consideration of the expected dilution. If needed, buffering welding should be considered. For instance, in HF alkylation unit, DMW between CS and Alloy 400 may produce very high hardness zones that are highly susceptible to corrosion cracking. DMW should be avoided wherever practical. Where this is not practical, WPS and associated PWHT procedures should be developed which limit hardness in the weld fusion zone and HAZ. A nickel filler per Table 4.67 should be used for the first pass over the CS to ensure low Fe levels at the surface of the weldment and thus minimize corrosion. See NACE Paper 14-3794 for a case study.
(d) DMW cracking should be evaluated before the selection of the base metal and welding electrode as well as joint design. The most common DMW appears at the joint of CS/LAS to ASS/nickel alloys in high temperature service. See API RP571 and NiDI publication 14,018 for more detailed information.
(e) The mechanical (TS, YS, fatigue, creep, shear stress, etc.) and metallurgical properties (intermetallic compounds, toughness, hardness, galvanic corrosion, SSC, SCC, etc.) of the weld should be complied with the end-user's requirements.
(f) When considered the joint of non-pressure parts to pressure parts, the filler metal chemistry should match the nominal chemical composition of the pressure part.
(g) PWHT for DMW between a ferritic alloy and an austenitic alloy should be carefully performed. Normally the purchaser's approval is required before the PWHT. The following requirements shall be included in the procedure qualification record:
   – Hardness test survey after PWHT should be performed for PQR.
   – The DMW joint should be welded using the preheat temperature of the ferritic material.
(h) The dissimilar welds for pressure components should be 100% RT or UT plus 100% PT or 100% MT inspected after welding. PMI (Sect. 2.5.1) also should be applied.

4.11.1.2 API RP582 Requirements for DMW

(a) When joining dissimilar ferritic steels (P-No. 1 through P-No. 5), the filler metal shall conform to the nominal chemical composition of either base metal or an intermediate composition. However, when attaching non-pressure parts to pressure parts, the filler metal chemical composition shall match the nominal chemical composition of the pressure part.
(b) When joining ferritic steels (P-No. 1 through P-No. 5 and P-No. 15E) to:
   1. MSS (P-No. 6), or
   2. FSS (P-No. 7), or
   3. ASS (P-No. 8), the filler metal shall be selected based on the following criteria:
      (a) 309(L) SS may be used for design temperatures not exceeding 315 °C (600 °F);
         – Due to high differential thermal expansion, nickel-based filler metals are preferred for temperatures above 315 °C (600 °F).
         – Type 309 Cb (Nb) should not be used when PWHT is required, except for weld overlay.
      (b) Nickel-based alloy filler materials may be selected using design conditions shown in API RP582, Table 2.
      (c) For service conditions exceeding the limits stated in API RP582, 6.2.2.c.1 and 6.2.2.c.2, the filler metal selection should be reviewed with the purchaser.
      (d) ASME/AWS ER310 (E310-XX) and ASME/AWS Classification ERNiCrFe-6 should not be used.
         – The use of dissimilar metal welds (CS or LAS to ASS) in services corrosive to CS or LAS should be carefully evaluated.
         – Failures have been reported due to hydrogen charging of zones exhibiting high hardness adjacent to the fusion line. It is unclear whether the charging is due to corrosion of the CS or LAS alone or accelerated due to the presence of a galvanic couple.
         – In addition, CS or LAS to ASS welds might be susceptible to brittle fracture at service temperatures below −29 °C (−20 °F).

4.11.1.3 DMW Between Carbon Steels and Low Alloy Steels: See Table 4.63

Table 4.63 shows the recommended Welding Electrodes for DMW (dissimilar metals wleing) between CS and LAS. This table refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classifications (ASME/AWS SFA-A5.14, A5.17, A5.18, A5.20, A5.23, A5.28, A5.29, A5.34). Refer to the texts of each API standard for information on other processes. Higher alloy electrode specified in Table 4.63 should normally be used to meet the required tensile strength or toughness after PWHT. The lower alloy electrode specified may be required in some applications to meet weld metal hardness requirements. PWHT can cause the strength of these filler metals to drop below minimum requirements. Care should be taken to insure adequate strength in the PWHT condition. Table 4.64 shows a typical welding material selection for dissimilar welding between Cr-Mo steels in several company standards. The DMW joint with Group 9xx may require the welding electrode with the lower strength of each side unless otherwise specified due to high risk of embrittlement cracking.

4.11.1.4 DMW Between Carbon Steels and Stainless Steels: Table 4.65

Table 4.63 Welding electrodes for DMW between CS and LAS – API RP582 and API RP577 – modified

Material group of base material (steel)	Carbon steel	C-Mo	1 to 1 ¼ Cr to 1/2 Mo	2 ¼ Cr-1 Mo	3 Cr-1 Mo or 5 Cr-1/2 Mo	9 Cr-1 Mo	2 ¼ Nickel	3 ½ Nickel	9% Nickel
CS	*AB* [1]	AC	AD	ADE	ADEF	ADEFH	AJ	AK	[2]
C-Mo		C	CD	CDE	CDE	CDEFH	[2]	[2]	[2]
1 to 1 ¼ Cr-1/2 Mo			D	DE	DEF	DEFH	[2]	[2]	[2]
2 ¼ Cr-1 Mo				E	EF	EFH[3]	[2]	[2]	[2]
3 Cr-1 Mo or 5 Cr-1/2 Mo					F	FH	[2]	[2]	[2]
9 Cr-1 Mo						H[3]	[2]	[2]	[2]
2 ¼ Nickel							J	JK	LM
3 ½ Nickel								K	LM
9% Nickel									LM

Keys:
A. ASME/AWS SFA/A 5.1, Class E70XX low hydrogen. See Note (5) below
B. ASME/AWS SFA/A 5.1, Class E6010 for root pass. See Note (5) below
C. ASME/AWS SFA/A 5.5, Class E70XX-A1, low hydrogen
D. ASME/AWS SFA/A 5.5, Class E70XX-B2L [see Note (6) below] or E80XX-B2, low hydrogen
E. ASME/AWS SFA/A 5.5, Class E80XX-B3L [see Note (6) below] or E90XX-B3, low hydrogen
F. ASME/AWS SFA/A 5.5, Class E80XX-B6 or E80XX-B6L [see Note (6) below], low hydrogen
H. ASME/AWS SFA/A 5.5, Class E80XX-B8 or E80XX-B8L [see Note (6) below], low hydrogen
J. ASME/AWS SFA/A 5.5, Class E80XX-C1 or E70XX-C1L, low hydrogen
K. ASME/AWS SFA/A 5.5, Class E80XX-C2 or E70XXC2L, low hydrogen
L. ASME/AWS SFA/A 5.11, Class ENiCrMo-3
M. ASME/AWS SFA/A 5.11, Class ENiCrMo-6, ENiCrFe-4/9, ENiCrMo-3/4/10, or ENiMo-8/9
Notes:
[1]Other E60XX and E70XX welding electrodes may be used if approved by the purchaser
[2]An unlikely or unsuitable combination. Consult the owner's engineer if this combination is needed
[3]Not covered modified versions of Cr-Mo steels (e.g., V-enhanced)
Commentary Notes for current API RP582 (2016):
(a) See Sect. 4.12.3.6 and Table 4.113 (LCPTT part) in this book for PWHT of dissimilar weld joints
(b) See Sect. 4.11.1 in this book for common requirements
(c) The DMW joint in pressure equipment normally requires to select the welding electrode of higher strength side unless otherwise required, or in EAC or fatigue service
(d) See Table 4.64 for welding materials selection of Cr-Mo steels in several company standards
(e) The WPS/PQR should be performed by the required full cycle PWHT
(f) See Sect. 4.11.3.1 for welding materials selection of V enhanced Cr-Mo steels

Table 4.64 Dissimilar welding material selection of Cr-Mo steels [1], [2] (only for reference)

Group No.	P-No./Gr. No.	11	22	23	9	91	911	92	SS
11	4 / 1	B2	B2	B2	B2	B2	B2	B2	309
22	5A / 1		B3	B3, G	B3	B3	B3, G	B3, G	309, Ni
23	5A / 1			W, B3, G, Ni	G, Ni	G, Ni	W, G	B, W, G, B9	G, Ni, SS
9	5B / 1				B9	B9	W, B9, G	W, G, B9	Ni
91	15E / 1					B9	W, B9, G	W, G, B9	Ni
911	15E / 1						W, G	B, W, B9, G	Ni
92	15E / 1							B, W, G	Ni
SS	Per SS								SS, Ni

Keys:
G = no chemical requirements
B2 = 1 ¼Cr-1/2Mo [e.g., SM: E7018-B2L, E8018-B2, E8016-B2/ GT: ER80S-G/ FC: E81T1-B2/B2M]
B3 = 2 ¼Cr-1Mo [e.g., SM: E9018-B3, B3L/ GT: ER-90S-G, ER-80S-G/ FC: E91T1-B3/B3M]
B9 = 9Cr-1Mo-V [e.g., SM: E9018-B9, E9016-G, B9 / GT: ER-90S-G, B9]
B = Boron/Others Modified
W = Tungsten Modified
Ni = Ni Base (ENiCrMo-1 or −2 or −3)
SS = Stainless Steels, 308H, 309H, 316H, 347H, 16-8-2
Notes
[1]ENiCrMo-3 (Alloy 625) should NOT be used because it will embrittle at the PWHT temperature required for Grade 91
[2]Reference: API Technical Report 938B and ESAB Technical Report

Table 4.65 Welding electrodes for DMW between CS and SS: API RP582 and API RP577 – modified

Base material[(1), (2)]	405 SS	410S SS	410 SS	304 SS	304L SS	304H SS	310 SS	316 SS	316 L SS	317L SS	321 SS	347 SS	347 H SS	*904L SS*	*6 wt% Mo SS*	*7 wt% Mo SS*	*Alloy 20Cb-3*
CS & LAS	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	*PL*	*LM*	*LM*	*ON*
405 SS	ABC	ABC	ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	*PL*	*LM*	*LM*	*ON*
410S SS		ABC	ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	*PL*	*LM*	*LM*	*ON*
410 SS			ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	*PL*	*LM*	*LM*	*ON*
304 SS [(3)]				D	DH	DJ	A	DF	DGH	DI	DE	DE	DE	*PL*	*LM*	*LM*	*ON*
304L SS [(3)]					H	DHJ	A	DF	GH	HI	DE	DE	DE	*PL*	*LM*	*LM*	*ON*
304H SS [(3), (5)]						J	A	DFJ	DGHJ	DIJ	DEJ	EJ	EJ	*PL*	*LM*	*LM*	*ON*
310 SS [(3)]							K	AK	A	A	A	A	A	*PL*	*LM*	*LM*	*ON*
316 SS [(3)]								F	FG	FI	EF	EF	EF	*PL*	*LM*	*LM*	*ON*
316L SS [(3)]									G	GI	EG	EG	EG	*PL*	*LM*	*LM*	*ON*
317L SS [(3)]										I	EI	EI	EI	*PL*	*LM*	*LM*	*ON*
321 SS [(3)]											E [(6)]	E	E	*PL*	*LM*	*LM*	*ON*
347 SS [(3)]												E	E	*PL*	*LM*	*LM*	*ON*
347H SS [(3),(5)]													E	*PL*	*LM*	*LM*	*ON*
904L SS														*PL*	*LM*	*LM*	*LMN*
6 wt% Mo SS (254SMO, AL-6XN)															*LM*	*LM*	*LMN*
7 wt% Mo SS (654SMO)															*LM*	*LM*	*LMN*
Alloy 20Cb-3																	*ON*

Keys:

A. ASME/AWS SFA/A 5.4, Classification E309-XX
B. ASME/AWS SFA/A 5.11, Classification ENiCrFe-2 (Alloy 718, Inco-Weld A) or ENiCrFe-3 (Alloy 182) or ENiCrMo-3 (Alloy 625). See Note (4) below
C. ASME/AWS SFA/A 5.4, Class E410-XX (0.05% C max.) (heat treatment at 760 °C (1400 °F) required)
D. ASME/AWS SFA/A 5.4, Class E308(L)-XX
E. ASME/AWS SFA/A 5.4, Class E347-XX
F. ASME/AWS SFA/A 5.4, Class E316-XX
G. ASME/AWS SFA/A 5.4, Class E316L-XX
H. ASME/AWS SFA/A 5.4, Class E308L-XX
I. ASME/AWS SFA/A 5.4, Class E317L-XX
J. ASME/AWS SFA/A 5.4, Class E308H-XX
K. ASME/AWS SFA/A 5.4, Class E310-XX
L. ASME/AWS SFA/A 5.11, Class ENiCrMo-3 (625)
M. ASME/AWS SFA/A 5.11, Class ENiCrMo-4 (C-276) or Class ENiCrMo-11 (G-30)
N. ASME/AWS SFA/A 5.11, Class ENiCrMo-11 (G-30) or Class ENiCrMo-10 (Inconel 122)
O. ASME/AWS E(R)320LR (20Cb-3LR)
P. ASME/AWS E(R)385 (904L)

Notes:

(1) This table refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classifications (ASME/ AWS SFA/A 5.9, SFA/A5.14, SFA/A5.22, SFA/A5.34). Refer to the text for information on other processes
(2) The higher alloy electrode specified in the table is normally preferred
(3) See API RP582, Section 6 for weld metal delta ferrite requirements
(4) See API RP582, para. 6.2.2 for the temperature limitation for nickel-based filler metals
(5) E(R)16-8-2 is often specified when the weld deposit will be exposed to high creep strains where σ phase may affect performance. See Table 4.82 (5/5) in this book for more details
(6) Either ER347 or ER321 may be used for GTAW or PAW of 321 SS if the appropriate WPS/PQR is prepared

Commentary Notes for current API RP582 (2016):

(a) The strength, toughness, ferrite number (including solidification cracking), PWHT, hydrogen baking out, hardness limits, and/or corrosion resistance on welds and HAZ should be confirmed to meet the requirements when a dissimilar filler is used
(b) See Sect. 4.11.1 in this book for common requirements for dissimilar weld joints
(c) See Sect. 4.12.3.6 and Table 4.113 (LCPTT part) in this book for PWHT of dissimilar weld joints
(d) See Sects. 2.1.6.1 and 4.2.7 in this book for weld metal delta ferrite requirements as well
(f) To comply with Fig. 2.53 in this book to avoid solidification cracking of 300 series ASS. Creq/Nieq >1.5 on weld metal is a key factor. It should be verified through the PQR

Table 4.66 DMW between DSS-ASS-nickel alloys [(1)(2)(3)] – API RP577, Annex D and RP582, Table A.3 – modified

Base metals↓ →		Duplex alloys						Under-matched alloys			Over-matched alloys		
DSS class/ TN	UNS No.	2304	2205	F255	Zeron 100	2507	DP3W	P1-P5	P8 (304 SS)	P8 (316 SS)	P8 (254 SMO)	P43 (Alloy 625)	P45 (Alloy 825)
2304	S32304	A-DF	A-DF	A-DF	A-DF	A-DF	A-DF	AEF	AEF	AF	GH	GH	GH
2205	S31803/ 32205		A-D	A-D	A-D	A-D	A-D	AEF	AEF	AF	GH	GH	GH
2205 (cast)	J92205		A-D	A-D	A-D	A-D	A-D	AEF	AEF	AF	GH	GH	GH
F255	S32550			B-D	B-D	B-D	B-D	ABEF	ABEF	ABEF	GH	GH	GH
Zeron 100	S32760				CDGH	CDGH	CDGH	A-DEF	A-DEF	A-DF	GH	GH	GH
Zeron 100 (cast)	J93380				CDGH	CDGH	CDGH	A-DEF	A-DEF	A-DF	GH	GH	GH
2507	S32750					CDGH	CDGH	A-DEF	A-DEF	A-DF	GH	GH	GH
DP3W	S39274						CDGH	A-DEF	A-DEF	A-DF	GH	GH	GH

General Notes: *TN* trade name

(1) This table refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classification (ASME/AWS SFA/A5.9, SFA/A5.14, SFA/A5.22, and SFA/A5.34)

(2) ENiCrMo-10 (W86022 – *Inconel 122*), ENiCrMo-13, and ENiCrMo-14 may be used for DSS and SDSS weld joints when severe corrosion is anticipated. Ni alloy fillers may give rise to a fully ferritic zone adjacent to the fusion line in DSS/SDSS, which would not meet the desired ferrite requirement. This zone tends to give reduced toughness of the weldment. See commentary note (h) below as well

(3) See Table 4.108 for weld overlay of DSS

Keys:

A. ASME SFA 5.4, E2209 – duplex filler material
B. ASME SFA 5.4, E2553 – duplex filler material
C. ASME SFA 5.4, E2594 – duplex filler material
D. DP3W (unclassified) – duplex filler material
E. ASME SFA 5.4, E309L – high alloy austenitic filler material
F. ASME SFA 5.4, E309LMo – high alloy austenitic filler material
G. ASME SFA 5.11, ENiCrMo-10 – nickel-based filler material
H. ASME SFA 5.11, ENiCrMo-14 – nickel-based filler material

Commentary Notes for current API RP582 (2016):

(a) UNS S82441 (LDX 2404): It can be used with the same as those of 2205 DSS. See ASTM A790
(b) All DSS materials shall be used at 316 °C (600 °F) and below
(c) Maximum interpass temperature should be restricted to 150 °C (300 °F) for DSS welding
(d) Do not use for the dissimilar welding with CS and LAS if they require PWHT
(e) 2205 (cast): CD3MN (J92205; see Table 2.56 in this book)
(f) Zeron 100 (cast): CD3MWCuN (J93380; see Table 2.56 in this book)
(g) S39274: DP3W (see Table 2.55 in this book)
(h) The nickel alloy filler metal with high Mo (>10 wt%*) may be more prone to sigma phase embrittlement [∗Hastelloy B & C, Alloy 686 & 59, etc. Mo is a strong ferrite former]
(i) (S)DSS to CS/LAS Welds: Use E(R)309L, E(R)309LMo, E(R)2209, E(R)2553, ER25.10.4L, or E(R)NiCrMo-3 per service condition

4.11.1.5 DMW Between DSS-ASS-Nickel Based Alloys

Duplex stainless steels (DSS) and super-duplex stainless steels (SDSS) are inevitably joined to other alloys. For most commonly used engineering alloys, this does not present any problem, provided the appropriate consumable used. Schaeffler and Delong diagrams (Table 2.60, Figs. 2.42, 2.54, 2.55, and 2.56) can prove useful in selecting the correct filler material. Table 4.66 shows a number of consumables which will provide an acceptable technical solution for any dissimilar joint, so the selection will often be based on practical aspects. For example, for reducing of the number of procedures and consumables utilized, if 2205 DSS consumables are being used, these can conveniently be used for joints between DSS/SDSS, carbon and low alloy, and most austenitic stainless steels (ASS). DSS/SDSS consumables can also be used for surfacing carbon and low alloy steels without any intermediate buffer layers. The dissimilar welding with carbon or low alloy steel shall be avoided if the heat treatment is required for carbon or low alloy steel because DSS/SDSS are very susceptible to 475 °C (885 °F) embrittlement.

4.11.1.6 DMW Between CS-ASS-SASS-Nickel Based Alloys: See Table 4.67 below

4.11.1.7 DMW Between Aluminum Based Alloys and Between Copper Based Alloys

See Sects. 4.11.9 and 4.11.10, respectively.

References for Guidelines and Case Studies of DMW

– API RP582/RP577/RP571
– NiDI Publication 14018
– WRC Bulletin 350
– MTI Bulletin 20
– Clad and Dissimilar Metals, p. 334–389, STD-AWS WHB-4 Part 2, 1998
– E.J. Barnhouse et al., Microstructure/Property Relationships in Dissimilar Welds between DSS and CS, Weld. J. 477s–487s, (1998)
– B.A. Soares et al., Characterization of the Dissimilar Welding-ASS with Filler Metal of the Nickel Alloy, INAC Conference, Sep.–Oct. 2007

Table 4.67 Welding Electrodes for DMW between CS-ASS-SASS-nickel alloys: API RP582 and API RP577 – modified

Base Material [(1)] Nickel 200 (N02200)	70-30 and 90-10 Cu-Ni	Alloy 400 (N04400)	*904L SS (N08904)*	*6wt % Mo SS*	*Alloy 20Cb-3*	Nickel 200 (N02200)	Alloy 800 (N08800), 800H (N08810), 800HT (N08811)	Alloy 600 (N06600)	Alloy 625 (N06625)	Alloy 825 (N08825)	Alloy C-22 (N06022)	Alloy C-276 (N10276)	Alloy B-2/3 (N10665/ 10675)	Alloy G-3 (N06985)	Alloy G-30 (N06030)
Carbon and low alloy steel	BC	BC	MJ	EJ	LH	C	A	A	A	A	D	E	F	G	H
300 series SS	BC	AC	MJ	EJ	LH	AC	A	A	A	A	D	E	F	G	H
400 series SS	B	B	MJ	EJ	LH	AC	A	A	A	A	D	E	F	G	H
70-30 & 90-10 Cu-Ni	B	B	J	EJ	H	C	C	C	C	C	[(3)]	[(3)]	[(3)]	[(3)]	[(3)]
Alloy 400 (N04400)		B	J	EJ	H	BC	A	A	A	A	A	A	F	A	A
904L SS (N08904)			MJ	EJ	EJH	HJ	JK	AJ	J	J	DJ	EJ	FJ	GJ	HJ
6 wt% Mo SS (254SMO, AL-6XN)				J	EJH	CEJ	EJK	AEJ	EJ	EJ	EJ	EJ	EFJ	EGJ	EHJ
Alloy 20Cb-3					LH	CH	HK	AH	HJ	HJ	DH	EH	FH	GH	H
Nickel 200 (N02200)						C	AC	AC	AC	AC	CD	CE	CF	CG	CH
Alloy 800 (H/HT) [(2)]							K	A	A	A	DJ	EJ	FJ	GJ	HJ
Alloy 600 (N06600)								A	AJ	A	DJ	EJ	FJ	GJ	HJ
Alloy 625 (N06625)									J	J	DJ	EJ	FJ	GJ	HJ
Alloy 825 (N08825)										J	DJ	EJ	FJ	GJ	HJ
Alloy C-22 (N06022)											D	EJ	FJ	GJ	HJ
Alloy C-276 (N10276)												E	FJ	GJ	HJ
Alloy B-2 (N10665), B-3 (N10675)													F	GJ	HJ
Alloy G-3 (N06985)														G	HJ
Alloy G-30 (N06030)															H

Keys:
A. ASME/AWS SFA/A 5.11, Class ENiCrFe-2 or −3
B. ASME/AWS SFA/A 5.11, Class ENiCu-7 (W84190)
C. ASME/AWS SFA/A 5.11, Class ENi-1 (W82141)
D. ASME/AWS SFA/A 5.11, Class ENiCrMo-10 (W86022)
E. ASME/AWS SFA/A 5.11, Class ENiCrMo-4 (C-276)
F. ASME/AWS SFA/A 5.11, Class ENiMo-7 (W08665)
G. ASME/AWS SFA/A 5.11, Class ENiCrMo-9 (W86985)
H. ASME/AWS SFA/A 5.11, Class ENiCrMo-11 (Alloy G-30)
J. ASME/AWS SFA/A 5.11, Class ENiCrMo-3 (Alloy 625)
K. ASME/AWS SFA/A 5.11, Class ENiCrCoMo-1 (W86117) or matching filler
L. ASME/AWS E(R)320LR (20Cb-3LR)
M. ASME/AWS E(R)385 (904L)
Notes
[(1)]Table A.4 refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classification (ASME/AWS SFA/A 5.14). Refer to the text for information on other processes
[(2)]For Alloys 800 (N08800), 800H (N08801), and 800HT (N08802), if sulfidation or stress relaxation cracking is a concern, use matching filler metals
[(3)]An unlikely or unsuitable combination. Consult the purchaser's engineer if this combination is needed
Commentary Notes for current API RP582 (2016):
(a) See Sect. 4.12.3.6 and Table 4.113 (LCPTT part) in this book for PWHT of dissimilar weld joints
(b) See Sect. 4.11.1 in this book for common requirements
(c) See Table 4.95 in this book for welding electrodes and maximum design temperature in sulfidation and non-sulfidation environments

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4.11.2 Welding of Cast Iron (CI)

4.11.2.1 General

Cast iron is considerably less weldable than low carbon steel. Cast iron contains much more C and Si than steel, with the result that cast iron is less ductile and is more metallurgically deformed when welded.

Weldability (including repair welding) of cast iron depends on microstructure and mechanical properties. For example, gray cast iron is inherently brittle and often cannot withstand stresses set up by a cooling weld. The lack of ductility is caused by the coarse graphite flakes, the graphite clusters in malleable irons, and the nodular graphite in spheroidal graphite (SG) irons, give significantly higher ductility which improves the weldability. The weldability may be lessened by the formation of hard and brittle microstructures in the HAZ, consisting of iron carbides and martensite. As nodular and malleable irons are less likely to form martensite, they are more readily weldable, particularly if the ferrite content is high. White cast iron which is very hard and contains iron carbides is normally considered to be unweldable. Iron castings are generally welded to:

- Repair defects in order to salvage or upgrade a casting before service
- Repair damaged or worn castings
- Fabricate castings into welded assemblies

Repair of defects in new iron castings represents the largest single application of welding cast irons. Defects such as porosity, sand inclusions, cold shuts, washouts, and shifts are commonly repaired. Fabrication errors, such as inaccurate machining and misaligned holes, can also be weld repaired. Due to the widely differing weldability of the various classes of cast iron, welding procedures must be suited to the type of cast iron to be welded. Some API valve standards specify that process wetted parts shall not be welded to ductile or cast iron; and welding, brazing, plugging, peening, or impregnation to repair defects in gray iron, ductile iron, or copper alloy castings is not permitted.

Table 4.68 shows description and intended use of fillers (electrodes and rods) for welding of CI.

Table 4.68 (1/3) Description and intended use of fillers for CI welding (OFW, SMAW, GMAW, FCAW, and brazing) (ASME Sec. II-C, SFA 5.15 unless otherwise specified)

Class	Intended use and characteristics
OFW – Oxyfuel gas welding	
RCI (for CI) ≤3.3C, ≤2.8Si, ≤0.7Mn, ≤0.6P, ≤0.1S, ≤bal.Fe [F10090]	– Ordinary machinable gray CI may vary from 20 to 40 ksi (140–280 MPa) of TS and 150–250 BHN. The use of a gray CI welding rod for OFW can produce a machinable weld metal of the same color, composition, and structure as the base metal. The weld may be as strong as the original casting. – RCI welding rods are used for filling in or building up new or worn castings and for general fabrication, salvage, and repair.
RCI-A (for CI) ≤3.3C, ≤2.3Si, ≤1.4Ni, ≤0.6Mn, ≤0.3Mo, ≤0.3P, ≤0.1S, ≤bal.Fe [F10091]	– This cast iron welding rod contains small amounts of Mo and Ni, which give it a slightly higher melting point than the ordinary CI welding rod, RCI. The molten weld metal is more fluid. Welding can be done more rapidly. – The RCI-A welding rod (with a weld metal hardness of 225–290 BHN) may be used if an alloy cast iron is being welded and when greater TS and finer grain structure are required. The weld metal is generally considered machinable.
RCI-B (for nodular/ductile CI) 3.6C-3.5Si-0.6 Mg-0.5Ni-0.2Mn-0.05P-0.01S-bal.Fe [F10092]	– These nodular (ductile) cast iron welding rods are capable of producing sound weld metal when used to weld higher-strength gray iron, malleable, and nodular iron castings with OFW. – Hardness of undiluted weld metal: 220–310 BHN as welded and 150–200 BHN for annealed.

Table 4.68 (2/3) Description and intended use of fillers for CI welding (OFW, SMAW, GMAW, FCAW, and brazing) (ASME Sec. II-C, SFA 5.15 unless otherwise specified)

Class	Intended use and characteristics
Brazing	
RBCuZn-A (for Naval Brass) 58Cu-0.6Sn-0.1Si, bal Zn [C47000]	– For improved strength when used on copper and copper alloys. – For brazing for CI, SS, and Ni alloys. – ASME Sec. II-C, SFA 5.8. – Discontinued in ASME Sec. II-C, SFA 5.7. – See ANSI/AWS A5.27.
RBCuZn-B (for low fuming Brass-Ni added) 58Cu-1Sn-0.7Fe-0.5Ni-0.3Mn-0.1Si, bal Zn [C68000]	– Increased hardness and strength by added Fe and Mn. – For brazing for CI, SS, and Ni alloys with low fuming. – ASME Sec. II-C, SFA 5.8. – Discontinued in ASME Sec. II-C, SFA 5.7. – See ANSI/AWS A5.27.
RBCuZn-C (for low fuming Brass-Ni) 58Cu-1Sn-0.7Fe-0.3Mn-0.1Si, bal Zn [C68100]	– For brazing for CI, SS, and Ni alloys with low fuming. – ASME Sec. II-C, SFA 5.8. – Discontinued in ASME Sec. II-C, SFA 5.7. – See ANSI/AWS A5.27.
RBCuZn-D (for Ni-Brass) 48Cu-10Ni-7.2P-bal Zn [C77300]	– For brazing of CI and cast steel to meet better color match over yellow brass, or for brazing of tungsten carbide. – ASME Sec. II-C, SFA 5.8. – Discontinued in ASME Sec. II-C, SFA 5.7. – See ANSI/AWS A5.27.
SMAW (Steel Base)	
ESt[(1)] ≤0.15C, ≤0.6Mn, ≤0.15Si, ≤0.04P, ≤0.04S, bal.Fe [K01520]	– For all welding positions. – It has a low melting point covering and differs from the ordinary CS electrodes for SMAW. – Weld metal from this electrode is not readily machinable. – Normally used for the repair of castings that require no postweld machining. – Since the shrinkage of steel is greater than that of CI (base metal), high stresses develop as the weld cools. Residual stresses may be severe enough to cause cracking. – Preheating is employed only when necessary to prevent excessive stresses in other parts of the casting. – This electrode generally is used at low amperage to minimize the dilution effect in the fusion zone and consequent weld and base metal cracking. – The recommended amperes: 60–95 amps for 3/32 in. (2.4 mm), 80–110 amps for 1/8 in. (3.2 mm), and 110–150 amps for 5/32 in. (4.0 mm) electrodes using DCEP (electrode positive) or AC. – Hardness of undiluted weld metal: 250–400 BHN. – The beads should be short and widely separated, to distribute the heat, and each bead should be peened lightly. – The slag volume is low but very alkaline. Residual slag should be removed completely if the weld area is to be painted.
SMAW (Ni-Base)	
ENi-CI[(1)] (Ni-Base) ≤2C, ≤2.5Mn, ≤4Si, ≤0.03S, ≤8Fe, ≤2.5Cu, ≤1Al, min. 85Ni [W82001]	– This electrode can be used to join ordinary gray CI to themselves, or to other ferrous and nonferrous materials, and to reclaim or repair castings. Satisfactory welds can be produced on small and medium size castings where the welding stresses are not overly severe, or where P (phosphorus) content of the CI is not high. Because of lower strength than the ENiFe-CI and lower ductility of the weld metal, these electrodes should be used only in applications where maximum machinability of highly diluted filler metal is necessary. Otherwise, the ENiFe-CI classification is preferred. – Hardness of undiluted weld metal: 135–218 BHN. – The ENi-CI classification may also be used on malleable or ductile iron.
ENi-CI-A[(1)] (Ni-Base) ≤2C, ≤2.5Mn, ≤4Si, ≤0.03S, ≤8Fe, ≤2.5Cu, ≤2Al, min. 85Ni [W82003]	– These electrodes frequently are used interchangeably with ENi-CI electrodes. The covering of ENi-CI electrodes contains more aluminum to improve operating characteristics such as slag coverage and flowability. However, the aluminum becomes an alloy of the weld metal and may affect ductility. – Hardness of undiluted weld metal: 135–218 BHN.
ENiFe-CI[(1)] (Ni-Base) ≤2C, ≤2.5Mn, ≤4Si, ≤0.03S, bal.Fe, ≤2.5Cu, ≤1Al, 45-60Ni [W82002]	– This electrode may be used for making repair welds on, as well as for joining, workpieces of various types of cast iron, including nodular iron, and for welding them to steel and some nonferrous base metals. – Castings containing phosphorus levels higher than normal (approximately 0.20% phosphorus) are more readily welded using these electrodes than with an electrode of the ENi-CI classification. – Hardness of undiluted weld metal: 165–218 BHN. – Experience has shown that satisfactory welds can be made on thick and highly restrained weldments and on high strength and engineering grades of cast iron.
ENiFe-CI-A[(1)] (Ni-Base) ≤2C, ≤2.5Mn, ≤4Si, ≤0.03S, bal.Fe, ≤2.5Cu, ≤2Al, 45-0Ni [W82004]	– ENiFe-CI-A electrodes frequently are used interchangeably with ENiFe-CI electrodes. The covering of ENiFe-CI-A electrodes contains more aluminum to improve operating characteristics such as slag coverage and flowability. However, the aluminum becomes an alloy of the weld metal and may affect ductility. – Hardness of undiluted weld metal: 165–218 BHN

Table 4.68 (3/3) Description and intended use of fillers for CI welding (OFW, SMAW, GMAW, FCAW, and brazing) (ASME Sec. II-C, SFA 5.15 unless otherwise specified)

Class	Intended use and characteristics
ENiFeMn-CI (Ni-Base) ≤2C, 10-14Mn, ≤1Si, ≤0.03S, bal.Fe, ≤2.5Cu, 35-45Ni [W82006]	– This electrode has a nominal addition of 12% Mn to the Ni-iron system which improves the flow of the molten metal and somewhat increases the crack resistance of the weld metal. Mn of the higher-strength grades of nodular CI base metals than can be achieved with the ENiFe-CI. ENiFeMn-CI electrodes are also used for surfacing to improve wear resistance or for buildup. – Hardness of undiluted weld metal: 165–210 BHN
ENiCu-A, *ENiCu-B*(1) (Ni-Base) 0.45C, ≤2.3Mn, ≤0.75Si, ≤0.025S, 3-6Fe, ∗Cu, ≤1Al, ∗Ni [W84001/ W84002]	– These electrodes have been used in many of the same applications as the ENi-Fe-CI, ENiFe-CI-A, and ENiFeMn-CI electrodes. They are used to produce a low depth of fusion weld, since high dilution by the base metal may cause weld cracking. *W84001: 35–45Cu/50–60Ni/W84002: 25–35Cu/60–70Ni
ECuSn-A (Cu-Base P-Bronze: bal.Cu, 5Sn, 0.2P) [W60518]	– For welding Cu base alloys not only to repairing wrought bronze, but to SS, CI, CS. This electrode may be used on AC current and as an electric brazing rod. PWHT desirable if the weld is cold worked. 65–75BHN on welds. – ANSI/AWS A5.6.
ECuSn-C (Cu-Base P-Bronze: bal.Cu, 8Sn, 0.2P) [W60521]	– For welding Cu base alloys not only to repairing wrought bronze, but to SS, CI, CS. This electrode may be used on AC current and as an electric brazing rod. 90–100BHN on welds. – ANSI/AWS A5.6.
ECuAl-A2 (Cu-Base Al Bronze: bal.Cu, 8Al, 0.5–5.0Fe, ≤1.5Si) [W60614]	– For high strength welding electrode is great for repairing all grades of Al bronze, Si-Mn bronze, high strength CuZn brass, and some Cu-Ni alloys. It resists corrosion, cavitation, erosion, and metal to metal wear. It is also excellent for overlays on CI, CS, copper, and copper alloys. – ANSI/AWS A5.6 and A5.13.
GMAW (Ni-Base)	
ERNi-CI ≤1C, ≤2.5Mn, ≤0.75Si- ≤0.03S, ≤4Fe, ≤4Cu, min.90Ni [N02215]	– This solid continuous bare electrode is composed of essentially pure Ni (99%) and contains no deoxidizers. – The electrode is used to weld iron castings when weld metal with highly diluted filler metal is to be machined.
ERNiFeMn-CI ≤0.5C, 12Mn- ≤1Si, ≤0.03S, bal.Fe, ≤2.5Cu, ≤1Al, 35-45Ni [N02216]	– This solid continuous bare electrode can be used for the same applications as the ENiFeMn-CI covered SMAW electrode. The strength and ductility of this classification makes it suitable for welding the higher strength grades of nodular iron castings. – Hardness of undiluted weld metal: 165–210 BHN.
FCAW (Ni-Base)	
ENiFeT3-CI ≤2C, 4Mn- ≤1Si, ≤0.03S, bal.Fe, ≤2.5Cu, ≤1Al, 45-60Ni [W82032]	– Designed to operate without an external shielding gas. For this reason, it is commonly referred to as a self-shielded FCAW electrode, but it may also be used with an external shielding gas if recommended by the manufacturer. The composition of this classification is similar to that of an ENiFe-CI except for a higher Mn content. It can be used in the same types of applications as the ENiFe-CI electrode. It is generally used for thick e metal or where processes can be automated. This electrode contains 3–5% Mn to aid in resisting weld metal hot cracking and to improve strength and ductility of the weld metal. – Hardness of undiluted weld metal: 150–165 BHN.

Notes
(1)Single layer weld metal which has high dilution may have a hardness as high as 350 BHN for ENiFe-CI, ENiFe-CI-A, and ESt electrodes and around 210 BHN for the ENi-CI, ENi-CI-A, and ENiCu-B weld metal

4.11.2.2 Preparation

The most important aspect of welding cast iron is to have the surface clean and free of defects by solvents, commercial cleaners, or paint removers prior to welding, since castings that have been in service are likely to be impregnated with oil or grease. Casting skin should be removed from surfaces to be welded. Blind cracks and pits must be completely dressed out to sound metal by mechanical means such as grinding, chipping, rotary filling, or shot blasting. Cracks should be excavated to their full length and depth, especially in the spongy areas and pinholes.

Impregnated oil or other volatile matters should be eliminated by using an oxidizing oxyacetylene flame to heat the casting or weld groove to approximately 482 °C (900 °F) for about 15 minutes and then wire brushing, grinding, or rotary filling to remove the residue. This method has an advantage of de-gassing the casting and removing some of the surface graphite as well.

New castings present less of a cleaning problem than castings that have been in service. However, casting skin, sand, and other foreign materials must be removed from the joint to be welded and the adjacent surfaces of the casting.

To repair cracked castings, drill a hole at each end of the crack to prevent it from spreading further and grind out to the bottom. Begin welding at the drilled end of the crack where restraint is greatest and move towards the free end. Castings which have to transmit fairly heavy working loads often have the weld joint assisted by mechanical means, such as bolt straps, or hoops which are shrunk on. For instance, broken teeth of large cast iron gears are sometimes repaired by studding. Holes are drilled and tapped in the face of the fracture and mild steel studs screwed in. These are then built up with weld metal to the required dimensions. They are machined afterwards or ground to shape.

4.11.2.3 Precautions

(a) Factors to consider are the same whatever the type of cast iron.

1. Low ductility with a danger of cracking due to stresses set up by welding. This is not so important when welding SG iron due to its good ductility.
2. Formation of a hard brittle zone in the weld area. This is caused by rapid cooling of molten metal to form a white cast iron structure in the weld area and makes the weld unsuitable for service where fairly high stresses are met.
3. Formation of a hard, brittle weld bead due to pickup of carbon from the base metal. This does not occur with weld metals which do not form hard carbides such as Monel and high nickel alloys. These are used where machinable welds are desired.

(b) Although some cases can be welded without preheating, the cracking (due to lack of ductility of castings, especially complicated shapes) may have to be minimized by suitable preheating.

In general, all cast irons need to be preheated when oxyacetylene welding. This preheating reduces the welding heat-input requirements. High preheat is needed when using a cast iron filler metal because the weld metal has low ductility near room temperature. The weld yields readily during cooling and relieves welding stresses that might otherwise cause cracking in the weld.

1. Local preheating occurs where parts not held in restraint may be preheated to about 500 °C (932 °F) in the area of the weld, with slow cooling after welding is completed. Cracking from unequal expansion can take place during the preheating of complex castings or when the preheating is confined to a small area of a large casting. This is why local preheating should always be gradual.
2. Indirect preheating involves preheat of 200 °C (392 °F) for other critical parts of the job in addition to local preheating. This is done so that they will contract with the weld and minimize contraction stresses.
3. Complete preheating is used for intricate casings, especially those varying in section thicknesses such as cylinder blocks. It involves complete preheating to 500 °C (932 °F) followed by slow cooling after welding. The preheating temperature should be maintained during welding. A simple preheating furnace may be made of bricks into which gas jets project.

4.11.2.4 Welding of Several Cast Irons

(a) Gray Cast Iron

As gray cast iron contains graphite in flake form, carbon can readily be introduced into the weld pool, causing weld metal embrittlement. Consequently, techniques that minimize base metal dilution are recommended. Care must be taken to compensate for shrinkage stresses, and the use of low strength filler metals helps reduce cracking without sacrificing overall joint strength.

Gray cast iron welds are susceptible to the formation of porosity. This can be controlled by lowering the amount of dilution with the base metal or by slowing the cooling rate so that gas has time to escape. Preheat helps reduce porosity and reduces the cracking tendency. A minimum preheat of 200 °C (392 °F) is recommended, but 315 °C (600 °F) is generally used.

The most common arc welding electrodes for gray cast iron are nickel and nickel-iron types. These electrodes have been used with or without preheating and/or PWHT. Cast iron and steel electrodes must be used with high preheats [550 °C (1022 °F)] to prevent cracking and the formation of hard deposits.

(b) Ductile Cast Iron

Ductile cast irons are generally more weldable than gray cast irons, but require specialized welding procedures and filler materials. Pearlitic ductile iron produces a larger amount of martensite in the HAZ than ferritic ductile iron and is generally more susceptible to cracking. MMA, using nickel-iron electrodes, is the most common welding technique for welding ductile iron. Most castings do not require preheating, but preheats of up to 315 °C (600 °F) are used on large components. Electrodes should be dried to minimize hydrogen damage and porosity. If machinability or optimum joint properties are desired, castings should be annealed immediately after welding. When welding ductile cast irons, penetration should be low and wide joints or cavities should be built up from the sides towards the center. Stringer beads or narrow weaves should be used. Deposit short beads and allow cooling to preheat temperature. Peening is advisable but not as critical as when welding gray cast iron.

(c) White Cast Iron

Because of its extreme hardness and brittleness, white cast iron is considered as unweldable.

(d) Malleable Cast Iron

During welding, the ductility of the HAZ of malleable cast iron is severely reduced because graphite dissolves and precipitates as iron carbide. Although postweld annealing softens the hardened zone, minimal ductility is regained. Despite these limitations, malleable cast irons can be welded satisfactorily and economically if precautions are taken.

Because most malleable iron castings are small, preheating is seldom required. If desired, small welded parts can be stress relieved at temperatures up to 550 °C (1022 °F). For heavy sections and highly restrained joints, preheating at temperatures up to 200 °C (392 °F) and a postweld malleabilizing heat treatment are recommended. However, this costly practice is not always followed, especially when the design of the component is based on reduced strength properties of the welded joint.

Ferritic malleable grades display the best weldability of the malleable cast irons, even though impact strength is reduced by welding. Pearlitic malleable irons, because of their higher combined carbon content, have lower impact strength and higher crack susceptibility when welded. If a repaired area must be machined, welding should be performed with a nickel-based electrode. MMA welding cast iron, using low carbon steel and low-hydrogen electrodes at low currents, produces satisfactory welds in malleable iron. If low carbon steel electrodes are used, the part should be annealed to reduce the hardness in the weld (due to carbon pickup) and in the HAZ.

4.11.2.5 Welding Procedures of Several Cast Irons

Bronze welding is frequently employed to avoid cracking. As oxides and other impurities are not removed by melting, and mechanical cleaning will tend to smear the graphite across the surface, surfaces must be thoroughly cleaned, for example, by means of a salt bath.

In fusion welding, the oxyacetylene, MMA, MIG, and FCAW processes can be used. In general, low heat input conditions, extensive preheating, and slow cooling are normally a prerequisite to avoid HAZ (heat-affected zone) cracking.

- MMA is widely used in the fabrication and repair of cast iron because the intense, high temperature arc enables higher welding speeds and lower preheat levels. MMA appears greater weld pool penetration and parent metal dilution, but using electrode negative polarity will help to reduce the HAZ.
- MIG (dip transfer as short-circuit transfer mode) and FCAW processes can be used to achieve high deposition rates (more in FCAW) while limiting the amount of weld penetration.

(a) GMAW of cast irons
  – GMAW for cast irons is normally not recommended due to poor quality unless the PQR is perfectly approved by user.

(b) FCAW of cast irons
  – FCAW of cast iron is carried out using higher current than that for SMAW. This is offset by faster travel speeds as for normal FCAW.
  – Gray, ductile and malleable cast irons can be welded using FCAW.

(c) Oxyacetylene welding of cast irons
  – Because of the relatively low temperature heat source of oxyacetylene, oxyacetylene welding will require a higher preheat than MMA. Penetration and dilution is low, but the wide HAZ and slow cooling will produce a soft microstructure. Powder welding in which filler powder is fed from a small hopper mounted on the oxyacetylene torch is a very low heat input process and often used for buttering the surfaces before welding.
  – For successful oxy-fusion welding, it is essential that the part be preheated to a dull, red heat [about 650 °C (1200 °F)].
  – A neutral or slightly reducing flame should be used with welding tips of medium or high flame velocity.
  – As with SMAW preparation, it is necessary to use a furnace to ensure even heating of large castings.
  – To protect draught during welding, preheat should be maintained.
  – Avoid sudden chilling of the casting; otherwise, white cast iron may be produced which is very hard and brittle. This may cause cracking or make subsequent matching impossible.

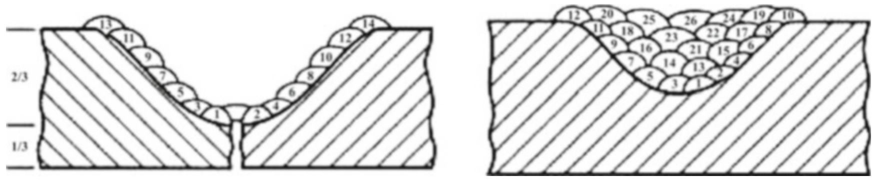
(d) Braze welding of cast irons
  – Should only be used to repair old casting because of the poor color match achieved with newer castings.
  – Suitable for gray, austenitic, and malleable cast irons; however, joint strength equivalent to fusion welds is only possible with gray cast iron.
  – A neutral or slightly oxidizing flame should be used.
  – Advantages over oxy-welding in that the consumable melts at a lower temperature than the cast iron. This allows lower preheat (320–400 °C).
  – As with other forms of welding, the surface must be properly cleaned so that carbon doesn't contaminate the weld deposit.
  – Any brazing processes suitable for steel are applicable to cast irons.
  – Pre- and post-braze operations should be similar to that of standard brazing processes.
  – Consumables suitable for brazing carbon steel can be used for cast irons.

(e) Powder spraying of cast irons
  – Particularly suited to edges, corners, shallow cavities, and thin sections as there are usually no undercut marks.
  – Porous areas must be ground out. Sharp corners, edges, and protruding points must be removed or radiuses as they may go into solution in the molten metal causing hard spots.
  – Spraying and fusing should be as per the normal powder spraying process.
  – Poor quality or difficult irons can be joined by coating both parts separately with 1–2 mm of spray-fused alloy and then joining the coating together with a suitable nickel SMAW electrode.
  – Consumables are based on a Ni-Si-B mixture.
  – Soldering of cast iron is usually limited to the repair of small surface defects, often sealing areas from leakage of liquid or gases. The casting must be thoroughly cleaned.

4.11.2.6 Weld Imperfections

The potential problem of high carbon weld metal deposits is avoided by using a nickel or nickel alloy consumable which produces finely divided graphite, lower porosity, and a readily machinable deposit. However, nickel deposits which are high in S and P from parent metal dilution may result in solidification cracking [see 2.1.6(1)].

The formation of hard and brittle HAZ structures makes cast irons particularly prone to HAZ cracking during postweld cooling. HAZ cracking risk is reduced by preheating and slow postweld cooling. As preheating will slow the cooling rate both in weld deposit and HAZ, martensitic formation is suppressed and the HAZ hardness is somewhat reduced. Preheating can also dissipate shrinkage stresses and reduce distortion, lessening the likelihood of weld cracking and HAZ.



(a) (b)

Figure 4.48 Typical repair welding of cast iron. (**a**) Bridging crack by weld bead from buttered layers. (**b**) Sequence of repair welding deposit

Table 4.69 Typical preheat levels for welding cast irons

Cast iron type	Preheat temperature, °C (°F)			
	MMA	MIG	Gas (fusion)	Gas (powder)
Ferritic flake	300 (572)	300 (572)	600 (1112)	300 (572)
Ferritic nodular	RT-150	RT-150	600 (1112)	200 (392)
Ferritic white heart malleable	RT*	RT*	600 (1112)	200 (392)
Pearlitic flake	300–330 (572–626)	300–330 (572–626)	600 (1112)	350 (662)
Pearlitic nodular	200–330 (392–626)	200–330 (392–626)	600 (1112)	300 (572)
Pearlitic malleable	300–330 (572–626)	300–330 (572–626)	600 (1112)	300 (572)

Source: TWI report, 2014
RT – room temperature, *200 °C (392 °F) if high C core involved

As cracking may also result from unequal expansion, especially likely during preheating of complex castings or when preheating is localized on large components, preheat should always be applied gradually. Also, the casting should always be allowed to cool slowly to avoid thermal shock.

An alternative technique is "quench" welding for large castings which would be difficult to preheat. The weld is made by depositing a series of small stringer weld beads at a low heat input to minimize the HAZ. These weld beads are hammer peened while hot to relieve shrinkage stresses and the weld area is quenched with an air blast or damp cloth to limit stress buildup.

4.11.2.7 Repair Welding of Castings

Repairs due to possibility of casting defects and their inherent brittle nature are frequently required. Normally MMA, oxyacetylene, brazing, and powder welding processes can be used for small repairs, while MMA or powder technique can be used for buttering the edges of the joint followed by MMA or MIG/FCA (flux-cored arc) welding to fill the groove for larger areas. Figure 4.48 shows a typical repair welding for multipass welding process.

The following repair welding sequence may be applicable.

(i) Remove defective area preferably by grinding or tungsten carbide burr.
(ii) If air arc or MMA gouging is used, the component must be preheated locally to minimum 300 °C (572 °F). After gouging, the prepared area should be lightly ground to remove any hardened material.
(iii) Preheat the casting before welding in accordance with Table 4.69.
(iv) Butter the surface of the groove with MMA (manual metal arc) welding using a small diameter (2.4 or 3 mm) electrode; use a nickel alloy rod to produce a soft, ductile "buttered" layer; alternatively use oxyacetylene with a proper consumable.
(v) Remove slags and foreigners in each weld bead while still hot.
(vi) Fill the groove using nickel (3 or 4 mm diameter) or nickel-iron electrodes for greater strength.
(vii) Finally, to avoid cracking through residual stresses, the weld area should cool slowly to room temperature.

4.11.2.8 Welding of Pump Castings

Table 4.70 shows typical requirements of welding for pump casting.

4.11.3 Welding of Cr-Mo Steels (Cr $\leq$ 3%)

As reviewed the characteristics of Cr-Mo steels in Sect. 2.1.4.2, these steels are subject to temper embrittlement, reheat cracking, as well as more susceptible hydrogen embrittlement, so that the weldability is worse than that of CS. So, careful considerations are required for sound welding. See Tables 4.63 and 4.64 for welding material selection of DMW of Cr-Mo steels. See Sect. 4.4.2 for preheat and interpass temperature before welding and Sect. 4.4.3 for post-heat after welding.

Table 4.70 Typical welding requirements for pump casting

Requirement	Applicable code or standard
Welder/operator qualification	ASME Sec. IX or ISO 9606 (all parts)
Welding procedure qualification	Applicable material specification or where weld procedures are not covered by the material specification, ISO 15609 (all parts), ASME Sec. IX or ASME B31.3
Non-pressure-retaining structural welding, such as baseplates or supports	ISO 10721-2
Magnetic particle or liquid penetrant examination of the plate edges	ASME Sec. VIII, Division 1, UG-93(d)(34)
PWHT	Applicable material specification, EN 13445-4, ASME Sec. VIII, Div. 1, UW 40, or ANSI/ASME B31.3
PWHT of casing fabrication welds	Applicable material specification, EN 13445-4, or ASME Sec. VIII, Div. 1

Source: API 610

Table 4.71 Composition requirements per AWS Class for 1.9~2.9Cr-Mo-V weld metal. ASME Sec. II-Part C, SFA-5.5(M) (SMAW electrodes), element: max. wt% unless otherwise specified

AWS Class		UNS No.	Elements								Additional Elements	
A5.5	A5.5M		C	Mn	Si	P	S	Ni	Cr	Mo	Others	Range
E9015-B23 E9016-B23 E9018-B23	E6215-B23 E6216-B23 E6218-B23	K20857	0.04–0.12	1.00	0.60	0.015	0.015	0.50	1.9–2.9	0.30	W V Nb B Al Cu N	1.50–2.00 0.15–0.30 0.02–0.10 0.006 0.04 0.25 0.05
E9015-B24 E9016-B24 E9018-B24	E6215-B24 E6216-B24 E6218-B24	K20885	0.04–0.12	1.00	0.60	0.020	0.015	0.50	1.9–2.9	0.80–1.20	V Nb Ti B Al Cu N	0.15–0.30 0.02–0.10 0.10 0.006 0.04 0.25 0.07

Table 4.72 Composition requirements for 2 1/4Cr-1Mo-1/4V weld metal. (ASME Sec. VIII, Div. 1, Table 31.2 and ASME Sec. VIII, Div. 2, Table 3.2) element: wt%

Welding Process	C	Mn	Si	Cr	Mo	P	S	V	Cb
SAW	0.05–0.15	0.50–1.30	0.05–0.35	2.00–2.60	0.90–1.20	0.015 max	0.015 max	0.20–0.40	0.010–0.040
SMAW	0.05–0.15	0.50–1.30	0.20–0.50	2.00–2.60	0.90–1.20	0.015 max	0.015 max	0.20–0.40	0.010–0.040
GTAW	0.05–0.15	0.30–1.10	0.05–0.35	2.00–2.60	0.90–1.20	0.015 max	0.015 max	0.20–0.40	0.010–0.040
GMAW	0.05–0.15	0.30–1.10	0.20–0.50	2.00–2.60	0.90–1.20	0.015 max	0.015 max	0.20–0.40	0.010–0.040

4.11.3.1 Requirements for Base Metal and Welding Electrodes (Cr $\leq$ 3%)

(a) Conventional Cr-Mo steels: J-factor for base metal and X-bar factor for welding electrodes in Sect. 2.1.4.2(c)2) should be applied.
(b) V-enhanced steels
In addition to comply with J-factor and X-bar factor above, RCS and K-factor for base metal and X-bar factor for welding electrodes in Sect. 2.1.4.2(c)2) should be also applied.
(c) SFA-5.5(M) (SMAW electrodes) for 1.9 to 2.9Cr-Mo-V weld metal (Table 4.71)
(d) For 2.25Cr-1Mo-0.25 V material, the weld metal shall meet the chemical composition requirements listed in ASME Sec. VIII-Div. 1, Table 31-2 and ASME Sec. VIII-Div. 2, Table 3.2 (Table 4.72). For all other materials, the minimum carbon content of the weld metal shall be 0.05%.
(e) For 2.25Cr-1Mo-V submerged arc welding (SAW) wire and flux combinations, testing for reheat cracking shall be performed per API RP934-A, Annex B of this practice. K-factor [see Sect. 2.1.4.2(c)3) in this book] based on ASME PVP paper 2009-78144 is also a good indicator for indicating reheat cracking susceptibility based on Pb/Bi contamination; however, the laboratory test methods with the required accuracy are not widely available. Also, the K-factor does not account for other possible contaminating element(s).
(f) Additional requirements for 2.25 to 3Cr steel pressure vessel (ASME Sec. VIII-Div. 1, Mandatory Appendix Figure 31.1/ ASME Sec. VIII-Div. 2, Figure 3.1) for welding and heat treatment. See Sect. 2.1.4.5 in this book for more details unless specified below.

1. Welding shall be limited to SAW and SMAW processes for 3Cr-1Mo-0.25V-Ti-B materials only. GTAW process may also be used for 3Cr-1Mo-0.25V-Cb-Ca material.
2. Weld metal from each heat or lot of electrodes and filler wire-flux combination shall be tested. The minimum and maximum tensile properties should be met in PWHT Conditions A and B in Fig. 2.21 in this book. The minimum CVN impact properties shall be met in PWHT Condition B in Fig. 2.21 in this book. Testing shall be in general conformance with SFA-5.5 for covered electrodes and SFA-5.23 for filler wire-flux combinations.
3. Duplicate testing in the PWHT Condition A and PWHT Condition B in Fig. 2.21 in this book is required. The minimum tensile strength and CVN impact properties for the base material should be met. CVN impact testing is only required for Condition B in Fig. 2.21 in this book.

4.11.3.2 Requirements for 9Cr-1Mo-V (Gr.91 metal): API TR938-B, EPRI 2015 Report, and Others

The welds of aged Gr.91 material can be readily lost the original properties as below.

- Coarsening of substructure
- Precipitation of intermetallic phases
- Loss of yield and ultimate strengths
- Loss of creep resistance
- Loss of toughness

Type IV cracking is the generic name assigned to this phenomenon. At high stress levels, the 9Cr-1Mo-V steel may suffer Type IV cracking due to presence of such soft zone of reduced creep rupture strength. The cross-weld creep strength at 600 °C (1112 °F) of T91/P91 weldment that contained Type IV fine-grained HAZ showed about 20% loss when compared to the base material (Fig. 4.49).

The Type IV cracking has become a significant problem for steel in creep service. The mechanism of Type IV failure is strongly linked to the relative overaging of precipitates in the intercritical and fine-grained regions of the HAZ. The welding thermal cycle causes a degree of premature aging before service and some softening of this HAZ region. These fine-grained regions of HAZ microstructure promote localized diffusion and expedite precipitate growth during service. The resulting creep weak region accumulates strain in a continuous narrow band known as soft zone of the HAZ, approximately parallel to the fusion boundary, leading to void nucleation, to cracking, and finally to low ductility fracture.

Despite the occurrence of Type IV failures in low alloy steels, Gr. 91 steel and other creep-resistant steels were employed with inadequate attention paid to cross-weld properties. Hence, many instances of Type IV cracking have been detected on operation in high temperature plant.

The extent of the disparity in creep strength between the parent steel and the Type IV region of the HAZ increases as the aging increases, i.e., as the applied stress decreases due to creep rupture.

The introduction of the ASME rules in 2008 addressing the poor creep strength of welded boiler components should help to eliminate the premature occurrence of Type IV damage in new fabrications. However, the recent code changes require the extended use of thicker

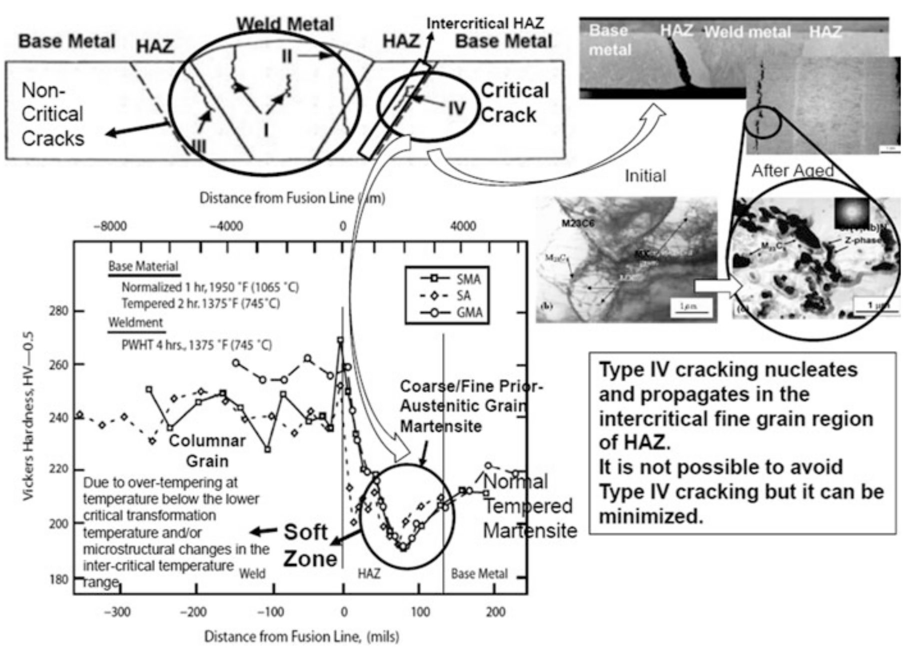


Figure 4.49 Type IV cracking at the soft zone in HAZ of 9Cr-1Mo-V steel welding

components that are more expensive to manufacture, and they may suffer from higher residual, system, and thermally induced stress levels. The increased thickness to mitigate Type IV cracking over component lifetimes and to comply with code requirements negates many of the advantages that these steels were designed to offer. The overall guideline of how to avoid Type IV cracking is still under investigation by the industry and technical committees, e.g., chemical control (base metal and weld metal for A_{C1} control), PWHT (holding temperature and time), heat treatment for base metal, and welding (heat input, process, gas, preheat, postheat, interpass temperature, process, etc.). The hardness of 225–280 HB will give toughness values of 27 J (20 ft-lbs) or better.
For welding electrode, the following requirements are to be selected partially or entirely.

- Hydrogen content: H4 (< 4 ml of hydrogen per 100 grams of weld metal) except H5 for SAW process.
- Mn/S ratio >50 [to avoid crater cracking].
- Ni + Mn $\leq$ 1.0%, except $\leq$1.5% for FCAW.
- Ratio of N/Al $\geq$ 4.0.
- Creq: above formula <10.
- X-bar = (10P + 5Sb + 4Sn + As)/100 $\leq$ 15 (except $\leq$25 for FCAW), where element, ppm.
- GTAW, SMAW, SAW: The filler metal shall be ER90S-B9 per SFA 5.28 for the GTAW process; E9015-B9 or E9016-B9 per SFA 5.5 for the SMAW process, and EB9 per SFA 5.23 for the SAW process.
- FCAW: Nitrogen is not an acceptable purging gas. Butt joints in 9Cr-1Mo-V (Gr.91) material shall have the root pass and hot pass welded with the GTAW process and shall have the interior of the pipe or module beneath the welding zone purged with an inert gas. The inert gas shall be held for the first two layers of weld metal.

For heat input (Q) for welding, the following requirements are to be selected partially or entirely.

- Q for SMAW and GTAW manual procedures: $\leq$1.2 kJ/mm (30 kJ/in.).
- Q for FCAW and SAW: $\leq$2.2 kJ/mm (55 kJ/in.).

For preheat and interpass temperature on welding, the following requirements are to be selected partially or entirely.

- Preheat should be at minimum 200 °C (400 °F) except 149 °C (300 °F) GTAW. Lower preheat temperature of 149 °C (300 °F) is acceptable for root pass and thin wall components where GTAW is utilized. 200–250 °C (400–480 °F) is preferable.
- Localized flame heating with oxyfuel torches is prohibited. Belch-fire torch heating is permitted for pipe NPS 2 and smaller provided it is qualified to a procedure approved by the purchaser.
- Interpass temperature: 250–350 °C (482–662 °F) for GTAW and 200–250 °C (392–482 °F) for SAW.
- For Si $\leq$ 0.50% and C $\leq$ 0.12%, lower interpass temperatures are recommended to avoid hot crack.
- The base metal normally contains Si (0.20–0.50%) and C (0.08–0.12%). The Si and C are close to the maximum values; lower interpass temperatures are recommended to avoid hot crack.

For cooling down from DHT during/after welding, the following requirements are to be selected partially or entirely.

- In order to minimize the retained austenite which will be transformed into untempered martensite and to maximize the regular martensite which will be transformed into tempered martensite after PWHT, the welds shall be cooled down to 93 °C (200 °F) with insulation wrapping, but not lower before performing a PWHT. Metal temperature shall not be allowed to cool to ambient prior to PWHT. Alternately after welding it's permissible to perform a dehydrogenation heat treatment (DHT) or (bake-out) to minimize the probability of hydrogen cracking in weld heat-affected zones. Postweld bake-out (DHT) of the weld joint and at least 75 mm (3 in.) on each side shall be performed by heating to 250–315 °C (482–600 °F) for a minimum 60 minutes for up to 25 mm (1 in.) thickness and 2 hours for all thicknesses over 25 mm (1 in.).
- After cooled down from DHT welds, the HAZ shall be wrapped and sealed in a waterproof covering (plastic) to prevent moisture contact prior to PWHT. This covering shall be maintained until the PWHT process begins.
- If exposed to moisture, the welds should be inspected with MT prior to PWHT.
  For PWHT, see Sect. 4.12.3.8 in this book.
  For hardness requirements on weld HAZ, the recommended maximum allowable hardness is 248 HBW for process applications and 275 HBW for utility services.

Table 4.73 shows SFA-5.5(M), SMAW electrodes for 9Cr-Mo-V weld metal.

4.11.4 Welding of Low Temperature Nickel Steels

Consumables are available for MMA (manual metal arc) and SAW (submerged arc welding) processes but not for TIG (tungsten inert gas), MAG (metal active gas), or FCAW (flux-cored arc welding) processes.

For depositing TIG root passes in the 3.5 Ni alloys, a 2.5% Ni filler metal is normally used. Although the 3.5% Ni consumables are capable of providing adequate toughness at −101 °C (−150 °F), they are very sensitive to variations in welding parameters, heat input, and welding position. This sensitivity results in a wide variability of impact test results so for the more demanding applications, alternative,

Table 4.73 Composition requirements per AWS Class for 9Cr-Mo-V weld metal. ASME Sec. II-Part C, SFA-5.5(M) (SMAW electrodes), element: max. wt % unless otherwise specified

AWS Class		UNS No.	Elements								Additional Elements	
A5.5	A5.5M		C	Mn	Si	P	S	Ni	Cr	Mo	Others	Range
E9015-B91 [1][2]	E6215-B91 [1][2]	W50425	0.08–0.13	1.20	0.30	0.01	0.01	0.80	8.0–10.5	0.85–1.20	V	0.15–0.30
E9016-B91 [1][2]	E6216-B91 [1][2]	W50426									Cu	0.25
E9018-B91 [1][2]	E6218-B91 [1][2]	W50428									Al	0.04
											Nb	0.02–0.10
											N	0.02–0.07
E9015-B92 [1]	E6215-B92 [1]	W59016	0.08–0.15	1.20	0.60	0.020	0.015	1.00	8.0–10.0	0.30–0.70	W	1.50–2.00
E9016-B92 [1]	E6216-B92 [1]										V	0.15–0.30
E9018-B92 [1]	E6218-B92 [1]										Nb	0.02–0.08
											B	0.006
											Al	0.04
											Cu	0.25
											N	0.03–0.08

Notes
[1]Mn + Ni $\leq$ 1.4%
[2]The E90XX-B91 [E62XX-B91] classifications were formerly classified as E90XX-B9 [E62XX-B9] in AWS A5.5(M): 2006

Table 4.74 Low temperature alloys and associated welding consumables[1]

Temperature °C (°F)	Alloy	GTAW/GMAW	SMAW		FCAW[2]
−50 (58)	C-Mn	ER80S-Ni1	E8018-C3		E81T1-Ni1
−60 (−76)	C-Mn (-Ni)	ER80S-Ni2	E8108-C1		–
−75 (−103)	2.25–3%Ni	ER80S-Ni2 or -Ni3	E8018-C2		–
−101 (−150)	3.25%Ni	ERNiCr-3	ENiCrFe-2 or −3		–
−196 (−320)	9%Ni	ERNiCrMo-3 or −4	ENiCrMo-6		–
−196 (−320)	304/304L	ER308L*	E308L*-16	E308L*-15	E308L*T1-4
−196 (−320)	316/316L	ER316L*	E316L*-16	E316L*-15	E316L*T1-4
−269 (−452)	304L/316L	EN E 20 16 3 MnL	EN E 18 15 3 LR	EN E 18 15 3 L B	EN T 18 16 5 NLR

Source: Metrode Manual, 2013
Notes: * Alternative: "LCF" instead of "L" is preferable for lower FN (2–5%)
[1]Based on the similar metal welding. Ferrite contents on welds should be minimized (FN < 5) without solidification cracking
[2]FCAW for cryogenic service should be carefully selected per the approved WPS/PQR

nickel-based filler metals such as AWS ENiCrFe-2 or ENiCrFe-3 are often used enabling all of the conventional arc welding processes to be used.

The 5% Ni and 9% Ni alloys are conventionally welded using a nickel-based filler metal. 6.5% Ni MMA electrodes are available, but these are not capable of consistently providing adequate toughness much below −110 °C (−166 °F). Consumables for welding the 9% Ni alloy have been developed; these typically contain 12% to 14% Ni. However, the cost of production is such that they do not compete with the nickel-based alternatives.

A problem with the nickel-based consumables that were initially used to weld these steels is that their tensile strength is substantially less than that of the parent metal. Higher-strength fillers of the AWS ENiCrMo-3 (Alloy 625) type are now readily available, and these enable all the arc welding processes to be used. They also match parent metals with respect to toughness and ultimate tensile strength although the 0.2% proof strength of TIG, MIG (metal inert gas), and SAW metals may fall below that specified for the 9%Ni steel.

See Tables 4.63 and 4.74 for welding electrode selection and Table 4.29 and 4.36 for preheat of low temperature Ni-alloyed steels.

In addition, the following are generally recommended.

(a) Unless the constructions are heavily restrained, there is no need for preheating or post-heat treatment when welding 5–9% Ni steels. Interpass temperature should be kept below 150 °C (302 °F).
(b) As with any steel where good toughness is required, heat input must be controlled. The peak hardness in HAZ will reach 250–320 Hv10 at normal heat input between 1 and 3 kJ/mm (25–76 kJ/in.). Heat input from welding should be limited to approximately 3.5 kJ/mm (89 kJ/in.) for SAW and 2.5 kJ/mm (64 kJ/in.) for MMA of 9% Ni steel.
(c) SAW is a high productivity welding method and is used for all the circumferential welds.
(d) SMAW is used manually for all the vertical welding of the shell plates together. The requirement on the toughness of the welded joints is extremely high to prevent initiation of a brittle fracture.
(e) The weld metal provides a combination of high strength and excellent ductility. Extensive investigations of weld metal properties have confirmed their high toughness at −196 °C (−320 °F).

(f) For cryogenic temperature applications, only nickel-based and austenitic weld metals are to be used in order to comply with the ductility and strength requirements.
(g) 9% Ni steel is not susceptible to underbead cracking or to excessive hardening in the HAZ.
(h) The portion of austenite in the steel may absorb hydrogen. It can be welded at a thickness of at least 60 mm (2.36 in.) without preheating, and no PWHT is required by the ASME pressure vessel code up to this thickness. The thermal expansion coefficient of nickel-based weld metals closely matches the 9% Ni steel itself.
(i) The magnetic properties of 9% Ni steel mean that arc blow will be encountered when welding.

4.11.5 Welding of Martensitic, Ferritic, and Precipitation Hardening Stainless Steels (MSS, FSS, and PHSS)

See Table 4.82 for chemical compositions and characteristics of various SS filler metal classes.

4.11.5.1 Martensitic Stainless Steels (MSS)

MSS are considered to be the most difficult of the stainless steel alloys to weld. Weldability is comparatively poor and becomes worse with increasing carbon content, as there is always a hard and brittle zone in the parent metal adjacent to the weld. So, MSS are considered to be the most difficult of the stainless steel alloys to weld.

Figure 4.50 shows that higher carbon contents produce greater hardness and, therefore, an increased susceptibility to cracking.

In addition to the problems that result from localized stresses associated with the volume change upon martensitic transformation, the risk of cracking will increase when hydrogen from various sources is present in the weld metal. A complete and appropriate welding process is needed to prevent cracking and produce a sound weld.

During welding, when martensitic steels are heated [to about 927 °C (1,700 °F)], austenite forms. Rapid cooling of the metal transforms the high temperature austenite to martensite, thereby introducing transformation stresses. Moreover, because of low thermal conductivities of these steels, sharp heat gradients (large temperature difference across small areas) are produced during welding. The unequal thermal expansion caused by these gradients plus volumetric changes (internal expansion produced by transformation of austenite into martensite) creates stresses that can cause cracking, especially in some of the brittle microstructures formed by rapid cooling rate.

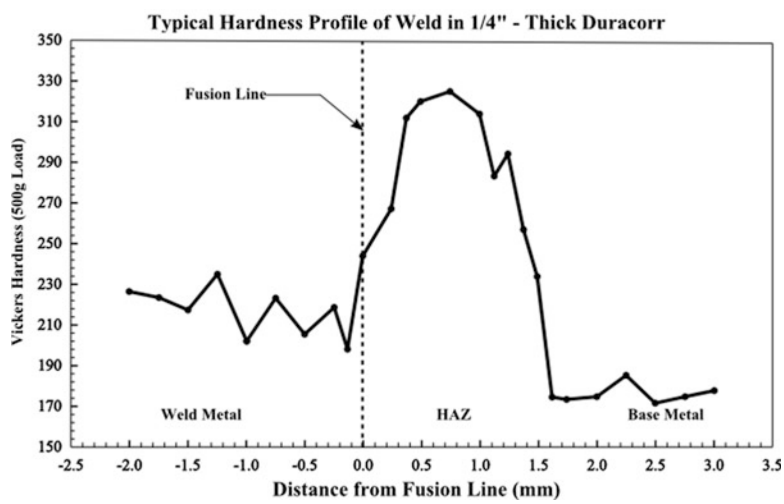


Figure 4.50 Typical hardness on HAZ of 12Cr SS weld. (Source: ASM SS H/B)

To reduce the welding and transformation stresses and to increase the toughness and ductility of the weld deposit, preheating, welding with a well-controlled minimum interpass temperature followed by cooling, tempering, and finally slow cooling is therefore normally required. If these are ignored, there is a significant risk of cold cracking in the hard and brittle HAZ region. Also, preheat and PWHT per thickness and material should be performed in accordance with Sects. 4.4.2 and 4.12, respectively. Martensitic-austenitic and super-martensitic grades require less or no preheating and PWHT.

Matching composition martensitic consumables are used when weld metal properties need to match those of the parent material. However, austenitic consumables are typically preferred as they decrease the risk of cracking. When complicated structures are to be welded, a buttering technique can be used. The groove faces are then covered with austenitic filler metal and heat treated as necessary to restore HAZ toughness. The buttered layer is thick enough to ensure no structural change occurs in the parent metal when completing the joint.

The recommended welding processes are FCAW, GMAW, GTAW, SMAW, and SAW (with fast travel) with minimizing HAZ.

Most end-users do not allow use of the MSS in the pressure-containing parts as a solid material (clad or weld overlay may be used). Table 4.75 shows the recommended filler metals for MSS similar welding. The E(R)309L or Ni alloys for filler metal are recommended unless there are corrosion issues (i.e., chloride SCC).

4.11.5.2 Ferritic Stainless Steels (FSS)

FSS which are non-hardenable by heat treatment have a low carbon content with Cr (and Mo). Weldability of FSS varies depending upon the composition. Modern grades with controlled martensite formation and limited carbide precipitation in the HAZ are reasonably weldable.

Table 4.75 Recommended filler metals for MSS similar welding[1]

Base metal, wrought (cast)	Coated electrode (MMA), SFA 5.4	Core wire (solid and metal)[2] SFA 5.9	FCAW, SFA 5.22
403	E410	ER410	E410TX-X
410 (CA-15)[3]	E410, E410NiMo	ER410, ER410NiMo	E410T, E410NiMoTX-X
414	E410	ER410	E410TX-X
416	E410	ER312, ER410	–
416Se	–	ER312	–
416PlusX	–	ER312	–
420 (CA-90)	E410, E430	ER410	E410TX-X
420F	–	ER312	–
431 (CB-30)	E410, E430	ER410	E410TX-X
440A	No welding recommended	–	–
440B	No welding recommended	–	–
440C	No welding recommended	–	–
(CA-6NM)	E410NiMo	ER410NiMo	E410NiMoTX-X
(CA-15)	E430	ER430	E430TX-X

Notes: "-" not applicable (source: Lincoln Electrodes SS Welding Manual, 2010 modified)
[1]Use of ASS or Ni Alloy fillers instead of MSS fillers may be preferable to avoid weld cracking. See Table 4.65
[2]See Tables 4.77, 4.79, and 4.82 for more details for each filler metal class
[3]17Cr-Nb electrodes for the first layer of 410/410S/405 SS clad restoration welding may be used (see NACE Paper 19-12754)

Table 4.76 Recommended filler metals for FSS similar welding

Base metal, wrought (cast)	Coated electrode (MMA) SFA 5.4	Core wire (solid & metal)[1] SFA 5.9	FCAW SFA 5.22
405[2]	E410NiMo, E430	ER410NiMo, ER430	E410NiMoTX-X
409	–	ER409, AM363, EC409	E409TX-X
410S	–	ER409Cb	–
429	E430	ER430	E430TX-X
430 (CB-30)	E430	ER430	E430TX-X
430F	E430	ER430	E430TX-X
430FSe	–	ER434	–
434	E442, E446	ER442	–
442	E316L	ER316L	–
444	E446	ER446	–
446 (CC-50)	–	ER26-1	–
26-1	No welding recommended	–	–

Notes: "-" not applicable (source: Lincoln Electrodes SS Welding Manual, 2010 modified)
[1]See Tables 4.79 and 4.82 for more details for each filler metal class
[2]17Cr-Nb electrodes for the first layer of 410/410S/405 SS clad restoration welding may be used (see NACE Paper 19-12754)

However, all FSS suffer from grain growth in the HAZ resulting in loss of toughness. Consequently, interpass temperature and heat input must be limited. Preheating is sometimes required to prevent cracking during cooling for thicknesses above 3 mm for grades forming some martensite. Consumables for the welding of FSS can be ferritic with a composition matching the parent metal or austenitic. FSS are resistant to corrosion in sulfur-containing atmospheres. Table 4.76 shows the recommended filler metals for FSS similar welding. The use of austenitic consumables is not recommended for this kind of application. Table 4.77 shows chemical composition requirements for undiluted FSS, MSS, and PHSS welding fillers. The typical chemical compositions are below:

$C \leq 0.08\%$
$10.5\% \leq Cr \leq 30\%$
$Mo \leq 4.5\%$

(a) Low Cr FSS (0.04%C–17%Cr)
 – Sensitive to embrittlement by grain coarsening above 1150 °C (2100 °F).
 – Poor toughness and ductility.
 – Sensitive to IGC.
 – PWHT at about 800 °C (1470 °F) restores the mechanical properties and IGC resistance.
(b) High Cr FSS (0.02%C–17 to 30%Cr)
 – Sensitive to embrittlement by grain coarsening above 1150 °C (2100 °F).
 – Improved toughness and satisfactory ductility compared to low Cr FSS.
 – Generally insensitive to IGC.

Table 4.77 Chemical composition requirements for undiluted FSS, MSS, and PHSS welding filler metals [(A)(B)(C)]

AWS Class.[(D)]	UNS No.[(F)]	Chemical composition (wt%)										
		C	Cr	Ni	Mo	Mn	Si[(E)]	P	S	N	Cu	Others
ER409	S40900	0.08	10.5–13.5	0.6	0.50	0.8	0.8	0.03	0.03		0.75	Ti 10 × C min./1.0 max
ER409Nb	S40940	0.08	10.5–13.5	0.6	0.50	0.8	1.0	0.04	0.03		0.75	Nb[(H)] 10 × C min./1.0 max
ER410	S41080	0.12	11.5–13.5	0.6	0.75	0.6	0.5	0.03	0.03		0.75	
ER410NIMo	S41086	0.06	11.0–12.5	4.0–5.0	0.4–0.7	0.6	0.5	0.03	0.03		0.75	
ER420	S42080	0.25–0.40	12.0–14.0	0.6	0.75	0.6	0.5	0.03	0.03		0.75	
ER430	S43080	0.10	15.5–17.0	0.6	0.75	0.6	0.5	0.03	0.03		0.75	
ER439	S43035	0.04	17.0–19.0	0.6	0.5	0.8	0.8	0.03	0.03		0.75	Ti 10 × C min./1.0 max
ER446LMo	S44687	0.015	25.0–27.5	(G)	0.75–1.50	0.4	0.4	0.02	0.02	0.015	(G)	
ER630	S17480	0.05	16.0–15.75	4.5–5.0	0.75	0.25–0.75	0.75	0.03	0.03		3.25–4.00	Nb[(H)] 0.15–0.30

Notes (source: ASME Sec. II-C)

[(A)]Classifications ER502 and ER505 have been discontinued. Classifications EB6 and ER80S-B6, which are similar to ER502, have been added to AWS A5.23 and A5.28, respectively. EB8 and ER80S-B8, which are similar to ER505, have been added to AWS A5.23 and AWS A5.28, respectively

[(B)]Analysis shall be made for the elements for which specific values are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total, excluding iron, does not exceed 0.50%

[(C)]Single values shown are maximum percentages

[(D)]In the designator for composite, stranded, and strip electrodes, the "R" shall be deleted. A designator "C" shall be used for composite and stranded electrodes, and a designator "Q" shall be used for strip electrodes. For example, ERXXX designates a solid wire and EQXXX designates a strip electrode of the same general analysis and the same UNS number. However, ECXXX designates a composite metal cored or stranded electrode and may not have the same UNS number

[(E)]For special applications, electrodes and rods may be purchased with less than the specified silicon content

[(F)]SAE HS-1086/ASTM DS-56, Metals & Alloys in the Unified Numbering System

[(G)]Nickel + copper equals 0.5% maximum

[(H)]Nb may be reported as Nb + Ta

4.11.5.3 Precipitation Hardening Stainless Steels (PHSS)

PHSS are rarely welded as the heat tends to over-ripen the HAZ precipitates. If PHSS are to be welded, they should be treated as low carbon MSS grades. The martensitic start (M_S) temperature is specific to the grade but is generally around 125 °C (257 °F). To limit the over-ripening of the precipitates in the HAZ, the heat input should be as low as possible. However, because precipitation strengthening can take place, it is then normally appropriate to heat treat the full component. Table 4.77 shows chemical composition requirements for undiluted PHSS welding fillers. Table 4.78 shows the recommended filler metals for PHSS similar welding.

Table 4.78 Recommended filler metals for PHSS similar welding

Base metal, (UNS No.)	Coated electrode (MMA), SFA 5.4	Bare welding wire[(1)] SFA 5.9	Between dissimilar PHSS
Martensitic PHSS			
17-4 (S17400) or 15-5 (S15500)	AMS 5827B, E630 (17-4), E308	AMS 5826 (17-4), ER308	E (ER)309, E (ER)309Cb
Stainless W (S17600)	E308 or ENiMo-3[(1)]	AMS 5805C (A-286), ERNiMo-3[(2)]	E (ER)NiMo-3, E (ER)309
Semi-austenitic PHSS			
17-7 (S17700)	AMS 5827B (17-7), E308, E309	AMS 5824A (17-7)	ENiCrFe-2, ERNiCr-3, E (ER)310
15-7Mo (S15700)	E308 or E309	AMS 5812C (15-7Mo)	E (ER) 309, E (ER) 310
Alloy 350 (S35000)	AMS 5775A (AM350)	AMS 5774B (AM350)	E (ER) 308, E (ER) 309
Alloy 355 (S35500)	AMS 5781A (AM355)	AMS 5780A (AM355)	E (ER) 308, E (ER) 309
Austenitic PHSS			
Alloy A-286 (K99286)	E309, E310	ERNiCeFe-6 or ERNiMo-3	E (ER) 309, E (ER) 310

General Notes:AMS standards in this subscription were developed and issued by SAE's Carbon and Low Alloy Steels committee

See https://www.totalmateria.com/page.aspx?ID=CheckArticle&LN=EN&site=kts&NM=38 for more details of AMS

Notes: "-" not applicable (source: Lincoln Electrodes SS Welding Manual, 2010 modified)

[(1)]See AWS A5.11 Ni and Ni Alloy Welding Electrodes for SMAW

[(2)]See AWS A5.14 Ni and Ni Alloy Bare Welding Electrodes and Rods

4.11.6 Welding of Austenitic Stainless Steels (ASS)

4.11.6.1 Chemical Composition and Purge Gas Requirements and Recommended Current for ASS Welding

Figure 4.51 indicates the simplified dilution and the welding electrode selection. A low carbon steel 1 is welded 316 L SS using P5 welding electrode.

First Step: A straight line is drawn between the two metals (1 and 2). Assuming that the metals melt equally into the weld, the halfway point 3 is marked on this line.

Second Step: Another straight line is then drawn between the point 3 and the electrode 5. After assuming that the composition of weld metal will be approximately 30% parent metal and 70% filler metal, a further point 4 which is the expected final point of the weld metal is marked.

However, Fig. 4.51 should be used only for the preliminary welding selection before the PQR performance.

Table 4.79 shows the chemical composition requirements for ASS welding electrodes.

Table 4.80 shows the recommended filler metals for ASS similar welding.

Table 4.81 recommends the welding current ranges for ASS SMAW process with DCEP.

Meanwhile, the root of ASS should be purged on the backside as well as on the weld side to avoid oxidation. Normally the selection of ASS is for its cleanliness properties and corrosion resistance. The ASS which is not effectively back purged will coke and oxidize and probably have porosity and uneven welds. When welding ASS pipes, a purge insert is often used to help minimize oxygen levels. Typically to minimize oxygen content (<50 ppm preferable) in the enclosure, it should be flushed at least seven times through full volume.

AWS A5.32 and D18.2 describe "specification for welding shielding gases" and "guide to weld discoloration levels on inside of ASS tube," respectively. In general, discolored welds with straw yellow (50–60 ppm oxygen) in Fig. 4.52 may be acceptable. However, more dark colors (oxygen >60 ppm) may not be acceptable. In this case, chemical cleaning (see Sect. 3.4.2) is recommended unless the user approved. See Sect. 2.1.6.11 for general heat tint of ASS.

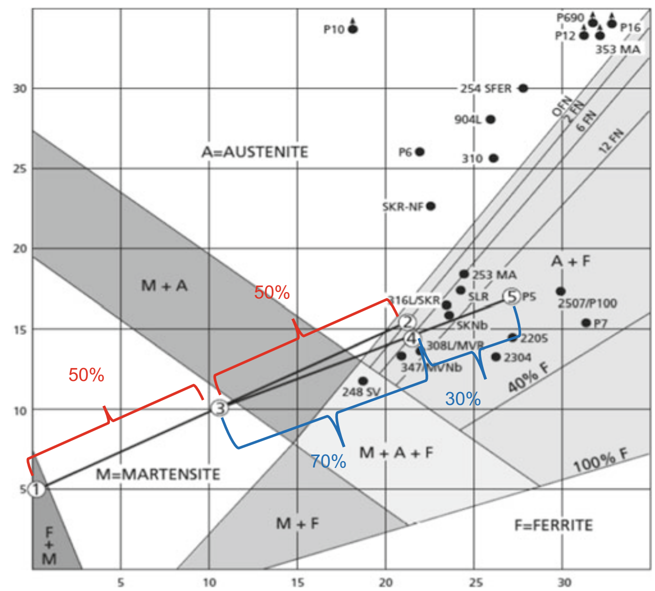


Figure 4.51 Welding electrode selection by Delong diagram to consider the dilution in dissimilar welding of ASS. (Source: Avesta Welding Manual, 2005 - modified)

4.11.6.2 Description and Intended Use of SS Electrodes (Table 4.82)

4.11.6.3 Welding of Stabilized Austenitic Stainless Steels (ASS)

It is important to maintain the level of stabilizing element present in 321 SS and 347 SS during welding. 321 SS is more prone to loss of titanium, while 347 SS is more resistant to loss of columbium. Therefore, 347 SS filler metal is used to weld the 321 SS. Care needs to be exercised to avoid pickup of carbon from oils and other sources and nitrogen from air. Weld practices which include attention to cleanliness and good inert gas shielding are recommended for these stabilized grades as well as other non-stabilized austenitic alloys.

Weld metal with a fully austenitic structure is more susceptible to cracking during the welding operation. For this reason, 321 SS and 347 SS are designed to re-solidify with a small amount of ferrite to minimize cracking susceptibility. Cb (Nb)-stabilized stainless steels are more prone to hot cracking than titanium-stabilized stainless steels.

These stabilized alloys may be joined to other stainless steels or carbon steel. 309 SS (23%Cr-13.5% Ni) or nickel-based filler metals have been used for this purpose.

Meanwhile the ferrite contents on weld to avoid solidification crack should be 5–11%, while those of unstabilized stainless steels should have 3–11% ferrite except 2–5% (sometimes less than 2%) for cryogenic service.

See Sect. 4.12.5 for stabilizing heat treatment.

Table 4.79 Chemical composition requirements for undiluted ASS welding filler metals(A)(B)

AWS Class.(D)	UNS No.(F)	Chemical composition (wt%)										
		C	Cr	Ni	Mo	Mn	Si(E)	P	S	N	Cu	Others
ER209	S20980	0.05	20.5–24.0	9.5–12.0	1.5–3.0	4.0–7.0	0.90	0.03	0.03	0.10–0.30	0.75	0.10–0.30V
ER218	S21880	0.10	16.0–18.0	8.0–9.0	0.75	7.0–9.0	3.5–4.5	0.03	0.03	0.08–0.18	0.75	
ER219	S21980	0.05	19.0–21.5	5.5–7.0	0.75	8.0–10.0	1.00	0.03	0.03	0.10–0.30	0.75	
ER240	S24080	0.05	17.0–19.0	4.0–6.0	0.75	10.5–13.5	1.00	0.03	0.03	0.10–0.30	0.75	
ER307	S30780	0.04–0.14	19.5–22.0	8.0–10.7	0.5–1.5	3.30–4.75	0.30–0.65	0.03	0.03		0.75	
ER308	S30880	0.08	19.5–22.0	9.0–11.0	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER308SI	S30881	0.08	19.5–22.0	9.0–11.0	0.75	1.0–2.5	0.65–1.00	0.03	0.03		0.75	
ER308H	S30880	0.04–0.08	19.5–22.0	9.0–11.0	0.50	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER308L	S30883	0.03	19.5–22.0	9.0–11.0	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER308LSI	S30888	0.03	19.5–22.0	9.0–11.0	0.75	1.0–2.5	0.65–1.00	0.03	0.03		0.75	
ER308Mo	S30882	0.08	18.0–21.0	9.0–12.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER308LMo	S30886	0.04	18.0–21.0	9.0–12.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER308LCF		0.025	18.0–21.0	9.0–11.0	0.50	0.5–2.0	0.90	0.03	0.025		0.50	FN = 2–5
ER309	S30980	0.12	23.0–25.0	12.0–14.0	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER309SI	S30981	0.12	23.0–25.0	12.0–14.0	0.75	1.0–2.5	0.65–1.00	0.03	0.03		0.75	
ER309L	S30983	0.03	23.0–25.0	12.0–14.0	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER309LSI	S30988	0.03	23.0–25.0	12.0–14.0	0.75	1.0–2.5	0.65–1.00	0.03	0.03		0.75	
ER309Mo	S30982	0.12	23.0–25.0	12.0–14.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER309LMo	S30986	0.03	23.0–25.0	12.0–14.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER309Nb	(W30917)	0.12	22.0–25.0	12.0–14.0	0.75	0.5–2.5	1.00	0.04	0.03		0.75	0.70–1.00Nb
ER310	S31080	0.08–0.15	25.0–28.0	20.0–22.5	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER312	S31380	0.15	28.0–32.0	8.0–10.5	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER316	S31680	0.08	18.0–20.0	11.0–14.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER316SI	S31681	0.08	18.0–20.0	11.0–14.0	2.0–3.0	1.0–2.5	0.65–1.00	0.03	0.03		0.75	
ER316H	S31680	0.04–0.08	18.0–20.0	11.0–14.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER316L	S31683	0.03	18.0–20.0	11.0–14.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER316LSI	S31688	0.03	18.0–20.0	11.0–14.0	2.0–3.0	1.0–2.5	0.65–1.00	0.03	0.03		0.75	
ER316LMn	S31682	0.03	19.0–22.0	15.0–18.0	2.5–3.5	5.0–9.0	0.30–0.65	0.03	0.03	0.10–0.20	0.75	
ER316LCF	S31683	0.03	17.0–20.0	11.0–13.0	2.0–3.0	0.5–2.0	0.90	0.03	0.025		0.50	FN = 2–5
ER317	S31780	0.08	18.5–20.5	13.0–15.0	3.0–4.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER317L	S31783	0.03	18.5–20.5	13.0–15.0	3.0–4.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER318	S31980	0.08	18.0–20.0	11.0–14.0	2.0–3.0	1.0–2.5	0.30–0.65	0.03	0.03		0.75	Nb(H) 8 × C min./1.0 max.
ER320	N08021	0.07	19.0–21.0	32.0–36.0	2.0–3.0	2.5	0.60	0.03	0.03		3.0–4.0	Nb(H) 8 × C min./1.0 max
ER320LR	N08022	0.025	19.0–21.0	32.0–36.0	2.0–3.0	1.5–2.0	0.15	0.015	0.02		3.0–4.0	Nb(H) 8 × C min./1.0 max
ER321	S32180	0.08	18.5–20.5	9.0–10.5	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	Ti 9 × C min./1.0 max
ER330	N08331	0.18–0.25	15.0–17.0	34.0–36.0	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	
ER347	S34780	0.08	19.0–21.5	9.0–11.0	0.75	1.0–2.5	0.30–0.65	0.03	0.03		0.75	Nb(H) 1 × C min./1.0 max
ER347SI	S34788	0.08	19.0–21.5	9.0–11.0	0.75	1.0–2.5	0.65–1.00	0.03	0.03		0.75	Nb(H) 8 × C min./1.0 max
ER383	N08028	0.025	26.5–28.5	30.0–33.0	3.2–4.2	1.0–2.5	0.50	0.02	0.03		0.75	
ER385	N08904	0.025	19.5–21.5	24.0–26.0	4.2–5.2	1.0–2.5	0.50	0.02	0.03		0.75	
ER19-10H	S30480	0.04–0.08	18.5–20.0	9.0–11.0	0.25	1.0–2.0	0.30–0.65	0.03	0.03		0.75	Nb(H) 0.05, Ti 0.05
ER16-8-2	S16880	0.10	14.5–16.5	7.5–9.5	1.0–2.0	1.0–2.0	0.30–0.65	0.03	0.03		0.75	
ER33-31	R20033	0.015	31.0–35.0	30.0–33.0	0.5–2.0	2.00	0.50	0.02	0.01	0.35–0.60	0.3–1.2	(G)
ER3556	R30556	0.05–0.15	21.0–23.0	19.0–22.5	2.5–4.0	0.50–2.00	0.20–0.80	0.04	0.015	0.10–0.30		(G) (C)

Notes: (source: ASME Sec. II-C)

(A)Analysis shall be made for the elements for which specific values are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total, excluding iron, does not exceed 0.50%

(B)Single values shown are maximum percentages

(C)Co 16.0–21.0, W 2.0–3.5, Nb 0.30, Ta 0.30–1.25, Al 0.10–0.50, Zr 0.001–0.100, La 0.005–0.100, B 0.02

(D)In the designator for composite, stranded, and strip electrodes, the "R" shall be deleted. A designator "C" shall be used for composite and stranded electrodes, and a designator "Q" shall be used for strip electrodes. For example, ERXXX designates a solid wire and EQXXX designates a strip electrode of the same general analysis and the same UNS number. However, ECXXX designates a composite metal cored or stranded electrode and may not have the same UNS number
(E)For special applications, electrodes and rods may be purchased with less than the specified silicon content
(F)SAE HS-1086/ASTM DS-56, Metals & Alloys in the Unified Numbering System
(G)Austenitic Alloys
(H)Nb may be reported as Nb + Ta

Table 4.80 Recommended filler metals for ASS similar welding

Base metal, wrought (Cast)	Coated electrode (MMA) SFA 5.4 & 5.11	Core wire (solid & metal) (1) SFA 5.9 & 5.14	FCAW SFA 5.22	Remark
201	E209, E219, E308	ER209, ER219, ER308, ER308Si	E308TX-X	
202	E209, E219, E308	ER209, ER219, ER308, ER308Si	E308TX-X	
205	E240	ER240	–	
216	E209	ER209	E316TX-X	
301	E308	ER308, ER308Si	E308TX-X	
302 (CF-20)	E308	ER308, ER308Si	E308TX-X	
304 (CF-8)	E308, E309	ER308, ER308Si, ER309, ER309Si	E308TX-X, E309TX-X	
304H	E308H	ER308H	–	
304L (CF-3)	E308L, E347	ER308L, ER308LSi, ER347	E308TX-X, E347TX-X	
304LN	E308L, E347	ER308L, ER308LSi, ER347	E308TX-X, E347TX-X	
304N	E308, E309	ER308, ER308Si, ER309, ER309Si	E308TX-X, E309TX-X	
304HN	E308H	ER308H	–	
305	E308, E309	ER308, ER308Si, ER309, ER309Si	E308TX-X, E309TX-X	
308	E308, E309	ER308, ER308Si, ER309, ER309Si	E308TX-X, E309TX-X	
308L	E308L, E347	ER308L, ER308LSi, ER347	E308TX-X, E347TX-X	
309 (CH-20)	E309, E310	ER309, ER309Si, ER310	E309TX-X, E310TX-X	
309S (CH-10)	E309L, E309Cb	ER309L, ER309LSi	E309LTX-X, ER309CbLTX-X	
309SCb	E309Cb	–	ER309CbLTX-X	
309CbTa	E309Cb	–	ER309CbLTX-X	
310 (CK-20)	E310	ER310	E310TX-X	
310S	E310Cb, E310	ER310	E310TX-X	
312 (CE-30)	E312	ER312	E312T-3	
314	E310	ER310	E310TX-X	
316 (CF-8M)	E316, E308Mo	ER316, ER308Mo	E316TX-X, E308MoTX-X	
316H (CF-12M)	E316H, E16-8-2	ER316H, ER16-8-2	E316TX-X, E308MoTX-X	
316L (CF-3M)	E316L, E308MoL	ER316L, ER316LSi, ER308MoL	E316LTX-X, E308MoTX-X	
316LN	E316L	ER316L, ER316LSi	E316LTX-X	
316N	E316	ER316	E316LTX-X	
317 (CG-8M)	E317, E317L	ER317L	E317LTX-X	
317L	E317L, E316L	ER317L	E317LTX-X	
321	E308L, E347	ER321(2)	E308LTX-X, E347TX-X	
321H	E347	ER321(2)	E347TX-X	
329	E312	ER312	E312T-3	
330 (HT)	E330	ER330	–	
330HC	E330H	ER330	–	
332	E330	ER330	–	
347 (CF-8C)	E347, E308L	ER347, ER347Si	E347TX-X, E308LTX-X	
347H	E347H	ER347H, ER347Si	E347TX-X(3)	
348	E347	ER347, ER347Si	E347TX-X	
348H	E347	ER347, ER347Si	E347TX-X	
Nitronic 30	E240	ER240	–	
Nitronic 40	E219	ER219	–	
Nitronic 50	E209	ER209	–	
Nitronic 60	–	ER218	–	
254SMo	ENiCrMo-3	ERNiCrMo-3	–	
AL-6XN	ENiCrMo10	ERNiCrMo10	–	

Notes: "-" not applicable (source: Lincoln Electrodes SS Welding Manual, 2010 modified)
(1)See Tables 4.79 and 4.82 for more details for each filler metal class
(2)Not suitable for SAW because a small portion of Ti will be recovered in the weld metal
(3)Use filler metal modified to a minimum of 0.04%C

Table 4.81 Recommended current ranges for ASS SMAW-DCEP(1)

Electrode size	Recommended current (Amp.)		
mm (in.)	E3xx-15(1)(2)(3)	E3xx-16(1)(4)	E3xx-17(1)
2.4 (3/32)	30–70	30–65	40–80
3.2 (1/8)	45–95	55–95	80–115
4.0 (5/32)	75–130	80–135	100–150
4.8 (3/16)	95–165	120–185	130–200
6.4 (1/4)	150–225	200–275	Per manufacturer

Notes: (source: Lincoln Electrodes SS Welding Manual, 2010 modified)
(1)Optimum current for flat position welding is about 10% below maximum
(2)Optimum current for vertical-up welding is about 20% below maximum
(3)Optimum current for vertical-down welding is about maximum
(4)AC range is about 10% higher

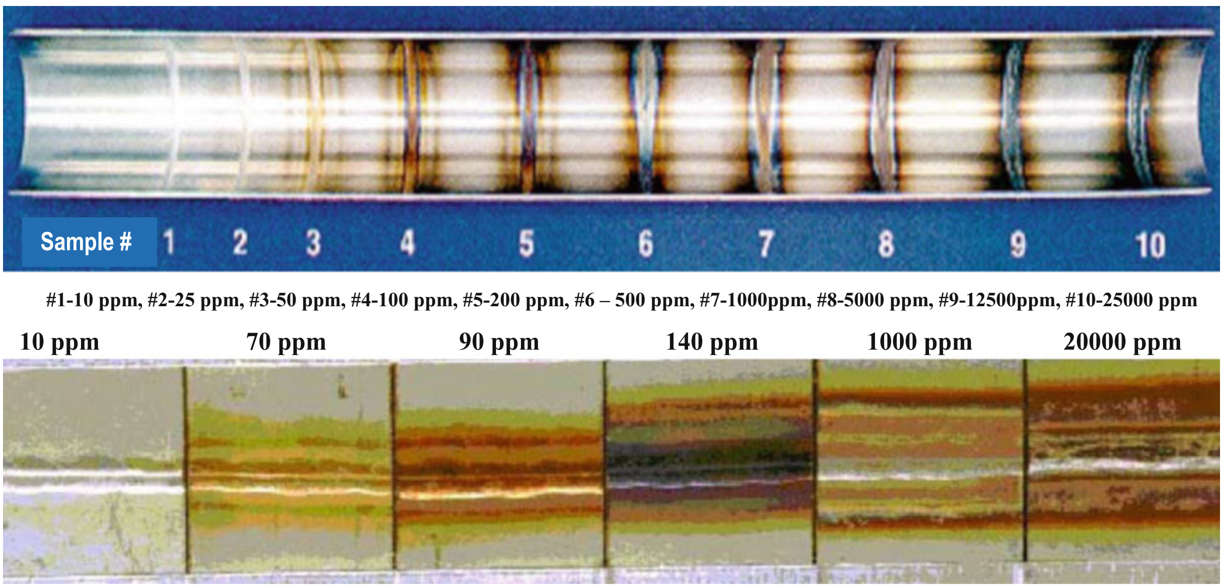


Figure 4.52 Discolored 304L SS welds due to oxygen contamination. (Source: AWS D18.2)

Table 4.82 (1/6) Description and intended use of non-stick consumables (GTAW, GMAW, SAW, PAW) (ASME Sec. II-C, SFA 5.9)

Class	Intended use and characteristics
ER209 (22Cr-11Ni-5.5Mn-2Mo-0.2N)	– Typically to weld UNS S20910 base metal. It is a nitrogen-strengthened, austenitic stainless steel (ASS) exhibiting high strength and good toughness over a wide range of temperature. – Weldments in the as-welded condition made using this filler metal are not subject to carbide precipitation. – Nitrogen alloying reduces the tendency for carbon diffusion and thereby increases resistance to intergranular corrosion. – It has sufficient total alloy content for use in welding dissimilar alloys like mild steel and the stainless steels and also for direct overlay on mild steel for corrosion applications when used with GMAW. – GTAW (gas tungsten arc welding), PAW (plasma arc welding), and EBW (electron beam welding) are not suggested for direct application of this filler metal on mild steel.
ER218 (17Cr-8.5Ni-8Mn-4Si-0.13N)	– Typically to weld UNS S21800 base metals. It is a nitrogen-strengthened ASS exhibiting high strength and good toughness over a wide range of temperature. – Nitrogen alloying in this base composition results in significant improvement in wear resistance in particle-to metal and metal-to-metal (galling) applications when compared to the more conventional austenitic stainless steels such as 304 SS. – It has sufficient total alloy content for use in welding dissimilar alloys like mild steel and the stainless steels and also for direct overlay on mild steel for corrosion and wear applications when used with GMAW. GTAW, PAW, and EBW are not suggested for direct application of this filler metal on mild steel.
ER219 (20Cr-6Ni-9Mn-0.20N)	– Typically to weld UNS S21900 base metals. This alloy is a nitrogen-strengthened austenitic stainless steel exhibiting high strength and good toughness over a wide range of temperatures. – Weldments made using this filler metal are not subject to carbide precipitation in the as-welded condition. Nitrogen alloying reduces the tendency for intergranular carbide precipitation in the weld area by inhibiting carbon diffusion and thereby increases resistance to intergranular corrosion. – It has sufficient total alloy content for use in joining dissimilar alloys like mild steel and the stainless steels and also for direct overlay on mild steel for corrosive applications when used with GMAW. GTAW, PAW, and EBW are not suggested for direct application of this filler metal on mild steel.

Table 4.82 (2/6) Description and intended use of non-stick consumables (GTAW, GMAW, SAW, PAW) (ASME Sec. II-C, SFA 5.9)

Class	Intended use and characteristics
ER240 (18Cr-5Ni-12Mn-0.20N)	– Typically to weld UNS S24000 and UNS S24100 base metals. These alloys are nitrogen-strengthened austenitic stainless steels exhibiting high strength and good toughness over a wide range of temperatures. Significant improvement of wear resistance in particle-to-metal and metal-to-metal (galling) applications is a valuable characteristic when compared to the more conventional ASS such as 304 SS. – Nitrogen alloying reduces the tendency towards intergranular carbide precipitation in the weld area by inhibiting C diffusion, thereby reducing the possibility for intergranular corrosion. Nitrogen alloying also improves resistance to pitting and crevice corrosion in aqueous chloride-containing media. – In addition, weldments in Type 240 exhibit improved resistance to transgranular stress corrosion cracking in hot aqueous chloride-containing media. – It has sufficient total alloy content for use in joining dissimilar alloys like mild steel and the stainless steels and also for direct overlay on mild steel for corrosion and wear applications when used with GMAW. GTAW, PAW, and EBW are not suggested for direct application of this filler metal on mild steel.
ER307 (21Cr-9.5Ni-4Mn-1Mo)	– Primarily for moderate strength welds with good crack resistance between dissimilar steels such as austenitic manganese steel and carbon steel forgings or castings.
ER308 (20Cr-10Ni)	– Commercial specifications for welding of unstabilized stainless steels such as 301, 302, 304, 305, and 308. It is used for general purpose applications where corrosion conditions are moderate. Typical applications include chemical tanks and distillery and restaurant equipment. See Note 4.
ER308Si (20Cr-10Ni-Si)	– The same as ER308 except for the higher Si content. This improves the usability of the filler metal in GMAW. If the dilution by the base metal produces a low ferrite or fully austenitic weld metal, the crack sensitivity of the weld is somewhat higher than that of a lower Si content weld metal.
ER308H (20Cr-10Ni-High C)	– Typically for welding 304H SS base metal. – Carbon content (0.04%–0.08%) provides higher strength at elevated temperatures.
ER308L (20Cr-10Ni-Low C)	– Low carbon ($\leq$0.03%) in this filler metal reduces the possibility of intergranular carbide precipitation. This increases the resistance to intergranular corrosion without the use of stabilizers such as Nb (Cb) or Ti. – Strength of this low carbon alloy, however, is less than that of the Nb (Cb)-stabilized alloys or 308H SS at elevated temperatures. – Ideal for welding 304L SS, 321 SS, and 347 SS. – See Note 4.
ER308LSi (20Cr-10Ni-Low C-Si)	– The same as ER308L except for higher Si content. This improves the usability of the filler metal in GMAW. – The Si content (about 0.85%) improves the fluidity of the melt pool with a minimum of spatter and porosity. This ensures a nice and smooth weld surface. The high Si content does not increase the risk of hot cracking. – If the dilution by the base metal produces a low ferrite or fully austenitic weld, the crack sensitivity of the weld is somewhat higher than that of a lower Si content weld metal.
ER308Mo (19Cr-10.5Ni-2 to 3Mo)	– The same as ER308, except for the addition of Mo. It is used for welding ASTM CF8M stainless steel castings and matches the base metal with regard to Cr, Ni, and Mo contents. It may be used for welding wrought materials such as 316 SS when a ferrite content in excess of that attainable with the ER316 classification is desired.
ER308LMo (19Cr-10.5Ni-2 to 3Mo-Low C))	– Typically for welding ASTM CF3M stainless steel castings and matches the base metal with regard to Cr, Ni, and Mo contents. It may be used for welding wrought materials such as 316L SS when a ferrite in excess of that attainable with ER316L is desired.
ER308LCF (20Cr-10Ni-C<0.025)	– Typically for welding in cryogenic service (−196 °C and warmer). – FN: 3-8. – See Notes 1 & 4.
ER309 (24 Cr-13Ni-C $\leq$ 0.15%)	– Typically for welding similar alloys in wrought or cast form. Occasionally to weld 304 SS and similar base metals where severe corrosion conditions exist requiring higher alloy weld metal. They are also used in dissimilar metal welds, such as joining 304 SS to carbon steel, welding the clad side of 304 SS clad steels (the first pass followed by 308 welding), and applying stainless steel sheet linings to carbon steel shells. – Typical ferrite levels from 3 FN to 20 FN. – See Note 3.
ER309Si (24 Cr-13Ni-C $\leq$ 0.15%-Si)	– The same as ER309 except for higher Si content. This improves the usability of the filler metal in GMAW. If the dilution by the base metal produces a low ferrite or fully austenitic weld metal deposit, the crack sensitivity of the weld is somewhat higher than that of a lower Si content weld metal.
ER309L (24 Cr-13Ni-Low C)	– The same as ER309 except for C content. Low carbon ($\leq$0.03%) in this filler metal increases the resistance to intergranular corrosion without the use of stabilizers such as Nb (Cb) or Ti. – Strength of this low carbon alloy, however, may not be as great at elevated temperatures as that of the Nb (Cb)-stabilized alloys or ER309. – See Note 3.
ER309LSi (24 Cr-13Ni-Low C-Si)	– The same as ER309L except for higher Si content. This improves the usability of the filler metal in GMAW. – The Si content (about 0.85%) improves the fluidity of the melt pool with a minimum of spatter and porosity. This ensures a nice and smooth weld surface. The weld beads are very smooth as compared with 309L or 309. The high Si content does not increase the risk of hot cracking. – If the dilution by the base metal produces a low ferrite or fully austenitic weld, the crack sensitivity of the weld is somewhat higher than that of lower silicon content weld metal.

Table 4.82 (3/6) Description and intended use of non-stick consumables (GTAW, GMAW, SAW, PAW) (ASME Sec. II-C, SFA 5.9)

Class	Intended use and characteristics
ER309Mo (24 Cr-13Ni-2 to 3 Mo)	– The same as ER309 except for the addition of 2.0–3.0% Mo to increase its pitting corrosion resistance in halide-containing environments. The primary application for this filler metal is surfacing of base metals to improve their corrosion resistance. – It is used to achieve a single-layer overlay with a chemical composition similar to that of a 316 SS. It is also used for the first layer of multilayer overlays with filler metals such as ER316 or ER317 SS. Without the first layer of 309Mo SS, elements such as Cr and Mo might be reduced to unacceptable levels in successive layers by dilution from the base metal. – Other applications include the welding of Mo-containing stainless steel linings to carbon steel shells, the joining of carbon steel base metals which had been clad with a Mo-containing stainless steel, and the joining of dissimilar base metals such as carbon steel to 304 SS.
ER309Cb (24Cr-13Ni-Cb)	– See Note 2.
ER309LMo (24 Cr-13Ni-Low C-2 to 3 Mo)	– The same as an ER309Mo except for a lower carbon content (≤0.03%). Low carbon contents in stainless steels reduce the possibility of Cr-carbide precipitation and thereby increase weld metal resistance to intergranular corrosion. – It is used in the same type of applications as the ER309Mo, but where excessive pickup of carbon from dilution by the base metal, where intergranular corrosion from carbide precipitation, or both are factors to be considered in the selection of the filler metal. – In multilayer overlays, the low carbon ER309LMo is usually needed for the first layer in order to achieve low carbon contents in successive layers with filler metals such as ER316L or ER317L.
ER310 (26.5Cr-21Ni)	– Typically to weld base metals of similar composition in wrought and cast form. – The weld deposit is fully austenitic and calls for low heat during welding. It can also be used for dissimilar welding.
ER312 (30Cr-9Ni)	– Typically to weld cast alloys of both dissimilar metals and for weld overlays. It also has been found to be valuable in welding dissimilar metals such as carbon steel to stainless steel, particularly those grades high in nickel. – It gives a two-phase weld deposit with substantial percentages of ferrite (promote higher FN) in an austenite matrix. Even with considerable dilution by austenite-forming elements such as Ni, the microstructure remains two-phase and thus highly resistant to weld metal cracks and fissures.
ER316 (19Cr- 12.5Ni-2.5Mo)	– This filler metal is used for welding 316 SS and similar alloys. It has been used successfully in certain applications involving special base metals for high temperature service. The presence of Mo provides creep resistance at elevated temperatures and pitting resistance in a halide atmosphere. The lower ferrite level of this alloy reduces the rate of corrosion and is suitable for high temperature service applications. – Rapid corrosion of ER316 weld metal may occur when the following three factors co-exist: (a) The presence of a continuous or semi-continuous network of ferrite in the weld metal microstructure (b) A composition balance of the weld metal giving a Cr to Mo ratio of less than 8.2 to 1 (c) Immersion of the weld metal in a corrosive medium – Attempts to classify the media in which accelerated corrosion will take place by attack on the ferrite phase have not been entirely successful. Strong oxidizing and mildly reducing environments have been present where a number of corrosion failures were investigated and documented. – The literature should be consulted for latest recommendations.
ER316Si (19Cr- 12.5Ni-2.5Mo-Si)	– The same as ER316 except for the higher Si content. This improves the usability of the filler metal in GMAW. If the dilution by the base metal produces a low ferrite or fully austenitic weld, the crack sensitivity of the weld is somewhat higher than that of a lower Si content weld metal.
ER316H (19Cr- 12.5Ni- 2.5Mo-High C)	– Typically for welding 316H SS base metal. – The same as ER316 except that the allowable carbon content has been restricted to the higher portion of 316 SS. Carbon content (0.04–0.08 wt%) provides higher strength at elevated temperatures.
ER316L (19Cr- 12.5Ni-2.5Mo-Low C)	– The same as ER316, except for the carbon content. Low carbon (≤0.03%) in this filler metal reduces the possibility of intergranular Cr-carbide precipitation and thereby increases the resistance to intergranular corrosion without the use of stabilizers such as Nb (Cb) or Ti. – This filler metal is primarily used for welding low-C and Mo-bearing austenitic alloys. This low carbon alloy, however, is not as strong at elevated temperature as the Nb (Cb)-stabilized alloys or ER316H.
ER316LSi (19Cr- 12.5Ni-2.5Mo-Low C-Si)	– The same as ER316L, except for the higher silicon content. This improves the usability of the filler metal in GMAW due to high productivity. – The Si content (0.65–1.00%) improves the fluidity of the melt pool with a minimum of spatter and porosity. This ensures a nice and smooth weld surface. The high Si content does not increase the risk of hot cracking. – If the dilution by the base metal produces a low ferrite or fully austenitic weld, the crack sensitivity is somewhat higher than that of a lower Si content weld metal.
ER316LMN (19Cr-15Ni-7Mn-3Mo-0.2N-Low C)	– A fully austenitic alloy with a typical ferrite content of ≤0.5 FN. One of the primary uses of this filler metal is for the joining of similar and dissimilar cryogenic steels (to join 201 SS, 304L SS, 316L SS, as well as 3–9% Ni steels) for applications down to −269 °C (−452 °F) per the base metal. – It also exhibits good corrosion resistance in acids and seawater and is particularly suited for corrosion conditions found in urea synthesis plants. It is also nonmagnetic. – The high Mn-content (austenite former) helps to stabilize the austenitic microstructure and aids in hot (solidification) cracking resistance. – To obtain low impact toughness and high strength (about 100 ksi of TS, and 63 ksi YS).
ER316LCF (18Cr-12Ni-2.2Mo-1Mn-Low C)	– Ferrite controlled. 2-5FN (≤2FN may be acceptable if solidification cracking can be avoided) for cryogenic service (e.g., −196 °C for LNG). – These consumables are used for Mo-bearing ASS with 1.5–3% Mo. – Also, it is widely used for good resistance to pitting, many acids, and general corrosion for 316/316L SS base metals.

Table 4.82 (4/6) Description and intended use of non-stick consumables (GTAW, GMAW, SAW, PAW) (ASME Sec. II-C, SFA 5.9)

Class	Intended use and characteristics
ER317 (19.5Cr-14Ni-3.5Mo)	– It is usually used for welding alloys of similar composition. It is utilized in severely corrosive environments where crevice and pitting corrosion are of concern.
ER317L (19.5Cr- 14Ni-3.5Mo-Low C)	– Low carbon (≤0.03%) in this filler metal reduces the possibility of intergranular carbide precipitation. This increases the resistance to intergranular corrosion without the use of stabilizers such as Nb (Cb) or Ti. This low C alloy, however, may not be as strong at elevated temperature as the Nb (Cb)-stabilized alloys or 317 SS. – This welding wire has extreme corrosion resistance to naphthenic acid, sulfuric and sulfurous acids, and their salts.
ER317LMN (19.5Cr- 14Ni-3.5Mo-0.2N-Low C)	– Nitrogen provides improved corrosion resistance relative to 316L SS and 317L SS, especially in acidic chloride-containing services as well as the corrosion-resistant services in ER317L. – Higher Mo (4.0–5.0%) and lower C (≤0.03%) may provide a good weldability without sensitization to intergranular corrosion.
ER318 (19Cr- 12.5Ni-2.5Mo-1.8Mn)	– The same as ER316 except for the addition of Nb (Cb). Nb (Cb) provides resistance to intergranular Cr-carbide precipitation and thus increased resistance to intergranular corrosion. – The filler metal is used primarily for welding base metals of similar composition.
ER320 (20Cr-34Ni-2.5Mo-3.5Cu-2Mn, Nb=8C-0.40)	– Typically to weld base metals of similar composition for applications where resistance to severe corrosion involving a wide range of chemicals, including sulfuric and sulfurous acids and their salts, is required. – Nb added to provide resistance to intergranular corrosion. It can be used to weld both castings and wrought alloys of similar composition without PWHT. – A modification of this classification without niobium is available for repairing castings which do not contain Nb (Cb), but with this modified composition, solution annealing is required after welding.
ER320LR (20Cr-34Ni-2.5Mo-3.5Cu-2Mn, Nb=8C-0.40, 0.2Si, 0.02C, 0.005S)	– The same basic composition as ER320; however, the elements C, Si, P, and S are specified at lower maximum levels and the Nb and Mn are controlled at narrower ranges. – These changes reduce the weld metal hot cracking and fissuring (while maintaining the corrosion resistance) frequently encountered in fully ASS weld metals. Consequently, welding practices typically used for ASS weld metals containing ferrite can be used in bare filler metal welding processes such as GTAW & GMAW. – ER320LR filler metal has been used successfully in SAW overlay welding, but it may be prone to cracking when used for joining base metal by the SAW. It has a lower minimum tensile strength than ER320.
ER321 (19.5Cr-9.5N)	– Ti acts in the same way as Nb in 347 SS in reducing intergranular Cr-carbide precipitation and thus increasing resistance to intergranular corrosion. The filler metal is used for welding Cr-Ni stainless steel base metals of similar composition, using an inert gas-shielded process. It is not suitable for use with the submerged arc process (SAW) because only a small portion of Ti will be recovered in the weld metal.
ER330 (35.Ni-1Cr)	– Commonly used where heat- and scale-resisting properties above 980 °C (1800 °F) are required, except in high-sulfur environments, as these environments may adversely affect elevated temperature performance. – Repairs of defects in alloy castings and the welding of castings and wrought alloys of similar composition are the most common applications.
ER347 (20Cr-10Ni-Nb added)	– The addition of Nb (Cb) reduces the possibility of intergranular Cr-carbide precipitation and thus susceptibility to intergranular corrosion. – The filler metal is usually used for welding Cr-Ni stainless steel base metals of similar composition stabilized with either Nb (Cb) or Ti. Although Nb (Cb) is the stabilizing element usually specified in 347 SS, it should be recognized that tantalum (Ta) is also present. Ta and Nb are almost equally effective in stabilizing carbon and in providing high temperature strength. – If dilution by the base metal produces a low ferrite or fully austenitic weld metal, the crack sensitivity of the weld may increase substantially.
ER348Si (20Cr-10Ni-0.3Si)	– The same as ER347, except for the higher silicon content. This improves the usability of the filler metal in GMAW. If the dilution by the base metal produces a low ferrite or fully austenitic weld, the crack sensitivity of the weld is somewhat higher than that of a lower silicon content weld metal.
ER383 (27.5Cr-31.5Ni- 3.7Mo-1Cu)	– The filler metal is used to weld UNS N08028 base metal to itself, or to other grades of stainless steel. – ER383 filler metal is recommended for sulfuric and phosphoric acid environments. The elements C, Si, P, and S are specified at low maximum levels to minimize weld metal hot cracking and fissuring (while maintaining the corrosion resistance) frequently encountered in fully ASS weld metals.
ER385 (20.5Cr-25Ni-4.7Mo-1.5Cu)	– Primarily for welding of ASTM B625, B673, B674, and B677 (UNS N08904) materials for the handling of sulfuric acid and many chloride-containing media. – It also may be used to join 317L SS where improved corrosion resistance in specific media is needed. It may be used for joining UNS N08904 base metals to other grades of stainless steel. – The elements C, S, P, and Si are specified at lower maximum levels to minimize weld metal hot cracking and fissuring (while maintaining corrosion resistance) frequently encountered in fully austenitic weld metals.
ER409 (12Cr-Ti=10C-1.5)	– It may be used to join matching or dissimilar base metals. The greatest usage is for applications where thin stock is fabricated into exhaust system components. – The Ti addition forms carbides to improve corrosion resistance, increase strength at high temperature, and promote the ferritic microstructure.
ER409Nb (12Cr-Nb=10C-0.75)	– The same as ER409, except that niobium is used instead of titanium to achieve similar results. Oxidation losses across the arc generally are lower. Applications are the same as those of ER409 filler metals.

Table 4.82 (5/6) Description and intended use of non-stick consumables (GTAW, GMAW, SAW, PAW) (ASME Sec. II-C, SFA 5.9)

Class	Intended use and characteristics
ER410 (12.5Cr- <0.12C)	– An air-hardening steel. Preheat and PWHT are required to achieve welds of adequate ductility for many engineering purposes. The most common application of filler metal of this type is for welding alloys of similar composition. It is also used for deposition of overlays on carbon steels to resist corrosion, erosion, or abrasion. ER309L filler instead of ER410 may be used in high corrosive service. – Welding wire for alloys such as 403 SS, 405 SS, 410 SS, and 416 SS. It is also used for overlays on carbon steels to resist corrosion, erosion, or abrasion. Usually requires preheat of 150°C (300°F) and post-heat treatments of 732–760 °C (1350–1400 °F).
ER410NiMo (12Cr-4.5Ni- 0.55Mo)	– Primarily for welding ASTM CA6NM castings or similar material, as well as light-gauge 410 SS, 410S SS, and 405 SS base metals. It is modified to contain less Cr and more Ni to eliminate ferrite in the microstructure as it has a deleterious effect on mechanical properties. – Final PWHT should not exceed 620 °C (1150 °F), as higher temperatures may result in rehardening due to untempered martensite in the microstructure after cooling to room temperature.
ER420 (13Cr-0.3C)	– Typically for many surfacing operations requiring corrosion resistance provided by 12% Cr along with somewhat higher hardness than weld metal deposited by ER410. This increases wear resistance.
ER430 (16Cr)	– The composition is balanced by providing sufficient Cr to give adequate corrosion resistance for the usual applications and yet retain sufficient ductility in the heat-treated condition. (Excessive Cr will result in lower ductility.) – Welding with filler metal of the ER430 classification usually requires preheating and PWHT. – Optimum mechanical properties and corrosion resistance are obtained only when the weldment is heat treated following the welding operation.
ER439 (18Cr-Ti=10C-1.10)	– ER439 provides improved oxidation and corrosion resistance over ER409 in similar applications. – Applications: similar to ER409 filler metals where thin stock is fabricated into exhaust system components.
ER446LMo (26Cr-1.1Mo, <0.015N, <0.015C)	– Formerly listed as ER26-1. It is used for welding base metal of the same composition with inert gas-shielded welding processes. Due to the high purity of both base metal and filler metal, cleaning of the parts before welding is most important. Complete coverage by shielding gas during welding is extremely important to prevent contamination by oxygen and nitrogen. – Nonconventional gas shielding methods (leading, trailing, and back shielding) often are employed.
ER630 (16.4Cr-4.7Ni-3.6Cu)	– Primarily for welding ASTM A 564 Type 630 and some other PHSS. – The composition is modified to prevent the formation of ferrite networks in the martensitic microstructure which have a deleterious effect on mechanical properties. Dependent on the application and weld size, the weld metal may be used as-welded; precipitation hardened; or welded, solution treated, and precipitation hardened.
ER19-10H (19Cr-10Ni, 1.5Mn, <0.75Cu, <0.25Mo, <0.05(Nb+Ta))	– Similar to ER308H except that the Cr content is lower and there are additional limits on Mo, Nb, and Ti. This lower limit of Cr and additional limits on other Cr eq. elements allows a lower ferrite range to be attained. A lower ferrite level in the weld metal decreases the chance of sigma embrittlement after long-term exposure at temperatures in excess of 540 °C (1000 °F). – It should be used in conjunction with welding processes and other welding consumables which do not deplete or otherwise significantly change the amount of Cr in the weld metal. – If used with SAW, a flux that neither removes nor adds Cr to the weld metal is highly recommended. – This filler metal also has the higher C level required for improved creep properties in high temperature service. – The user is cautioned that actual weld application qualification testing is recommended in order to be sure that an acceptable weld metal carbon level is obtained. If corrosion or scaling is a concern, special testing should be included in application testing.
ER16-8-2 (15.5Cr-8.5Ni-1.5Mo)	– The welds can be used for wide temperature range, such as from −196 °C (−320 °F) to around 800 °C (1472 °F). – The filler metal is used primarily for SS welding such as types 16-8-2, 316, and 347 for high pressure, high temperature piping systems. The weld deposit usually has ≤ 5FN. Even though it has low ferrite contents, the risk of solidification crack is very low due to strong fissure resistance property and Cr eq/Ni eq > 1.5. The low ferrite can greatly reduce the formation of intermetallic compounds (i.e., sigma & chi) during high temperature operation. The deposit also has good hot ductility and fatigue resistance properties which offer greater freedom from weld or crater cracking even under restraint conditions. The weld metal is usable in either the as-welded condition or solution-treated condition. This filler metal depends on a very carefully balanced chemical composition to develop its fullest properties. Especially careful chemical composition control is required to escape the presence of as-deposited martensite. – Corrosion tests indicate that the 16-8-2 weld metal may have less corrosion resistance than 316 SS base metal, depending on the corrosive media. Where the weldment is exposed to severe corrodants, the surface layers should be deposited with a more corrosion-resistant filler metal. – Careful application of bending or forming is required to escape the presence of strain-induced martensite.
ER2209 (22.5Cr-8.5Ni-3Mo-0.15N)	– The filler metal is used primarily to weld DSS which contain approximately 22% Cr such as UNS S31803 and S32205. Deposits of this alloy have "duplex" microstructures consisting of an austenite-ferrite matrix. These stainless steels are characterized by high tensile strength, resistance to stress corrosion cracking, and improved resistance to pitting.

Table 4.82 (6/6) Description and intended use of non-stick consumables (GTAW, GMAW, SAW, PAW) (ASME Sec. II-C, SFA 5.9)

Class	Intended use and characteristics
ER2553 (25.5Cr-5.5Ni-3.4Mo-2Cu-0.2N)	– Primarily to weld DSS UNS S32550 which contain approximately 25% Cr. – Deposits of this alloy have a "duplex" microstructure consisting of an austenite-ferrite matrix. These stainless steels are characterized by high tensile strength, resistance to SCC, and improved resistance to pitting.
ER2594 (25.5Cr-9.2Ni-3.5Mo-0.25N)	– The Pitting Resistance Equivalent Number [PREN = Cr + 3.3(Mo + 0.5 W) + 16 N] is at least 40, thereby allowing the weld metal to be called a "super-duplex stainless steel." This number is a semi-quantitative indicator of resistance to pitting in aqueous chloride-containing environments. It is designed for the welding of super-duplex stainless steels UNS S32750 and 32760 (wrought) and UNS J93380, J93404 (cast). It can also be used for the welding of UNS S32550, J93370, J93372 when not subject to sulfurous or sulfuric acids in service. – It can also be used for the welding of carbon and low alloy steels to DSS as well as to weld "standard" DSS such as UNS S32205 and J92205 especially for root runs in pipe.
ER33-31 (33Cr-31Ni-1.6Mo)	– Typically for welding Ni-Cr-Fe alloy (UNS R20033) to itself and to CS and for weld overlay on boiler tubes. – The weld metal is resistant to high temperature corrosive environments of coal-fired power plant boilers.
ER3556 (31Fe, 20Ni, 22Cr, 18Co, 3Mo,2.5W (UNS R30556))	– The filler metal is used for welding 31 Fe, 20 Ni, 22 Cr, 18 Co, 3 Mo, 2.5 W(UNS R30556) base metal to itself, for joining steel to other Ni alloys, and for surfacing steel by GTAW, GMAW, and PAW. The filler metal is resistant to high temperature corrosive environments containing S. Typical specifications for 31 Fe, 20 Ni, 22 Cr, 18 Co, 3 Mo, 2.5 W base metal are ASTM B435, B572, B619, B622, and B626, UNS R30556.

Notes (Commentary):
1. It is not susceptible to solidification crack due to high ratio of Creq/Nieq (14.8–17.2). It shows that the lateral expansion at FN 5 or lower is more than 0.4 mm at −196 °C (−320 °F) CVN impact test
2. 309Cb(Nb) SS in dissimilar welding (P.No. 1 through 5 to P.No. 8) should not be used when PWHT is required except for weld overlay (see API RP582)
3. Embrittlement or cracking can occur if these dissimilar steel welds are subjected to a PWHT or to service above 370 °C (700 °F)
4. Figure 4.53 shows the lateral expansion per FN

4.11.6.4 Solidification Crack and Delta Ferrite Effect: See Sect. 2.1.6.1

4.11.6.5 Sensitization and IGC: See Sect. 2.1.6.3

4.11.6.6 Weld Decay

One of the best known types of IGA is the result of "sensitization," and when this is the result of a welding process, one often uses the term "weld decay" for the IGC phenomenon (Fig. 4.54). Typically, the Cr-carbide (Cr-enriched M23C6) is the same mechanism as sensitization in Sect. 2.1.6.3.

4.11.6.7 Knife-Line Attack (KLA)

(a) Mechanism

Weld decay in ASS is caused by precipitation of Cr-carbide at grain boundaries, which is called sensitization during welding. Typically, the Cr-carbide (Cr-enriched M23C6) is the same mechanism as sensitization in Sect. 2.1.6.3.

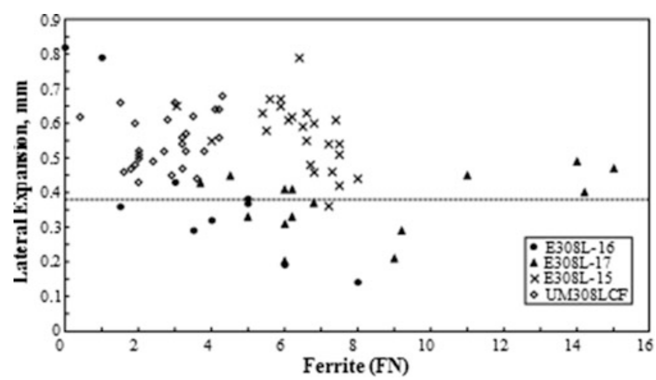


Figure 4.53 Lateral expansion per FN. (Source: ASM SS Handbook)

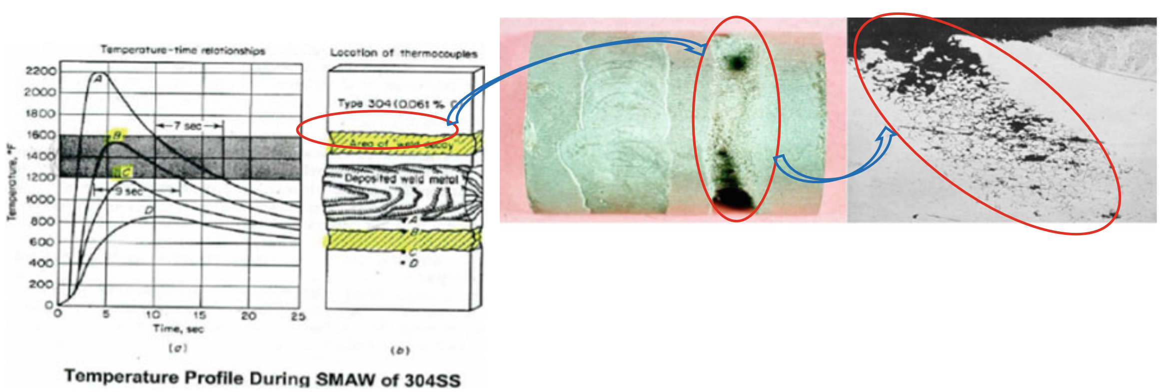


Figure 4.54 Weld decay at HAZ of 304 SS welds

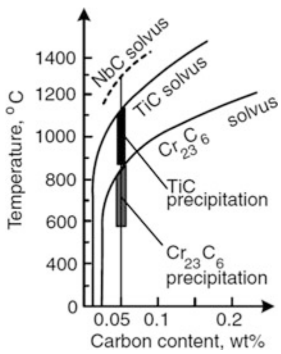


Figure 4.55 Solvus curves for $Cr_{23}C_6$ and TiC in 304 SS. (Source: *Sindo Kou, Welding Metallurgy, John Wiley & Sons, 2003)*

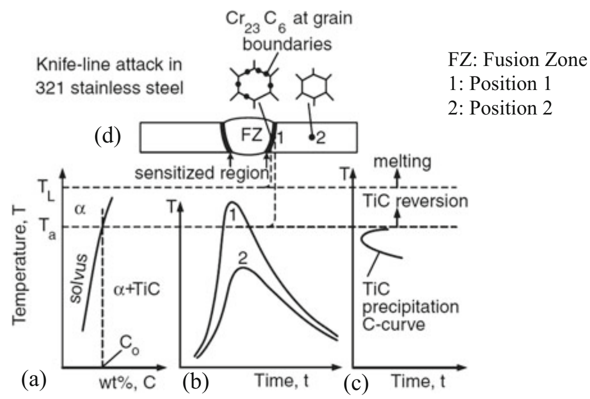


Figure 4.56 Sensitization in stabilized ASS phase diagrams and TTT Curves. (**a**) Phase diagram (**b**) Thermal cycle (**c**) Precipitation (**d**) Microstructure. (Source: *Sindo Kou, Welding Metallurgy, John Wiley & Sons, 2003)*

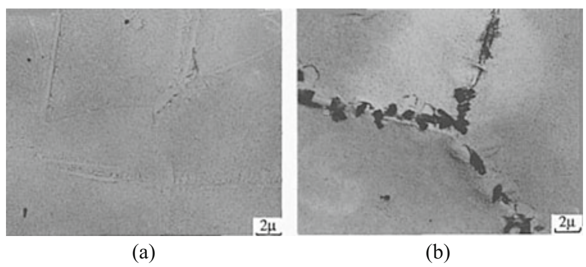


Figure 4.57 TEM near fusion boundary of 347 SS. (**a**) As-Welded. (**b**) 650 °C × 50 hours. (Source: Ikawa et al., *Technol. Repts. Osaka Univ.*, 28 in 1978)

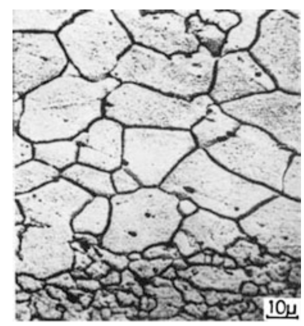


Figure 4.58 Intergranular corrosion near fusion boundary of 347 SS. (Source: Ikawa H. et al., *Technol. Repts. Osaka Univ.*, 28 in 1978)

Although stabilized austenitic stainless steels such as 321 SS and 347 SS are not susceptible to weld decay, they can be susceptible to a different type of intergranular corrosion attack, called KLA. Like weld decay, KLA is also caused by precipitation of $Cr_{23}C_6$ at grain boundaries. KLA differs from weld decay in two ways: (i) KLA occurs in a narrow region immediately adjacent to the weld metal and (ii) KLA occurs in stabilized-grade SS. Figure 4.55 shows the solvus curves of Cr23C6 and Ti-carbide, TiC (and Nb-carbide, NbC), in 304 SS (18Cr-8Ni). The marked areas indicate the precipitation temperature ranges of the carbides, about 600–850 °C (1112–1562 °F) for $Cr_{23}C_6$, up to about 1100°C (2012 °F) for TiC, and up to about 1300 °C (2372 °F) for NbC. $Cr_{23}C_6$ dissolves at the temperatures above its solvus curve.

Upon cooling slowly from above the solvus temperature, $Cr_{23}C_6$ can precipitate again. However, if the cooling rate is high, $Cr_{23}C_6$ may not have enough time to precipitate, and the material can be supersaturated with free carbon.

KLA in stabilized ASS can be explained with the help of thermal cycles during welding, as shown in Fig. 4.56. Position 1 is very close to the fusion boundary and is thus subjected to a high peak temperature and a high cooling rate during welding. Since this peak temperature is above the solvus temperature of TiC, the TiC dissolves in this area. Due to the rapid cooling rate through its precipitation temperature range, TiC does not reprecipitate during cooling, thus leaving abundant free carbon atoms in this area. When the weld is reheated in the $Cr_{23}C_6$ precipitation range (for stress relief or in multiple-pass welding), TiC does not form appreciably since the temperature level is not high enough. Consequently, $Cr_{23}C_6$ precipitates at grain boundaries, and this area becomes susceptible to intergranular corrosion attack. Position 2, however, is not susceptible because of its low peak temperature. Because of the high temperate gradient near the fusion boundary (this is especially true for ASS due to the low thermal conductivity) and the high TiC dissolution temperature, the region in which TiC dissolves during welding is very narrow. As a result, subsequent intergranular corrosion attack occurs in a very narrow strip immediately adjacent to the fusion boundary, and thus the name KLA.

Figure 4.57 shows the transmission electron micrographs (TEM) in the area immediately outside the fusion boundary of a 347 SS. Precipitation of Cr-carbides is clearly visible at grain boundaries after postweld sensitizing heat treating at 650 °C (1202 °F) for 50 hours. Figure 4.58 shows the intergranular corrosion attack in the same area by a corrosive liquid for 15 hours.

(b) Remedies: The knife-line attack of stabilized ASS can be avoided as follows.

1. Postweld heat treatment annealing in the temperature range of 1000–1100 °C (1832–2012 °F) after welding helps Cr-carbide dissolve. Since Ti-carbide and Nb-carbide form in this temperature range (Fig. 4.55), subsequent quenching to avoid Cr-carbide precipitation is not necessary.

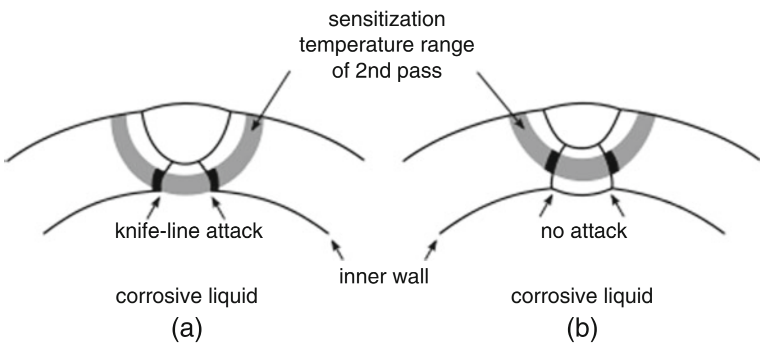


Figure 4.59 Dual-pass weld of stabilized ASS: (**a**) KLA; (**b**) no attack. Modified from Principle and Technology of the Fusion Welding of Metals (source: *Principle and Technology of the Fusion Welding of Metals*, Vol. 2, Mechanical Engineering Publishing Co., Peking, 1979)

2. Using low carbon grades. In the case of weld decay, low-carbon grades reduce the chance of Cr-carbide precipitation.
3. Adjusting welding procedure sometimes. It is possible to avoid knife-line attack by modifying the welding procedure. Figure 4.59 shows one such example involving the dual-pass seam weld of a stainless steel pipe of the stabilized grade, the first pass on the inside of the pipe and the second pass on the outside. During the deposition of the first pass, Ti- or Nb-carbide near its fusion boundary dissolve. As shown in Fig. 4.59, the sensitization temperature range, 600–850 °C (1112–1562 °F), of the second pass overlaps the fusion boundary of the first pass at the pipe inner wall and causes Cr-carbide to precipitate, thus making the inner wall susceptible to attack by the corrosive liquid inside the pipe. To correct the problem, the size of the first pass should be increased and that of the second pass decreased so that the sensitization temperature range of the second pass overlaps the fusion boundary of the first pass away from the pipe inner wall, as shown in Fig. 4.59. The problem can also be corrected by making the first pass from the outside of the pipe and the second pass from the side if this is possible to do.
4. Adding rare earth metals (REMs). It has been shown that adding rare earth metals such as La and Ce can reduce the knife-line attack of stabilized stainless steels. High-resolution electron micrographs reveal that carbide precipitation in the grain interior is accelerated in these materials, thus leaving less free carbon atoms for carbide precipitation at grain boundaries.
5. Figure 4.60 shows the reduction in the rate of intergranular corrosion in a 347 SS by addition of a small amount of REMs. Similar results have been observed in REM-treated 321 SS. Addition of small amounts of REMs in stabilized stainless steels does not appear to have an adverse effect on their mechanical properties.

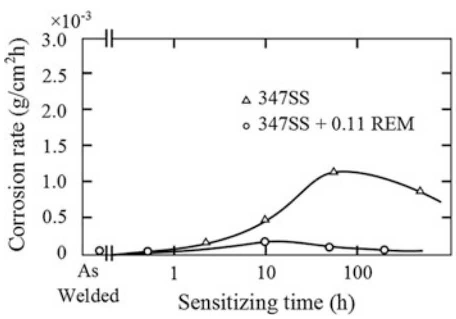


Figure 4.60 Effect of addition of REMs on KLA sensitivity of 347 SS. (Source: Ikawa, H. et al., *Trans. Japan Weld. Soc.* **8**: 9, 1977)

(c) Susceptibility Tests*:* The susceptibility of austenitic stainless steels to weld decay or KLA can be evaluated by the Huey test (ASTM A-262, Practice C). A less time-consuming method is the Streicher test (ASTM A-262, Practice B). See Table 2.63 for IGC test methods of ASTM A262.

4.11.7 Welding of Duplex Stainless Steels (DSS)

4.11.7.1 Weldability of DSS

DSS have roughly equal proportions of austenite (γ) and ferrite (α), with ferrite being the matrix (α → α + γ on solidification). The DSS alloying additions are either austenite or ferrite formers. It occurs by extending the temperature range over which the phase is stable. Cr and Mo are ferrite formers, whereas Ni, C, N, and Cu are austenite formers. N (nitrogen) causes γ to begin formation from α at a higher temperature, so that allows the desired phase balance to develop quickly at temperatures high enough to enable the diffusion of all elements closer to their preferred equilibrium positions during initial solidification. In addition, N additions provide improving pitting corrosion resistance.

The weldability and welding characteristics of DSS are not as good as ASS. A suitable welding process is needed to obtain sound welds. Control of heat input is important to maintain the desirable phase balance as well as to avoid the harmful intermetallic phases (sigma-σ, chi-χ, Cr_2N, etc.; see Sect. 2.1.6.5) at high temperatures, 700–955 °C (1300–1750 °F), during welding. The intermetallic phases formation in lean DSS welding is much more tolerant (>10 hours) than that (<10 hours) of other duplex grades. Solidification cracking (see Sect. 2.1.6.1) and hydrogen cracking on DSS welding may not be significant as much as ASS welding.

Rapid cooling (low heat input) in DSS welding at heavy wall section including H/EX tube-to-tubesheet joints increases ferrite contents which are subject to high risk of 475 °C (885 °F) embrittlement. Higher nitrogen can greatly reduce this problem. The 475 °C (885 °F) embrittlement is the most critical issue in the welding and/or in the high temperature. So most codes allow to use DSS up to 316 °C (600 °F) of design temperature.

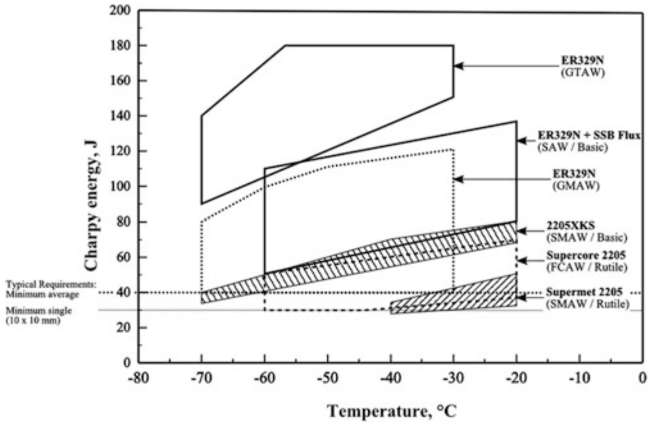


Figure 4.61 CVN impact toughness of ASS and DSS. (Source: Metrode DSS Technical Profile, 2009)

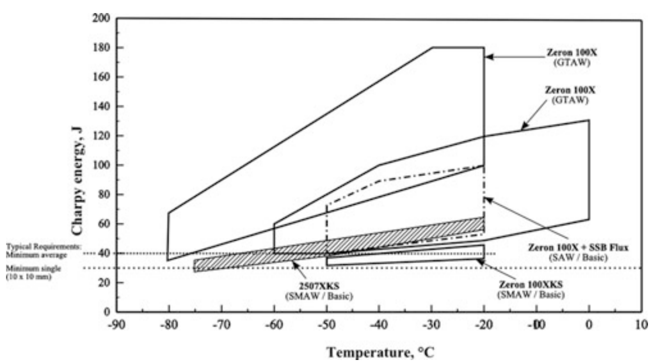


Figure 4.62 CVN impact toughness of SDSS. (Source: Metrode DSS Technical Profile, 2009)

Current commercial grades of DSS contain between 22 and 26% Cr, 4 to 7% Ni, up to 4.5% Mo, as well as some Cu, W, and N. Modifications to the alloy compositions have been made to improve corrosion resistance, workability, and weldability.

The properties of DSS can be appreciably affected by welding. Due to the importance of maintaining a balanced microstructure and avoiding the formation of undesirable metallurgical phases, the welding procedures must be properly specified and controlled. If the welding procedure is improper and disrupts the appropriate microstructure, loss of material properties can occur.

Because these steels derive properties from both austenitic and ferritic portions of the structure, many of the single-phase base material characteristics are also evident in DSS. A DSS microstructure with high ferrite content can therefore have poor low temperature notch toughness, whereas a structure with high austenite content can possess low strength and reduced resistance to chloride SCC.

The high alloy content of DSS also makes them susceptible to the formation of intermetallic phases from extended exposure to high temperatures. Significant intermetallic phases precipitation may lead to a loss of corrosion resistance and sometimes to a loss of toughness. This intermetallic phases precipitation may also form during PWHT for dissimilar weld joints (e.g., PWHT required CS + DSS), so that this combination should be avoided or buttering welding (see Sect. 4.5.3) may be used if PWHT needs.

CVN impact toughness versus temperature curves describe a shallow sloping relationship, free from the pronounced ductile-brittle transition characteristics of CS weld metals.

Consequently, CVN impact test values show low scatter and, overall, reflect a more consistent pattern of weld toughness than achieved from carbon steel weld metal.

Figures 4.61 and 4.62 show the effective toughness ranges of several DSS materials and SDSS materials, respectively.

Weld metal oxygen content, in the form of oxide/silicate micro-inclusions, strongly influences toughness. As oxygen increases, toughness is reduced. Gas-shielded TIG, PAW, and MIG processes promote lower weld metal oxygen levels than flux-shielded MMA, FCAW, and SAW processes.

CVN impact test absorbed energy (joules), for standard 10 mm × 10 mm (0.4 in. × 0.4 in.) test specimens, and lateral expansion values show a close relationship up to the 100 J level:

$$\text{Lateral Expansion (mm/in.)} \approx \text{CVN Impact Test Absorbing Energy (J)}/100$$

Figure 4.63 indicates the pitting resistance per shielding gas of several SDSS materials. The combination of shield gas and filler material shows a key factor for the pitting resistance.

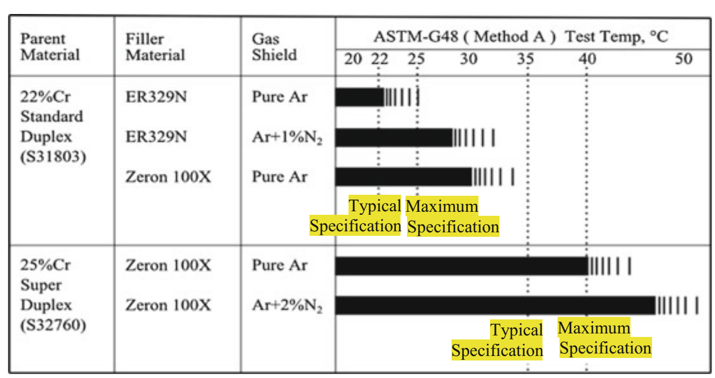


Figure 4.63 Pitting resistance per shielding gas of DSS/SDSS. (Source: Metrode DSS Technical Profile, 2009)

4.11.7.2 Heat Input (Q) and Preheat: Recommendation

Typically heat input (Q) promotes the following trends.

- Cooling Rate ↓ (slow enough) ≈ optimized Q (at lower level in the applicable range); γ ↑ from matrix α

  → 30–55% α may be achieved [Best Practice]

- Cooling Rate ↓↓ (too slow) ≈ Q ↑↑; γ ↑↑ from matrix $\alpha \rightarrow \alpha <$ 30–55% and intermetallic phases form

  → Embrittlement↑, Toughness ↓, and Corrosion (SCC) Resistance ↓

- Cooling Rate ↑↑ (too fast) ≈ Q ↓↓; γ ↓ from matrix α ($\alpha \gg$ 30–50%)

  → Toughness ↓ and Corrosion Resistance ↓

The most critical factor on welding of DSS is to minimize the heat input because high heat input greatly promotes the formation of intermetallic phases. Also the shield gas processing (e.g., GTAW with Ar) can lose some nitrogen (N) in the weldment; as a result, the corrosion resistance may be more reduced. For example, if we apply the heat input 2.5 kJ/mm (62.5 kJ/in.) on GTAW with Ar, the weld metal can lose most N in the metal. So, the classification per welding process is very important to minimize the heat input practically as below (but minimum heat input should be 0.5 kJ/mm (13 kJ/in.) except tube-to-tubesheet weld joints or heavy wall welds). The following are typical heat input as maximum values for DSS (22Cr).

Max. 1.6–2.4 kJ/mm (40–60 kJ/in.) for first pass (cold pass) and 0.8–1.2 kJ/mm (20–30 kJ/in.) for second pass (cold pass) for GTAW
Max. 1.8 kJ/mm (45 kJ/in.) for FCAW
Max. 2.0 kJ/mm (50 kJ/in.) for SMAW and GMAW
Max. 2.4 kJ/mm (60 kJ/in.) for SAW
Max. 1.2 kJ/mm (30 kJ/in.) for highly restrained SAW

The maximum heat input of SDSS (25–27Cr) should be 0.25 kJ/mm less than the maximum values for DSS per welding process.

Typically preheat is not required. However 66–93 °C (150–200 °F) for ≤16 mm (5/8 in.) thickness and 93–150 °C (200–300 °F) for >16 mm (5/8 in.) thickness may be applied if the joints have high restraint.

4.11.7.3 Other Requirements for DSS Welding: Recommendation

- Ferrite contents in weldment: 35–65%
- Shielding gas: Nitrogen- and hydrogen-containing mixture gases should not be used for purging or back shielding. Oxygen shall be less than 500 ppm. The shielding gas for GTAW should be 99.99% argon or mixture of argon with maximum 2% nitrogen. When back-gouging and welding on the reverse side are not possible, the root pass should be made with GTAW root pass and back purged with 100% argon. Argon-helium-CO_2 mixture as recommended by consumable manufacturer may be used for GMAW pulsed-arc-transfer mode.
- Purge gas should be maintained until at least 6 mm (¼ in.) depth of weld metal has been deposited except through completion of the socket welding or attachment weld when the base metal is thin (1/4 in. and less).
- Backing gas shall be used and flow shall be maintained until the weld is completed.
- Semiautomatic SAW or FCAW process is preferable for thick wall of 25 mm (1 in.) and above.
- The bead width for all welding processes should not exceed three times the electrode diameter or 9.5 mm (3/8 in.), whichever is greater.
- The average value of the readings on each weld shall be 30 to 65%. Ferrite content range shall be 40% to 63% for all alloys except ASTM A890, Grade 4A and ASTM A182, Grade F51. Ferrite content range shall be 35% to 60% for ASTM A890, Grade 4A and ASTM A182, Grade F51.
- Corrosion test if required: Recommended per ASTM G48A (Pitting and Crevice Corrosion) or ASTM A923 method C (Detecting Detrimental Intermetallic Phase).
- See Tables 4.66, 4.82, 4.83, 4.84, 4.85, and 4.86 for filler metal classes of similar/dissimilar DSS welding.
- Table 4.87 shows additional chemical requirements for DSS and SDSS consumables and as-welded deposits to control effectively the phase balance (30–65% for weld metal, 40–65% for HAZ, and 40–60% for base metal).
- See Table 4.82 for characteristics and Table 4.86 for chemical composition of various DSS filler metal classes.
- API RP582 committee is on developing a new Annex C for DSS (all types) which indicates some guidelines and requirements for WPS/PQR, ferrite content measurement, mechanical testing, microstructural testing, shielding/purging gases, CVN impact testing, production welding requirements, etc.

Table 4.83 Welding consumables for DSS (API TR938-C)

Process	2205 DSS	2507 DSS
SMAW	SFA 5.4 E2209	SFA 5.4 E2553
GTAW	SFA 5.9 ER2209 (1)	SFA 5.9 ER2553
SAW	SFA 5.9 ER2209 with a flux designed for DSS	SFA 5.9 ER2553 with a flux designed for DSS

Note: (1) ER2509 or Ni-based (Nb free) filler metal may also be considered in order to provide a better HAZ phase balance, even with the inherent low heat input

Table 4.84 Pipe and filler metal specification for DSS (ASTM A790)

Pipe	Filler metal	
UNS No.	AWS A5.9 class	UNS No.
S31803	ER2209	S39209
S32205	ER2209	S39209
S31200	ER2553	S39553
S82441	ER2209	S39209

Table 4.85 Recommended filler metals for DSS similar welding(1),(2)

Base metal, (UNS No.)	Coated electrode (MMA), SFA 5.4	Core wire (solid & metal) SFA 5.9	FCAW SFA 5.22	Remark
2205 (S31803/S32205)	E2209	ER2209	–	
2304 (S32304)	E2209	ER2209	–	
255 (S32550)	E2553	ER2553	–	

Notes: "-" not applicable
(1)See Table 4.66 for more details of welding consumables between other DSS classes
(2)See Table 4.82 for more details for each filler metal class of DSS welding

Table 4.86 Chemical composition requirements for undiluted DSS welding consumables (ASME Sec. II-C)

AWS Class. (D)	UNS No. (F)	Chemical composition (wt%)										
		C	Cr	Ni	Mo	Mn	Si (E)	P	S	N	Cu	Others
ER2209	S39209	0.03	21.5–23.5	7.5–9.5	2.5–3.5	0.50–2.00	0.90	0.03	0.02	0.08–0.20	0.75	
ER2553	S39553	0.04	24.0–27.0	4.5–6.5	2.9–3.9	1.5	1.0	0.04	0.03	0.10–0.25	1.5–2.5	
ER2594	S32750	0.03	24.0–27.0	8.0–10.5	2.5–4.5	2.5	1.0	0.03	0.02	0.20–0.30	1.5	W 1.0

4.11.8 Welding of Nickel and Nickel-Based Alloys

The weldability of nickel alloys is easier than that of ASS. Nickel alloys are widely used for dissimilar welding, such as carbon and low alloy steels, MSS, FSS, ASS, 5-9 Nickel steels, etc. Normally preheating and PWHT are not required like ASS. See API TR942-A for the recommendable welding of hydrogen reformer furnace outlet pigtails and manifolds and TR942-B for the recommendable welding of austenitic alloys subjected to embrittlement and cracking in high temperature 565–760 °C (1050–1400 °F) of refinery services. Tables 4.88, 4.89, 4.90, 4.91, 4.92, 4.93, 4.94, 4.95, 4.96, and 4.97 show the characteristic, properties, and DMW data for the welding metals of nickel based alloys which are based on several resources.

Table 4.87 Additional chemical requirements for DSS and SDSS consumables and as-welded deposits (API RP582) (1)

Element	Minimum chemical composition (DSS)	Minimum chemical composition (SDSS)
Nitrogen (N)	0.14%	0.20%
Nickel (Ni)	8.0%	9.0%
Molybdenum (Mo)	3.0%	3.5%

Note: (1) A minimum Pitting Resistance Equivalent Number (PREN) may be specified by the purchaser as an option

4.11.9 Welding of Aluminum and Aluminum-Based Alloys

4.11.9.1 Traditionally the Welding of Aluminum Alloys Is Not Easy Compared to Steel Welding. Also, Dissimilar Welding Is Very Difficult.

The following differences are important for aluminum welding:

(a) Considerably lower melting point compared with steel
(b) Three times higher heat conductivity of steel (Fig. 4.64)
(c) Considerably lower electrical resistance
(d) Double expansion coefficient of steels
(e) Melting point (2072 °C) of Al_2O_3 considerably higher than that (660 °C) of Al; metal and iron oxide melt approximately at the same temperature. If the oxide is not removed or displaced, the result is incomplete fusion. In some joining processes, chlorides and fluorides are used in order to remove the oxides contained. Chlorides and fluorides must be removed after the joining operation to avoid a possible corrosion problem in service.

Figure 4.64 shows the heat emission of aluminum from the weld pool is very high. Preheat and continuous welding may minimize the weld defects.

4.11.9.2 Traditional Defects of Aluminum Alloy Welding

(a) Hot crack

Figure 4.65 shows hot crack in aluminum alloy welding due to the high thermal expansion of aluminum. High tensions develop during solidification of the weld pool in the course of the welding cycle. If the welded alloy indicates a high melting interval, cracks may easily develop in the weld. The preheat may prevent this crack.

Figure 4.66 shows the influence of preheat temperature and Mg and Si to prevent hot crack in aluminum alloy welding. With an increasing preheat temperature, the amount of fractured welds decreases. The different behavior of the three different alloys can be explained using the right part of the figure. One can see that the manganese content influences significantly the hot crack susceptibility. The maximum of this hot crack susceptibility is likely with about 1% Mg content (corresponds with alloy 1). With increasing Mg content, hot crack susceptibility decreases strongly.

To avoid hot cracking, partly very different preheat temperatures are recommended for the alloys. Zschötge proposed a calculation method which compares the heat conductivity conditions of the Al alloy with those of a carbon steel with 0.2%°C. The formula is shown in Fig. 4.67, together with the related calculation result. These results are only to be regarded as approximate; the individual application is subject to the information of the manufacturer.

Table 4.88 Chemical composition requirements for undiluted SMAW electrodes (ASME Sec. II-C, SFA 5.11)

Weight %[a,b]																		
AWS classification	UNS number[c]	C	Mn	Fe	P	S	Si	Cu	Ni[d]	Co	Al	Ti	Cr	Nb (Cb) plus Ta	Mo	V	W	Others
EN-1	W82141	0.10	0.75	0.75	0.03	0.02	1.25	0.25	92.0	–	1.0	1.0	–	–	–	–	–	0.50
ENiCr-4	W86172	0.10	1.5	1.0	0.02	0.02	1.0	0.25	Rem.	–	–	–	48.0–52.0	1.0–2.5	–	–	–	0.50
ENiCu-7	W84190	0.15	4.0	2.5	0.02	0.015	1.5	Rem	62.0–69.0	–	0.75	1.0	–	–	–	–	–	0.05
ENiCrFe-1	W86132	0.08	3.5	11.0	0.03	0.015	0.75	0.50	62.0 min.	–	–	–	13.0–17.0	1.5–4.0[f]	–	–	–	0.05
ENiCrFe-2	W86133	0.10	1.0–3.5	12.0	0.03	0.02	0.75	0.50	62.0 min.	(e)	–	–	13.0–17.0	0.5–3.0[f]	0.5–2.5[f]	–	–	0.05
ENiCrFe-3	W86182	0.10	5.0–9.5	10.0	0.03	0.015	1.0	0.50	59.0 min.	(e)	–	1.0	13.0–17.0	1.0–2.5	–	–	–	0.05
ENiCrFe-4	W86134	0.02	1.0–3.5	12.0	0.03	0.02	1.0	0.05	60.0 min.	–	–	–	13.0–17.0	1.0–3.5	1.0–3.5	–	–	0.50
ENiCrFe-7 [g]	W86152	0.05	5.0	7.0–12.0	0.03	0.015	0.75	0.50	Rem.	(e)	0.50	0.50	28.0–31.5	1.0–2.5	0.5	–	–	0.50
ENiCrFe-9	W86094	0.15	1.0–4.5	12.0	0.02	0.015	0.75	0.50	55.0 min.	–	–	–	12.0–17.0	0.5–3.0	2.5–5.5	–	1.5	0.50
ENiCrFe-10	W86095	0.20	1.0–3.5	12.0	0.02	0.015	0.75	0.50	55.0 min.	–	–	–	13.0–17.0	1.0–3.5	1.0–3.5	–	1.5–3.5	0.05
ENiCrFe-12	W86025	0.10–0.25	1.0	8.0–11.0	0.04	0.02	1.0	1.20	Rem.	1.0	1.5–2.2	0.10–0.04	24.0–26.0	–	–	–	–	0.50
ENiCrFe-13 [h]	W86155	0.05	1.0	Rem.	0.020	0.015	0.75	0.30	52.0–62.0	0.10	0.50	0.50	28.5–31.0	2.1–4.0	3.0–5.0	–	–	0.50
ENiCrFeSi-1	W86045	0.05–0.20	2.5	21.0–25.0	0.04	0.03	2.5–3.0	0.30	Rem.	1.0	0.30	–	26.0–29.0	–	–	–	–	0.50
ENiMo-1	W80001	0.07	1.0	4.0–7.0	0.04	0.03	1.0	0.50	Rem	2.5	–	–	1.0	–	26.0–30.0	0.60	1.0	0.50
ENiMo-3	W80004	0.12	1.0	4.0–7.0	0.04	0.03	1.0	0.50	Rem	2.5	–	–	2.5–5.5	–	23.0–27.0	0.60	1.0	0.50
ENiMo-7	W80665	0.02	1.75	2.25	0.04	0.03	0.2	0.50	Rem	1.0	–	–	1.0	–	26.0–30.0	–	1.0	0.50
ENiMo-8	W80008	0.10	1.5	10.0	0.02	0.015	0.75	0.50	60.0 min.	–	–	–	0.5to3.5	–	17.0–20.0	–	2.0–4.0	0.05
ENiMo-9	W80009	0.10	1.5	7.0	0.02	0.015	0.75	0.3–1.3	62.0 min.	–	–	–	–	–	18.0–22.0	–	2.0–4.0	0.05
ENiMo-10	W80675	0.02	2.0	1.0–3.0	0.04	0.03	0.2	0.50	Rem	3.0	–	–	1.0–3.0	–	27.0–32.0	–	3.0	0.50
ENiMo-11	W80629	0.02	2.5	2.0–5.0	0.04	0.03	0.2	0.5	Rem	1.0	0.1–0.5	0.3	0.5–1.5	0.5	26.0–30.0	–	–	0.50
ENiCrMo-1	W86007	0.05	1.0–2.0	18.0–21.0	0.04	0.03	1.0	1.5–2.5	Rem	2.5	–	–	21.0–23.5	1.7 5–2.50	5.5–7.5	–	1.0	0.50
ENiCrMo-2	W86002	0.05–0.15	1.0	17.0–20.0	0.04	0.03	1.0	0.50	Rem	0.50–2.50	–	–	20.5–23.0	–	8.0–10.0	–	0.2–1.0	0.50
ENiCrMo-3	W86112	0.10	1.0	7.0	0.03	0.02	0.75	0.50	55.0 min.	(e)	–	–	20.0–23.0	3.15–4.15	8.0–10.0	–	–	0.50
ENiCrMo-4	W80276	0.02	1.0	4.0–7.0	0.04	0.03	0.2	0.50	Rem	2.5	–	–	14.5–16.5	–	15.0–17.0	0.35	3.0–4.5	0.05

ENiCrMo-5	W80002	0.10	1.0	4.0–7.0	0.04	0.03	1.0	0.50	Rem	2.5	–	–	14.5–16.5	–	15.0–17.0	0.35	3.0–4.5	0.50
ENiCrMo-6	W86620	0.10	2.0–4.0	10.0	0.03	0.02	1.0	0.50	55.0 min.	–	–	–	12.0–17.0	0.5–2.0	5.0–9.0	–	1.0–2.0	0.50
ENiCrMo-7	W86455	0.015	1.5	3.0	0.04	0.03	0.2	0.50	Rem	2.0	–	0.70	14.0–18.0	–	14.0–17.0	–	0.5	0.50
ENiCrMo-9	W86985	0.02	1.0	18.0–21.0	0.04	0.03	1.0	1.5–2.5	Rem	5.0	–	–	21.0–23.5	0.5	6.0–8.0	–	1.5	0.50
ENiCrMo-10	W86022	0.02	1.0	2.0–6.0	0.03	0.015	0.2	0.50	Rem	2.5	–	–	20.0–22.5	–	12.5–14.5	0.35	2.5–3.5	0.50
ENiCrMo-11	W86030	0.03	1.5	13.0–17.0	0.04	0.02	1.0	1.0–2.4	Rem	5.0	–	–	28.0–31.5	0.3–1.5	4.0–6.0	–	1.5–4.0	0.05
ENiCrMo-12	W86032[h]	0.03	2.2	5.0	0.03	0.02	0.7	0.50	Rem	–	–	–	20.5–22.5	1.0–2.8	6.8–10.0	–	–	0.50
ENiCrMo-13	W86059	0.02	1.0	1.5	0.015	0.01	0.2	–	Rem	–	–	–	22.0–24.0	–	15.0–16.5	–	–	0.50
ENiCrMo-14	W86026	0.02	1.0	5.0	0.02	0.02	0.25	0.50	Rem	–	–	0.25	19.0–23.0	–	15.0–17.0	–	3.0–4.4	0.50
ENiCrMo-17	W86200	0.02	0.5	3.0	0.030	0.015	0.2	1.3–1.9	Rem	2.0	–	–	22.0–24.0	–	15.0–17.0	–	–	0.50
ENiCrMo-18	W86650	0.03	0.7	12.0–15.0	0.03	0.02	0.6	0.3	Rem	1.0	0.5	–	19.0–22.0	0.3	10.0–13.0	0.15	1.0–2.0	0.50
ENiCrMo-19	W86058	0.02	1.5	1.5	0.03	0.02	0.2	0.5	Rem	0.3	0.4	–	20.0–23.0	–	19.0–21.0	–	0.3	0.50

Notes

[a] The weld metal shall be analyzed for the specific elements for which values are shown in this table. If the presence of other elements is indicated in the course of the work, the amount of those elements shall be determined to ensure that their total does not exceed the limit specified for "Other Elements, Total" in the last column of the table

[b] Single values are maximum, except where otherwise specified. Rem p remainder

[c] ASTM D5-56/SAE-1086 Metals and Alloys in the Unified Numbering System

[d] Includes incidental cobalt. Rem p remainder

[e] Cobalt (Co) — 0.12 maximum, when specified by the purchaser

[f] Tantalum (Ti) — 0.30 maximum, when specified by the purchaser

[g] Boron (B) is 0.005% maximum and Zirconium (Zr) is 0.020% maximum when specified by purchaser

[h] Boron (B) is 0.003% maximum and Zirconium (Zr) is 0.020% maximum

[i] UNS formerly was W86040

[j] Nitrogen (N) = 0.02–0.15

Table 4.89 (1/3) Description and intended use of SMAW electrodes (ASME Sec. II-C, SFA 5.11)

Class	Intended use and characteristics[1]
ENi-1 (95Ni-2.5Ti) *Nickel welding electrode 141* *(W82141)*	– Typically for welding wrought and cast forms of commercially pure Ni to themselves and to steel (i.e., joining Ni to steel and surfacing steel with Ni). – Typically for ASTM B160/B161/B162/B163, all of which have UNS N02200 or N02201. – Electrodes through the 3.2 mm (1/8 in.) size can be used in all positions. – Normally used only in the horizontal and flat positions.
ENiCr-4 (50Cr-50Ni-(Cb)) – Inco IN-657 & 671 *(W86172)*	– Typically for weld cast grade, ASTM A560-R20500/20501. – ENiCr-4 is resistant to carburizing furnace atmospheres and fuel ash corrosion which occurs when burning low-grade heavy fuels. – ENiCr-4 is scale resistant up to 1150 °C (2100 °F).
ENiCu-7 (66Ni-30Cu-3 Mn-1Fe) Monel weld *electrode 190* *(W84190)*	– Typically for welding Ni-Cu alloys to themselves and to steel, for welding the clad side of joints in steel clad with a Ni-Cu alloy, and for surfacing steel with Ni-Cu alloy weld metal. – Typically for Ni-Cu base metal, ASTM B127/B163/B164/B165, all of which have UNS N04400. – Electrodes through the 3.2 mm (1/8 in.) size can be used in all positions. Electrodes larger than that are used only in the flat and horizontal positions. – The weld metal is suitable for service both in the as-welded condition and after an appropriate PWHT. – Qualification tests should be conducted beforehand to make certain the necessary properties can be obtained after the particular heat treatment is employed.
ENiCrFe-1 (70Ni-15Cr-8Fe-3.5Mn-2.5Nb (Cb) plus Ta) *(W86132)*	– Typically for welding Ni-Cr-Fe alloys, for the clad side of joints in steel clad with Ni-Cr-Fe alloy, and for surfacing steel with Ni-Cr-Fe weld metal. – The electrodes may be used at temperatures ranging from cryogenic to around 980 °C (1800 °F). However, for temperatures above 820 °C (1500 °F), weld metal produced by these electrodes does not exhibit optimum oxidation resistance and strength. These electrodes are also suitable for joining steel to Ni-based alloys. – Typically for ASTM B163/B166/B167/B168, all of which have UNS N06600. – Electrodes through the 3.2 mm (1/8 in.) size can be used in all positions. Electrodes larger than that are used only in the horizontal and flat positions.
ENiCrFe-2 (70Ni-15Cr-8Fe-2Mn-2Nb plus Ta-1.5Mo) *Inco-weld A* *(W86133)*	– Typically for welding Ni-Cr-Fe alloys, 9% Ni steel, and a variety of dissimilar metal joints (involving carbon steel, stainless steel, Ni, and Ni-based alloys). For wrought or cast (welding grade), or both. – The electrodes may be used at temperatures ranging from cryogenic to around 980 °C (1800 °F). However, for temperatures above 820 °C (1500 °F), weld metal produced by ENiCrFe-2 does not exhibit optimum oxidation resistance and strength. – Typically for ASTM B163/B166/B167/B168, all of which have UNS N06600. – Electrodes through the 3.2 mm (1/8 in.) size can be used in all positions. Electrodes larger than that are used only in the horizontal and flat positions.
ENiCrFe-3 (65Ni-15Cr-8Fe-7.5Mn-2Nb plus Ta) *Inconel 182 (W86182)*	– Typically for welding Ni-Cr-Fe alloys, for welding the clad side of joints on steel clad with Ni-Cr-Fe alloy, and for surfacing steel with Ni-Cr-Fe weld metal, when comparatively high Mn contents are not detrimental. – The electrode may be used at temperatures ranging from cryogenic to about 480 °C (900 °F). Typically for ASTM B163/B166/B167/B168, all of which have UNS N06600. – These electrodes can also be used for welding steel to other Ni-based alloys. Fewer fissures are permitted on the bend test for this weld metal than for weld metal of the ENiCrFe-1 and ENiCrFe-2 classifications. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the horizontal and flat positions.
ENiCrFe-4 (70Ni-15C-8Fe-2.5Mn-2.5Nb plus Ta-2.5Mo) *(W86134)*	– Typically for 9% Ni steel base metal, ASTM A333/A334/A353/A522/A553, all of which have UNS K81340. – The strength of the weld metal is higher than that of the ENiCrFe-2 classification.
ENiCrFe-7 (55Ni-29Cr-9.5Fe-3Mn-1.5Nb plus Ta) *Inconel 152(M)* *(W86152)*	– Typically for welding the Ni-Cr-Fe alloy of the UNS N06690. – Typically for ASTM B166/B167/B168. The electrodes may also be used for the welding of Ni-Cr-Fe alloys to steels and stainless steels and for corrosion-resistant overlays on steels. Specification of values for boron and zirconium is helpful in reducing the tendency for ductility dip cracking. – Electrodes through the 3.2 mm (1/8 in.) size can be used in all positions. Electrodes larger than that are used only in the flat and horizontal positions.
ENiCrFe-9 (70Ni-14Cr-9Fe-1.5Nb plus Ta-4 Mo) *(W86094)*	– Typically for welding 9% Ni steel. – Typically for ASTM A333/A334/A353/A522/A553, all of which have UNS K81340. – Electrodes through the 4.0 mm (5/32 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat and horizontal positions.
ENiCrFe-10 (65Ni-15Cr-10Fe-1.5Nb plus Ta-3Mo-2W) *(W86095)*	– Typically for welding 9% Ni steel. – Typical specifications for ASTM A 333/A334/A353/A522/A553, all of which have UNS K81340. – Electrodes through the 4.0 mm (5/32 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat and horizontal positions.
ENiCrFe-12 (63Ni-25 Cr-9.5Fe-2.1Al) *(W86025)*	– Typically for welding UNS N06025, welding Ni-Cr-Fe to steel and to other Ni-based alloys. – Typically for ASTM B163/B166/B167/B168/B366/B516/B517/B546/B564, all of which have UNS N06025.

Table 4.89 (2/3) Description and intended use of SMAW electrodes (ASME Sec. II-C, SFA 5.11)

Class	Intended use and characteristics[(1)]
ENiCrFeSi-1 (46Ni-28Cr-23Fe-2.75Si) *(W86045)*	– Typically for welding UNS N06045 and dissimilar welding Ni-Cr-Fe to CS/LAS and to other Ni-based alloys. – Typically for ASTM B163/B166/B167/B168/B366/B516/B517/B546/B564, all of which have UNS N06045.
ENiMo-1 (67Ni-28Mo-5 Fe) *(W80001)*	– Typically for welding Ni-Mo alloys as well as the clad side of joints in steel clad with a Ni-Mo alloy and for dissimilar welding Ni-Mo alloys to CS/LAS and to other Ni-based alloys. – Typical specifications for the Ni-Mo base metal are ASTM B33/B335/B619/B622/B626, all of which have UNS N10001. Normally used only in the flat position.
ENiMo-3 (63Ni-25Mo-5.5Fe-4Cr) *(W80004)*	– Typically for welding dissimilar metal combinations of Ni-, Co-, and Fe-based alloys. – Normally used only in the flat position.
ENiMo-7 (69Ni-28Mo-1.5Fe-1.5Mn) *(W80665)*	– Electrodes of this classification which have controlled low levels of carbon, Fe, and Co are used for welding Ni-Mo alloys, for welding the clad side of joints in steel clad with a Ni-Mo alloy, and for dissimilar welding Ni-Mo alloys to CS/LAS/SS and to other Ni-based alloys. – Typical specifications for the Ni-Mo base metals are ASTM B333/ B335/ B619/ B622/ B626, all of which have UNS N10665. – Normally used only in the flat position.
ENiMo-8 (70Ni-18Mo-7Fe-3W-2 Cr) *(W80008)*	– Typically for welding 9% Ni steel, but they can be used in other applications as well. – Typically for ASTM A333/A334/A353/A522/A553, all of which have UNS K81340. – Electrodes through the 4.0 mm (5/32 in.) size can be used for welding in all positions. – Electrodes larger than that are used only in the flat and horizontal positions.
ENiMo-9 (70Ni-19Mo-3 Fe-3W-1Cu) *(W80009)*	– Typically for welding 9% Ni steel, but they can be used in other applications as well. – Typically for ASTM A333/A334/A353/A522/A553, all of which have UNS K81340. Electrodes through the 4.0 mm (5/32 in.) size can be used for welding in all positions. – Electrodes larger than that are used only in the flat and horizontal positions.
ENiMo-10 (69Ni-28Mo-1.5Cr-1.5Fe and low levels of C) *(W80675)*	– The filler materials are used for welding Ni-Mo alloys (UNS N10665 and N10675), for welding the clad side of joints in steel clad with a Ni-Mo alloy, and for dissimilar welding Ni-Mo alloys to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B333/B335/B366/B564/B619/B622/B626. – These coated electrodes are normally used in the flat position.
ENiMo-11 (67Ni-28Mo-3 Fe-1.3Cr and low C) *(W80629)*	– The filler materials are used for welding Ni-Mo alloys (UNS N10665 and N10629), for welding clad side of joints in steel clad with Ni-Mo alloy, and for dissimilar welding Ni-Mo alloys to CS/LAS/SS and to other Ni-based alloys. – Typically for B333/B335/B366/B564/B619/B622/B629. – These coated electrodes are generally used in flat position.
ENiCrMo-1 (43Ni-22Cr-19.5 Fe-6.5Mo-2Nb plus Ta-2Cu-1.5Mn) *(W86007)*	– Electrodes of this classification are used for welding Ni-Cr-Mo alloys, for welding the clad side of joints in steel clad with Ni-Cr-Mo alloy, and for dissimilar welding Ni-Cr-Mo alloy to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B581/B582/B619/B622, all of which have UNS N06007. – Normally used only in the flat position. – For turbine fabrication.
ENiCrMo-2 (47Ni-22Cr-18Fe-9Mo-1.5Co) *(W86002)*	– Typically for welding Ni-Cr-Mo alloys, for welding the clad side of joints in steel clad with Ni-Cr-Mo alloy, and for dissimilar welding Ni-Cr-Mo alloys to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B435/B572/B619/B622/B626, all of which have UNS N06002. – Normally used only in the flat position.
ENiCrMo-3 (60-Ni-22Cr-9Mo-5Fe-3.5Nb plus Ta) *– Alloy 112 (W86112) for alloy 625 or 601*	– Typically for welding Ni-Cr-Mo alloys to themselves and to CS/LAS/SS and for surfacing steel with Ni-Cr-Mo weld metal. Used extensively in overlay cladding where a similar chemical composition is required on the clad side. These electrodes also can be used for dissimilar welding Ni-based alloys to CS/LAS/SS. – The electrodes are used in applications where the temperature ranges from cryogenic to 540 °C (1000 °F). – Typically for ASTM B443/B444/B446, all of which have UNS N06625. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat and horizontal positions.
ENiCrMo-4. (57Ni-16Mo-15.5Cr-5.5Fe-4W-low C) *Alloy C-276 (W80276)*	– Typically for welding low carbon Ni-Cr-Mo alloy, for welding the clad side of joints in steel clad with low carbon-Ni-Cr-Mo alloy, and for dissimilar welding low carbon-Ni-Cr-Mo alloy to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B574/B575/B619/B622/B626, all of which have UNS N10276. – Normally used only in the flat position.
ENiCrMo-5. (53Ni-16Mo-15.5Cr – 5.5Fe-4W) *(W80002)*	– Typically for surfacing steel clad with a Ni-Cr-Mo alloy. – Normally used only in the flat position.
ENiCrMo-6 (65Ni-14.5C- 7 Fe-7Mo-3Mn-1.5W-1.5Nb plus Ta) *(W86620)*	– Typically for welding 9% Ni steel, but they can be used in other applications as well. – Typically for ASTM A333/A334/A353/A522/A553, all of which have UNS K81340. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat and horizontal positions.

The nominal composition (wt.-%) of filler metal: wt% e.g., 65 Ni, 30 Cu = 65wt%Ni + 30wt%Cu

Table 4.89 (3/3) Description and intended use of SMAW electrodes (ASME Sec. II-C, SFA 5.11)

Class	Intended use and characteristics[(1)]
ENiCrMo-7 (65Ni-16Cr-15.5Mo-1.5Fe) *(W86455)*	– Typically for welding Ni-Cr-Mo alloy, for the welding of the clad side of joints in steel clad with Ni-Cr-Mo alloy, and for dissimilar welding Ni-Cr-Mo alloys to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B574/ B575/ B619/ B622/ B626, all of which have UNS N06455. – These electrodes normally are used only in the flat position.
ENiCrMo-9 (44Ni-22Cr-19.5Fe-7Mo-2Co-2Cu) *(W86985)*	– Typically for welding Ni-Cr-Mo alloys, for the welding of the clad side of joints in steel clad with Ni-Cr-Mo alloys, and for dissimilar welding Ni-Cr-Mo alloys to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B581/ B582/ B619/ B622/ B626, all of which have UNS N06985. – Normally used only in the flat position.
ENiCrMo-10 (56Ni-22Cr-13Mo-4Fe-3W) *Inconel electrode 122 (W86022)*	– Typically for the welding of the clad side of joints in steel clad with Ni-Cr-Mo alloy, to CS/LAS/SS and to other Ni-based alloys; and for joining Ni-Cr-Mo alloys. – Typically for ASTM B574/ B575/ B619/ B622/ B626, all of which have UNS N06022. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat position.
ENiCrMo-11 (43Ni-30Cr-15Fe-5Mo-2Co-3 W-2Cu) *(W86030)*	– Typically for Ni-Cr-Mo alloys, for the welding of the clad side of joints in steel clad with Ni-Cr-Mo alloys, and for joining Ni-Cr-Mo alloys to steel and to other Ni-based alloys. – Typically for ASTM B581/ B582/ B619/ B622/ B626, all of which have UNS N06030. – Normally used only in the flat position.
ENiCrMo-12 (58Ni-21.5Cr-9.5Mo-3Fe-2Nb plus Ta) *(W86032)*	– Typically for welding Cr-Ni-Mo ASS to themselves, to duplex ferritic-austenitic stainless steels, to Ni-Cr-Mo alloys, and to steel. The EniCrMo-12 composition is balanced to provide corrosion-resistant welds for use at temperatures below the creep range of highly alloyed ASS. – Typically for A240/ A167/ A182/ A249/ A276/ A312/ A358/ A373/ A479, most particularly the grade UNS S31254 contained in those specifications. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that can be used only for welding in the flat and horizontal positions.
ENiCrMo-13 (59Ni-23Cr-16Mo-1Fe-low C) *(W86059)*	– Typically for welding low carbon Ni-Cr-Mo alloys, for welding the clad side of joints in steel clad with low carbon Ni-Cr-Mo alloys, and for dissimilar welding low carbon Ni-Cr-Mo alloy to CS/LAS/SS and to other Ni-based alloys. – Typically for ASTM B574/ B575/ B619/ B622/ B626, all of which have UNS N06059.
ENiCrMo-14 (57Ni-21Cr-16Mo-4W) *Inco-Weld 686CPT (W86026)*	– Typically for welding Ni-Cr-Mo alloys (UNS N06686, N06625, N10276, and N06022) that are used in severe corrosion applications where resistance to reducing, oxidizing, crevice, and pitting conditions is required. – It is recommended for corrosion-resistant overlay cladding of Fe-based metals for the same environments.
ENiCrMo-17 (59Ni-23Cr-16Mo-1.6Cu) *(W86200)*	– Typically for welding Ni-Cr-Mo alloys, for the welding of the clad side of joints in steel clad with Ni-Cr-Mo alloy, to CS/LAS/SS and to other Ni-based alloys; and for joining Ni-Cr-Mo alloys. – Typically for ASTM B574/ B575/ B619/ B622/ B626, all of which have UNS N06200. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat position.
ENiCrMo-18 (50Ni-20Cr-13.5Fe-11.5Mo-1.5W) *(W86650)*	– Typically for welding Ni-Cr-Mo alloys like UNS N06625, for welding of the clad side of joints in steel clad with Ni-Cr-Mo alloy, to CS/LAS/SS and to other Ni-based alloys; and for joining some other Ni-Cr-Mo alloys, such as UNS N06625, N08825, N06985, N08020, N08926, and N08031. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat position.
ENiCrMo-19 (58Ni-21Cr-20Mo-1Fe) *(W86058)*	– Typically for welding Ni-Cr-Mo alloys, for welding of the clad side of joints in steel clad with Ni-Cr-Mo alloy, to CS/LAS/SS and to other Ni-based alloys; and for joining Ni-Cr- Mo alloys. – Typically for ASTM B574/ B575/ B366/ B564/ B619/ B622/ B626, all of which are UNS N06058. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. Electrodes larger than that are used only in the flat position.
ENiCrCoMo-1 (52Ni-23Cr-12Co-9Mo-2Fe-1.5Mn) *Inconel 117 (W86117)*	– Typically for welding Ni-Cr-Co-Mo alloys (UNS N06617) to themselves and to steel and for surfacing steel with Ni-Cr-Co-Mo weld metal. – Electrodes are also used for applications where optimum strength and oxidation resistance are required above 820 °C (1500 °F) up to 1150 °C (2100 °F), especially when welding on base metals of Ni-Fe-Cr alloys. – Electrodes through the 3.2 mm (1/8 in.) size can be used for welding in all positions. – Electrodes larger than that are used for welding in the flat or horizontal positions.
ENiCrWMo-1 (57Ni-22Cr-14W, <5 Co, <3 Fe-2Mo) *(W86231)*	– Typically for welding Ni-Cr-W-Mo-La (lanthanum) alloy ASTM B366/ B435/ B564/ B572 having UNS N06230. – Normally used only in the flat position.

The nominal composition (wt.-%) of filler metal: wt% e.g., 65 Ni, 30 Cu = 65wt%Ni + 30wt%Cu

Notes

[(1)]ASME Sec. VIII states that:

The Cb (or Nb) content of weld metal shall be $\leq$1.00%, except that ENiCrMo-3, ERNiCrMo-3, and ENiCrMo-12 weld filler metal made to SFA-5.11 and SFA-5.14 may be used to weld S31254, S31603, S31703, S31725, S31726, and Sec. VIII, Div. 2, Table 3-A.6 to a maximum design temperature of 482 °C (900 °F)

Table 4.90 Chemical composition requirements for undiluted SMAW metal (ASME Sec. II-C, SFA 5.11)

AWS classification	UNS number	Material[a,b]	ASTM specifications[c]	Equivalent UNS number for plate
ENi-1	W82141	Ni	B160, B162	N02200, N02201
ENiCr-4	W86172	Ni-Cr	A560	R20500
ENiCu-7	W84190	Ni-Cu alloy	B127, B164	N04400
ENiCrFe-1,2, 3,4, 9,10	W86132, 86133, 86182, 86134, 86094, 89095	Ni-Cr-Fe alloy	B166, B168	N06600
ENiCrFe-7	W86152	Ni-Cr-Fe alloy	B166, B167, B168	N06690
ENiCrFe-12	W86025	Ni-Cr-Fe alloy	B168	N06025
ENiCrFeSi-1	W86045	Ni-Cr-Fe-Si alloy	B168	N06045
ENiMo-1,3, 7,8, 9,10	W80001, 80004, 80665, 80008, 80009, 80675	Ni-Mo alloy	B333	N10001, N10665, N10675
ENiMo-11	W80629	Ni-Mo alloy	B333	N10629
ENiCrMo-1,9, 11	W86007, 86985, 86030	Ni-Cr-Mo alloy	B582	N06007, N06985, N06030
ENiCrMo-2	W86002	Ni-Cr-Mo alloy	B435	N06002
ENiCrMo-3	W86112	Ni-Cr-Mo alloy	B443, B446	N06625
ENiCrMo-4,5, 7,10, 13,14, 19	W80276, 80002, 86455, 86022, 86059, 86026, 86058	Low carbon Ni-Cr-Mo alloy	B575	N10276, N06455, N06022, N06059, N06686
ENiCrMo-6	W86620	Ni-Cr-Mo alloy	B166, B168	N06600
ENiCrMo-12	W86032	Cr-Ni-Mo alloy (ASS)	A240	S31254
ENiCrMo-17	W86200	Low carbon Ni-Cr-Mo alloy	B575	N06200
ENiCrMo-18	W86650	Ni-Cr-Fe-Mo-W alloy	B446	N06650
ENiCrCoMo-1	W86117	Ni-Cr-Co-Mo alloy	B166, B168	N06617
ENiCrWMo-1	W86231	Ni-Cr-W-Mo alloy	B435	N06230

Note:
[a] Either the base metals specified or carbon steel (A131, A285, A515) may be used. If carbon steel is used, two layers of buttering shall be applied to the surface and backing strip if appropriate. For chemical analysis, base metals other than those specified may be used as the base for the undiluted weld pad provided that, for electrodes of the 3.2 mm (1/8 in.) size and smaller, the minimum height shown is 19 mm (3/4 in.) and the sample for analysis is taken at least 16 mm (5/8 in.) from the nearest surface of the base metal. For electrode sizes 4 mm (5/32 in.) through 6.4 mm (1/4 in.), these dimensions are 25 mm (1 in.) and 22 mm (7/8 in.), respectively
[b] All specified base metals shall be in the annealed condition prior to welding
[c] Equivalent material specifications may be used

(b) Excessive porosity

Figure 4.68 shows excessive porosity in aluminum alloy welding. The porosity is based on the interplay of several characteristics and hard to suppress. Pores in aluminum alloy welding are mostly formed by hydrogen, which is driven out of the weld pool during solidification. Solubility of hydrogen in aluminum changes abruptly on the phase transition melt-crystal, i.e., the melt dissolves many times more of the hydrogen than the just forming crystal at the same temperature. This leads to a surplus of hydrogen in the melt due to the crystallization during solidification. Hydrogen dissolves very rapidly in molten aluminum. However, hydrogen has almost no solubility in solid aluminum, and it has been determined to be the primary cause of porosity in aluminum welds. High temperatures of the weld pool allow a large amount of hydrogen to be absorbed, and as the pool solidifies, the solubility of hydrogen is greatly reduced. Hydrogen that exceeds the effective solubility limit forms gas porosity, if it does not escape from the solidifying weld.

This surplus precipitates in form of a gas bubble at the solidifying front. As the melting point of aluminum is very low and aluminum has a very high heat conductivity, the solidification speed of aluminum is relatively high. As a result, in the melt ousted gas bubbles have often no chance to rise all the way to the surface. Instead, they passed by the solidifying front and remain in the weld metal as pores shown in Fig. 4.68. To suppress such pore formation, it is therefore necessary to minimize the hydrogen content in the melt.

(c) Excessive distortion

Figure 4.69 indicates that the large thermal expansion of the aluminum along with the relatively large HAZ causes in combination with a parallel gap adjustment a strong distortion of the welded parts. To minimize this distortion, the workpieces must be set at a suitable angle before welding.

4.11.9.3 Weldability of Several Aluminum Alloys

Ease of welding is the first consideration for most welding applications. In general, the non-heat-treatable aluminum alloys can be welded with a filler alloy of the same basic composition as the base alloy.

Table 4.91 (1/2) Chemical composition requirements for undiluted weld metal (ASME Sec. II-C, SFA 5.14)

AWS classification[m]	UNS number[c]	C	Mn	Fe	P	S	Si	Cu	Ni[d]	Co	Al	Ti	Cr	Nb + Ta	Mo	V	W	Total other elements
ERNi-1[k]	N02061	0.15	1.0	1.0	0.03	0.015	0.75	0.25	≥93.0	–	1.5	2.0–3.5	–	–	–	–	–	0.50
ERNiCu-7[k]	N04060	0.15	4.0	2.5	0.02	0.015	1.25	Rem	62.0–69.0	–	1.25	1.5–3.0	–	–	–	–	–	0.50
ERNiCu-8[k]	N05504	0.25	1.5	2.0	0.03	0.015	1.00	Rem	63.0–70.0	–	2.0–4.0	0.25–1.00	–	–	–	–	–	0.05
ERNiCr-3[k,l]	N06082	0.10	2.5–3.5	3.0	0.03	0.015	0.50	0.50	≥67.0	e	–	0.75	18.0–22.0	2.0–3.0[f]	–	–	–	0.50
ERNiCr-4	N06072	0.01–0.10	0.20	0.50	0.02	0.015	0.20	0.50	Rem	–	–	0.3–1.0	42.0–46.0	–	–	–	–	0.50
ERNiCr-6[k]	N06076	0.08–0.15	1.00	2.00	0.03	0.015	0.30	0.50	≥75.0	–	0.40	0.15–0.50	19.0–21.0	–	–	–	–	0.50
ERNiCr-7[r]	N06073	0.03	0.50	1.0	0.02	0.015	0.30	0.30	Rem	1.0	0.75–1.20	0.25–0.75	36.0–39.0	0.25–1.00	0.50	–	–	0.50
ERNiCrFe-5[k]	N06062	0.08	1.0	6.0–10.0	0.03	0.015	0.35	0.50	≥70.0	e	–	–	14.0–17.0	1.5–3.0[f]	–	–	–	0.50
ERNiCrFe-6[k]	N06072	0.08	12.0–2.7	8.0	0.03	0.015	0.35	0.50	≥67.0	–	–	2.5–3.5	14.0–17.0	–	–	–	–	0.50
ERNiCrFe-7[i]	N06052	0.04	1.0	7.0–11.0	0.02	0.015	0.50	0.30	Rem	–	1.10	1.0	28.0–31.5	0.10	0.50	–	–	0.50
ERNiCrFe-7A[j,p]	N06054	0.04	1.0	7.0–11.0	0.02	0.015	0.50	0.30	Rem	0.12	1.10	1.0	28.0–31.5	0.5–1.0	0.50	–	–	0.50
ERNiCrFe-8[k]	N07069	0.08	1.0	5.0–9.0	0.03	0.015	0.50	0.50	≥70.0	–	0.4–1.0	2.0–2.75	14.0–17.0	0.7–1.20	–	–	–	0.50
ERNiCrFe-11	N06601	0.10	1.0	Rem	0.03	0.015	0.50	1.0	58.0–63.0	–	1.0–1.7	–	21.0–25.0	–	–	–	–	0.50
ERNiCrFe-12	N06025	0.15–0.25	0.50	8.0–11.0	0.02	0.010	0.50	0.1	Rem	1.0	1.8–2.4	0.10–0.20	24.0–26.0	–	–	–	–	0.50
ERNiCrFe-13[r]	N06055	0.03	1.0	Rem	0.02	0.015	0.50	0.30	52.0–62.0	0.10	0.50	0.50	28.5–31.0	2.1–4.0	3.0–5.0	–	–	0.50
ERNiCrFe-14	N06043	0.04	3.0	7.0–12.0	0.02	0.015	0.50	0.30	Rem	–	0.50	0.50	28.5–31.0	1.0–2.5	0.50	–	–	0.50
ERNiCrFeSi-1	N06045	0.05–0.12	1.0	21.0–25.0	0.02	0.01	2.5–3.0	0.3	Rem	1.0	0.30	–	26.0–29.0	–	–	–	–	0.50
ERNiCrFeAl-1	N06693	0.15	1.0	2.5–6.0	0.03	0.01	0.5	0.5	Rem	–	2.5–4.0	1.0	27.0–31.0	0.5–2.5	–	–	–	0.50
ERNiFeCr-1[k]	N08065	0.05	1.0	≥22.0	0.03	0.03	0.50	1.5–3.0	38.0–46.0	–	0.20	0.6–1.2	19.5–23.5	–	2.5–3.5	–	–	0.50
ERNiFeCr-2[g]	N07718	0.08	0.35	Rem	0.015	0.015	0.35	0.30	50.0–55.0	–	0.20–0.80	0.65–1.15	17.0–21.0	4.75 to5.50	2.8–3.30	–	–	0.50
ERNiMo-1	N10001	0.08	1.0	4.0–7.0	0.025	0.03	1.0	0.50	Rem	2.5	–	–	1.0	–	26.0–30.0	0.20–0.40	1.0	0.50
ERNiMo-2	N10003	0.04–0.08	1.0	5.0	0.015	0.02	1.0	0.50	Rem	0.2	–	–	6.0–8.0	–	15.0–18.0	0.50	0.50	0.50

ERNiMo-3	N10004	0.12	1.0	4.0–7.0	0.04	0.03	1.0	0.50	Rem	2.5	–	–	4.0–6.0	–	23.0–26.0	0.60	1.0	0.50
ERNiMo-7	N10665	0.02	1.0	2.0	0.04	0.03	0.10	0.50	Rem	1.0	–	–	1.0	–	26.0–30.0	–	1.0	0.50
ERNiMo-8	N10008	0.10	1.0	10.0	0.015	0.015	0.50	\0.50	≥60.0	–	–	–	0.5–3.5	–	18.0–21.0	–	2.0–4.0	0.50
ERNiMo-9	N10009	0.10	1.0	5.0	0.015	0.015	0.50	0.3–1.3	≥65.0	–	1.0	–	–	–	19.0–22.0	–	2.0–4.0	0.50
ERNiMo-10[n]	N10675	0.01	3.0	1.0–3.0	0.03	0.01	0.10	0.20	≥65.0	3.0	0.50	0.20	1.0–3.0	0.2	27.0–32.0	0.20	3.0	0.50
ERNiMo-11	N10629	0.01	1.0	2.0–5.0	0.02	0.01	0.10	0.50	Rem	1.0	0.1–0.5	0.30	0.5–1.5	0.5	26.0–30.0	–	–	0.50
ERNiMo-12[g]	N10242	0.03	0.80	2.0	0.03	0.015	0.80	0.50	Rem	1.0	0.5	–	7.0–9.0	–	24.0–26.0	–	–	–
ERNiCrFeAl-1	N06693	0.15	1.0	2.5–6.0	0.03	0.01	0.5	0.5	Rem	–	2.5–4.0	1.0	27.0–31.0	0.5–2.5	–	–	–	0.50
ERNiFeCr-1[k]	N08065	0.05	1.0	≥22.0	0.03	0.03	0.50	1.5–3.0	38.0–46.0	–	0.20	0.6–1.2	19.5–23.5	–	2.5–3.5	–	–	0.50
ERNiCrMo-1	N06007	0.05	1.0–2.0	18.0–21.0	0.04	0.03	1.0	1.5–2.5	Rem	2.5	–	–	21.0–23.5	1.75–2.50	5.5–7.5	–	1.0	0.50
ERNiCrMo-2	N06002	0.05–0.15	1.0	17.0–20.0	0.04	0.03	1.0	0.50	Rem	0.50–2.5	–	–	20.5–23.0	–	8.0–10.0	–	0.20–1.0	0.50
ERNiCrMo-3[k]	N06625	0.10	0.5	5.0	0.02	0.015	0.50	0.50	58.0 min	–	0.40	0.40	20.0–23.0	3.15–4.15	8.0–10.0	–	–	0.50
ERNiCrMo-4	N10276	0.02	1.0	4.0–7.0	0.04	0.03	0.08	0.50	Rem	2.5	–	–	14.5–16.5	–	15.0–17.0	0.35	3.0–4.5	0.50
ERNiCrMo-7	N06455	0.015	1.0	3.0	0.04	0.03	0.08	0.50	Rem	2.0	–	0.70	14.0–18.0	–	14.0–18.0	–	0.50	0.50
ERNiCrMo-8	N06975	0.03	1.0	Rem	0.03	0.03	1.0	0.7–1.20	47.0–52.0	–	–	0.70–1.50	23–26.0	–	5.0–7.0	–	–	0.50
ERNiCrMo-9	N06985	0.015	1.0	18.0–21.0	0.04	0.03	1.0	1.5–2.5	Rem	5.0	–	–	21.0–23.5	0.50	6.0–8.0	–	1.5	0.50
ERNiCrMo-10	N06022	0.015	0.5	2.0–6.0	0.02	0.010	0.08	0.50	Rem	2.5	–	–	20.0–22.5	–	12.5–14.5	0.35	2.0–4.5	0.50
ERNiCrMo-11	N06030	0.03	1.5	13.0–17.0	0.04	0.02	0.80	1.0–2.4	Rem	5.0	–	–	28.0–31.5	0.30–1.50	4.0–6.0	–	1.5–4.0	0.50
ERNiCrMo-13	N06059	0.01	0.5	1.5	0.015	0.005	0.10	–	Rem	0.3	0.1–0.4	–	22.0–24.0	–	15.0–16.5	–	–	0.50
ERNiCrMo-14	N06686	0.01	1.0	5.0	0.02	0.02	0.08	0.5	Rem	–	0.5	0.25	19.0–23.0	–	15.0–17.0	–	3.0–4.4	0.50
ERNiCrMo-15	N07725	0.03	0.03	0.35	Rem	0.015	0.01	0.20	–	55.0–59.0	–	0.35	1.0–1.7	19.0–22.5	2.75–4.00	7.0–9.5	–	0.50
ERNiCrMo-16	N06057	0.02	1.0	2.0	0.04	0.03	1.0	–	Rem	–	–	–	29.0–31.0	–	10.0–12.0	0.4	–	0.50
ERNiCrMo-17	N06200	0.010	0.5	3.0	0.025	0.010	0.08	1.3–1.9	Rem	2.0	0.50	–	22.0–24.0	–	15.0–17.0	–	–	0.50
ERNiCrMo-18°	N06650	0.03	0.5	12.0–16.0	0.020	0.010	0.50	0.30	Rem	1.0	0.5	–	19.0–21.0	0.05–0.50	9.5–12.5	0.03	0.5–2.5	0.50
ERNiCrMo-19[q]	N06058	0.01	0.5	1.5	0.015	0.010	0.10	0.50	Rem	0.3	0.4	–	20.0–23.0	–	19.0–21.0	–	0.3	0.50
ERNiCrMo-20	N06660	0.03	0.5	2.0	0.015	0.015	0.5	0.3	Rem	0.2	0.4	0.4	21.0–23.0	0.2	9.0–11.0	–	2.0–4.0	–
ERNiCrMo-21	N06205	0.03	0.5	1.0	0.015	0.015	0.5	0.2	Rem	0.2	0.4	0.04	24.0–26.0	–	14.0–16.0	–	0.3	–
ERNiCrMo-22	N06035	0.05	0.5	2.0	0.03	0.015	0.60	0.3	Rem	1.0	0.4	0.2	32.25–34.25	0.5	7.60–9.00	0.2	0.6	0.50
ERNiCrCoMo-1	N06617	0.05–0.15	1.0	0.3	0.03	0.015	1.0	0.50	Rem	10.0–15.0	0.8–1.5	0.60	20.0–24.0	–	8.0–10.0	–	–	0.50

Table 4.91 (2/2) Chemical composition requirements for undiluted weld metal (ASME Sec. II-C, SFA 5.14) – Cont'd

AWS classification[m]	UNS number[c]	C	Mn	Fe	P	S	Si	Cu	Ni[d]	Co	Al	Ti	Cr	Nb + Ta	Mo	V	W	Total other elements
ERNiCoCrSl-1	N12160	0.02–0.10	1.0	3.5	0.030	0.015	2.4–3.0	0.50	Rem	27.0–32.0	0.40	0.20–0.60	26.0–29.0	0.30	0.7	–	0.5	0.50
ERCiCrWMo-1[h,i]	N06231	0.05–0.15	0.3–1.0	3.0	0.03	0.015	0.25–0.75	0.50	Rem	5.0	0.2–0.5	–	20.0–24.0	–	1.0–3.0	–	13.0–15.0	0.50

Notes

[a]The weld metal shall be analyzed for the specific elements for which values are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total does not exceed the limit specified for "Total Other Elements" column of the table

[b]Single values are maximum, except where otherwise indicated that "Rem" is remainder

[c]ASTM DS-56H/SAE HS-1086, Metals & Alloys in UNS

[d]Includes incidental Cobalt (Co)

[e]Cobalt (Co) is 0.12% maximum when specified by the purchaser

[f]MIL-E-21562 grade; Tantalum (Ta) is 0.30% maximum

[g]Boron (B) is 0.006% maximum

[h]Boron (B) is 0.003% maximum

[i]Lanthanum (La) is 0.050% maximum

[j]Al + Ti is 1.5% maximum

[k]MIL-E-21562 grade; Lead (Pb) <0.010%. "Other Elements Total" shall include Lead (Pb), Tin (Sn), Zinc (Zn)

[l]MIL-E-21562 grades EN82H or RH82H; Carbon is 0.03 to 0.10%

[m]For strip, the classification designator "R" in ERxxxxx shall be replaced with "Q" as EQxxxxx

[n]Ni + Mo is 94.0 to 98.0; Tantalum (Ta) is 0.02 maximum; Zirconium (Zr) is 0.10 maximum

[o]Nitrogen (N) is 0.05 to 0.20%

[p]Boron (B) is 0.005% maximum and Zirconium (Zr) is 0.02% maximum

[q]Nitrogen (N) is 0.02 to 0.15%

[r]Boron (B) is 0.003% maximum and Zirconium (Zr) is 0.02% maximum

[s]Ta is 0.10 maximum

Table 4.92 Comparison of industrial standards (ASME Sec. II-C, SFA 5.14)

Present classification	UNS number of equivalent plate	Military designation[a]	Corresponding classification In A5.11/A5.11M	Proposed ISO designation[b]
ERNi-1	N02061	EN61 & RN61	ENI-1	SNi2061
ERNiCu-7	N04060	EN60 & RN60	ENiCu-7	SNi4060
ERNiCu-8	N05504	EN64 & RN64	_	SNi5504
ERNiCr-3	N06082	EN82 & RN82 EN82H & RN82H	ENiCrFe-3	SNi6082
ERNiCr-4	N06072	–	–	SNi6072
ERNiCr-6	N06076	EN6N & RN6N	–	SNi6076
ERNiCr-7	N06073	–	–	–
ERNiCrFe-5	N06062	EN62 & RN62	ENiCrFe-1	SNi6062
ERNiCrFe-6	N07092	EN6A & RN6A	ENiCrFe-2	SNi7072
ERNiCrFe-7	N06052	–	ENiCrFe-7	SNi6052
ERNiCrFe-7A	N06054	–	–	
ERNiCrFe-8	N07069	RN69	–	SNi7069
ERNiCrFe-11	N06601	–	–	SNi6601
ERNiCrFe-12	N06025	–	ENiCrFe-12	SNi6025
ERNiCrFe-13	N06055	–	–	–
ERNiCrFe-14	N06043	–	–	SNi6043
ERNiCrFeSi-1	N06045	–	ENiCrFeSi-1	–
ERNiCrFeAl-1	N06693	–	–	SNi6693
ERNiFeCr-1	N08065	RN65	–	SNi8065
ERNiFeCr-2	N07718	–	–	SNi7718
ERNiMo-1	N10001	–	ENiMo-1	SNi1001
ERNiMo-2	N10003	–	–	SNi1003
ERNiMo-3	N10004	–	ENiMo-3	SNi1004
ERNiMo-7	N10665	–	ENiMo-7	SNi1066
ERNiMo-8	N10008	–	ENiMo-8	SNi1008
ERNiMo-9	N10009	–	ENiMo-9	SNi1009
ERNiMo-10	N10675	–	ENiMo-10	SNi1067
ERNiMo-11	N10627	–	ENiMo-11	SNi1067
ERNiMo-12	N10242	–	–	–
ERNiCrMo-1	N06007	–	ENiCrMo-1	–
ERNiCrMo-2	N06002	–	ENiCrMo-2	SNi6002
ERNiCrMo-3	N06625	EN625 & RN625	ENiCrMo-3	SNi6625
ERNiCrMo-4	N10276	–	ENiCrMo-4	SNi6276
ERNiCrMo-7	N06455	–	ENiCrMo-7	SNi6455
ERNiCrMo-8	N06975	–	–	SNI6975
ERNiCrMo-9	N06985	–	ENiCrMo-9	SNi6985
ERNiCrMo-10	N06022	–	ENiCrMo-10	SNi6022
ERNiCrMo-11	N06030	–	ENiCrMo-11	SNi6030
ERNiCrMo-13	N06059	–	ENiCrMo-13	SNi6059
ERNiCrMo-14	N06686	–	ENiCrMo-14	SNi6686
ERNiCrMo-15	N07725	–	–	SNi7725
ERNiCrMo-16	N06057	–	–	SNi6057
ERNiCrMo-17	N06200	–	ENiCrMo-17	SNi6200
ERNiCrMo-18	N06650	–	ENiCrMo-18	SNi6650
ERNiCrMo-19	N06058	–	ENiCrMo-19	–
ERNiCrMo-20	N06660	–	–	SNi6660
ERNiCrMo-21	N06205	–	–	SNi6205
ERNiCrCoMo-1	N06617	–	ENiCrCoMo-1	SNi6617
ERNiCoCrSi-1	N12160	–	–	SNi6160
ERNiCrWMo-1	N06231	–	–	SNi6231

Notes:
[a]The requirements for the equivalent classifications shown are not necessarily identical in every respect
[b]For strip, the classification designator “R” in ERxxxxx shall be replaced with “Q” as EQxxxxx
[c]MIL-E-21562E
[d]For strip, the classification designator “S” shall be replaced with “B”

Table 4.93 (1/3) Description and intended use of welding consumables (ASME Sec. II-C, SFA 5.14)

Class	Intended use and characteristics
ERNi-1 (96Ni-3Ti) *(N02061)*	– The filler metal is intended for welding wrought and cast forms of commercially pure Ni alloy (ASTM B160, B161, B162, and B163 having UNS N02200 or N02201) to itself using the GTAW, GMAW, SAW, and PAW processes. – The filler metal contains sufficient Ti to control weld metal porosity with these welding processes.
ERNiCu-7 (65Ni-30Cu-3Mn- 2Ti) - *Alloy 400 (N04060)*	– The filler metal is used for welding Ni-Cu alloy (ASTM B127, B163, B164, and B165 having UNS N04400) to itself using the GTAW, GMAW, SAW, and PAW processes. – The filler metal contains sufficient Ti to control porosity with these welding processes.
ERNiCu-8 (66Ni-29Cu-3Al- 1Fe-0.5Ti) **Alloy 500 (N05504)**	– The filler metal is used for welding age-hardening Ni-Cu alloy (ASTM F67 and F68 having UNS N05500) to itself using the GTAW, GMAW, SAW, and PAW processes. – The filler metal will age harden on heat treatment. For specific information concerning age hardening, consult the supplier or the supplier's technical literature.
ERNiCr-3 (72Ni-20 Cr-3Mn-2.5Nb plus Ta) *Alloy 600 (N06082)*	– The filler metal is used for welding Ni-Cr-Fe alloy (ASTM B163, B166, B167, and B168 having UNS N06600) to itself, for the clad side of joints in steel clad with Ni-Cr-Fe alloy, for surfacing steel with Ni-Cr-Fe weld metal, for dissimilar welding of Ni-based alloys, and for joining steel to stainless steel or Ni-based alloys using the GTAW, GMAW, SAW, and PAW processes.
ERNiCr-4 (55Ni-44Cr) *(N06072)*	– The filler metal is used for GTAW of 50Ni-50Cr alloy, cladding Ni/Cr alloy onto Ni-Fe-Cr tubing, and casting repair. – The filler metal is resistant to high temperature corrosion, including fuel ash corrosion in atmospheres containing S and V.
ERNiCr-6 (78Ni-20Cr-1Fe- 0.4Ti) - *Alloy 600 (N06076)*	– The filler metal is used for welding Ni-Cr-Fe alloy (ASTM B163, B166, B167, and B168 having UNS N06600) to itself, for the clad side of joints in steel clad with Ni-Cr-Fe alloy, for surfacing steel with Ni-Cr-Fe weld metal, and for joining steel to Ni-based alloys using the GTAW, GMAW, SAW, and PAW processes. – Use ERNiCrFe-5 for heavy wall welding.
ERNiCr-7 (60Ni-37.6Cr-0.95Al- 0.6Nb) *Alloy 690 (N06073)*	– The filler metal is used for the overlay cladding of ferrous materials used in high temperature applications and the welding of Ni-Cr-Fe alloy (ASTM B163, B166, B167, and B168 having UNS N06690) to itself and to steels using the GTAW, GMAW, SAW, ESW, and PAW processes. – The welds are particularly resistant to high temperature oxidation, carburization, and sulfidation.
ERNiCrFe-5 (74Ni-16Cr-8Fe- 2Nb + Ta) *Alloy 600 (N06062)*	– The filler metal is used for welding Ni-Cr-Fe alloy (ASTM B163, B166, B167, and B168 having UNS N06600) to itself using the GTAW, GMAW, SAW, and PAW processes. – The higher Nb content of the filler metal is intended to minimize cracking where high welding stresses are encountered, as in thick-section base metal.
ERNiCrFe-6 (71Ni-16Cr-6Fe- 3Ti-2.5Mn) *(N06072)*	– The filler metal is used for cladding steel with Ni-Cr-Fe weld metal and for joining steel to Ni-based alloys using the GTAW, GMAW, SAW, and PAW processes. – The filler metal will age harden on heat treatment. For specific information concerning age hardening, consult the supplier or the supplier's technical literature.
ERNiCrFe-7 (60Ni-29Cr- 9Fe) *Inconel 690 (N06052)*	– The filler metal is used for welding Ni-Cr-Fe alloy (ASTM B163, B166, B167, and B168 having UNS N06690) to itself, to steels, to overlay on steels, and to weld steels clad with the Ni-Cr-Fe alloys using the GTAW, GMAW, SAW, and PAW processes.
ERNiCrFe-7A (60Ni-29Cr-9Fe- 0.75Nb) *(N06054)*	– Filler metal of this composition is used for welding Ni-Cr-Fe alloy (ASTM B163, B166, B167, and B168 having UNS N06690) to itself, to steels, and to weld overlay steels using the GTAW, GMAW, SAW, ESW, and PAW processes. – Welds made with this composition are particularly resistant to ductility dip cracking (DDC) and oxide inclusions.
ERNiCrFe-8 (73Ni-15.5Cr-7Fe-2.4Ti- 1Nb-0.7Al) *(N07069)*	– The filler metal is used for cladding steel with Ni-Cr-Fe weld metal and for joining steel to Ni-based alloys using the GTAW, GMAW, SAW, and PAW processes. – The weld metal will age harden on heat treatment. For specific information concerning age hardening, consult the supplier or the supplier's technical literature.
ERNiCrFe-11 (61Ni-23Cr-14Fe-1.4Al) *(N06601)*	– The filler metal is used for welding Ni-Cr-Fe-aluminum alloy (ASTM B166, B167, and B168 having UNS N06601) to itself and to other high temperature compositions using the GTAW process. – It is used for severe applications where the exposure temperature can exceed 1150 °C (2100 °F).
ERNiCrFe-12 (63Ni-25Cr-9.5Fe-2.1Al) *(N06025)*	– The filler metal is used for welding Ni-Cr-Fe-aluminum alloy (ASTM B163, B166, B167, B168, B366, B516, B517, B546, and B564 having UNS N06025) to itself and welding Ni-Cr-Fe to steel and to other Ni-based alloys.
ERNiFeCr-1 (42Ni-30Fe-21Cr-3Mo- 2Cu) *Alloy 825(N08065)*	– The filler metal is used for welding the Ni-Fe-Cr-Mo Cu alloy (ASTM B423 having UNS N08825) to itself using the GTAW and GMAW processes.
ERNiFeCr-2 (52Ni-18Fe-19Cr-5Nb- 3Mo-1Ti- Ta) *Alloy 718 (N07718)*	– The filler metal is used for welding Ni-Cr-Nb-Mo alloy (ASTM B637 and AMS 5589 having UNS N07718) to itself using the GTAW processes. – The weld metal will age harden on heat treatment. – For specific information concerning age hardening, consult the supplier or the supplier's technical literature.
ERNiCrFeSi-1 (46Ni-28Cr-23Fe-2.75Si) *(N06045)*	– The filler metal is used for welding Ni-Cr-Fe alloy (ASTM B163, B166, B167, B168, B366, B516, B517, B546, and B564 having UNS N06045) to itself, to steel, and to other Ni-based alloys.
ERNiCrFeAl-1 (59Ni-29Cr-4Fe-3Al) Alloy 693 *(N06693)*	– The filler metal is used for welding Ni-Cr-Fe alloy (ASTM B166, B167, and B168 having UNS N06693) to itself, to steels, and to weld overlay steels using the GTAW and GMAW processes. – Welds made with this composition are particularly resistant to metal dusting in chemical and petrochemical applications as well as resistant to carburization, sulfidation, and other high temperature corrosion forms.

The nominal composition (wt.-%) of filler metal: wt% e.g., 65 Ni, 30 Cu = 65wt%Ni + 30wt%Cu

Table 4.93 (2/3) Description and intended use of welding consumables (ASME Sec. II-C, SFA 5.14)

Class	Intended use and characteristics
ERNiMo-1 (66Ni-28Mo-5.5Fe) *(N10001)*	– The filler metal is used for welding Ni-Mo alloy (ASTM B333 having UNS N10001) to itself using the GTAW and GMAW processes.
ERNiMo-2 (71Ni-16Mo-7Cr-3Fe) *(N10003)*	– The filler metal is used for welding Ni-Mo alloy (ASTM B366, B434, and B573 having UNS N10003) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Mo weld metal using the GTAW and GMAW processes.
ERNiMo-3 (63Ni-24Mo-6Fe-5Cr) *(N10004)*	– The filler metal is used for weld repair of various Ni-, Co-, and Fe-based alloys and for dissimilar joining applications of Ni-, cobalt-, and Fe-based alloys.
ERNiMo-7 (69Ni-28Mo) *(N10665)*	– The filler metal is used for welding Ni-Mo alloy (ASTM B333 and B335 having UNS N10665) to itself and for cladding steel with Ni-Mo weld metal using the GTAW and GMAW processes.
ERNiMo-8 (70Ni-19Mo-5Fe-3W-2Cr) *(N10008)*	– The filler metal is used for welding 9% Ni steel (ASTM A333, A334, A353, and A553 having UNS K81340) to itself using the GTAW and SAW processes.
ERNiMo-9 (70Ni-20Mo-3W-1Fe) *(N10009)*	– The filler metal is used for welding 9% Ni steel (ASTM A333, A334, A353, and A553 having UNS K81340) to itself using the GTAW and SAW processes.
ERNiMo-10 (68Ni-28.5Mo-1.5Cr- 1.5Fe-low C) *(N10675)*	– The filler metal is used for welding Ni-Mo alloy (ASTM B333, B335, B366, B564, B619, B622, and B626 having UNS N10675) to itself, for welding the clad side of joints in steel clad with Ni-Mo alloy, and for welding Ni-Mo alloys to steel and to other Ni-based alloys using the GTAW, GMAW, and PAW processes.
ERNiMo-11 (67Ni-28 Mo-3Fe-1.3Cr- low C) *(N10629)*	– The filler metal is used for welding Ni-Mo alloy (ASTM specifications B333, B335, B366, B564, B619, B622, and B626 having UNS N10625) to itself, for welding the clad side of joints clad with Ni-Mo alloy, and for welding Ni-Mo alloys to steel and other Ni-based alloys using the GTAW, GMAW, and PAW processes.
ERNiMo-12 (65Ni-25Mo-8Cr) *(N10242)*	– The filler metal is used for welding Ni-Mo alloy (ASTM B366, B434, B564, B619, B622, and B626 having UNS N10242) to itself and for cladding steel with Ni-Mo weld metal using the GTAW and GMAW processes.
ERNiCrMo-1 (44Ni-22Cr-20Fe-6.5Mo- 2Nb plus Ta-2Cu-1.5Mn) *(N06007)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B581 and B582 having UNS N06007) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-2 (47Ni-22 Cr-18Fe-9 Mo- 1.5Co) *Alloy (Hastelloy)* *X (N06002)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B366, B435, and B572 having UNS N06002 & W86002) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-3 (61Ni-22Cr-9Mo-3.5Nb plus Ta) *Alloy 625 (N06625)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B443, B444, and B446 having UNS N06625) to itself, to steel, and to other Ni-based alloys, for cladding steel with Ni-Cr Mo weld metal, and for welding the clad side of joints in steel with Ni-Cr-Mo alloy using the GTAW, GMAW, SAW, and PAW processes. – This filler metal is recommended for applications where the operating temperature ranges from cryogenic to 540 °C (1000 °F).
ERNiCrMo-4 (57Ni-16Cr-15.5Mo-5.5Fe- 4W) *Alloy C-276 (N10276)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B574, B575, B619, B622, and B628 having UNS N10276) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW and GMAW processes.
ERNiCrMo-7 (65Ni-16Cr-15.5Mo-2Fe)- *Monel Filler Alloy C-4*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B574, B575, B619, B622, and B628 having UNS N06455) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-8 (50Ni-25Cr-17Fe-6Mo-1Cu) *(N06975)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B581, B582, B619, B622, and B626 having UNS N06975) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-9 (44Ni-22Cr-20Fe-7Mo- 2Co-2Cu) *(N06985)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B581, B582, B619, B622, and B626 having UNS N06007 or N06985) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-10 (56Ni-22Cr-13Mo-4Fe- 3W) *(N06022)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B574, B575, B619, B622, and B628 having UNS N06022) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-11 (43Ni-30Cr-15Fe-5Mo- 3W-2Co-2Cu) *(N06030)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B581, B582, B619, B622, and B626 having UNS N06030) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-13 (59Ni-23Cr-16Mo-1Fe, and low C) *Alloy 59 (N06059)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B564, B574, B575, B619, B622, and B626 having UNS N06059) to itself, to steel, and to other Ni-based alloys and for cladding steel using the GTAW, GMAW, SAW, and PAW processes.
ERNiCrMo-14 (57Ni-21Cr-16Mo-4W) *Alloy 686 (N06686)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B574, B575, B619, B622, and B628 having UNS N06686) to itself, to steel, and to other Ni-based alloys and for cladding steel using the GTAW, GMAW, and SAW processes.
ERNiCrMo-15 (57Ni-21Cr-8Mo-7Fe -3Nb plus Ta-1.4Ti) *Alloy 725 (N07725)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B805, having UNS N07725) to itself and for cladding steel using the GMAW and GTAW processes. The weld metal age hardens on heat treatment. For specific information concerning age hardening, consult the supplier or the supplier's technical literature.

The nominal composition (wt.-%) of filler metal: wt% e.g., 65 Ni, 30 Cu = 65wt%Ni + 30wt%Cu

Table 4.93 (3/3) Description and intended use of welding consumables (ASME Sec. II-C, SFA 5.14)

Class	Intended use and characteristics
ERNiCrMo-16 (60Ni-30Cr-10Mo) *(N06057)*	– The filler metal is used for corrosion-resistant (especially excellent to crevice corrosion) overlaying by the GTAW, GMAW, and PAW processes.
ERNiCrMo-17 (59Ni-23Cr-16Mo-1.6Cu) *(N06200)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B574, B575, B619, B622, and B629 having UNS N06200) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-18 (50Ni,-20Cr-1.5Mo -14Fe-1.5W) *(N06650)*	– The filler metal is used for welding Ni-Cr-Mo alloys having UNS N06650 to itself, to steel, to SASS, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-19 (58Ni-21Cr-20Mo-1Fe) *(N06058)*	– The filler metal is used for welding Ni-Cr-Mo alloy (ASTM B574, B575, B366, B564, B619, B622, and B626 having UNS N06058) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrMo-20 (64Ni-22Cr- 9Mo-Nb free) *(N06660)*	– The properties of this filler metal are suitable to weld SDSS for low temperature applications with high-impact toughness. Filler metal of this composition is used for welding of Ni-Cr-Mo alloys of similar composition as well as for cladding using GTAW, GMAW, SAW, and PAW processes.
ERNiCrMo-21 (55Ni-25Cr-15Mo-1Fe) *(N06205)*	– The filler metal is used for welding of Ni-Cr-Mo alloys (ASTM B574, B575, B366, B564, B619, B622, and B626 having UNS N06205) to itself, to steel, and to other Ni-based alloys and for cladding steel with Ni-Cr-Mo weld metal using the GTAW, GMAW, and PAW processes.
ERNiCrCoMo-1 (53Ni-23Cr-12Co-9Mo-1Fe) *Alloy 617(N06617)*	– The filler metal is used for welding Ni-Cr-Co-Mo alloy (UNS N06617) to itself using the GTAW and GMAW processes.
ERNiCoCrSi-1 (38Ni-30Co-28Cr-2.8Si-1Fe) *(N12160)*	– The filler metal is used for welding Ni-Co-Cr-Si alloy (ASTM B435, B572, B619, and B626 having UNS N12160) to itself using the GTAW, GMAW, and PAW processes. – This alloy is sensitive to iron (Fe) pickup; therefore, its use is not recommended for the welding of the Ni-Co-Cr-Si alloy to Fe-based alloys.
ERNiCrWMo-1 (57Ni-22 Cr-14W-2Co-2Fe -2Mo) *Alloy 230 (N06231)*	– The filler metal is used for welding Ni-Cr-W-Mo-La (lanthanum) alloy (ASTM B366, B435, B564, and B572 having UNS N06230) to itself using the GTAW and GMAW processes.

The nominal composition (wt.-%) of filler metal: wt% e.g., 65 Ni, 30 Cu = 65wt%Ni + 30wt%Cu

Table 4.94 Typical tensile strengths of weld metal (ASME Sec. II-C, SFA 5-14)

AWS classification	Tensile strength (typical)		AWS classification	Tensile strength (typical)	
	ksi	MPa		ksi	MPa
ERNi-1	55	380	ERNiMo-10	110	760
ERNiCu-7	70	480	ERNiMo-11	100	690
ERNiCu-8	800[b]	690[b]	ERNiMo-12	100	690
ERNiCr-3	80	550	ERNiCrMo-1	85	590
ERNiCr-4	100	690	ERNiCrMo-2	95	660
ERNiCr-6	80	550	ERNiCrMo-3	110	760
ERNiCrFe-5	80	550	ERNiCrMo-4	100	690
ERNiCrFe-6	80	550	ERNiCrMo-7	100	690
ERNiCrFe-7	80	550	ERNiCrMo-8	85	590
ERNiCrFe-7A	85	590	ERNiCrMo-9	85	590
ERNiCrFe-8	125[c]	860[c]	ERNiCrMo-10	100	690
ERNiCrFe-11	94	650	ERNiCrMo-11	85	590
ERNiCrFe-12	95	660	ERNiCrMo-13	110	760
ERNiCrFeSi-1	90	620	ERNiCrMo-14	110	760
ERNiCrFeAl-1	85	590	ERNiCrMo-15	174[e]	1200[e]
ERNiFeCr-1	80	550	ERNiCrMo-16	85	590
ERNiFeCr-2	165[d]	1140[d]	ERNiCrMo-17	100	690
ERNiMo-1	100	690	ERNiCrMo-18	95	660
ERNiMo-2	100	690	ERNiCrMo-19	120	830
ERNiMo-3	100	690	ERNiCrMo-20	110	830
ERNiMo-7	110	760	ERNiCrMo-21	115	780
ERNiMo-8	95	660	ERNiCrCoMo-1	90	620
ERNiMo-9	95	660	ERNiCrWMo-1	110	760

Notes

[a]Tensile strength in the as-welded condition, unless otherwise specified

[b]Age-hardened condition: Heat treated at 802 °C (1475 °F) for 2 hours plus 593 °C (1100 °F) for 16 hours, then furnace cooled at 14 °C (25 °F) per hour to 482 °C (900 °F), and then air cooled

[c]Age-hardened condition: Heat treated at 1066 °C (1950 °F) for 2 hours plus 704 °C (1300 °F) for 20 hours, and then air cooled

[d]Age-hardened condition: Heat treated at 718 °C (1325 °F) for 8 hours, then furnace cooled to 620 °C (1150 °F) at 56 °C (100 °F) per hour, held for 8 hours, and then air cooled

[e]Age-hardened condition: Heat treated at 1038 °C (1900 °F) for 1 hour plus 732 °C (1350 °F) for 8 hours, then furnace cooled at 56 °C (100 °F) per hour to 621 °C (1150 °F) and held for 8 hours, and then air cooled

Table 4.95 Nickel-based welding electrodes in sulfur and non-sulfur environments (API RP582, Table 2)

ASME/AWS filler material class.	Max. design temperature (non-sulfur environment)	Max. design temperature (sulfur environment)
ENiCrFe-3 [Alloy 182] *[W86182]*	540 °C (1000 °F)	370 °C (700 °F)
ERNiCr-3 [Alloy 82], ENiCrFe-2 [Alloy 152] *[N06082]*	760 °C (1400 °F)	400 °C (750 °F)
ERNiCrMo-3, ENiCrMo-3 [Alloy 625] *[N06625]*	590 °C (1100 °F)	480 °C (900 °F)

Notes
1. Comparable FCAW consumables may be applied for DMW application provided they are approved by the purchaser
2. Definition of sulfidation (or sulfidic corrosion): It may occur at 230–540 °C (450–1000 °F). See API RP939-C

Commentary for current API RP582
(a) Nickel alloys can be subject to sulfidation at high temperature so that the maximum design temperature should be limited in sulfur environment. See Table 2.16 in this book for more information
(b) See Table 2.13 in this book for limits of service temperature of nickel alloys in non-corrosive service
(c) API RP939-C indicates that a threshold limit for sulfur content is not provided because within the past decade significant corrosion has occurred in the reboiler/fractionator sections of some hydroprocessing units at sulfur or H_2S levels as low as 1 ppm, and nickel-based alloy corrosion is excluded from the scope of API RP939-C

Table 4.96 Welding electrodes of nickel based alloys - pipes, forgings, fittings, and castings

Alloy	UNS no.	ASTM plate spec	A5.11 (SMAW)		A5.9 (GTA,GMA,PA,SA,ES,EG)		A5.14 (GTA,GMA,PA,SA)	
			Class	UNS no.	Class	UNS no.	Class	UNS no.
200 (Nickel 200)	N02200	B162	ENi-1	W82141	–	–	ERNi-1	N02061
(Nickel 201)	N02201	B162	ENi-1	W82141	–	–	ERNi-1	N02061
(CZ-100)	N02100	A494	ENi-1	W82141	–	–	ERNi-1	N02061
N (Alloy 400)	N04400	B127	ENiCu-7	W84190	–	–	ERNiCu-7	N04060
(R-405/ M35–1)	N24135	A494	ENiCu-7	W84190				
X	N06002	B435	ENiCrMo-2	W86002	–	–	ERNiCrMo-2	N06002
C-22[*B*]	N06022	B575	ENiCrMo-10	W86022	–	–	ERNiCrMo-10	N06022
(CX2MW)	N26022	A494	ENiCrMo-10	W86022	–	–	ERNiCrMo-10	N06022
C-2000[*B*]	N06200	B575	ENiCrMo-17[*C*]	W86200C	–	–	ERNiCrMo-17[*C*]	N06200[c]
C-30[*B*]	N06030	B582	ENiCrMo-11	W86030	–	–	ERNiCrMo-11	N06030
230[*B*]	N06230	B435	ENiCrWMo-1[*C*]	W86231C	–	–	ERNiCrWMo-1	N06231
600 (Alloy 600)	N06600	B168	N/A[*D*]	–	–	–	ERNiCr-3	N06082
(CY-40)	N06040	A494	ENiCrFe-3	W86182	–	–	ERNiCr-3	N06082
601	N06601	B168	[*E*]	–	–	–	*E*	–
625 (Alloy 625)	N06625	B443	ENiCrMo-3	W86112	–	–	ERNiCrMo-3	N06625
(CW6MC)	N26625	A494	ENiCrMo-3	W86112	–	–	ERNiCrMo-3	N06625
(Alloy 690)	N06690	B167	Inconel® WE152		–	–	Nicrofer® FM 52	
(Alloy 59)	N06059	B462	VDM 2.4609	N06059			(or ERNiFeCr-1)	
G-3	N06985	B582	ENiCrMo-9	W86985	–	–	ERNiCrMo-9	N06985
(G-30)	N06030	B462	ENiCrMo-11	W86030	–	–	ERNiCrMo-11	N06030
20Cb	N08020	B463	–	–	ER320(LR)	N08021 (N08022)	–	–
Cr-Ni-Fe-Mo-Cu	N08024	B463	N/A[*D*]	–	–	–	N/A[*D*]	–
20Mo6[*F*]	N08026	B463	ENiCrMo-3	W86112	–	–	ERNiCrMo-3	N06625
825 (Alloy 825)	N08825	B424	ENiCrMo-3[*G*] (or Inconel® WE152)	W86112	–	–	ERNiCrMo-3[*G*] (or ERNiFeCr-1)	N06625
Alloy C-22 & 622	N06022	B366	ENiCrMo-10	W86022	–	–	ERNiCrMo-10	N06022
C-276	N10276	B575	ENiCrMo-4	W80276	–	–	ERNiCrMo-4	N10276
(CW2M)	N26455	A494	ENiCrMo-4	W80276	–	–	ERNiCrMo-4	N10276
(Alloy 686)	N06686	B564	Inco-Weld® WE 686 CPT		–	–	Inco-Weld® FM 686 CPT	
B-2	N10665	B333	ENiMo-7	W80665	–	–	ERNiMo-7	N10665
B-3[*B*] (Ally B-3)	N10675	B333	ENiMo-10 (ENiMo-7)	W80875	–	–	ERNiMo-10 (ERNiMo-7)	N10675
(B-4)	N10629	B462	ENiMo-7	W80665	–	–	ERNiMo-7	N10665
(N-7 M)	N30007	A494	ENiMo-7	W80665	–	–	ERNiMo-7	N10665

Filler metal classification and UNS designation[A] for applicable AWS specification (Source: ASTM B474 Pipes, Table 2 and NiDI Reference Book No.11012, Table 5) – ( ) from NiDI, *WE* welding electrode, *FM* filler metal
Notes – from ASTM B474, Table 2

[A]New designation established in accordance with ASTM E527 and SAE J 1086, Practice for Numbering Metals and Alloys (UNS)
[B]Registered Trademark of Haynes International
[C]Approved by AWS but not published
[D]No AWS classification existed at the time of this writing – consult material manufacturer for recommended filler metal
[E]Filler metal used is highly dependent on intended service temperature – consult material manufacturer for specific filler metal for end use temperature
[F]Registered Trademark of Carpenter Steel
[G]Recommended filler metal – this material is highly dependent on intended service temperature for best filler metal selection; consult material manufacturer for specific filler metal given the end use temperature
Notes – from NiDI Reference Book Series No.11012, Table 5
[H]SMAW is preferable
[I]Group D – Precipitation hardening alloys. Contact the base metal producers for filler recommendations
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The heat-treatable aluminum alloys are somewhat more metallurgically complex and more sensitive to "hot short" cracking, which results from heat-affected zone (HAZ) liquidation during the welding operation. In general, a dissimilar alloy filler having higher levels of solute (e.g., copper or silicon) is used in this case.

Mercury (Hg) embrittlement normally involves penetration of the liquid metal along the grain boundaries of the structural alloy and consequent loss of structural strength and ductility. Finally, it results in the brittle failure of a normally ductile metal alloy in the presence of tensile stress (either applied or residual) and a specific liquid metal. Temperature, stress, and good liquid metal wetting are the principal factors that influence mercury embrittlement in a specific alloy/liquid metal couple. Removal of any one of these factors eliminates the risk of mercury embrittlement. The most common case of mercury embrittlement is in aluminum alloy welds (HAZ).

The mercury in aluminum alloys of LNG/ammonia/ethylene industry facilities is normally controlled max. 0.01 μg/Nm^3 in a gas stream to avoid this embrittlement. See Sect. 2.3.6 for LME-general.

Figures 4.70 and 4.71 show the typical phenomena of mercury embrittlement in aluminum alloy welding.

Table 4.97 (1/2) Welding electrodes in dissimilar welding of nickel alloys

SMAW Electrodes (below highlighted diagonal) **GMAW/GTAWAW Filler Metals (above highlighted diagonal)**

Alloys	Nickel 200	Alloy 400	Alloy 600	Alloy 625	Alloy 686	Alloy 800 and 800H/HT	Alloy 825	Carbon, Low alloy & Nickel Steels	3 - 30% Chromium Steels	Austenitic Stainless Steels	Duplex and Super Duplex Stainless Steels	Cast High-Temperature Alloys	Copper-Nickel Alloys
Nickel 200	Nickel 61 Nickel 141	MONEL 60 Nickel 61	INCONEL 82 Nickel 61	INCONEL 625 INCONEL 82 Nickel 61	I-W 686CPT INCONEL 625 INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	INCONEL 625 INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	I-W 686CPT INCONEL 82	INCONEL 82 Nickel 61	MONEL 60 MONEL 67 Nickel 61
Alloy 400	MONEL 190 Nickel 141	MONEL 60 INCONEL 625 INCONEL 112 MONEL 190	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 Nickel 61	I-W 686CPT INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 MONEL 60	INCONEL 625 INCONEL 82 MONEL 60	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	MONEL 60 MONEL 67 Nickel 61
Alloy 600	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 82 INCO-WELD A INCONEL 182	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
Alloy 625	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 625 INCONEL 112	I-W 686CPT INCONEL 625	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 625	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 Nickel 61
Alloy 686	INCO-WELD A I-W 686CPT Nickel 141	I-W 686CPT INCO-WELD A INCONEL 112	INCO-WELD A INCONEL 82 I-W 686CPT	I-W 686CPT INCONEL 112	I-W 686CPT I-W 686CPT	I-W 686CPT INCONEL 617 INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT	I-W 686CPT INCONEL 617 INCONEL 82	I-W 686CPT INCONEL 625 Nickel 61
Alloy 800 and 800H/HT	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 117 INCONEL 182	INCO-WELD A I-W 686CPT	INCONEL 617 INCONEL 82 INCO-WELD A INCONEL 117	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
Alloy 825 & Super ASS	INCO-WELD A Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 112 INCONEL 122 I-W 686CPT	I-W 686CPT INCONEL 112 INCONEL 122	INCO-WELD A INCONEL 112	INCONEL 625 I-W 686CPT INCONEL 112 I-W 686CPT	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 622	INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
Carbon Low alloy & Nickel Steels	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182 MONEL 190	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 112 INCO-WELD A	INCO-WELD A I-W 686CPT INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 625 INCONEL 82 INCO-WELD A INCONEL 112	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61

Source: Special Metals Joining Manual, 2011

Table 4.97 (2/2) Welding electrodes in dissimilar welding of nickel alloys

SMAW Electrodes (below highlighted diagonal) **GMAW/GTAWAW Filler Metals (above highlighted diagonal)**

Alloys	Nickel 200	Alloy 400	Alloy 600	Alloy 625	Alloy 686	Alloy 800 and 800H/HT	Alloy 825	Carbon, Low alloy & Nickel Steels	3 - 30% Chromium Steels	Austenitic Stainless Steels	Duplex and Super Duplex Stainless Steels	Cast High-Temperature Alloys	Copper-Nickel Alloys
3 - 30% Chromium Steels	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCONEL 112 INCO-WELD A	INCO-WELD A I-W 686CPT INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112	INCONEL 625/52 INCONEL 82 INCO-WELD A INCONEL 112/152	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 INCONEL 617	INCONEL 82 Nickel 61
Austenitic Stainless Steels	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 190	INCO-WELD A INCONEL 112 INCONEL 117 INCONEL 182	I-W 686CPT INCONEL 112	INCO-WELD A I-W 686CPT INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	I-W 686CPT INCONEL 82/625 I-W A/686CPT INCONEL 112	I-W 686CPT INCONEL 82	INCONEL 82	INCONEL 82 Nickel 61
Duplex and Super Duplex Stainless Steels	I-W 686CPT INCO-WELD A Nickel 141	I-W 686CPT INCO-WELD A	I-W 686CPT INCO-WELD A	I-W 686CPT INCONEL 112	I-W 686CPT	I-W 686CPT INCO-WELD A	I-W 686CPT INCONEL 112	I-W 686CPT INCO-WELD A	I-W 686CPT INCO-WELD A	I-W 686CPT INCO-WELD A	I-W 686CPT I-W 686CPT	I-W 686CPT INCONEL 82	I-W 686CPT INCONEL 82
Cast High-Temperature Alloys	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182 MONEL 190	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 117	I-W 686CPT INCONEL 117	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 112	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 117	I-W 686CPT INCO-WELD A	INCONEL 617 INCONEL 82 INCO-WELD A INCONEL 117	INCONEL 82 Nickel 61
Copper-Nickel Alloys	MONEL 187 MONEL 190 Nickel 141	MONEL 187 MONEL 190 Nickel 141	INCO-WELD A MONEL 182 Nickel 141	INCO-WELD A MONEL 112 Nickel 141	I-W 686CPT Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 182 INCONEL 190 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	I-W 686CPT INCO-WELD A	INCO-WELD A INCONEL 182 Nickel 141	MONEL 67 MONEL 187

Source: Special Metals Joining Manual, 2011

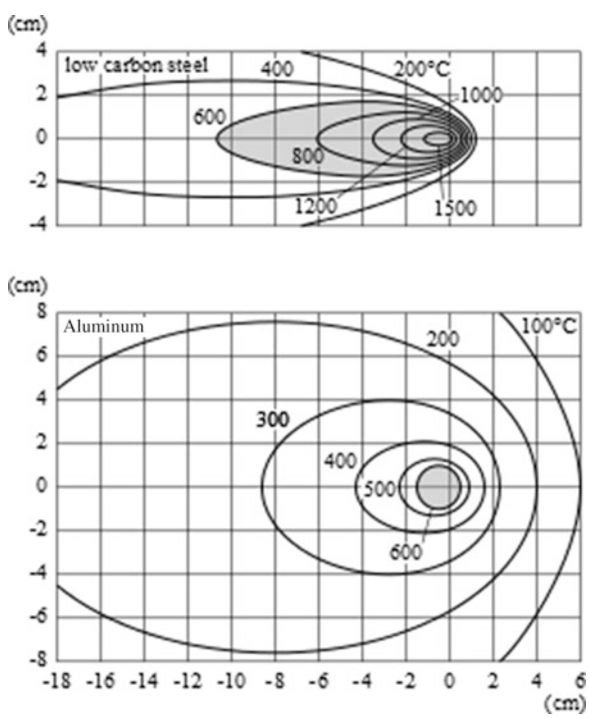


Figure 4.64 Isothermal curves of CS and aluminum due to different thermal conductivity. (Source: ISF report, 2010)

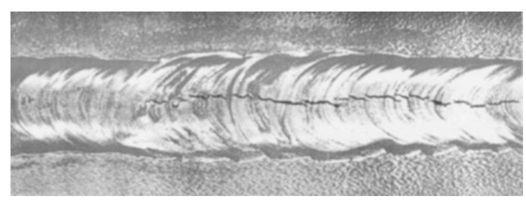


Figure 4.65 Hot crack in aluminum alloy welding. (Source: ISF report, 2010)

(a) *The high-purity Al 1xxx series alloys and Al 3003* are easy to weld with a base alloy filler, Al 1100 alloy, or an aluminum – silicon alloy filler, such as Al 4043.
(b) *Al 2219* exhibits the best weldability of the Al 2xxx series base alloys and is easily welded with Al 2319, Al 4043, and Al 4145 fillers.
(c) *Aluminum-silicon-copper filler alloy Al 4145* provides the least susceptibility to weld cracking with 2xxx series wrought copper-bearing alloys, as well as aluminum-copper and aluminum-silicon-copper aluminum alloy castings.
(d) The cracking of *aluminum-magnesium alloy* welds decreases as the magnesium content of the weld increases above 2%.
(e) *Al 6xxx series* base alloys are most easily welded with the aluminum-silicon type filler alloys, such as Al 4043 and Al 4047. However, the aluminum-magnesium type filler alloys can also be employed satisfactorily with the low copper-bearing 6xxx alloys when higher shear strength and weld metal ductility are required.

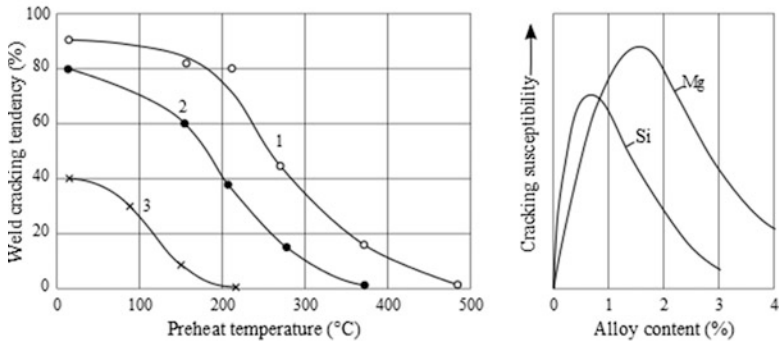


Figure 4.66 Influence of preheat temperature and Mg and Si to prevent hot crack in aluminum alloy welding. Alloy 1: AlMgMn, Alloy 2: AlMg 2,5, Alloy 3: AlMg 3,5. (Source: ISF report, 2010)

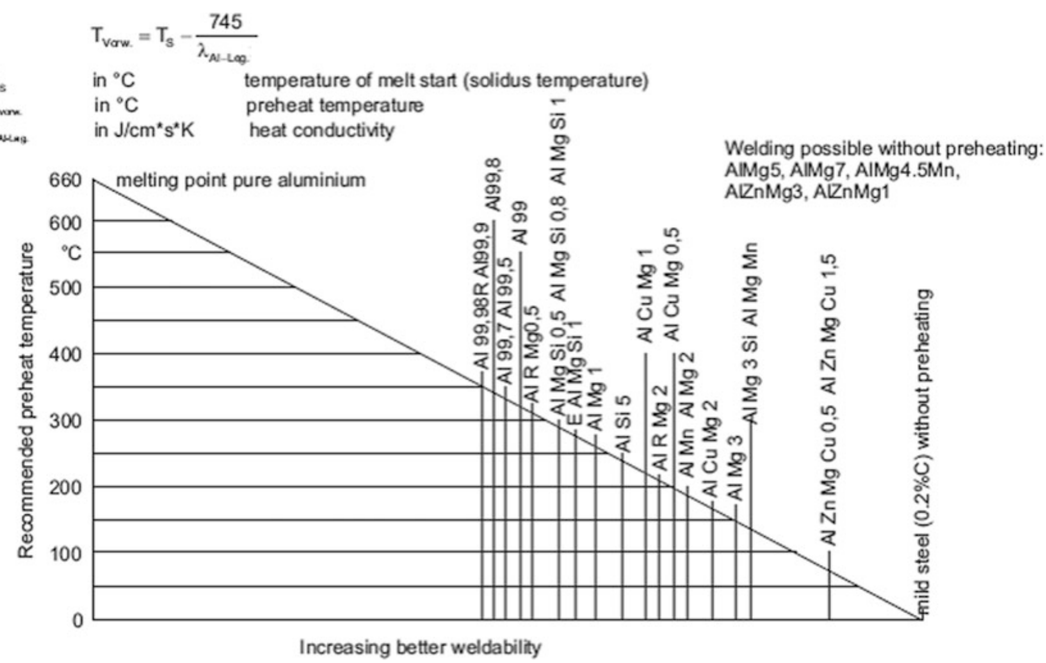


Figure 4.67 Recommended preheat by Zschötge. (Source: ISF report, 2010)

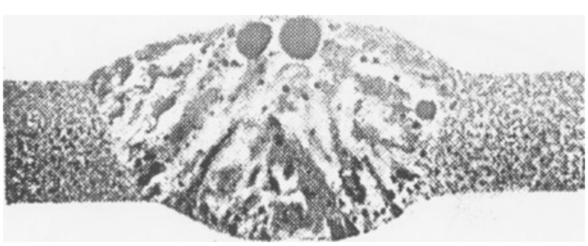


Figure 4.68 Excessive porosity in aluminum alloy welding. (Source: ISF report, 2010)

(f) *Al 7xxx series* (aluminum-zinc-magnesium) alloys exhibit a wide range of crack sensitivity during the welding. Al 7005 and Al 7039, with a low copper content (<0.1%), have a narrow melting range and can be readily joined with the high magnesium filler alloys Al 5356, Al 5183, and Al 5556. Al 7xxx series alloys that possess a substantial amount of copper, such as Al 7975 and Al 7178, have a very wide melting range with a low solidus temperature and are extremely sensitive to weld cracking when welded.

4.11.9.4 Key factors of Aluminum Filler Selection

When an aluminum filler metal is chosen, you need to ask yourself which of the variables associated with weld performance are most important. Also, you must realize selection of a filler metal not recommended for a specific application may result in inadequate service performance and possibly premature failure of the welded joint. Filler metals for welding aluminum are evaluated against the following variables:

(a) *Ease of Welding*. This is the relative freedom from weld cracking. By use of hot cracking sensitivity curves for the various aluminum alloys and through the consideration of dilution between filler metal and base metal, the filler metal/base metal crack sensitivity rating can be established.

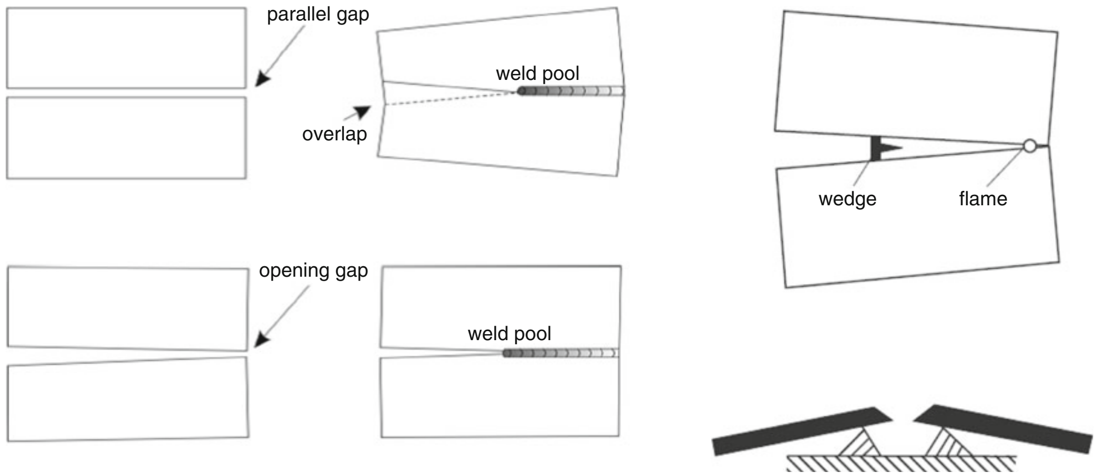


Figure 4.69 Excessive distortion and prevention on aluminum alloy welding. (Source: ISF report, 2010)

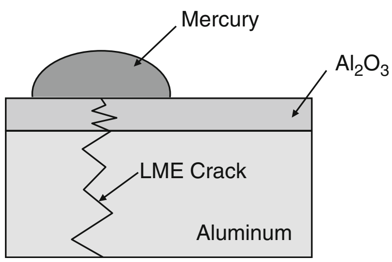


Figure 4.70 Typical phenomena of mercury embrittlement of aluminum-based alloys

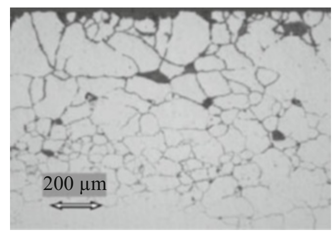


Figure 4.71 IGC Attack by mercury of Al 5083

(b) *Strength of Welded Joint*. Consideration of the tensile strength of groove welds and their strength of fillet welds, when welded with different filler metals, can prove to be extremely important during weld design. Different filler metals, which may both exceed the as-welded tensile strength of the base material, can be significantly different in shear strength performance.
(c) *Ductility*. This is consideration if forming operations are to be used during fabrication and may also be a design consideration for service if fatigue and shock loading are of importance.
(d) *Corrosion Resistance*. This is a consideration for some environmental conditions and is typically based on exposure to fresh and salt water.
(e) *Service Temperature*. The reaction of some filler metals at sustained elevated temperatures (above 150 °F). This may promote premature component failure due to stress corrosion cracking.
(f) *Color Match*. Base metal and filler metal color match after anodizing can be of major concern in some cosmetic applications.
(g) *PWHT*. The ability of the filler metal to respond to postweld heat treatment associated with filler metal chemistry and joint design.
(h) *Sensitivity to Weld Cracking*.

4.11.9.5 Recommended Filler Metals for Welding of Aluminum

Table 4.98 shows the recommendable filler metals for dissimilar joints of several aluminum alloys.

4.11.10 Welding of Copper and Copper-Based Alloys

Table 4.99 shows the weldability per welding processes of several copper alloys.

Table 4.100 shows the recommendable filler metals for fusion welding of several copper alloys.

See Sect. 4.12.3.11 in this book for heat treatment of copper alloys.

References

– Welding Handbook. Welding Copper and Copper Alloys, AWS, 1997

Table 4.98 Filler metal selection for dissimilar joints of aluminum-based alloys

Base metal Group A	Group B						
	Same Group A metal	7005	6006 [3], 6061, 6082	5154A 5454	5083 5086	5052 5251	5005 5050A
1050 [4]	1100 [7]	5356 [7]	4043	4043 [9]	5356 [7]	4043 [9]	4043 [9]
5005, 5050A	4043 [8,9]	5356 [9]	4043 [6]	5356 [6]	5356 [9]	4043 [9]	4043 [9]
5052, 5251	5356 [5,6,7]	5356 [9]	5356 [6,7]	5356 [6]	5356 [6]		
5083	5183 [9]	5183 [9]	5356 [9]	5356 [6]			
5086	5356 [9]	5356 [9]	5356 [9]	5356 [6]			
5154A, 5383	5356 [5,6,8] 5183 [9]	5356 [6] 5183 [9]	5356 [6,7] 5356 [9]	5356 [6] 5356 [9]			
5454	5554 [7,9,11]	5356 [6]	5356 [6,7]				
6060 [3], 6061, 6082	4043 [6]	5356 [6,7]					
7005	5356 [9,10]						

Source: WTIA (Welding Technology Institute of Australia), Technical Report and ASME Sec. II-part C, SFA 5.10, Table A.1

Notes

[1] Service conditions such as immersion in fresh or salt water, exposure to specific chemicals, or a sustained high temperature (over 65 °C/149 °F) may limit the choice of filler metals. Filler metals Al 5356, 5183, 5556, and 5654 are not recommended for sustained temperature service over 65 °C (149 °F)

[2] Recommendations in the main body of this table are the preferred choice and apply for most applications. See ASME Sec. II-part C, SFA 5.10(M), Table A.1 for more detailed information

[3] Other alloys in this group include: Al 6005A, 6101, 6106, and 6261

[4] Other alloys in this group include: Al 1080A, 1150, 1350, and 3203

[5] Al 5654 filler is used for welding base metal alloys for low temperature hydrogen peroxide service (less 65 °C/149 °F)

[6] Al 5183, 5356, 5554, 5556, and 5654 may be used. Al 5554 is only 5xxx series filler alloy listed suitable for service temperature over 65 °C (149 °F)

[7] Al 4043 may be used

[8] Filler metal with the same analysis as the base metal may be used

[9] Al 5183, 5356, or 5556 may be used

[10] Al 5039 is preferred but not readily available

[11] Al 5554 is only Al 5xxx series filler alloy listed suitable for service temperatures over 65 °C (149 °F)

Table 4.99 Applicable joining processes for copper and copper-based alloys

Copper alloy	UNS No.	OGW	SMAW	GMAW	GTAW	ERW	Solid-state welding	Brazing	Soldering	EBW
ETP copper	C11000-C11900	NR	NR	F	F	NR	G	E	G	NR
Oxygen-free copper	C10200	F	NR	G	G	NR	E	E	E	G
Deoxidized copper	C12000-C12300	G	NR	E	E	NR	E	E	E	G
Beryllium copper	C17000-C17500	NR	F	G	G	F	F	G	G	F
Cadmium-chromium copper	C16200/C18200	NR	NR	G	G	NR	F	G	G	F
Red brass – 85%	C23000	F	NR	G	G	F	G	E	E	–
Low brass – 80%	C24000	F	NR	G	G	G	G	E	E	–
Cartridge brass- 70%	C26000	F	NR	F	F	G	G	E	E	–
Leaded brass	C31400-C38590	NR	NR	NR	NR	NR	NR	E	G	–
Phosphor bronze	C50100-C52400	F	F	G	G	G	G	E	E	–
70Cu-30Ni	C71500	F	F	G	G	G	G	E	E	F
90Cu-10Ni	C70600	F	G	E	E	G	G	E	E	G
Nickel silver	C75200	G	NR	G	G	F	G	E	E	–
Aluminum bronze	C61300 C61400	NR	G	E	E	G	G	F	NR	G
Silicon bronze	C65100 C65500	G	F	E	E	G	G	E	G	G

Source: AWS Welding Handbook, Copper Alloys

Abbreviation: *OGW* oxyfuel gas welding, *SMAW* shield metal arc welding, *GMAW* gas metal arc welding, *GTAW* gas tungsten arc welding, *ERW* electric resistance welding, *EBW* electron beam welding, *E* excellent, *G* good, *F* fair, *NR* not recommended

Table 4.100 Filler metals for fusion welding of several copper alloys

AWS classification		Common name	Base metal applications	Remark
Covered electrode[a]	Bare wire[b]			
ECu	ERCu	Copper	Coppers	Marine applications Good resistance to the corrosive effects of sea water. ECuNi: Used for the clad side of copper-nickel clad steels
ECuSi	ERCuSi-A	Silicon bronze	Silicon bronzes, brasses	
ECuSn-A	ERCuSn-A	Phosphor bronze	Phosphor bronzes, brasses	
ECuSn-C	ERCuSn-A	Phosphor bronze	Phosphor bronzes, brasses	
ECuNi	ERCuNi	Copper-nickel	Copper-nickel alloys	
ECuAl-A2	ERCuAl-A1	Aluminum bronze	Aluminum bronzes, brasses, silicon bronzes, manganese bronzes	
	ERCuAl-A2	–	–	
ECuAl-B	ERCuAl-A3	Aluminum bronze	Aluminum bronzes	
ECuNiAl	ERCuNiAl	–	Nickel-aluminum bronzes	
ECuMnNiAl	ERCuMnNiAl	–	Manganese-nickel aluminum bronzes	
	RBCuZn-A	Naval Brass	Brasses, coppers	
	RBCuZn-B	Low-fuming Brass	Brasses, manganese bronzes	
	RBCuZn-C	Low-fuming Brass	Brasses, manganese bronzes	
	RBCuZn-D	–	Nickel-silvers	

Source: AWS Welding Handbook, Copper Alloys
Notes
[a]See ANSI/AWS A5.6, Specification for Covered Copper and Copper Alloy Arc Welding Electrodes
[b]See ANSI/AWS A5.7, Specification for Covered Copper and Copper Alloy Bare Welding Rods and Electrodes, and ANSI/AWS A5.8, Specification for Filler Metals for Brazing and Braze Welding

Table 4.101 Welding electrodes for titanium and titanium-based alloy welded pipes (ASTM B862, Table 5)

Base metal	Filler metal	Base metal	Filler metal	Base metal	Filler metal
Gr. 1	ERTi-1	Gr. 15	ERTi-15	Gr. 26	ERTi-26 or ERTi-7
Gr. 2	ERTi-2	Gr. 16	ERTi-16 or ERTi-7	Gr. 26H	ERTi-26 or ERTi-7
Gr. 2H	ERTi-2	Gr. 16H	ERTi-16 or ERTi-7	Gr. 27	ERTi-27 or ERTi-11
Gr. 3	ERTi-3	Gr. 17	ERTi-17 or ERTi-11	Gr. 28	ERTi-28
Gr. 5	ERTi-5	Gr. 18	ERTi-18	Gr. 29	ERTi-29
Gr. 7	ERTi-7	Gr. 19	ERTi-19	Gr. 32	ERTi-33
Gr. 7H	ERTi-7	Gr. 20	ERTi-20	Gr. 33	ERTi-33
Gr. 9	ERTi-9	Gr. 21	ERTi-21	Gr. 34	ERTi-34
Gr. 11	ERTi-11	Gr. 22	ERTi-22	Gr. 35	ERTi-35
Gr. 12	ERTi-12	Gr. 23	ERTi-23	Gr. 38	ERTi-38
Gr. 13	ERTi-13	Gr. 24	ERTi-24		
Gr. 14	ERTi-14	Gr. 25	ERTi-25		

General Note: ERTi-XX Filler metal grades as listed in AWS A5.16/A5.16M

4.11.11 Welding of Titanium and Titanium-Based Alloys

Titanium and its alloys shall not be welded to other materials (ASME Sec. VIII, Div. 1, UNF-19). For vessels constructed of titanium and its alloys, all joints of Categories A and B shall be of Joint Type No. (1) or No. (2) of Table 1.54 in this book (ASME Sec. VIII, Div. 1, UNF-19). Table 4.101 shows the recommendable filler metals for welding of several titanium alloys.

Meanwhile the titanium welds can be readily discolored. The tempering colors are showed in Fig. 2.102. See Fig. 4.7 for titanium cladding details and Sect. 4.12.3.13 in this book for heat treatment of titanium alloys.

4.11.12 Welding of Zirconium and Zirconium-Based Alloys

Zirconium and its alloys shall not be welded to other materials (ASME Sec. VIII, Div. 1, UNF-19). For vessels constructed of zirconium and its alloys, all joints of Categories A and B shall be of Joint Type No. (1) or No. (2) of Table 1.54 in this book (ASME Sec. VIII, Div. 1, UNF-19). Zirconium alloys are readily welded utilizing practical inert gas fusion welding techniques in similar weld metal joints, but require extra attention to cleanliness and inert gas shielding to protect the weld surface, weld root, and adjacent hot metal from foreign materials and atmospheric contamination during welding and until the weld metal cools from its 1835 °C (3334 °F) melting point to less than *333* °C (600 °F) because molten zirconium reacts with and is embrittled by most materials including organic and inorganic compounds, iron, and most other metals. Under the influence of welding heat, surface contaminants left by inadequate cleaning of the metal surface are volatized and absorbed by the weld pool. This is evident by visual inspection as a bright silver line immediately adjacent to the weld toe with a dark brown or gray fringe just beyond it. The used shielding gases for welding are typically similar with those for titanium alloys.

The most common process used for zirconium alloy welding is GTAW. GTAW manual allows all-position welding of any configuration the torch can access. GTAW automatic usually is limited to flat or horizontal positions. Tube-to-tubesheet of heat exchangers and small pipe butt welds using automatic orbital GTAW equipment also are very common. PAW often is used for single-pass welds up to about 9 mm (3/8 in.) thick using automated equipment, copper backing bars, and square butt weld preparations. Typically, a GTAW cover pass is used to correct underfill, and the root side may require a cosmetic fusion pass or mechanical removal of excessive drop-through.

A high-current process, such as keyhole GTAW, should be considered for repetitive welding of heavy sections. Electron beam (EBW) and laser beam welding (LBW) also are suitable.

The requirements for Zr alloy clad and weld overlay processes are very similar with Fig. 4.7 for titanium cladding details. Meanwhile the zirconium welds can be readily discolored. The tempering colors are shown in Fig. 2.103. See Sect. 4.12.3.13 in this book for heat treatment of zirconium alloys.

Table 4.102 shows filler metal chemical requirements for zirconium alloys.

Zirconium alloys show typical characteristics for several welding processes in Table 4.103.

Table 4.102 Zirconium alloy filler metal chemical requirements (wt%) – ASME Sec. II, Part D, SFA-5.24

AWS class	Base metal UNS no.[2]	Wt% [1]								
		Zr + Hf	Hf	Fe + Cr	Sn	O_2 [3]	H_2 [3]	N_2 [3]	C [3]	Nb (Cb)
ERZr2	R60702	≤99.0	4.5	0.20	–	0.11–0.15	0.005	0.015	0.03	–
ERZr3	R60704	≤97.5	4.5	0.20–0.40	1.00–2.00	0.11–0.16	0.005	0.015	0.03	–
ERZr4	R60705	≤95.5	4.5	0.20	–	0.11–0.16	0.005	0.015	0.03	2.0–3.0

Notes
(1) Single values are maximum, except as noted
(2) SAE HS-1086 Metals and Alloys in the Unified Numbering System
(3) Analysis of the interstitial elements C, O, H, and N shall be conducted on samples of filler metal taken after the filler metal has been reduced to its final diameter and all processing operations have been completed. Analysis of the other elements may be conducted on these same samples or it may have been conducted on samples taken from the ingot or the rod stock from which the filler metal is made. In case of dispute, samples from the finished filler metal shall be the referee method

Table 4.103 Typical characteristics of several welding processes of zirconium alloys

Welding process	Advantage	Disadvantage
GTAW manual or auto-manual	– Universal application process (all assembly types and all positions	– Great heat input (grain enlargement deformations, shrinkage) – Necessity for protective gas device specific to each assembling configuration
GTAW manual with two operators	– Butt welding up to 6–7 mm in one pass	– Reserved for butt welding with back access possible for the second operator
GTAW manual in glove box	– No specific equipment for each type of assembly	– Difficult welding conditions (reduced visibility, stationary welder position) – Limited parts sizes (relative to the capacity of the chamber) – Preparation time
TIG manual or automatic with active solid flux	– Increase in penetration effect (possible to assemble a thickness of 7–8 mm in one pass) – Decrease in deformations and shrinkage, reduction of heat-affected zone width	– Limited to the first layer
PAW	– Reduced specific heat input (limited HAZ width, reduced deformations and shrinkage) – Increased welding speed	– Only applicable for butt welds root passes – Precision of weld preparation (machined welding edges, no gap)
EBW	– Greatly increased specific heat input, yielding little HAZ width and deformations – Very strong penetration effect (possible to assemble a thickness of 100 mm or more with only one layer)	– Stringent welding preparations – Very sophisticated positioning equipment – Limited parts sizes (relative to the capacity of the vacuum chamber

Source: Etienne, S., "Welding and Heat Treating in Zirconium Alloys: Practical Aspects and Recent Examples of Realization," Zirconium/Organics Conference, 1997. pp. 125–138

4.11.13 Welding of Tantalum Alloys

Tantalum may be welded to itself and certain other metal by resistance welding and to itself by inert gas arc welding, plasma, and electron beam welding. Acetylene torch welding is destructive to the metal. Resistance welding can be done with conventional equipment, and methods are not substantially different from those used in welding other materials. Because its melting point is 1500 °C (2700 °F) higher than that of SAE 1020 steel and its resistivity is only two-thirds that of SAE 1020 steel, tantalum requires a higher power input to accomplish a sound weld. The weld duration should be kept as short as possible in the range of one and ten cycles (60 cps) to prevent excessive external heating. Where possible, the work should be flooded with water for cooling and reduction of oxidation.

Resistance Welding Manufacturing Alliance (RWMA) Class 2 electrodes for dissimilar welding are recommended with internal water cooling. As in all resistance welding, the work must be cleaned free of dirt and oxides. The electrode contours should be kept of constant area and contour to prevent lowering of current and pressure densities. A common mistake in welding tantalum is to apply too much electrode force which causes so little interface resistance that no weld is made. Strong, ductile welds can be made by GTAW method. Extreme care must be taken to cover with an inert gas all surfaces which are raised above 316 °C (600 °F) by the welding heat; helium, argon, or a mixture of the two gases creates an atmosphere which prevents embrittlement by absorption of oxygen, nitrogen, or hydrogen into the heated metal. Where a pure, inert atmosphere is provided, the fusion and adjacent area will be ductile. Extremely high ductility can be obtained in a welding chamber which can be evacuated and purged with inert gas.

Where the use of a welding chamber is not practical, the heated surfaces can be protected by proper gas-backed fixturing. This usually serves three purposes:

(i) To hold the work in alignment.
(ii) To chill the work in order to limit the heat area.
(iii) To act as a conduit for the inert gas and to exclude air from the heat area.

Weld ductility in the order of a 180° bend over on metal thickness can be consistently accomplished where backup gas fixtures and gas-filled trailing cup are used.

References

– Weldability of tantalum alloys. Weld. J. 304-s (1972)
– Study of GTAW Procedures for Tantalum Alloy T-111 (Ta-8W-2Hf) Plate, NASA CR-121198, 1973

4.11.14 Brazing

The term brazing as used in ASME Section VIII, Div. 1, UB is defined as a group of welding processes that produce coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having liquidus above 450 °C (840 °F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction. Specific brazing processes which are permitted for use under ASME Section VIII, Div. 1, are classified by method of heating as follows:

– Torch brazing
– Furnace brazing
– Induction brazing
– Electrical resistance brazing
– Dip brazing; salt and flux bath

Even though the use of brazing process is greatly limited in the medium and high pressure/loaded facilities (see ASME Sec. VIII, Div. 1, UB-3 as well), this process shows the following advantages.

– Joint strength (but greatly lower than fusion weld joint)
– Lower temperatures/lower cost
– Maintains integrity of base metals
– Dissimilar metals easily joined
– Good joint appearance
– Operator skill easily acquired
– Process easily automated

Table 4.104 shows brazing materials selection in dissimilar welding.

Table 4.105 shows the classification of brazing flux materials and Table 4.106 shows the maximum design temperatures for brazing filler metals.

Operating temperature of facilities is dependent on the brazing filler metal as well as on the base metals being joined. The maximum allowable operating (Design) temperatures for the brazing filler metals are shown in Table 4.106.

Table 4.104 Brazing materials selection in dissimilar welding

	Al & Mg alloys	Mg & Mg alloys	Cu & Cu alloys	Carbon & low alloy steels	Cast iron	Stainless steels	Ni & Ni alloys	Ti & Ni alloys	Be, Zr, & alloys (refractory metals)	W, Mo, Ta, Cb & alloys (refractory metals)	Tool steels
Al & Al alloys	BAISi										
Mg & Mg alloys	X	BMG									
Cu & Cu alloys	X	X	BAg, BAu, BCuP, RBCuZn								
Carbon & low alloy steels	BAISi	X	BAg, BAu, RBCuZn	BAg, BAu. BCu. RBCuZn, BNi							
Cast iron	X	X	BAg, BAu, RBCuZn	BAg, RBCuZn	BAg, RBCuZn BNi						
Stainless steels	BAlSi	X	BAg, BAu.	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi					
Ni & Ni alloys	X	X	BAg, BAu RBCuZn	BAg, BAu, BCu RBCuZn, BNi	BAg, BAu, RBCuZn	BAg, BAu, RBCuZn	BAg BAu, RBCuZn				
Ti & Ti alloys	BAlSi	X	BAg	BAg	BAg	BAg	BAg	Y			
Be, Zr & alloys (refractory metals)	X BAlSi (Be)	X	BAg	BAg, BNi	BAg, BNi	BAg, BNi	BAg, BNi	Y	Y		
W, Mo, Ta, Cb & alloys (refractory metals)	X	X	BAg	BAg, BCu, BNi	BAg, BCu, BNi	BAg, BCu, BNi	BAg, BCu, BNi	Y	Y	Y	
Tool steels	X	X	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, RBCuZn, BNi	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, RBCuZn. BNi	X	X	X	BAg, BAu. BCu. RBCuZn. BNi

Source: T. Eun, Welding Materials and Codes, D.S. Publisher, 2000

Table 4.105 (1/2) Classifying brazing flux materials. AWS Brazing Handbook and A5.3 – Specification for Fluxes of Brazing and Braze Welding

AWS spec	Flux category	Form	Base materials	Filler metals	Application method	Heat source	Active temp, °C (°F)	Range, °C (°F)
FBIA	Aluminum brazing	Powder	Aluminum alloys	BAlSi	Manual	Torch, furnace	582–616 (1080–1140)	304–324 (580–615)
FBIB	Aluminum brazing	Powder	Aluminum alloys	BAlSi	Manual	Furnace	560–616 (1040–1140)	293–324 (560–615)
FBIC	Aluminum brazing	Powder	Aluminum alloys	BAlSi	Dip brazing	Salt bath	538–616 (1000–1140)	282–324 (540–615)
FB4A	Aluminum bronze	Paste	Aluminum bronze	BAg, BCuP[1]	Manual	Torch, furnace, induction	593–871 (1100–1600)	313–466 (595–870)
FB3D	High temperature brazing	Paste[2]	Copper, ferrous & nickel alloys, carbides	BAg, BCu, BNi, BAu, RBCuZn	Manual, automatic	Torch, furnace, induction	616–1204 (1400–2200)	404–652 (760–1205)
FB3I	High temperature brazing	Sluny[2]	Copper, ferrous & nickel alloys, carbides	BAg, BCu, BNi, BAu, RBCuZn	Automatic	Torch	616–1204 (1400–2200)	404–652 (760–1205)
FB3J	High-temperature brazing	Powder[2]	Copper, ferrous & nickel alloys, carbides	BAg, BCu, BNi, BAu, RBCuZn	Manual	Torch, furnace	616–1204 (1400–2200)	404–652 (760–1205)
FB3K	High temperature brazing	Flammable liquid	Copper. ferrous & nickel alloys, carbides	BAg, RBCuZn	Manual, automatic	Torch	616–1204 (1400–2200)	404–652 (760–1205)

Table 4.105 (2/2) Classifying brazing flux materials. AWS Brazing Handbook and A5.3 – Specification for Fluxes of Brazing and Braze Welding

AWS spec	Flux category	Form	Base materials	Filler metals	Application method	Heat source	Active temp, °C (°F)	Range, °C (°F)
FB2A	Magnesium brazing	Powder	Magnesium alloys	BMg	Dip brazing	Salt bath	482–621 (900–1150)	249–327 (480–620)
FB3A	Silverbrazing	Paste	Copper, ferrous & nickel alloys, carbides	BAg, BCuP[1]	Manual, automatic	Torch, induction	566–871 (1050–1600)	296–466 (565–870)
FB3C	Silverbrazing	Paste[3]	Copper, ferrous & nickel alloys, carbides	BAg, BCuP[1]	Manual, automatic	Torch, induction	566–927 (1050–1700)	296–496 (565–925)
B3E	Silverbrazing	Water base liquid	Copper, ferrous & nickel alloys, carbides	BAg, BCuP[1]	Manual, automatic	Torch, furnace	566–871 (1050–1600)	296–466 (565–870)
B3F	Silver brazing	Powder	Copper, ferrous & nickel alloys, carbides	BAg, BCuP[1]	Manual	Torch, furnace	649–871 (1200–1600)	343–466 (650–870)
B3G	Silver brazing	Slurry	Copper, ferrous & nickel alloys, carbides	BAg, BCuP[1]	Automatic	Torch	566–871 (1050–1600)	296–466 (565–870)
B3H	Silver brazing	Slurry[3]	Copper, ferrous & nickel alloys	BAg	Automatic	Torch	566–927 (1050–1700)	296–496 (565–925)

Notes
[1] Used with copper and copper-alloy base metals only
[2] May contain elemental boron or silicon dioxide
[3] Boron-modified
General Note: Pastes have high viscosities and are typically applied by brushing. Slurries have low viscosities and can be sprayed or automatically dispensed

Table 4.106 Maximum design temperatures for brazing filler metals (ASME Sec. VIII, Div. 1, Table UB-2)

Filler metal classification	Temperature, °C (°F), below which ASME Sec. IX tests only are required	Temperature, °C (°F), range requiring ASME Sec. IX and additional tests (by UB-11)
BCuP	150 (300)	150–180 (300–350)
BAg	200 (400)	200–260 (400–500)
BCuZn	200 (400)	200–260 (400–500)
BCu	200 (400)	200–340 (400–650)
BAlSi	150 (300)	150–180 (300–350)
BNi	650 (1200)	650–815 (1200–1500)
BAu	430 (800)	430–480 (800–900)
BMg	120 (250)	120–135 (250–275)

General Note: Temperatures are based on AWS recommendations

4.11.15 Weld Overlay

Solid corrosion/erosion-resistant alloy may be very expensive compared to clad or weld overlay steel. Clad also can be more expensive than weld overlay in a certain size, surface area, surface roughness, etc. The weld overlay may provide the most economic practice in moderate and thick wall base metal. See Fig. 2.107 for the lowest cost of clad options. The disadvantages are greatly rough surfaces and higher deformation compared to cladding. Figure 4.72 shows typical weld overlay surfaces in pipe and elbow. Most welding processes can be applied to weld overlay; however, SAW and ESW may provide highest productivity and lowest cost for large surface application. The strip SAW and ESW show excellent productivity compared to wire welding (see Table 4.45 and Fig. 4.44). Table 4.107 shows a general application guide for various overlay welding processes with stainless steel.

Figure 4.72 Weld overplayed surfaces in pipe and elbow

Table 4.107 Various overlay welding processes with stainless steel

Overlay welding process	Application	Remarks
Strip welding (SAW, ESW)	– Internal surfaces (pressure vessels) – End plate	– High welding efficiency (penetration ratio: 15–20% for SAW, 5–15% for ESW)
SMAW	– Wide applications	– No specific device is needed – Dilution ratio: 15–20%
GTAW	– Internal surfaces (thin or small nozzles) – TTS joints for heat exchangers	– High purity and clean weld bead – Easier to deposit low carbon steel welds. – Dilution ratio: 10–20% – A mechanized weld process is desirable for better control of penetration ratios.
PAW	– End plates of heat exchangers – Clad steels	– Welding efficiency can be improved by adopting and electricity-conveying filler wire or dual-feeding filler wire – Dilution ratio: < 5% for DCEP current, 5–10% for ordinary DCEN current – A mechanized weld process is desirable for better control of penetration ratios
GMAW-solid wire	– Internal surfaces (thin tubes or nozzles) – End plates and flange faces	– Penetration ratio: 20–30% for pulsed current – The use of a high Si wire (ER309LSi) is desirable – A mechanized weld process is desirable for better control of penetration ratios
FCAW	– Internal surfaces (thin tubes or nozzles) – End plates and flange faces – Clad plates	– Penetration ratio: 20–30% – Bead appearance can be smoother than in GMAW with solid wire – A mechanized weld process is desirable for better control of penetration ratios

Source: Kobelco report, 2010 – modified
Notes: *DCEP* direct current and electrode positive, *DCEN* direct current and electrode negative (straight polarity)

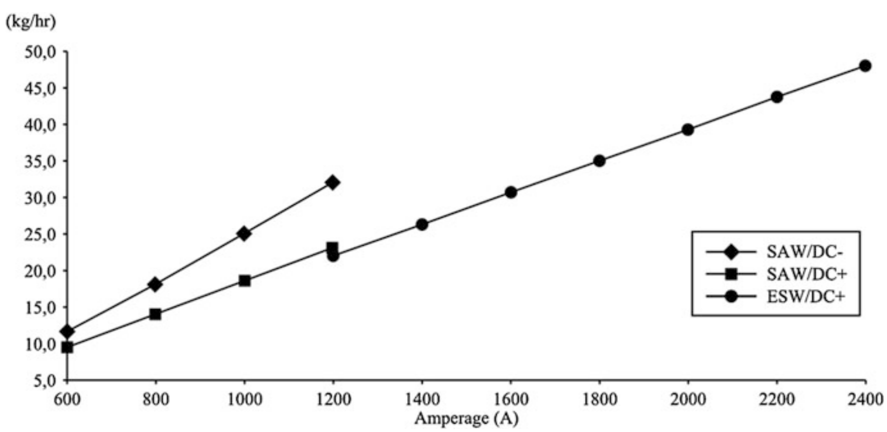


Figure 4.73 Deposition rates comparison between strip (60 × 0.5 mm) SAW and ESW. (Source: ESAB report, 2015)

The overlay chemistry requirements shall be measured at the minimum 1.5 mm (1/16 in) depth of the final deposit.

Figure 4.73 indicates the deposition rates of strip SAW and ESW per amperage. ESW normally requires higher amperage and higher deposition rate (productivity).

As there is no arc present in ESW, it shows low dilution into the base material, typically 10% while it is 20% for SAW using 60 mm width × 0.5 mm thickness strip. Figure 4.74 shows the influence of the current and the welding speed on the dilution and the thickness deposited during a 304L SS ESW welding of 60 mm width × 0.5 mm thickness strip.

See Table 4.108 for welding electrodes for SS and nickel alloy weld overlay and Table 4.109 for filler metals for weld overlay of copper alloys on carbon and low alloy steels.

Figure 4.75 shows the repair weld overlay at horizontal position with nickel alloy welding electrode on coke drum made by 1 1/4Cr Cr-1/2 Mo steels with 410S SS clad.

4.11.16 Explosion Cladding

Explosive cladding is a cold pressure weld process (at room temperature) that is used for the metallurgical joining of dissimilar metals. It is a useful method to weld metals that cannot be welded by conventional processes, such as titanium-steel, aluminum-steel, and aluminum-copper. It can also be used to weld compatible metals, such as stainless steels and nickel alloys to steel. The cladding metals are typically applied to stainless steel, duplex steel, titanium, aluminum, copper, copper alloys, nickel, nickel alloys, tantalum, and zirconium. The metal surfaces are compressed together under high pressure from the explosion, and an atomistic bonding between the dissimilar metals will be

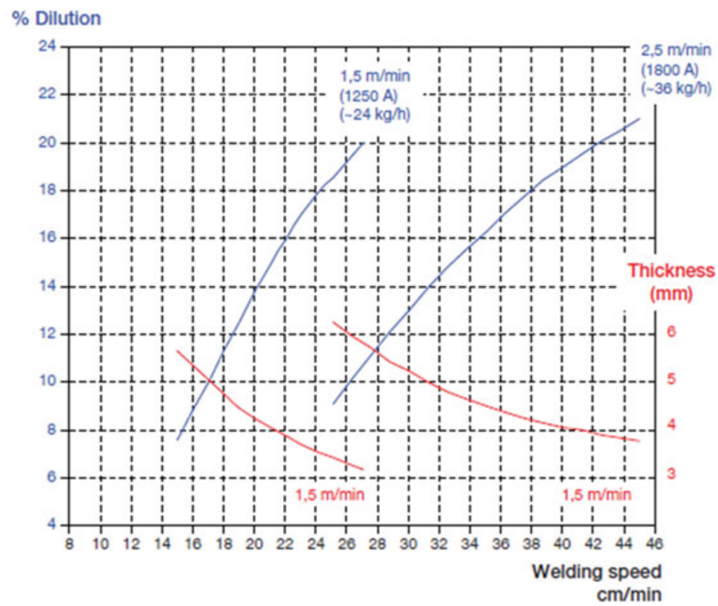


Figure 4.74 Dilution and thickness related to current and welding speed. (Source: Oerlikon report, 2017)

Table 4.108 Welding electrodes for weld overlay on CS or LAS[f]

Overlay material	Weld overlay materials[1][4]			
	Equipment requiring PWHT		Equipment not requiring PWHT[c]	
	First layer	Top layer(s)	First layer	Top layer(s)
405/410S	ENiCrFe-2 or −3 or ERNiCr-3 or E(R)309/309L[a]		ENiCrFe-2 or-3or ERNiCr-3 or E(R)309/309L[a]	
304 SS[d][e]	[2]	[2]	E(R)309	E(R)308
304 LSS[e]	E(R)309L	E(R)308L	E(R)309L	E(R)308L
316 SS[d][e]	[2]	[2]	E(R)309Mo	E(R)316
316L SS[e]	E(R)309LMo	E(R)316L	E(R)309LMo	E(R)316L
317L SS[b]	E/R309LMo	E(R)317L	E(R)309LMo	E(R)317L
321/347 SS	E(R)309L/E309Cb(Nb)	E(R)347	E(R)309L/E309Cb(Nb)	E(R)347
2205 DSS	N/A[g]	N/A[g]	E(R)2209, E(R)309L/E309LMo	[h]
2507 DSS	N/A[g]	N/A[g]	E(R)2209, DP-3W, E(R)309L/ E309LMo	[h]
Alloy 20-Cb3	E(R)320LR	E(R)320LR	E(R)320LR	E(R)320LR
Alloy 400	E(R)NiCu-7[3]	E(R)NiCu-7	E(R)NiCu-7[3]	E(R)NiCu-7
Alloy C276	ENiCrMo-4	ENiCrMo-4	ENiCrMo-4	ENiCrMo-4
Alloy C22	ENiCrMo-10	ENiCrMo-10	ENiCrMo-10	ENiCrMo-10
Alloy 600	ERNiCR-3 or ENiCRFe-2	ERNiCR-3 or ENiCRFe-2	ERNiCR-3 or ENiCRFe-2	ERNiCR-3 or ENiCRFe-2
Alloy 625	ERNiCR-3 or E(R)NiCRMo-3 or ENiCRFe-2	E(R)NiCRMo-3	ERNiCR-3 or E(R)NiCRMo-3 or ENiCRFe-2	E(R)NiCRMo-3

Source: API RP582, Table A.5 – modified

Commentary Notes: *N/A* not applicable

[a]ENiCrFe-2 (UNS W86133), ERNiCr-3 (UNS N06082), or ENiCrMo-3 (UNS W86112) is recommended for cyclic service (e.g., coke drums)

[b]For Nb (Cb)-bearing grades (e.g., 347 and 309 Nb (Cb)), the ratio Nb/C of the deposited metal should not exceed 16:1

[c]For 300 series SS, the welding consumables that are subject to PWHT shall be selected to minimize sigma phase formation during the heat treatment

[d]When the weld overlay/cladded base metal is subject to PWHT, the CRA clad materials should have low carbon (0.3% or lower) and/or stabilized elements (e.g., Ti, Nb, etc.)

[e]See Sect. 2.1.6.1 for delta ferrite control of ASS weld overlay

[f]The chemical elements required in the overlay welds should be verified by drilling samples from three separated areas of the overlay. Drillings should be to a minimum depth of 3 mm (0.125 in.) unless otherwise specified

[g]If it is to butter-weld the CS or LAS with ASS (e.g., 309L or 309L Mo) and followed by PWHT and then weld to the DSS using an applicable DSS filler metal or G. Note (h) below

[h]E(R)2209 or ENiCrMo-4/10/13/14 for 2205 DSS and E(R)2594, DP3W, or ENiCrMo-10/14 for 2507 DSS

Notes

[1]Use or this table is limited to carbon and low alloy steel backing materials

[2]E(R)308 and E(R)316 are not normally used in the PWHT'd condition. The purchaser shall approve the use of non-low carbon E(R)308 and E(R)316 in the PWHT'd condition

[3]ENi-1 or ERNi-1 may be used as an alternative

[4]Refer to the text for information on other processes

Table 4.109 Filler metals for weld overlay of copper alloys

Cladding type	For covering steel with first pass or layer		For completing the weld	
	Covered electrode[(1)]	Bare rod or electrode[(2)]	Covered electrode[(1)]	Bare rod or electrode[(2)]
70–30 copper-nickel	ECuNi	ERNiCu-7	ECuNi	RCuNi[(3)]
90–10 copper-nickel	ECuNi	ERNiCu-7	ECuNi	RCuNi[(3)]
Copper	ENi-1 ECuA1-A2	ECu, ERNiCu-7 ERNi-3, ECuAl-A1-A2	N/A N/A N/A	ECu, RCu[(3)] ECu, RCu[(3)] ECu, RCu[(3)]

Notes
[(1)]See AWS Specification A5.6
[(2)]See AWS Specification A5.7
[(3)]GTAW

Figure 4.75 Weld overlay repair welding on Cr-Mo coke drum (Horizontal SAW Process) – source: API RP572 and others

accomplished. Figure 4.76 shows the dissimilar metal combination for commercial use of explosion bonding. Most combinations are feasible, but the commercial productions have some limitations.

Figure 4.77 shows hardness change per composite thickness after explosion bonding and stress relieving for 304L SS. Figure 4.78 shows the effect of 621 °C (1150 °F) PWHT upon hardness after explosion bonding for ASTM A212-B steel. 30–50 BHN near the bond is reduced after PWHT.

	Magnesium	Molybdenum	Platinum	Gold	Silver	Niobium	Tantalum	Zirconium	Titanium	Nickel Alloys[c]	Copper Alloys	Aluminum	Stainless Steels	Alloy Steels	Carbon Steels
Carbon Steels	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Alloy Steels	a	a	b	b	b	b	a	a	a	a	a	a	a	a	
Stainless Steels	b	b	b	b	a	a	a	a	a	a	a	a	a		
Aluminum	b	b	b	b	a	a	a	b	a	a	a	a			
Copper Alloys	b	a	b	b	a	a	a	b	a	a	a				
Nickel Alloys[c]	b	b	b	a	b	b	a	b	a	a					
Titanium	a	b	a	b	a	a	a	a	a						
Zirconium	a	b	b	b	b	b	b	a							
Tantalum	b	b	b	a	b	a	a								
Niobium	b	b	a	b	b	a									
Silver	b	b	a	b	a										
Gold	b	b	b	a											
Platinum	b	b	a												
Molybdenum	b	a													
Magnesium	a														

a. Metal combinations that have been explosion bonded for commercial use.
b. Combinations for which explosion bonding may be feasible but have not been produced commercially.

Figure 4.76 Dissimilar metal combination for commercial use of explosion bonding. (Source: AWS Clad and Dissimilar Metals, Chapter 6, 1998)

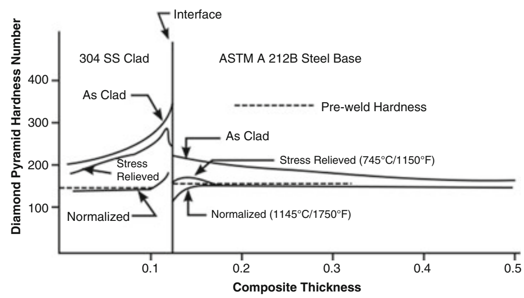


Figure 4.77 Hardness change after explosion bonding and stress relieving (304L SS on ASTM A212B of base metal). (Source: DMC report, 2010)

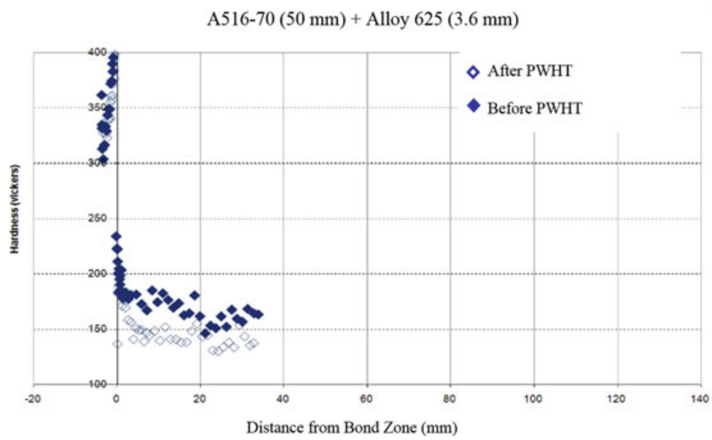


Figure 4.78 Effect of 621 °C (1150 °F) PWHT upon hardness after explosion bonding. (Source: Robert Kosturek, Effects of the heat treatment on the microstructure of Inconel 625/steel bimetal joint obtained by explosive welding, Materials in Tehnologies, 2018)

4.11.17 Specific Considerations for Heavy/Thin Wall Welding

4.11.17.1 Additional Considerations for Heavy Wall Welding

As thicker the metal, most properties, such as strength, toughness, homogeneous microstructures, purity, environmental cracking corrosion resistance, and weldability can be degraded. Careful consideration from design to maintenance is required.

Typically, heavy wall welding may be applicable for pressure vessels and high pressure heat exchangers. The welding of thicker wall produces several degradation results of the material, such as segregation, porosity, hardened structure locally, coarse grain locally, easy impurity/crack propagation, difficult impurity/crack detecting, etc. Therefore, the following considerations should be additionally checked before the heavy wall welding with 50 mm (2 in.) thick and above. Some companies control the heavy wall specification for 38 mm (1.5 in.) thick and above. The requirements for mechanical design of heavy wall equipment are not included in this book.

(a) Requirements for Base Metal and Weld Metal
1. If required multi-time PWHT, all mechanical test results (strength at atmosphere and/or creep/toughness-CVN impact test, CTOD, etc./metallurgy test-temper embrittlement, reheat crack, etc.) of the base metal should be completely specified in the MTR.
2. The sampling locations and numbers of the test coupons should be specified by the purchaser.
3. If the base metal is supplied by Q-T or N-T, the tempering temperature should be higher than the PWHT temperature unless approved by the purchaser and/or if all material test results passed the requirements.
4. All plate and forging grades of material in moderate and low temperature services should be produced with a fine-grained practice unless approved by the purchaser because fine-grained materials provide superior toughness.
5. All plate and forging grades of CS and LAS should be normalized unless otherwise approved by the purchaser because normalizing can minimize the non-homogeneous microstructures and improve the toughness in heavy wall.
6. All plate grades of material 100 mm (or 4 in.) thick and greater shall be UT per the applicable code.
7. (S)A105 or (S)A350-LF2 in large size forging should be carefully selected if the MDMT is −10 °C (14 °F) and colder or −29 °C (−20 °F) and colder, respectively. See Sect. 2.6.2.4 for more details.
8. See Sect. 2.1.4.2 for the requirements of Cr-Mo steels.
9. Casting materials are prohibited unless approved by the purchaser.
10. All machined surfaces of forgings, regardless of thickness, should be MT per the applicable code because forgings can have surface flaws that may propagate during service and cause failure. Typically, MT will detect all significant surface flaws (up to about 10 mm depth) that could compromise integrity and reliability in the metals other than austenitic SS and alloys.
11. All welding consumables should be of a low-hydrogen type certified by the consumable supplier, or tested by the fabricator, to result in less than 8 ml of diffusible hydrogen (DH) per 100 gm (H8) of deposited weld metal. See Sect. 4.3.2 for DH.
12. PMI program should be applied per the industrial standard and/or purchaser’s specification.

(b) Design, Fabrication, and Maintenance
1. All vertical pressure vessels should be supported on a skirt or lugs except spherical tanks. The welds should be continuous type.
2. All plate and sheet cut by shearing should be ground to have shear damaged material removed from all edges because welding on shear damaged surfaces can cause numerous weld defects.
3. Nozzle reinforcement should be integral; reinforcing pads should not be used unless otherwise approved by the purchaser. The stress concentration on Category D joints should be greatly reduced after minimizing weld joints, misalignment, and/or sharp corner design.
4. Formed head should be made by one piece; do not allow the weld joints in the head.
5. On horizontal vessels, no Category A weld joint shall be located more than 30 degrees below the horizontal centerline.
6. MPT (minimum pressurizing temperature) may be considered.
7. The temperature deviation of each part should be minimized by sufficient number of thermocouples during PWHT.

(c) Welding
1. All welds in pressure-containing parts should be full penetration type. Partial penetration welds are not acceptable because they create crack/fatigue corrosion initiators at locations with potentially high stress concentration, bending moments, or hydrogen nests.
2. All support welding shall utilize continuous seal-welded construction.
3. All Category A and B weld joints should be double butt welded except closing seam or small bore (inaccessible joint to inside or other side) because the double butt joint provides the highest integrity weld joint. Permanent backup rings should not be used because aggressive corrosion attack under/near the ring may occur.
4. Dissimilar metal welds should be avoided for all Category A, B, C, and D weld joints, unless approved by the purchaser.
5. The weld bevel for butt welding should be optimized to minimize metallic degradation if available, such as J groove, compound bevel (i.e., combined with 30–37.5 deg. and 10–15 deg.), and narrow gap.
6. The welded joint between the shell and skirt should merge smoothly with the shell.
7. Production weld test plates are required for all vessels.
8. Efforts should be made to avoid covering or intersecting pressure-containing welds in the vessel with internal attachments.
9. All fillet welds larger than 5 mm (3/16 in.) of leg length on shell/heads should be welded in multiple passes and meet the following.
   (a) Fillet welds shall have a smooth flat or slightly concave profile at the specified design throat thickness.
   (b) Undercut shall not be permitted.
   (c) Single-pass welds tend to be of poor quality, especially if they are 8 mm (5/16 in.) and larger of leg length, unless they are made by machine SAW/ESW. With small fillets 5 mm (3/16 in.) and less of leg length can be made with most weld processes and be of high quality, so multiple pass may not be required.
10. The measurement of preheat and interpass temperature should be performed at the welding area. For instance, the temperatures outside and inside may be greatly different in heavy wall. So, the preheat and interpass temperature for root pass should be measured near the root area just before the welding.
11. FCAW is a high productivity welding process that is used by some fabricators, especially for Category D nozzle welds. However, a relatively high occurrence of defects can be experienced. FCAW should not be used for Category A, B, C, and D joints of heavy wall pressure parts unless approved by the purchaser.
12. For repair welding, the use of controlled deposit welding (temper bead welding) in Sect. 4.5.1 is preferable.

(d) Test and Inspection
1. Examination for final acceptance should be performed after final PWHT.
2. The skirt to vessel weld shall be subject to full examination. Butt welds in the skirt should be spot RT as a minimum and should include all weld intersections.
3. All butt-welded joints in the shell/heads should be 100% RT and/or 100% UT after hydrotest.
4. All nozzle-to-shell or nozzle-to-head welds should be 100% UT after hydrotest.
5. All weld buildups, for the attachment of the skirt or vessel internals to the shell/head, should be 100% UT before completion of the attachment weld and after intermediate PWHT.
6. The following welds shall also be examined by the magnetic particle or liquid penetrant method:
   (a) Any repair area prior to the start of repair welding.
   (b) For nozzles with an inside diameter of 4 inches and less which are not radiographable, a magnetic particle examination shall be applied to every 1/4 in. of weld buildup in place of radiography (liquid penetrant inspection shall be used for nonmagnetic materials).
   (c) All internal and external attachment welds to the shell (e.g., tray support rings, gussets, insulation and platform clips).
7. For all seam and nozzle attachment welds, the backside of the root pass should be examined after back-gouging to sound metal. For nozzles less than 4 in. ID which are not readily radiographable, a MT should be applied to every 1/4 in. weld buildup in place of the radiographic examination.
8. The heating record of PWHT should be shown full time-temperature, such as heating from 200 °C (392 °F), holding time, and cooling to 200 °C (392 °F).

4.11.17.2 Specific Considerations for Thin Wall Welding

The most common concerns are deformation and burn-through during/after welding. The deformation may be minimized by the sufficient bracing before the welding, but the protection of burn-through may not be easy. The prevention and cautions for burn-through on hot tap welding in Sect. 4.6.5 may be the best guideline for the thin wall welding.

4.12 Heat Treatment and Stress Relieving for Fabrication of Equipment and Piping

4.12.1 Roles and Purpose of Heat Treatment for Equipment and Piping

To eliminate fabrication cracking in some instances, it may be necessary to do PWHT directly after welding and not allow the weldment to cool below the preheat temperature, or after complete welding. It may be also necessary to do stress relieving after all other thermal treatments during fabrication of CS or LAS exceeding 480 °C (900 °F) except exempted by applicable codes. Post-heat can accomplish many objectives, including stress relief, dimensional stability, resistance to stress corrosion, and sometimes even improvements in toughness and mechanical properties. Stress relief is the main method used to reduce residual stress. It is used to relieve and discharge the residual stress and hydrogen in weldments, respectively. An example of stress relief of CS is to maintain a postweld temperature of 595–675 °C

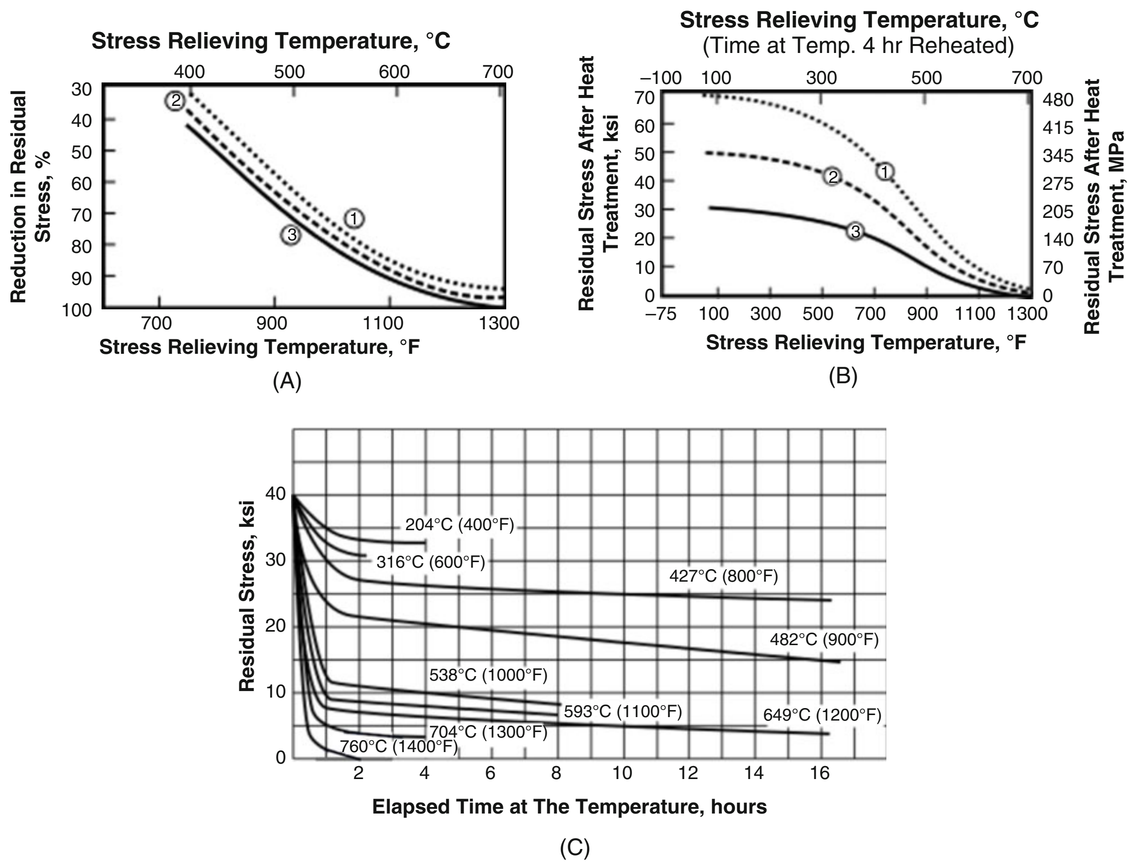


Figure 4.79 Stress-relieving effect to reduce the residual stresses of CS. (Source: ASM Metal Handbook Vol.6). (**a**) The effect of three different times at various temperatures on the reduction in residual stress by %. (1) Time at temperature = 1 hour. (2) Time at temperature = 4 hours. (3) Time at temperature = 6 hours. (**b**) The effect of steel relief is shown on three different strength levels of steel. (1) 70 ksi (480 MPa) yield strength. (2) 50 ksi (345 MPa) yield strength. (3) 30 ksi (205 MPa) yield strength. (**c**) The effect of stress relief on different temperature-time

(1100–1250 °F) for 1 hour/in. of thickness, which is a temperature range below that of the steel's transition temperature. The steel is then cooled very slowly or slowly until 371–427 °C (700–800 °F). The rule of thumb is slow heating and cooling in carbon steels and low alloy steels. Figure 4.79 shows the stress-relieving effect to reduce the residual stresses of carbon steel weldment. See Sect. 1.3.3 for Larson-Miller parameter (LMP) and Hollomon (or Hollomon-Jaffe) parameter (HP) for effects of high temperature operation and various heat treatments.

Meanwhile, the microstructure of most metals after cold work can be brittle. See Sect. 4.12.3.2 for the stress-relieving requirements to reduce the risk of cracking due to post-fabrication strain.

4.12.2 Classes of Heat Treatment for Equipment and Piping

Table 4.110 shows characteristics of several heat treatments for equipment and piping in oil and gas industries. This table does not include specific heat treatments, such as aesthetic (bright annealing), roughness control, sub-zero heat treatment, age and precipitation hardening, hardfacing, post-heating, etc. Table 4.111 shows the classes, purpose and cautions of several heat treatment processes applied during fabrication of CS and LAS. Table 4.12 shows the check points for PWHT and stress relieving of CS and LAS.

4.12.3 PWHT, Stress Relief, Annealing, and Solution Heat Treatment for Several Metals and Environments

4.12.3.1 General Requirements for Heat Treatment in Codes

Table 4.115 shows the locations in the code addressed heat treatment or stress-relieving requirements in ASME Sec. VIII and BS EN 13445.

Table 4.110 Characteristics of several heat treatments for equipment and piping

Classes	Characteristics/reference requirements	Raw materials	On fabrication
As-rolled	The final plates are from air cooling and hot rolling at 1100–1200 °C (2012–2192°F) of that the slab produced by continuous casting. Generally it is considered to low-grade steels because the structures have coarse and low toughness.	Yes	No
Normalizing (N)[4]	Through the normalizing (over Ac3 temperature + air cooling) of as-rolled steels, the metal structures have fine grain, high toughness, as well as stress relief.	Yes	Yes (for cracking environment)
Normalizing-tempering (N-T)[1]	– Relieving of the thermal stress during air cooling of normalizing. – To promote carbon diffusion with intention of softening and/or toughening the steel.	Yes	No
Normalizing- accelerated cooling and tempering (NACT)	– See Para. 2.1.4 (7).	Yes	No
Quenching-tempering (Q-T)[1]	– The metals are tempering treated below 650 °C (1202 °F) after quenching. The steel has more fine-grained structure, high strength & toughness, and more developed anti-corrosion properties. – The steels are mainly used for the low temperature-pressurized vessels because the DBTT is very low (e.g., A537-cl.2). – The PWHT should be below the tempering temperature of raw materials. – It can be easily cracked at HAZ after/during welding for over 1 1/2 in thickness due to breaking of tempering effect.	Yes	No
Quenched-self tempering (QST)	See Para. 2.1.4 (8).	Yes	No
Solution heat treatment (SHT)[5]	To dissolve the Cr-carbide precipitation of austenite stainless steels and nickel-chrome alloys during mill manufacturing and shop fabrication.	Yes	Yes for SS & Ni Alloys (rarely)
Stabilizing heat treatment (St.HT)[5]	To dissolve the Cr-carbides and promote the Ti/Nb-carbides precipitation of stabilized austenite stainless steels & nickel-chrome alloys during mill manufacturing and shop fabrication.	Yes	Yes for 321, 347, 348, Alloy 20
TMCP (thermommechanical-controlled processed) See Para. 2.1.4 (6).	– Double rolling system (DRS): 1st: over than γ (austenite, 930 °C (1706 °F)) for CS 2nd: below Ac1 temperature, 730 °C (1346 °F), for CS – DRS makes more fine-grained structure (than N or N-T), good toughness & strength, and excellent weldability (Ceq; very low). – PWHT should not be applied unless otherwise proved the mechanical properties and toughness.	Yes	No
Stress Relief Annealing[4]	– To remove or decrease the residual stress due to cold work or cracking environment. – It is normally applied with the PWHT procedure for carbon and low alloy steel.	Yes	Yes
PWHT (Postweld heat treatment)[4]	– To remove or decrease the residual stress due to welding. – It may be called as annealing.	Yes for specimen	Yes
Dehydrogenation treatment (DHT)[3] See API 934-A.	Dehydrogenation treatment for baking out. Conventional Cr-Mo steel: min. 593 °C (1100 °F), min. 2 hours. Advanced Cr-Mo steel: min. 650 °C (1200 °F), min. 4 hours or min. 680 °C (1250 °F), min. 2 hours.	Yes (rarely)	Yes for Cr-Mo steel ($4 > Cr \geq 2\ 1/4\%$)
Intermediate stress relief (ISR) See API RP934-A.[2],[3]	Intermediate stress relieving for proving temper embrittlement resistance. Conventional Cr-Mo steel: min. 300 °C (570 °F), min. 1 hour. Advanced Cr-Mo steel: min. 350 °C (660 °F), min. 4 hours.	Yes (rarely)	
Post-heat after Welding	To remove residual stress or deformation, or bake out the absorbed hydrogen, and somewhat to remove the residual stress or deformation (not completely)	No	Yes

Notes

(1) The tempering temperature shall not exceed 954 °C (1750 °F) because of grain growth in CA and LAS

(2) ISR is required before cooling below preheat temperature prior to PWHT, unless approved the use of DHT by the purchaser. ISR should not be waived for restrained welds such as all nozzle welds for advanced grades and nozzle welds in conventional grades with shell or head thickness 8″ and greater. See Sect. 4.12.3.7 for more details

(3) Approval of DHT in lieu of ISR should be done only after careful consideration of the metallurgical factors and possible risks. Higher concern levels with DHT are typically applied to advanced steels, as they can have low as-welded toughness. Although a DHT will remove hydrogen, it will not sufficiently restore toughness, especially for advanced materials which remain very brittle during pre-PWHT handling. To approve the use of DHT, purchaser requires test and/or experiential data. Typical information to be included in the manufacturer's request should include detailed information and data concerning hydrogen controls for procurement and handling of welding consumables, hydrogen content of weld metals after the DHT, and NDE of weld joint. The purchaser may require the manufacturer to demonstrate high sensitivity UT procedures to detect flaws at weld joints after using a DHT. Factors to be considered when reviewing possible use of DHT are the degree of weld restraint, weld joint thickness, experience of the manufacturer, and type of steel. DHT is commonly allowed for conventional steels on non-restrained welds such as shell welds and shell-to-head welds. See Sect. 4.12.3.7. for more details of DHT

(4) Temperature ranges of normalizing, full annealing, and annealing for carbon steel: See Fig. 4.80(a)

(5) Solution Annealing and Quenching: See Fig. 4.80(b)

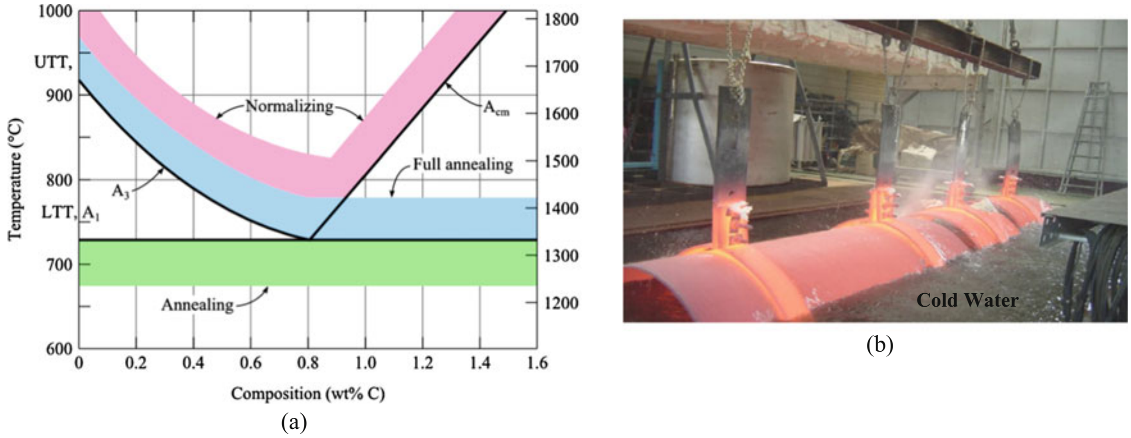


Figure 4.80 Normalizing and solution annealing followed by quenching. (**a**) Temperature ranges of normalizing, full annealing, and annealing for CS. (**b**) Solution annealing and quenching

Table 4.111 Classes of heat treatments during fabrication of CS and LAS

Classes	Purpose and effectiveness	Caution
PWHT (air cooling)	1. Reduce tensile strength 2. Reduce residual stresses 3. Reduce weld and HAZ hardness 4. Improve toughness [decrease the DBTT, 11 to 17 °C (20 to 30 °F)] 5. Outgas hydrogen from the weld 6. Remove cold work form the weld 7. Increase the ductility (improve the fatigue stress) 8. Improve the resistance of SCC or SSC 9. Increase dimensional stability during machining	1. Q-T steels: PWHT temperature should be below the normalizing temperature of raw materials in order to prevent the loss of normalizing effects (e.g., toughness). 2. Heavy wall or complicated structures: To keep strictly minimum holding time with sufficient thermocouples. 3. 2¼Cr-1Mo steels: can form coarse grain in metal structure during high temperature-long holding time. Also, decrease the strength when multi-heat cycles are applied. 4. Ni steels for low temperature: can be decreased the toughness by PWHT. 5. Cr-Mo steels can create segregations by V, Nb, Sb, P, As, and B during high temperature-long holding time.
Stress relieving	Remove the residual stress during cold or hot work	Normally the same as PWHT in low carbon steel. See Tables 4.136, 4.137, 4.138, 4.139, 4.140, and 4.141 for stainless steels. See Table 4.142 for DMW of Cr-Mo steels.
Preheating for welding	1. To prevent crack during and after welding 2. To reduce residual stresses 3. To improve the toughness 4. To control metallurgical properties of HAZ	To be considered max. interpass temperature.
Interpass temperature control during welding	Not only to maintain the proper preheat temperature range but also to prevent overheating which can lead to undesirable microstructures and lowered hardness during multipass welding	1. It is important factor for the joints of pipe to pipe in pre-welding (for tack welding), repair welding, and high energy consumable welding (e.g., automatic SMAW). 2. Normally described as only max. temperature because min. temperature can be covered by preheating temperature.
Post-heating after welding	1. To outgas hydrogen from the weld 2. To escape the rapid cooling that can increase the hardness	Wrapping method.
Normalizing (furnace cooling above A3 transition temp.)	1. To remove internal stresses 2. To sustain homogeneous microstructure 3. To obtain the grain refinement and toughness	1. Requires to recover the normalizing effects when the working temperature is over the normalized temperature during hot forming of N, N-T or Q-T steels. 2. When N, N-T or Q-T steels are ordered, the normalizing temperature must be controlled in accordance with shop fabrication condition.

Table 4.112 (1/2) Check points for PWHT/stress relieving of CS and LAS[3],[4]

No	Items (code requirements)	Purpose and check points (see the project specification as well)
1.	Maximum holding temperature[2]	1. To avoid recrystallization and/or grain growth and/or forming precipitation/second phases
		2. To be below than the lower critical phase transformation temperature (LCPTT)[1]
		3. To be below than the tempering temperature for N-T or Q-T steels[5]
		4. To be below than the temperature worried any damage of the materials, welds, and deterioration of performance
2.	Minimum holding temperature[2],[8] [e.g., 593 °C (1100 °F) for P-No. 1]	1. Requirements of codes and specifications
		2. Discharging of hydrogen gas in CS and LAS
		3. Softening the hardened parts (stress relieving)
		Solution of the precipitations/second phases for stainless steel and nickel alloys
		4. The PWHT required due to environmental cracking service should have higher holding temperature than the minimum PWHT holding time per material and thickness in the codes for equipment in order to fully remove the residual stresses. See the applicable API/NACE standards, such as for sour, HF, caustic, amine, carbonate, ammonia, etc.
3.	Maximum heating rate for CS and LAS [above 427 °C (800 °F) for CS and LAS in ASME Sec. VIII, Div. 1 & 2]	1. Requirements of codes and specifications
		2. To avoid the non-homogeneous temperature profile due to change of shapes and dimension 3. To avoid the non-homogeneous temperature profile in heavy wall materials
		1. ASME Sec. VIII, Div. 1, UCS-56 and ASME Sec. VIII, Div. 2, 6.4.4: The rate of heating shall be not more than 222 °C/hr (400 °F/hr) divided by the maximum metal thickness* of the shell or head plate in inches, but in no case more than 222 °C/hr (400 °F/hr) in ASME Sec. VIII, Div. 1. *See Table 4.9 Note (1)
4.	Minimum heating rate for CS and LAS	1. To minimize the temperature gradient in the metal
		2.2Furnace facility protection
5.	Maximum holding period for CS and LAS [mainly in heavy wall and/or multi-cycle PWHT applied]	1. To keep below the temperature worried any damage of the materials, welds, and deterioration of performance
		2. To avoid reducing of creep rupture strength and/or toughness because LMP increased
		3. To avoid recrystallization and/or grain growth and/or forming precipitation/second phases
		4. To reduce the time of PWHT (productivity)
		5. The required total PWHT cycles (based on the minimum holding time)[6] should be considered. In this case, the final tensile strength and impact test results after PWHT with the total PWHT holding time shall comply with the strength calculation
6.	Temperature variation between thermocouples on holding period [above 427 °C (800 °F) for CS and LAS in ASME Sec. VIII, Div. 1& 2]	1. Requirements of codes and project specifications∗
		2. High differential temperature profile between thermocouples can create the second residual stress after PWHT
		3. ASME Sec. VIII, Div. 1, UCS-56 and ASME Sec. VIII, Div. 2, 6.4.4: During the holding period, there shall not be a greater difference than 83 °C (150 °F)∗ between the highest and lowest temperature throughout the portion of the vessel being heated, except where the range is further limited in ASME Sec. VIII, Div. 1, Table UCS-56-1 through UCS-56-11 and ASME Sec. VIII, Div. 2, 6.4.2. ∗Some company specification may require the reduced value
		4. ASME Sec. VIII, Div. 1, UHT-80: Furnaces for heating, for quenching, for normalizing, and for tempering shall be provided with suitable equipment for the automatic recording of temperatures. The temperature of the vessel or vessel part during the holding period shall be recorded and shall be controlled within ±15 °C (±25 °F)
		5. ASME Sec. VIII, Div. 2, 6.6.6.4: Furnaces for heating and for quenching and tempering shall be provided with suitable equipment for the automatic recording of temperatures. The metal temperature of the vessel or vessel components during the holding period shall be recorded and shall be controlled within ±15 °C (±25 °F)
7.	Minimum holding period[8] (e.g., 1 hr/in, 15 minutes minimum for P-No. 1, thickness < 2″)	1. Requirements of codes and specifications
		2. To obtain the homogeneous microstructure
		3. To discharge the hydrogen gas in the metal
		4. Softening the hardened parts (stress relieving)
		5. Expected holding time for total PWHT cycles (three or four times) – Cr-Mo steel (about 50 mm and thicker) and CS (about 100 mm and thicker).

Table 4.112 (2/2) Check points for PWHT/stress relieving of CS and LAS[(3),(4)]

No	Items (code requirements)	Purpose and check points (see the project specification as well)
8.	Maximum cooling rate[(7)] for CS and LAS [above 427 °C (800 °F)[(9)] for CS and LAS in ASME Sec. VIII, Div. 1 & 2]	1. Requirements of codes and specifications
		2. Non-homogeneous temperature profile due to change of shapes and dimension Non-homogeneous temperature profile of heavy wall materials
		3. The second residual stresses, deformation, and cracking
		4. ASME Sec. VIII, Div. 1, UCS-56 and ASME Sec. VIII, Div. 2, 6.4.4; Max. 278 °C/hr (500 °F/hr) divided by the thickness in inches (if thicker than 1 in.)
9.	Minimum cooling rate[(7)]	1. Furnace facility protection
		2. Performance (grain growth, precipitations, softened, etc.) of materials and welds due to long time heat treatment
		3. ASME Sec. VIII, Div. 2, 6.4.4; Min. 55 °C/hr (100 °F/hr)
10.	Temperature variation during heating up to holding temperature [above 427 °C (800 °F)[(9)] for CS and LAS in ASME Sec. VIII, Div. 1 & 2]	1. Requirements of codes and specifications
		2. High differential temperature profile between thermocouples can create the second residual stress after PWHT
		3. ASME Sec. VIII, Div. 1, UCS-56 and ASME Sec. VIII, Div. 2, 6.4.4: During the heating period, there shall not be a greater variation in temperature throughout the portion of the vessel being heated than 140 °C (250 °F) within any 4.6 m (15 ft) interval
11.	Temperature variation during cooling from holding temperature [above 427 °C (800 °F) for CS and LAS in ASME Sec. VIII, Div. 1 & 2]	1. Requirements of codes and specifications
		2. High differential temperature profile between thermocouples can create the second residual stress, deformation, and crack after PWHT
		3. ASME Sec. VIII, Div. 1, UCS-56 and ASME Sec. VIII, Div. 2, 6.4.4: During the cooling period, there shall not be a greater variation in temperature throughout the portion of the vessel being heated than 140 °C (250 °F) within any 4.6 m (15 ft) interval
12.	Maximum furnace open temperature in air at 427 °C (800 °F) or below during cooling for CS and LAS	1. Requirements of codes and specifications
		2. Non-homogeneous rate of heating and cooling due to change of shapes and dimension
		3. Residual stresses, deformation, and cracking
		4. To reduce the time of PWHT (productivity)
13.	Quantity of thermocouples	1. Requirements of specifications
		2. Company standard as per size, shape, and thickness to reduce the scattered temperature profile for each facility
14.	Equipment location and position in furnace	1. Location to prevent direct impingement of the flame on the vessel
		2. Location to minimize the temperature gradient
		3. Position to remove any deformation and/or distortion during heat treatment
15.	Calibration	1. Recorder for temperature profile (recommended every 6 months as a minimum)
		2. Chart sticker for temperature profile (recommended every 6 months as a minimum)
16.	Local heat treatment	1. Deformation because the allowable stress at PWHT temperature will be very low
		2. Effective holding temperature range because the cooling rate from the end of the thermal insulation for heat treatment may have a big gradient
		3. See Para. 4.12.6 for more details

Notes: LMP = Larson-Miller Parameter

(1)Lower critical phase transformation temperature (LCPTT as Ac1 temperature)
The temperature should not exceed the maximum PWHT temperature (Ac1 temperature minus 30 °C at least).
For dissimilar welds in ferrite (P-1 thru P-5) steel, the PWHT shall match the requirements of the higher P-number materials, but shall not be higher than the LCPTT of the lower P-number material. LCPTT for CS and LAS are shown in Table 4.113. The data for power piping are a little bit different from those of Table 1.70 for fired heaters

(2)For pressure-retaining dissimilar welds in ferrite (P-1 thru P-5A/B) steel, the PWHT shall match the requirements of the higher P-number materials, but shall not be higher than the maximum PWHT temperature in Table 4.113 for lower P Number (P-No.) material unless otherwise approved by the responsible metallurgist

(3)See Table 3.4 for recrystallization temperature of several nonferrous metals

(4)TMCP steel: If the steel is to be subjected to warm forming or PWHT, the test coupons shall be subjected to heat treatment to simulate such fabrication operations. Consult with the responsible metallurgist

(5)Tempered steel: If the steel is to be subjected to PWHT above the tempered temperature, consult with the responsible metallurgist

(6)The total PWHT cycles (total period of fabrication + field repair welding) should be based on the minimum holding time, not included the heating and cooling period (see Fig. 1.35 Hollomon parameter) unless otherwise the purchaser requires

(7)Lower holding temperature and/or higher cooling rate increase the TS and YS, but reduce the toughness (Fig. 4.81)

(8)Alternative holding (lower) temperature and time (longer) may be applicable as seen in Tables 4.123b, 4.124d, and 4.128a

(9)The 427 °C (800 °F) limit is reduced to 315–343 °C (600–650 °F) for piping materials as seen in Table 4.114

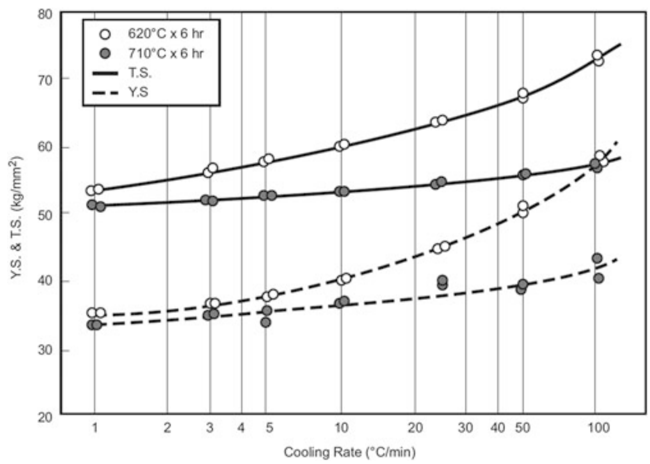


Figure 4.81 Effect of cooling rate on TS and YS of 1.25Cr-0.5Mo steel. (Source: API TR934-D, Figure 1)

Table 4.113 Lower critical phase transformation temperature (LCPTT, A_{C1}) and Max. PWHT temperature for carbon and ferritic alloy steels[(1),(2),(3),(6),(7)]

P-No.	Typical material	Approx. LCPTT (A_{C1})	Approx. max. PWHT temperature (LCPTT – 30 °C)[(5)]	Remark (min. PWHT temperature in ASME Sec. VIII, Div. 1)
1	CS (P-No.1)	725 °C (1340 °F)	695 °C (1283 °F)	595 °C (1100 °F)
3	C-Mo or Mn-Mo steel	730 °C (1350 °F)	700 °C (1292 °F)	595 °C (1100 °F)
4-Gr.1	1Cr-1/2Mo	745 °C (1375 °F)	715 °C (1319 °F)	650 °C (1200 °F)
4-Gr.1	1 1/4Cr-1/2Mo	775 °C (1430 °F)	745 °C (1373 °F)	650 °C (1200 °F)
5A	2 ¼ to 3Cr-1Mo	805 °C (1480 °F)	775 °C (1427 °F)	675 °C (1250 °F)
5B-Gr.1	5 Cr-1/2Mo	820 °C (1505 °F)	790 °C (1454 °F)	675 °C (1250 °F)
5B-Gr.1	9Cr-1Mo	802 °C (1475 °F)	772 °C (1422 °F)	675 °C (1250 °F)
5C-Gr.1	2 ¼ to 3Cr-1Mo-V	805 °C (1480 °F)	775 °C (1427 °F)	675 °C (1250 °F)
15E-Gr.1	9Cr-1Mo-V	800 °C (1470 °F)	770 °C (1418 °F)	720–775 °C (1325–1425 °F) per thick
9A-Gr.1	2.25Ni	780 °C (1435 °F)	750 °C (1382 °F)	595 °C (1100 °F)
9B-Gr.1	3.5Ni	730 °C (1345 °F)	700 °C (1292 °F)	595 °C (1100 °F)
11A-Gr.2	5 to 5.5Ni	700 °C (1290 °F)	670 °C (1238 °F)	550–585 °C (1025–1085 °F) per thick
11A-Gr.1	9Ni	650 °C (1200 °F)	620 °C (1148 °F)	550–585 °C (1025–1085 °F) per thick
6	12Cr (410 SS)	790–820 °C (1455–1505 °F)[(4)]	760–790 °C (1292–1454 °F)	760 °C (1400 °F) 732–788 °C (1350–1450 °F) – B31.3

Notes: (sources: API 530, ASME VIII-D1, B31.1, Handbook of SS, and NiDI #1232)

(1)The given approx. LCPTT are based on the ASME B31.1, Table 129.3.2 and API 530, Table 5 (as a reference). The data above in API 530, Table 5 are a little bit different with those in API 530, Table 5 (see Table 1.70 in this book)

(2)PWHT ranges shown in API RP582, Table 5 are recommended for the industrial practice unless it is for dissimilar weld joints or specific heat treatment condition

(3)A_{C1} [°C] on heating = 739 – 22.8C – 6.8Mn + 18.2Si + 11.7Cr – 15Ni – 6.4Mo – 5V – 28Cu on heating [element: wt%] by J. Trzaska & L.A. Dobrzański (2007)

(4)A_{C1} (°C) on heating for MSS = 301 + 35Cr + 3.5(Cr-17)^2 + 60Mo + 73Si + 170Cb + 290V + 620Ti + 750Al + 1400B – 250C – 280 N – 115Ni – 66Mn – 18Cu [element: wt%] – (source: Handbook of SS)

(5)No round-up. Based on API 530, 6.7: only permitted for short-term operating conditions, such as those that exist during steam-air decoking or regeneration. However, the use of up to 50 °C (90 °F) below LCPTT is recommended/preferred for short-term exposure

(6)ASME B31.1 addresses that hot bending or forming is performed at a temperature equal to or above the *LCPTT* minus 56 °C (100 °F) except at a temperature equal to or above 705 °C (1300 °F) for P-No 15E

(7)Cold work: When performed below the *LCPTT* minus 56 °C (100 °F) except at a temperature below 705 °C (1300 °F) for P-No 15E in ASME B31.1. When performed below the *minimum PWHT holding temperature* minus 30 °C (54 °F) except at a temperature below 300 °C (572 °F) for ASS and DSS in BS EN 13445-4

Table 4.114 Comparison of maximum rates of heating and cooling during PWHT (WRC 452, Table 9 modified)

Code	Limitation of heating rate	Limitation of cooling rate
ASME Sec. III, Subsection NB CS & LAS	Above 425 °C (800 °F), max. 222 °C/hr (400 °F/hr) divided by the thickness in in. (if thicker than 1 in.)	Above 425 °C (800 °F), max. 280 °C/hr (500 °F/hr) divided by the thickness in in. (if thicker than 1 in.)
ASME Sec. VIII, Div. 1, CS & LAS	Above 425 °C (800 °F), max. 222 °C/hr (400 °F/hr) divided by the thickness in in. (if thicker than 1 in.)	Above 425 °C (800 °F), max. 280 °C/hr (500 °F/hr) divided by the thickness in in. (if thicker than 1 in.)
ASME Sec. VIII, Div. 2, CS & LAS	Above 425 °C (800 °F) Max. 220 °C/hr (400 °F/hr) divided by the thickness in in. (if thicker than 1 in.) Min. 55 °C/hr (100 °F/hr)	bove 425 °C (800 °F), Max. 280 °C/hr (500 °F/hr) divided by the thickness in in. (if thicker than 1 in.) Min. 55 °C/hr (100 °F/hr)
ASME Sec. VIII, Div. 1, P. 7-Gr.1 & 2), and P. 8		Max. 56 °C/h (100 °F/hr) in the range above 650 °C (1,200 °F) after which the cooling rate shall be sufficiently rapid to prevent embrittlement.
ASME Sec. VIII, Div. 2, P. 9A/9B-Gr.1 P. 10A/C/I-Gr.1	When the heating rate is <30 °C/h (50 °F/hr) at ≥425 °C (800 °F) or where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 0.6 min/mm (15 min/in.) holding time is not required	[For P. 10I-1] The cooling rate shall be a maximum of 55 °C/h (100 °F/hr) in the range above 650 °C (1,200 °F) after which the cooling rate shall be rapid to prevent embrittlement.
BS PD5500 (2006) Depending upon complexity of vessel, material, and thickness (t), heating rates	[Ferritic steel] from 300 °C ($t \geq 60$ mm), 400 °C ($t < 60$ mm) $t \leq 25$ mm: max. 220 °C/hr (400 °F/hr) 25 mm $< t \leq$ 100 mm: max. 5500 °C/hr (9900 °F/hr) divided by the thickness in mm $t >$ 100 mm: max. 55 °C/hr (100 °F/hr) [ASS and nickel alloys] from 300 °C (572 °F) $t \leq 25$ mm: max. 220 °C/hr (400 °F/hr) $t >$ 25 mm: max. 200 °C/hr (360 °F/hr)	[Ferritic steel] to 400 °C (752 °F) $t \leq 25$ mm: max. 220 °C/hr (400 °F/hr) 25 mm $< t \leq$ 100 mm: max. 5500 °C/hr (9900 °F/hr) divided by the thickness in mm $t >$ 100 mm: max. 55 °C/hr (100 °F/hr) [ASS and Nickel alloys] from room temperature Rapid cooling by air or quenched.
ASME B31.3/31.1	From 315 °C (600 °F) to the holding temperature Max. *333* °C/hr (600 °F/hr) divided by ½ tn max. in inch at the weld (but in no case shall the rate exceed *333* °C/hr (600 °F/hr))	

Notes: P. 9A-Gr.1: 2 ¼ Ni steel, P. 9B-Gr.1: 3 1/2Ni steel, P. 7-Gr.1 & 2 (FSS), P.8: ASS

Table 4.115 (1/2) Heat treatment (PWHT or stress relieving) requirements in ASME Sec. VIII, Div. 1 (including BS EN & PD)

Remarks	Code reference(1)
All carbon and low alloy steel seams must be PWHT'd if nominal thickness exceeds 32 mm (1.25 in.) or 38 mm (1.5 in.) if preheated to 93 °C (200 °F) before welding	UCS-56
Some materials must be PWHT'd at lower thickness	Table UCS-56
Vessels containing lethal substances must be PWHT'd	UW-2
Unfired steam boilers	UW-2
Carbon-steel vessels for service at lowered temperature must be PWHT'd unless exempted from impact test	UCS-66, UCS-67, UCS-68
Welded vessels	UW-10, UW-40
Carbon and low alloy steel vessels	UCS-56, UCS-66, UCS-67, UCS-85
High alloy steel vessels	UHA-32
Cast-iron vessels	UCI-3
Clad-plate vessels	UCL-34 BS EN 13445-4, para. 9.4.4(7), BS EN 13445-4, para. 9.4.6(8)
Bolted flange connections	Appendix 2
Castings	UG-24
Forgings	UF-31
When only part of vessel is PWHT'd, extent of PWHT must be stated on manufacturer's data report from U-1	UG-116
The letters HT must be stamped under the code symbol when the entire vessel has been PWHT'd	UG-116
The letters PHT must be stamped under the code symbol when only part of the vessel has been PWHT'd	UG-116
Low temperature vessels	ULT-56
Ferrite steel vessels	UHT-80, UHT-81
Nonferrous vessels	UNF-56

Table 4.115 (2/2) Heat treatment (PWHT or stress relieving) requirements in ASME Sec. VIII, Div. 1 (including BS EN & PD)

Remarks	Code reference[1]
Nonferrous vessels	UNF-56
Layered vessels	ULW-26
Vessels or parts subject to direct firing, when thickness exceeds 16 mm (5/8 in.)	UW-2
Fiber elongation (formed heads, cylinders, pipes, and tubes) after cold forming [requirements for post-fabrication heat treatment due to straining]	UG-79[2], UCS-79[2][10], UHA-44[3], UNF-79[3], UHT-79[2] ASME Sec VIII, Div. 2, 6.1.2 and Table 6.1[4] ASME B31.1[11], 129.3.3.1 & 129.3.4.1 ASME B31.3, (K)332.4.2[12] BS EN 13445-4[5] PD5500[5]
Heat treatment after hot forming	BS EN 13445-4[6] PD5500[6]
Heat treatment of CS and LAS components [operating below 0 °C (32 °F)] after forming	PD5500, D.8.3[9]

General Notes

a. Definition of cold forming: The cold-formed part is the component worked below the lower critical phase transformation temperature (LCPTT) in Table 4.113

Notes

[1]ASME Sec. VIII, Div. 1 unless otherwise specified.
PWHT (or stress-relieving) requirements of austenitic steels – ASME Sec. VIII Div. 1 Table UHA-32 Note
PWHT is neither required nor prohibited

[2]ASME Sec. VIII, Div. 1, Table UG-79-1, UCS-79 and UHT-79: When the % extreme fiber elongation (EFE) from below formulas is above 5% except some specific conditions in the code: See UCS-79 and UHT-79 for more details

Table UG-79-1 Equations for calculating forming strains (for CS and LAS)

(a) For double curvature (i.e., heads)

$$\%\text{extreme fiber elongation} = \frac{75t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$

(b) For single curvature (i.e., cylinders formed from plate)

$$\%\text{extreme fiber elongation} = \frac{50t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$

(c) For tube and pipe bends: *% extreme fiber elongation (EFE) = 100r/R*

where

% EFE = extreme fiber elongation or calculated forming strain
R = nominal bending radius to centerline of pipe or tube
Rf = final mean radius
Ro = original mean radius (equal to infinity for flat plate)
r = nominal outside radius of pipe or tube
t = nominal thickness of the plate, pipe, or tube before forming

UCS-79 (Forming pressure parts) indicates the requirements for post-fabrication heat treatment due to straining as below

(d) CS and LAS plates shall not be formed cold by blows, but may be formed by blows at a forging temperature provided the blows do not objectionably deform the plate and it is subsequently PWHT'd.

Unless otherwise specified, cold-formed areas of vessel shell sections, heads, and other pressure parts shall be heat treated if the resulting EFE determined in accordance with Table UG-79-1 EFE > 5% from the supplied condition. Heat treatment shall be applied in accordance with UCS-56 (PWHT requirements), except that alternative heating and cooling rates and hold times may be applied to formed pipe and tube having a nominal thickness ≤6 mm (0.25 in.) when the heat treatment method is demonstrated to achieve a thorough heating of the pipe or tube

1) Cold-formed and bent P-No. 1 pipe and tube material having a nominal thickness ≤19 mm (3/4 in.) does not require post-forming heat treatment

2) For P-No. 1, Group Nos. 1 and 2 materials other than those addressed by 1) above, post-forming heat treatment is required when the EFE > 40% or if the EFE > 5% and any of the following conditions exist:

(-a) The vessel will contain lethal liquid or gaseous substances (see UW-2)
(-b) The material is not exempt from impact testing by ASME Sec. VIII, Div. 1, or impact testing is required by the material specification
(-c) The nominal thickness of the part before cold forming >16 mm (5/8 in.)
(-d) The reduction by cold forming from the nominal thickness >10% at any location where the EFE > 5%
(-e) The temperature of the material during forming is in the range of 120–480 °C (250–900 °F)

3) Cold-formed or bent P-Nos. 3 through 5C pipe and tube materials having an OD < 114 mm (4.5 in.) and a nominal thickness <13 mm (0.5 in.) do not require a post-forming heat treatment

(e) Menawhile, API 620 (Design and Construction of Large, Welded, Low-Pressure Storage Tanks) requires the stress relieving for the storage tanks (−198°C and warmer) fabricated by 5% or 9% nickel plates when the extreme fiber elongation (strain) exceeds 3% per the following calculation.

$$;\%\ \text{extreme fiber strain} = \frac{65t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$

[3]ASME Sec. VIII, Div. 1, UHA-44 and UNF-79: When the % EFE strain from below formulas is above xx% or yy% (xx, see ASME Sec. VIII, Div. 1, Table UHA-44; and yy, see ASME Sec. VIII, Div. 1, Table UNF-79) except some specific conditions in the code: See UHA-44 and UNF-79 for more details. The formulas for the determination of % EFE shall be the same as ASME Sec. VIII, Div. 1, UCS-79 (see above[2])

UHA-44 indicates the requirements for post-fabrication heat treatment due to straining as below

(a) The following rules shall apply in addition to general rules for forming given in UHA-40

(1) If the following conditions prevail, the cold-formed areas of pressure-retaining components manufactured of austenitic alloys shall be solution annealed by heating at the temperatures given in Table UHA-44 for 20 min/in. (20 min/25 mm) of thickness followed by rapid cooling:

(-a) The finishing-forming temperature is below the minimum heat-treating temperature given in Table UHA-44
(-b) The design metal temperature and the forming strains exceed the limits shown in Table UHA-44

(2) Forming strains shall be determined by the equations in Table UG-79-1

(b) When forming strains cannot be calculated as shown in (a) above, the manufacturer shall have the responsibility to determine the maximum forming strain. For flares, swages, or upsets, heat treatment in accordance with Table UHA-44 shall apply, regardless of the amount of strain

UNF-79 indicates the requirements for post-fabrication heat treatment due to straining as below

(a) The following rules shall apply in addition to general rules for forming given in UNF-77

(1) If the following conditions prevail, the cold-formed areas of pressure-retaining components manufactured of austenitic alloys shall be solution annealed by heating at the temperatures given in Table UNF-79 for 20 min/in. (20 min/25 mm) of thickness followed by rapid cooling:

(-a) The finishing-forming temperature is below the minimum heat-treating temperature given in Table UNF-79

(-b) The design metal temperature and the forming strains exceed the limits shown in Table UNF-79

(2) Forming strains shall be determined by the equations in Table UG-79-1

(b) When forming strains cannot be calculated as shown in (a) above, the manufacturer shall have the responsibility to determine the maximum forming strain. For flares, swages, or upsets, heat treatment in accordance with Table UNF-79 shall apply, regardless of the amount of strain

(4) ASME Sec. VIII, Div. 2: When the extreme fiber elongation (EFE-ε_f) from below formulas is above 5% from the as-rolled condition of CS and LAS except some specific conditions in the code. See ASME Section VIII, Div. 2, 6.1.2 and Table 6.1 (see below (a) through (d)) for more details

(a) For all one-piece double-curved circumferential products, formed by any process that includes dishing or cold spinning (e.g., dished heads or cold spun heads):

$$\varepsilon_f = 100 \ln\left(\frac{D_b}{D_f - 2t}\right)$$

(b) For cylinders formed from plate:

$$\varepsilon_f = \frac{50t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$

(c) For heads that are assembled from formed segments (e.g., spherical dished shell plates or dished segments of elliptical or torispherical heads):

$$\varepsilon_f = \frac{75t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$

(d) For tube and pipe bends:

$$\varepsilon_f = \max\left[\left(\frac{r}{R_f}\right), \left(\frac{t_A - t_B}{t_A}\right)\right] \cdot 100$$

where

Db = diameter of the blank plate or the diameter of the intermediate product
Df = final outside diameter of component after forming
Rf = final mean radius
Ro = original mean radius (equal to infinity for flat plate)
t = nominal thickness of the plate, pipe, or tube before forming
r = nominal outside radius of pipe or tube or blend grind radius
t_A *= measured average wall thickness of pipe or tube*
t_B *= measured minimum wall thickness of extrados of the bend*

Meanwhile, pieces that are formed after quenching and tempering (Q-T) at a temperature lower than the final tempering temperature shall be heat treated in accordance with ASME Section VIII, Div. 2, Table 6.17 when the EFE from forming exceeds 5% as determined by the lesser of the applicable equations in ASME Section VIII, Div. 2, Table 6.1

(5) BS EN 13445-4 and PD5500
BS EN 13445-4, Table 9.4.1 Heat Treatment of Flat Products After Cold Forming
BS EN 13445-4, Table 9.4.2 Heat Treatment of Tubular Products After Cold Forming
BS EN 13445-4, Para. 9.4.4 Heat Treatment of Clad Steels After Cold Forming
PD5500, Table 9.4-3 Heat Treatment After Cold Forming

(6) BS EN 13445-4 and PD5500
BS EN 13445-4, Table 9.4.3 Heat Treatment After Hot Forming
BS EN 13445-4, Para. 9.4.6 Heat Treatment of Clad Steels After Hot Forming
PD5500, Table 9.4-3

(7) Heat treatment of clad steels after cold forming: Post-forming heat treatments of clad steels after cold forming shall be carried out in accordance with BS EN 13445-4, 9.4.1 and BS EN 13445-4, Table 9.4-1. For calculation of the ratio of deformation, the total thickness of the clad material shall be considered. The influence of this heat treatment to the cladding shall be considered, particularly regarding the corrosion resistance

(8) Heat treatment of clad steels after hot forming: The conditions for heat treatment of clad steels after hot forming shall be carried out in accordance with BS EN 13445-4, 9.4.1 and BS EN 13445-4, Table 9.4-3 based on the material backing steel. The influence of this heat treatment on the cladding shall be considered, particularly regarding the corrosion resistance

(9) All plates that have been cold-formed to an internal radius less than ten times the plate thickness (more than 5% deformation) shall be given a normalizing treatment afterwards.

Cold-formed dished ends with flanges shall be normalized; plates that are cold pressed to form the segments of a sphere or a hemispherical end shall be normalized if the radius is less than ten times the thickness.

Normalizing is required in all other cases, except where the manufacturer produces evidence that the forming technique used does not significantly change the impact properties.

Pipe that has been locally bent (with or without local heating) to an internal radius less than ten times the outside diameter of the pipe shall be normalized.

Unless it can be demonstrated that the temperature control during the forming operation is equivalent to the normalizing procedure, ferritic steel parts that have been hot formed shall always be normalized afterwards

(10) Post-Cold Forming Strain Limits and Heat Treatment Requirements for P-No. 15E Material (Gr. 91/ UNS K90901) – See Table 4.116 in this book for more details

(11) ASME B31.1: Cold-formed areas of components manufactured of austenitic alloys shall be heat treated after forming if they exceed both the design temperatures and forming strains shown in B31.1, Table 129.3.3.1 and 129.3.4.1. Forming strains shall be calculated as follows: See B31.1, para. 129.3.3.1 and 129.3.4.1 for more details

(a) For cylinders formed from plate:

$$\%\ \text{strain} = 50t_n/R_f(1 - R_f/R_g)$$

(b) For spherical or dished heads formed from plate:
$\%\ \text{strain} = 75t_n/R_f(1 - R_f/R_g)$
(c) For tube and pipe bends:
$\%\ \text{strain} = 100\,r_{od}/R$
where
R = *centerline radius of bend*
Rf = *mean radius after forming*
Rg = *original mean radius (equal to infinity for a flat plate)*
r_{od} = *nominal outside radius of pipe or tube*
t_n = *nominal thickness of the plate, pipe, or tube before forming*

(12) ASME B31.3: Stress-relieving requirements for cold bending and forming in ASME B31.3, High Pressure Piping
(a) After cold bending and forming, heat treatment in accordance with (b) below is required, regardless of thickness, when specified in the engineering design or when the maximum calculated fiber elongation exceeds 5% strain or 50% of the basic minimum specified longitudinal elongation for the applicable specification, grade, and thickness for P-No. 1 through 6 materials (unless it has been demonstrated that the selection of the pipe and the procedure for making the components provide assurance that the most severely formed portion of the material has retained an elongation of not less than 10%)
(b) Heat treatment is required regardless of thickness and shall conform to the temperatures and durations given in B31.3, Table 331.1.1, except that for quenched and tempered (Q-T) materials, the stress-relieving temperature shall not exceed a temperature 28 °C (50 °F) below the tempering temperature of the material

4.12.3.2 Requirements for Post-Fabrication Strain Limits in ASME Codes

The remained strain after post-fabrication (e.g., cold forming) can increase the residual stresses; as a result, it may be very susceptible to brittle failure. The stress relieving may be typically required in accordance with material and strain (fiber elongation). ASME Sec. VIII, Div. 1 requires post-fabrication heat treatment as seen in Table 4.115 including the notes.

Tables 4.116, 4.117, 4.118, 4.119, 4.120, 4.121, and 4.122 show the stress-relieving requirements in ASME, API, and BS EN 13445.

Table 4.116 Post-fabrication strain limits and required heat treatment (SR) for P-No.15E (Gr. 9-K90901) (ASME Sec. VIII, Div. 1, Table UCS-79-1 and ASME Sec. VIII Div. 2, Table 6.2.A)

Limitations in lower temperature range			Limitations in higher temperature range		Required heat treatment, when design temperature and forming strain limits are exceeded
For design temperature, °C (°F)					
Exceeding	But less than or equal to	Forming strains, %	For design temperature, °C (°F) exceeding	Forming strains, %	
540 (1000)	600 (1150)	>25	600 (1150)	>20	Normalizing-Tempering(1)
540 (1000)	600 (1150)	>5 to ≤25	600 (1150)	>5 to ≤20	Post-forming heat treatment (2), (3), (4)

General Notes (from ASME Sec. VIII, Div. 1 unless otherwise noted)
The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends. The forming strain limits tabulated above shall be divided by 2 if the equation, from ASME Sec. VIII, Div. 1, Table UG-79-1 and ASME Sec. VIII, Div. 2, Table 6.1, for double-curvature products such as heads is applied
Notes (from ASME Sec. VIII, Div. 1 unless otherwise noted)
(1) Normalization and tempering shall be performed in accordance with the requirements of the base material specification and shall not be performed locally. Either the material shall be heat treated in its entirety, or the cold-strained area (including the transition to the unstrained portion) shall be cut away from the balance of the component and heat treated separately or replaced
(2) Post-forming heat treatments shall be performed at 730–775 °C (1350–1425 °F) for 1 h/25 mm (1 hr/in.) or 30 min, minimum. Alternatively, a normalization and temper in accordance with the requirements in the base metal specification may be performed
(3) For materials with greater than 5% strain but less than or equal to 25% strain with design temperatures less than or equal to 600 °C (1115 °F), if a portion of the component is heated above the heat treatment temperature allowed in Note(2) above, one of the following actions shall be performed:
(a) The component in its entirety shall be renormalized and tempered.
(b) The allowable stress shall be that for Grade 9 material (i.e., SA-213 T9, SA-335 P9, or equivalent product specification) at the design temperature, provided that portion of the component that was heated to a temperature exceeding the maximum holding temperature is subjected to a final heat treatment within the temperature range and for the time required in Note(2) above. The use of this provision shall be noted on the Manufacturer's Data Report
(4) If a longitudinal weld is made to a portion of the material that is cold strained, that portion shall be normalized and tempered, prior to or following welding. This normalizing and tempering shall not be performed locally

Table 4.117 Post-cold-forming strain limits and heat treatment (SR) requirements for P-No.15E (Gr. 91-K90901) (ASME B31.1, Table 129.3.3.1)

Limitations in lower temperature range			Limitations in higher temperature range		Required heat treatment, when design temperature and forming strain limits are exceeded
For design temperature, °C (°F)					
Exceeding	But less than or equal to	Forming strains, %	For design temperature, °C (°F) Exceeding	Forming strains, %	
540 (1000)	600 (1150)	>25	600 (1150)	>20	Normalizing-tempering (1)
540 (1000)	600 (1150)	>5 to ≤25	600 (1150)	>5 to ≤20	Post-forming heat treatment (2), (3), (4)

General Note (from ASME B31.1 unless otherwise noted)

The limits shown are for pipe and tube formed from plates, spherical or dished heads formed from plate, and tube and pipe bends. The forming strain limits tabulated in this table shall be divided by 2 if para. 129.3.4.2 is applied

Notes (from ASME B31.1 unless otherwise noted)

(1) Normalization and tempering shall be performed in accordance with the requirements in the base material specification and shall not be performed locally. The material shall either be heat treated in its entirety, or the cold-strained area (including the transition to the unstrained portion) shall be cut away from the balance of the tube or component and heat treated separately or replaced

(2) Post-bend heat treatments shall be performed at 730–775 °C (1350–1425 °F) for 1 h/25 mm (1 hr/in.) or 30 min minimum
Alternatively, a normalization and temper in accordance with the requirements in the base material specification may be performed

(3) For materials with greater than 5% strain but less than or equal to 25% strain with design temperatures less than or equal to 600 °C (1115 °F) if a portion of the component is heated above the heat treatment temperature allowed above, one of the following actions shall be performed:
(a) The component in its entirety must be renormalized and tempered.
(b) For BEP piping only, the allowable stress shall be that for Grade 9 material (i.e., SA-213 T9, SA-335 P9, or equivalent product specification) at the design temperature, provided that the portion of the component that was heated to a temperature exceeding the maximum holding temperature is subjected to a final heat treatment within the temperature range and for the time required in Note (2) above. The use of this provision shall be noted on the Manufacturer's Data Report

(4) If a longitudinal weld is made to a portion of the material that is cold strained, that portion shall be normalized and tempered prior to or following welding. This normalizing and tempering shall not be performed locally

Table 4.118 Post-cold-forming strain limits and heat treatment (SR) requirements for ASS and austenitic alloys (ASME B31.1, Table 129.3.4.1)

Grade	UNS number	Limitations in lower temperature range			Limitations in higher temperature range		Minimum heat treatment temperature, °C (°F), when design temperature and forming strain limits are exceeded [Notes 1 and 2]
		For design temperature, °C (°F)					
		Exceeding	But less than or equal to	Forming strains exceeding, %	For design temperature, °C (°F) exceeding	Forming strains exceeding, %	
304	S30400	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304H	S30409	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304N	S30451	580 (1075)	675 (1250)	15	675 (1250)	10	1040 (1900)
309S	S30908	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
310H	S31009	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
310S	S31008	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
316	S31600	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
316H	S31609	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
316N	S31651	580 (1075)	675 (1250)	15	675 (1250)	10	1040 (1900)
321	S32100	540 (1000)	675 (1250)	15(Note 3)	675 (1250)	10	1040 (1900)
321H	S32109	540 (1000)	675 (1250)	15(Note 3)	675 (1250)	10	1095 (2000)
347	S34700	540 (1000)	675 (1250)	15	675 (1250)	10	1040 (1900)
347H	S34709	540 (1000)	675 (1250)	15	675 (1250)	10	1095 (2000)
348	S34800	540 (1000)	675 (1250)	15	675 (1250)	10	1040 (1900)
348H	S34809	540 (1000)	675 (1250)	15	675 (1250)	10	1095 (2000)
600	N06600	580 (1075)	650 (1200)	20	650 (1200)	10	1040 (1900)
617	N06617	650 (1200)	760 (1400)	15	760 (1400)	10	1150 (2100)
690	N06690	580 (1075)	650 (1200)	20	650 (1200)	10	1040 (1900)
800	N08800	595 (1250)	675 (1250)	15	675 (1250)	10	980 (1800)
800H	N08810	595 (1250)	675 (1250)	15	675 (1250)	10	1120 (2050)
–	S30815	580 (1075)	675 (1250)	15	675 (1250)	10	1050 (1920)
–	N06022	580 (1075)	675 (1250)	15	–	–	1120 (2050)

General Note (from ASME B31.1 unless otherwise noted)

The limits shown are for pipe and tube formed from plates, spherical or dished heads formed from plate, and pipe and tube bends. When the forming strains cannot be calculated as shown in para. 129.3.4.1, the forming strain limits shall be half those tabulated in this table (see para. 129.3.4.2)

Notes (from ASME B31.1 unless otherwise noted)

(1) Rate of cooling from heat treatment temperature not subject to specific control limits

(2) While minimum heat treatment temperatures are specified, it is recommended that the heat treatment temperature range be limited to 85 °C (150 °F) above that minimum and 140 °C (250 °F) for 347 SS, 347H SS, 348 SS, and 348H SS

(3) For simple bends of tubes or pipes whose outside diameter is less than 89 mm (3.5 in.), this limit is 20%

Table 4.119 Post-fabrication strain limits and required heat treatment. (ASME Sec. VIII, Div. 1, Table UHA-44 – modified)

Grade	UNS Number	Limitations in lower temperature range			Limitations in higher temperature range		Minimum heat treatment temperature, °C (°F), when design temperature and forming strain limits are exceeded [Notes 1 and 2]
		For design temperature, °C (°F)					
		Exceeding	But less than or equal to	Forming strains exceeding, %	For design temperature, °C (°F) exceeding	Forming strains exceeding, %	
201-1	S20100 heads	All	All	All	All	All	1065 (1950)
201-1	S20100 all others	All	All	4	All	4	1065 (1950)
201-2	S20100 heads	All	All	All	All	All	1065 (1950)
201-2	S20100 all others	All	All	4	All	4	1065 (1950)
201LN	S20153 heads	All	All	All	All	All	1065 (1950)
201LN	S20153 all others	All	All	4	All	4	1065 (1950)
204	S20400 heads	All	All	All	All	All	1065 (1950)
204	S20400 all others	All	All	4	All	4	1065 (1950)
304	S30400	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304H	S30409	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304L	S30403	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304N	S30451	580 (1075)	675 (1250)	15	675 (1250)	10	1040 (1900)
309S	S30908	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
310H	S31009	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
310S	S31008	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
316	S31600	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
316H	S31609	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
316N	S31651	580 (1075)	675 (1250)	15	675 (1250)	10	1040 (1900)
321	S32100	540 (1000)	675 (1250)	15(Note 3)	675 (1250)	10	1040 (1900)
321H	S32109	540 (1000)	675 (1250)	15(Note 3)	675 (1250)	10	1095 (2000)
347	S34700	540 (1000)	675 (1250)	15	675 (1250)	10	1040 (1900)
347H	S34709	540 (1000)	675 (1250)	15	675 (1250)	10	1095 (2000)
347LN	S34751	540 (1000)	675 (1250)	15	675 (1250)	10	1040 (1900)
348	S34800	540 (1000)	675 (1250)	15	675 (1250)	10	1040 (1900)
348H	S34809	540 (1000)	675 (1250)	15	675 (1250)	10	1095 (2000)

General Notes (from ASME Sec. VIII, Div. 1 unless otherwise noted)

(a) The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends

(b) When the forming strains cannot be calculated as shown in ASME Sec. VIII, Div. 1, UHA-44(a) – Table 4.115, Note (3) in this book, the forming strain limits shall be half those tabulated in this table [see UHA-44(b) – Table 4.115, Note (3) in this book]

Notes (from ASME Sec. VIII, Div. 1 unless otherwise noted)

1. Rate of cooling from heat treatment temperature is not subject to specific control limits [Commentary: see Table 4.115, Note (3) in this book]
2. While minimum heat treatment temperatures are specified, it is recommended that the maximum heat treatment temperature range be limited to 83 °C (150 °F) except 139 °C (250 °F) temperature range for 347 SS, 347H SS, 348 SS, and 348H SS [Rationale: Because Nb-containing stabilized SS have higher solvus temperature as shown in Fig. 4.55 in this book]
3. For simple bends of tubes or pipes whose outside diameter is less than 88 mm (3.5 in.), this limit is 20%

Commentary Notes:

(1) The heat treatment for 317 SS and 317L SS should be the same as that of 316 SS

(2) DSS: See Table 4.123a in this book for post-fabrication heat treatment of various duplex stainless steels (DSS)

Table 4.120 Post-fabrication strain limits and required heat treatment for high alloy materials. ASME Sec. VIII, Div. 2, Table 6.2.B (Note 1)

Grade	UNS number	Limitations in lower temperature range: For design temperature, °C (°F) Exceeding	Less than or equal to	Forming strains exceeding %	Limitations in higher temperature range: For design temperature exceeding, °C (°F)	Forming strains exceeding, %	Minimum heat treatment temperature when design temperature limits and forming strain limits are exceeded (Notes 1 and 2), °C (°F)
201-1	S20100 heads	All	All	All	All	All	1065 (1950)
201-1	S20100 all others	All	All	4	All	4	1065 (1950)
201-2	S20100 heads	All	All	All	All	All	1065 (1950)
201-2	S20100 all others	All	All	4	All	4	1065 (1950)
201LN	S20153 heads	All	All	All	All	All	1065 (1950)
201LN	S20153 all others	All	All	4	All	4	1065 (1950)
204	S20400 heads	All	All	All	All	All	1065 (1950)
204	S20400 all other	All	All	4	All	4	1065 (1950)
304	S30400	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304H	S30409	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304L	S30403	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
304N	S30451	580 (1075)	675 (1250)	15	675 (1250)	10	1040 (1900)
309S	S30908	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
310H	S31009	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
310S	S31008	580 (1075)	675 (1250)	20	675 (1250)	10	1095 (2000)
316	S31600	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
316H	S31609	580 (1075)	675 (1250)	20	675 (1250)	10	1040 (1900)
316N	S31651	580 (1075)	675 (1250)	15	675 (1250)	10	1040 (1900)
321	S32100	595 (1100)	675 (1250)	15 (Note 3)	675 (1250)	10	1040 (1900)
321H	S32109	595 (1100)	675 (1250)	15 (Note 3)	675 (1250)	10	1040 (2000)
347	S34700	595 (1100)	675 (1250)	15	675 (1250)	10	1040 (1900)
347H	S34709	595 (1100)	675 (1250)	15	675 (1250)	10	1095 (2000)
347LN	S34751	595 (1100)	675 (1250)	15	675 (1250)	10	1040 (1900)
348	S34800	595 (1100)	675 (1250)	15	675 (1250)	10	1040(1900)
348H	S34809	595 (1100)	675 (1250)	15	675 (1250)	10	1095 (2000)

General Note (from ASME Sec. VIII, Div. 2 unless otherwise noted)
The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends
Notes (from ASME Sec. VIII, Div. 2 unless otherwise noted)
1. The rate of cooling from heat treatment temperature is not subject to specific control limits
2. While minimum heat treatment temperatures are specified, it is recommended that the heat treatment temperature range be limited to 85 °C (150 °F) above that minimum. The range can be extended to 140 °C (250 °F) above the maximum temperature range for 347 SS, 347H SS, 347LN SS, 348 SS, and 348H SS
3. For simple bends of tubes or pipes whose outside diameter is less than 90 mm (3 1/2 in.), this limit is 20%
Commentary Notes:
(1) The heat treatment for 317 SS and 317L SS should be the same as that of 316 SS
(2) DSS: See Table 4.124b in this book for post-fabrication heat treatment of various duplex stainless steels (DSS)

Table 4.121 Post-fabrication strain limits and required heat treatment of nickel alloys. (ASME Sec. VIII, Div. 1, Table UNF-79)

Grade	UNS number	Limitation in lower temperature range			Limitations in higher temperature range		Minimum heat treatment temperature, °C (°F), when design temperature and forming strain limits are exceeded [Note (1)]
		For design temperature, °C (°F)		Forming strains exceeding, %	For design temperature, °C (°F), exceeding	Forming strain exceeding, %	
		Exceeding	But less than or equal To				
–	N06022	580 (1075)	675 (1250)	15	–	–	1120 (2050)
	N06230	595 (1100)	760 (1400)	15	760 (1400)	10	1205 (2200)
600	N06600	580 (1075)	650 (1200)	20	650 (1200)	10	1040 (1900)
601	N06601	580 (1075)	650 (1200)	20	650 (1200)	10	1040 (1900)
617	N06617	540 (1000)	675 (1250)	15	675 (1250)	10	1150 (2100)
625	N06625	540 (1000)	675 (1250)	15	675 (1250)	10	1095 (2000)
690	N06690	580 (1075)	650 (1200)	15	650 (1200)	10	1040 (1900)
800	N08800	595 (1100)	675 (1250)	15	675 (1250)	10	980 (1800)
800H	N08810	595 (1100)	675 (1250)	15	675 (1250)	10	1120 (2050)
800HT	N08811	595 (1100)	675 (1250)	15	675 (1250)	10	1120 (2050)

General Notes (from ASME Sec. VIII, Div. 1 unless otherwise noted)
(a) The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends.
(b) When the forming strains cannot be calculated as shown in UNF-79(a) – Table 4.115, Note (3) in this book, the forming strain limits shall be half those tabulated in this table [see UNF-79(b) – Table 4.115, Note (3) in this book]
Notes (from ASME Sec. VIII, Div. 1 unless otherwise noted)
(1) Rate of cooling from heat treatment temperature is not subject to specific control limits

Table 4.122 Post-fabrication strain limits and required heat treatment for nonferrous materials. [ASME Sec. VIII, Div. 2, Table 6.3 (Note 1)]

Grade	UNS number	Limitations in lower temperature range			Limitations in higher temperature range		Minimum heat treatment temperature when design temperature limits and forming strain limits are exceeded (Note 1), °C (°F)
		For design temperature °C(°F)		Forming strains exceeding %	For design temperature exceeding °C (°F)	Forming strains exceeding %	
		Exceeding	Less than or equal to				
–	N06230	595 (1100)	760 (1400)	15	760 (1400)	10	1205 (2200)
600	N06600	580 (1075)	650 (1200)	20	650 (1200)	10	1040 (1900)
617	N06617	540 (1000)	675 (1250)	15	675 (1250)	10	1150 (2100)
800	N08800	595 (1100)	675 (1250)	15	675 (1250)	10	985 (1800)
800H	N08810	595 (1100)	675 (1250)	15	675 (1250)	10	1120 (2050)
800HT	N08811	595 (1100)	675 (1250)	15	675 (1250)	10	1120 (2050)

General Note (from ASME Sec. VIII, Div. 2 unless otherwise noted)
The limits shown are for cylinders formed from plates, spherical or dished heads formed from plate, and tube and pipe bends
Notes (from ASME Sec. VIII, Div. 2 unless otherwise noted)
1. The rate of cooling from heat treatment temperature is not subject to specific control limits

4.12.3.3 Requirements for PWHT in ASME Codes

In addition to facility codes and standards as well as company specifications, see ASME Sec. II, Part C, SFA-5.1/5.4/5.5/5.17/5.22/5.23/5.28/5.29/5.36 for PWHT requirements of the welds in ASME application. See Tables 4.123, 4.124, 4.125, and 4.126 for ASME BPVC; Tables 4.127, 4.128, and 4.129 for ASME Piping; and Tables 4.129 for the requirements in ASME Piping and EN 13445-4 in cryogenic service.

Table 4.127 shows PWHT requirements in ASME B31.3 (Process Piping). In addition, ASME B31.3 has some following specific requirements.

Table 4.123 (1/2) Requirements for PWHT and RT in ASME Sec. VIII, Div. 1 pressure vessels

Materials group	P-No.	Gr. No.	Classified	Material description (Examples)	Thickness for PWHT	PWHT holding temperature, °C (°F) (12)	Full RT (4)
CS (1), (11), (13)	1	1	SMTS<70 ksi	SA36, SA285-C, SA515/516 Gr.55, 60, 65	>1.5″ (14)	595 (1100)	>1.25″
		2	SMTS≥70 ksi	SA515/516 Gr.70, SA-455-1 or II	>1.5″ (14)	595 (1100)	>1.25″
		3 (18)	Q-T (3)	SA537-2 & 3	>1.5″ (14)	595 (1100)	>1.25″
		4 (19)	Alloyed Q-T(3)	SA724-A & B	–(5)(28)	–(5)(28)	–
				SA724-C	>1.5″ (14)(28)	565–620 (1050–1150) (28)	–

Table 4.123 (2/2) Requirements for PWHT and RT in ASME Sec. VIII, Div. 1 pressure vessels

Materials group	P-No.	Gr. No.	Classified	Material description (Examples)	Thickness for PWHT	PWHT holding temperature, °C (°F) (12)	Full RT (4)
LAS (1), (11), (13)	3	1		C-0.5Mo (SA204-A)	>0.625″	595 (1100)	>0.75″
		2		0.5Cr-0.5Mo (SA204-B & C)	>0.625″	595 (1100)	>0.75″
		3	N or Q-T (3)	Mn-0.5Mo (SA533-C-1&2, SA543-Type B&C-Cl.3)	All	595 (1100)	>0.75″
	4	1		Only SA202-A & B (1/2Cr-1 1/4Mn-Si)	>0.625″	650 (1200)	>0.625″
		1		Cr $\leq$ 1.25, Mo $\leq$ 0.5 (SA387-Gr.12)	All (8)	650 (1200)	>0.625″
		2		0.75Cr-0.5Ni-Cu, etc. (SA423-1 & 2)	All (8)	650 (1200)	>0.625″
	5A	1		2.25 to 3Cr-1Mo (SA387-21/22-1/2)	All	675 (1250)(13)	All
	5B	1		5 to 9Cr-0.5 to 1Mo (SA387-5/9)	All	675 (1250)(13)	All
	5C	1	Q-T (3)	2.25Cr-1Mo-V (SA541-21-Cl.3) 3Cr-1Mo-V-Cb-Ti-B (SA541-3V)	All	675 (1250)(13)	All
	15E	1	V enhanced	9Cr-1Mo-V (A387-91)	>0.5″	705 (1300) (23)	All
					$\leq$0.5″	675 (1250) (23)	
	9A	1		2.5Ni (SA203-A, B)	>0.625″	595 (1100) (21)	>0.625″
	9B	1		3.5Ni (SA203-D, E)	>0.625″	595–635(1100–1175) (21)	>0.625″
	10A	1	Q-T (3) N-T (3)	Mn-(0.5Ni)-V (SA-487-1Q) Materials other than SA487-1Q	All >0.625″	595 (1100) (22) 595 (1100) (22)	>0.75″ >0.75″
	10B	1		1Cr-V (SA213-T17)	All	650 (1200) (22)	>0.625″
	10C	1		C-Mn-Si (SA612)	>1.5″ (14)	540 (1000) (22)	>0.625″
Low alloy ferrite steel T.S enhanced (15), (24)	11A	1/2	5,8,9 Ni	8 to 9Ni (SA353, SA553/522-I&II, SA333/ 334-8)/5Ni (SA645-A)	>2″	550–640 (1025–1085)	(38)
		3/4	N-T/ Q-T (3)	(SA487-4B & 4E/ SA533-B & D-Cl.3)	>0.58″	540–565 (1000–1050)	(38)
		5	3.5Ni	(SA543-B/C-Cl.1/3, SA508-4N Cl.1)	(26)	540–565 (1000–1050)	(38)
	11B	1/2	Q-T (3)	(SA517/592-A/ SA517/592-E)	>0.58″ (25)	540–595 (1000–1100)	(38)
		3/4	Q-T (3)	(SA517/592-F/ SA517-B)	>0.58″ (25)	540–595 (1000–1100)	(38)
		6/8	Q-T (3)	(SA517-J/ SA517-P)	>0.58″ (25)	540–595 (1000–1100)	(38)
		10	Q-T (3)	(SA543-B & C-Cl.2, SA508-4N Cl.2)	(26)	540–565 (1000–1050)	(38)
High alloy steel (2), (37)	6	1	MSS	13Cr (410)	(9)	760 (1400) (27)	(20)
		2	MSS	15Cr (429)		760 (1400) (27)	(20)
		3	MSS	13Cr (F6a-2)		760 (1400) (27)	(37)
		4	MSS	13Cr-4.5Ni-Mo (S41500) CA-6NM (28)	– >0.58″	– 565–620 (1050–1150)	(37) (37)
	7	1	FSS	13Cr (405, 410S)	(10), (29), (30)	730 (1350)	(20)
		2	FSS	17Cr (430)	(10), (29), (30)	730 (1350)	(20)
	8	1	ASS	18Cr-8Ni (304, 316, 321, 347)	(7)	(7)	>1.5″
		2	ASS	>20Cr- > 10Ni (309, 310)	(7)	(7)	>1.5″
		3	ASS	TPXM-11, 19 & 29	(7)	(7)	(37)
		4	ASS	S31254, S31725	(7)	(7)	(37)
	10H	1	DSS	S31803, S32205 (2205), S32750 (2507)	(6)	(6)	(37)
	10I	1	FSS	XM-27 & 33	>0.5″ (31)	730 (1350) (29) (33)	(37)
	10K	1	FSS	S44660	(32)	(32)	(37)
			FSS	Others (S44800)	–	–	(37)
Ni alloys	45	–	(36)	N08800/10/11 (alloy 800/800H/800HT)	All (17)	885 (1625) (17)	>0.375″
				N02200/N02201/N04400/N04401/ N06600	(35)	(35)	>0.375″
				Others	(35)	(35)	(37)
Al alloys	21–25				(35)	(35)	(37)
Cu alloys	31–34				(35)	(35)	(37)
Al-bronze	35	–		SB148-CDA954 Others	All (35)	620–650 (1150–1200) (35)	(37) (37)
Ti alloys	51				(35)	(35)	All
Zr alloys	62	–		R60705 Others	All (35)	540–595 (1000–1100) (16) (35)	All All
Hardfacing				(34)			

Abbreviation
TS tensile stress, *Q-T* quenched and tempered, *bc* by clients or manufacturer, *SS* stainless steel, *MSS* martensitic stainless steel, *FSS* ferritic stainless steel, *ASS* austenitic stainless steel, *DSS* duplex stainless steel, *SCC* stress corrosion cracking, *IGC* intergranular corrosion, *EGW* electrogas welding, *ESW* electroslag welding

5″ = 125 mm, 2″ = 50 mm, 1.5″ = 1½″ = 38 mm, 1.25″ = 1¼″ = 32 mm, 1″ = 25.4 mm, 0.94″ = 15/16″ = 24 mm, 0.75″ = 3/4″ = 19 mm, 0.625″ = 5/8″ = 16 mm, 0.58″ = 19/32″ = 15 mm, 0.5″ = 1/2″ = 13 mm, 0.38″ = 3/8″ = 10 mm, 0.25″ = 1/4″ = 6 mm, 0.18″ = 3/16″ = 5 mm, 0.13″ = 1/8″ = 3 mm, 0.09″ = 3/32″ = 2.5 mm

General Notes

(a) This table does not cover the PWHT requirements in EAC and low temperature service. Most nonferrous metals do not require the PWHT mandatorily except the materials listed in this table unless otherwise noted. See ASME Sec. VIII, Div. 1, PWHT Tables for pipes, tubes, and fillet welds

(b) Welded joints shall be PWHT'd in accordance with the requirements of UW-40 when required by other rules (e.g., cyclic service, lethal services, etc.) of this division

(c) PWHT temperatures required for corrosion cracking environments in API, NACE, ISO, etc. may be 20–50 °C (36–90 °F) higher than the PWHT holding temperatures in this table

(d) The PWHT (or stress relieving) should be performed in the furnace unless otherwise approved by end-users. If the local heat treatment is performed, WRC Bulletin 452 should be complied in accordance with ASME Sec. VIII, Div. 1, UW-40(a)

(e) When the MDMT is colder than −48 °C (−55 °F), and the coincident ratio defined in Figure UCS-66.1 is 0.35 or greater, PWHT is required, except that this requirement does not apply to the following welded joints, in vessels or vessel parts fabricated of P-No. 1 materials that are impact tested at the MDMT or colder in accordance with UG-84:

Type 1 Category A and B joints, not including cone-to-cylinder junctions, which have been 100% RT.

Category A and B joints attaching sections of unequal thickness shall have a transition with a slope not exceeding 3:1

(f) See Table 2.117 in this book for compensation of impact test requirements by heat treatment

(g) The thickness is based on the nominal thicknesses (t) refer to thinner of two butt-welded materials being jointed

(h) PWHT requirements of cladding vessels

1) Vessels or the components constructed of base material with corrosion-resistant integral or weld metal overlay cladding or applied corrosion-resistant lining materials shall be PWHT when the base material is required to be PWHT. The determining thickness shall be the total thickness of the base material.

2) Vessels or the components constructed of chromium stainless steel integral or weld metal overlay cladding and those lined with Cr stainless applied linings shall be PWHT in all thicknesses, except vessels that are integrally clad or lined with 405 SS or 410S SS and welded with an austenitic electrode or non-air-hardening Ni-Cr-Fe electrode need not be PWHT unless required by 1) above

(i) See ASME Sec. VIII, Div. 1, UW-40 and Table UCS-56.1 for the procedures of PWHT

(j) See ASME Sec. VIII, Div. 1, UG-24(b), UCS-56(f), UHA-32(e), UNF-56(c)(3), UF-37(b) for PWHT and RT requirements after repair welding

(k) See ASME Sec. VIII, Div. 1, UF-31 for PWHT requirements of body forgings

(l) Stress-relieving requirements other than PWHT: See ASME Sec. VIII, Div. 1, UCS-79, UHA-44, UNF-79, UHT-79, and UF-31

(m) RT is based on Type (1) in ASME Sec. VIII, Div. 1, UW-12 and shall be performed per ASME Sec. VIII, Div. 1, UW-51 and 52 after PWHT when required

(n) All WPS/PQR and P Number (P-No.) system shall comply with ASME Sec. IX and ASME Sec. VIII, Div. 1, UW

(o) The temperature of PWHT should be less than the tempering temperature performed for the base materials (i.e., NT or Q-T) unless otherwise proved the acceptable mechanical test data

Notes

(1) See ASME Sec. VIII, Div. 1, Table UCS-56 series, Table UCS-56.1, and UW-2, for more detailed concessions/restrictions

(2) PWHT or RT depends upon carbon content, grade of material, and type of welding, thickness, preheat and interpass temperature, and types of electrodes. See ASME Sec. VIII, Div. 1, Table UHA-32 series and paragraph UHA 32 and 33 for concessions/restrictions

(3) The temperature of PWHT should be less than the tempering temperature performed for the base materials (NT or Q-T) unless otherwise proved the acceptable mechanical test data

(4) Based on butt-welded joints of shell and heads. See ASME Sec. VIII, Div. 1, UW-11, Table UW-12 (Table 1.54 in this book), UW-51, and UCS-57 (basic requirements for CS and LAS). UW-11 states full RT requires for all butt welds that:

1) Are in the shell and heads of vessels used to contain lethal substances [see UW-2(a)]

2) Are in the shell and heads of vessels in which the nominal thickness [see (g) below] at the welded joint exceeds 38 mm (1.5 in.) or exceeds the lesser thicknesses prescribed in UCS-57, UNF-57, UHA-33, UCL-35, or UCL-36 for the materials covered therein, or as otherwise prescribed in UHT-57, ULW-51, ULW-52(d), ULW-54, or ULT-57

3) (-a) Are having DP exceeding 50 psi (350 kPa) [see UW-2(c) for more details]

4) Are in nozzles, communicating chambers, etc., with the nominal thickness at the welded joint that exceeds the thickness in *2)* above or attached to the shell or heads of vessels under *1), 2), or 3)* above except as required by UHT-57(a): Categories B and C in nozzles and communicating chambers that neither exceed NPS 10 (DN 250) nor 29 mm (1.125 in.) wall thickness do not require any RT

5) Are all Categories A and D in the shell and heads of vessels where the design of the joint or part is based on a joint efficiency permitted by UW-12(a), in which case:

(-a) Categories A and B connecting the shell or heads of vessels shall be of Joint Type No. (1) or (2) of Table 1.54 in this book

(-b) Category B or C [but not including those in nozzles and communicating chambers except as required in (4) above] which intersect the Category A butt welds in the shell or heads of vessels or connect seamless vessel shell or heads shall, as a minimum, meet the requirements for spot RT in accordance with UW-52. Spot RT required by this paragraph shall not be used to satisfy the spot RT rules as applied to any other weld increment

6) Are joined by electrogas welding with any single pass greater than 38 mm (1.5 in.) and all butt welds joined by electroslag welding

7) Are all Category A welds in a tubesheet which shall be of Joint Type (1) of Table 1.54 in this book

8) Are exemptions from RT for certain welds in nozzles and communicating chambers as described in *2), 4), and 5)* which above take precedence over the RT requirements of Subsection C of ASME Sec. VIII, Div. 1

(5) PWHT is not applicable because PWHT will reduce the mechanical properties. Max. thicknesses are 22 mm (7/8 in.) for SA724-Gr. A and B and 50 mm (2 in.) for A724 Gr. C

(6) PWHT is neither required nor prohibited. Consideration should be given to the possibility of SCC and IGC and to the needs of dimension stabilization for high alloy steels and the possibility of temper embrittlement for ferrite steels

Once PWHT is performed, the following temperature for several materials in Table 4.123a below shall be performed by heating for 20 min/25 mm (20 min/in.) of thickness or 10 min, whichever is greater, followed by liquid quenching or rapid cooling

Table 4.123a Required PWHT holding temperatures for several DSS pressure vessels

Alloys	PWHT holding temperature	Alloys	PWHT holding temperature
J93345	Min. 1120 °C (2050 °F)	S32750	1025–1125 °C (1880–2060 °F)
S31200, S31803, and S32550	Min. 1040 °C (1900 °F)	S32760	1000–1140 °C (2010–2085 °F)
S31260	1020–1100 °C (1870–2010 °F)	S32900 (max. 0.08%C)	940–970 °C (1725–1775 °F)
S31500	975–1025 °C (1785–1875 °F)	S32950	995–1025 °C (1825–1875 °F)
S32202	980–1080 °C (1800–1975 °F)	S39274	1050–1150 °C (1925–2100 °F)
S32304	Min. 980 °C (1800 °F)		

(7) PWHT is neither required nor prohibited for joints between ASSs of P-No.8. See Nonmandatory Appendix HA, UHA-100 through UHA-108 for corrosion cracking and metallic embrittlement
(8) All P-No.4 Gr.1 and 2 materials other than SA202-Gr.A and B
(9) P-No.6: PWHT is not required for SA-182 Gr. F6a, SA-240/268/479-410 SS with C ≤ 0.08% and an austenitic Cr-Ni or non-hardening Ni-Cr-Fe weld deposit, provided the plate thickness ≤10 mm (0.375 in.) or up to 38 mm (1.5 in.) with preheating, min. 230 °C (450 °F), and full RT performed
(10) P-No.7: PWHT is not required for S41003 (3CR12) of SA-1010, 405 SS, 410S SS, and 430Ti SS with C ≤ 0.08% of SA-240/268 and an austenitic Cr-Ni or non-hardening Ni-Cr-Fe weld deposit, provided the plate thickness ≤ 10 mm (0.375 in.) or up to 38 mm (1.5 in.) with preheating, min. 230 °C (450 °F), and full RT performed
(11) Alternative PWHT requirements per Table 4.123b for carbon and low allow steels may be acceptable. It is applicable only when permitted in ASME Sec. VIII, Div. 1, Table UCS-56 series. Source: ASME Sec. VIII, Div. 1, Table 56.1

Table 4.123b Alternative PWHT holding temperatures and time[(a)]

Decrease in temperature between minimum specified temperature, °C (°F)	Minimum holding time[(b)] at decreased temperature, hr	Notes
28 (50)	2	–
56 (100)	4	–
83 (150)	10	[(c)]
111 (200)	20	[(c)]

Notes:
[(a)] Only for CS and LAS listed in ASME Sec. VIII, Div. 1, Table UCS 56-1 through UCS 56-11
[(b)]Minimum holding time for <25 mm (1 in.) thickness. Add 15 minutes per in. (25 mm) for thicknesses >25 mm (1 in)
[(c)]These lower PWHT temperatures permitted only for P-No. 1 Gr. No. 1 and 2 materials
Commentary Note: Some end-users' specifications indicate that Table 4.123b above should not be used for new construction

(12) The temperature is minimum requirement unless otherwise specified
(13) When it is impractical to postweld heat P-5A/5B/5C Gr. No. 1 materials at 675 °C (1250 °F), it is permissible to perform the postweld heat treatment at 650 °C (1200 °F) minimum provided that, for material up to 50 mm (2 in.) nominal thickness, the holding time is increased to the greater of 4 hr minimum or 4 hr/in. (25 mm) of thickness; for thickness over 50 mm (2 in.), the specified holding times are multiplied by 4. The requirements of ASME Sec. VIII, Div. 1, UCS-85 must be accommodated in this reduction in PWHT
(14) Min. 93 °C (200 °F) preheat for butt welding is required for over 32 mm (1.25 in.) to 38 mm (1.5 in.) thickness
(15) The temperature of the vessel or vessel part during the holding period shall be recorded and shall be controlled within ±15 °C (±25 °F)
(16) Within 14 days after welding, all products of zirconium Grade R60705 (see Table 2.87 and Sect. 4.12.3.13 in this book) shall be heat treated at 500–610 °C (1000–1100 °F) for a minimum of 1 hr for thicknesses up to 25 mm (1 in.) plus 0.5 hr for each additional 25 mm (1 in.) of thickness. Above 425 °C (800 °F) cooling shall be done at a rate not greater than 280 °C/hr (500 °F/hr) divided by the maximum metal thickness* of the shell or head plate in inches but in no case more than 280 °C/hr (500 °F/hr). From 425 °C (800 °F), the vessel may be cooled in still air. *See Table 4.9, Note (1).
(17) Alloy 800/800H/800HT: For design temperatures >538 °C (1000 °F), PWHT is required at 885 °C (1625 °F) for 1.5 hr for thicknesses up to 25 mm (1 in.) and for 1.5 hr + 1 hr/in. of thickness for thicknesses in excess of 25 mm (1 in)
(18) SMTS ≥ 80 ksi
(19) SMTS ≥ 90 ksi
(20) 405 SS welded with straight Cr electrodes, and to 410 SS, 429 SS, and 430 SS welded with any electrode, shall be radiographed in all thicknesses. The final RT of all straight Cr ferritic welds including major repairs to these welds shall be made after PWHT has been performed
(21) When the heating rate is less than 28 °C/hr (50 °F/hr) between 425 °C (800 °F) and the holding temperature, the additional 15 minutes per 25 mm (15 min/in.) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 minutes per 25 mm holding time is not required
(22) P-No.10A/B/C-Gr.1: Consideration should be given for possible embrittlement of materials containing up to 0.15% V when postweld heat treating is performed at the minimum temperature and at lower temperature for longer holding times
(23) See ASME Sec. VIII, Div. 1, Table UCS-56-11 for more detailed concessions/restrictions. The requirements are the same as Table 4.124, Notes (18), (19), and (20)
(24) See ASME Sec. VIII, Div. 1, UHT-56, Table UHT-56, and UW-2, for more detailed concessions/restrictions
(25) See ASME Sec. VIII, Div. 1, UHT-82(g)

(26) PWHT is neither required nor prohibited. Consideration should be given to the possibility of temper embrittlement. The cooling rate from PWHT, when used, shall not be slower than that obtained by cooling in still air
(27) PWHT shall be performed as prescribed in ASME Sec. VIII, Div. 1, UW-40 and UCS-56(e)
(28) See ASME Sec. VIII, Div. 1, Table UHT-56 for more detailed concessions/restrictions
(29) PWHT shall be performed as prescribed in ASME Sec. VIII, Div. 1, UW-40 and UCS-56(e) except that the cooling rate shall be a maximum of 56 °C (100 °F)/hr above 650 °C (1200 °F) after which the cooling rate shall be sufficiently rapid to prevent embrittlement
(30) P-No.7: PWHT is not required for UNS S40910 (409S), S40920, S40930, S40935, S40936, S40945, S40975, S40977, S43932, and S43940 as well as SA-268/479-TP XM08 and SA-240/268-TP 18Cr-2Mo
(31) PWHT is neither required nor prohibited for a thickness <13 mm (0.5 in)
(32) P-No. 10K: For Alloy S44660, the rules for ferritic chromium stainless steel shall apply, except that PWHT is neither required nor prohibited. If heat treatment is performed after forming or welding, it shall be performed at 816–1066 °C (1500–1950 °F) for a period not to exceed 10 minutes followed by rapid cooling
(33) P-No. 10I: For Alloy S44635, the rules for ferritic chromium stainless steel shall apply, except that PWHT is neither prohibited nor required. If heat treatment is performed after forming or welding, it shall be performed at 1010 °C (1850 °F) minimum followed by rapid cooling to below 430 °C (800 °F)
(34) For vessels constructed of UNS R31233 (ULTIMET® – see Table 2.89 in this book) during weld procedure qualification testing, when using a matching filler metal composition, the minimum specified tensile strength of the weld metal shall be 120 ksi (828 MPa). Longitudinal bend tests are permitted per ASME Sec. IX, QW-160 (ASME Sec. VIII, Div. 1, UNF-19). PWHT of UNS R31233 is required prior to cold forming when the cold-forming bend radius at the weld is less than four times the thickness of the component. PWHT shall consist of annealing at 1121 °C (2050 °F) immediately followed by water quenching
(35) PWHT for nonferrous materials is not normally necessary nor desirable unless otherwise noted
(36) See ASME Sec. VIII, Div. 1, Table UNF-79 for stress relieving after cold work. See Table 4.120 in this book as well
(37) RT requirements shall comply with ASME Sec. VIII, Div. 1, UW-11, 51, 52 unless otherwise specified
(38) RT for the complete length of weld in accordance with the requirements of ASME Sec. VIII, Div. 1, UW-51 is required for all welded joints of Joint Type No. (1) of Table 1.54 in this book. The required RT shall be made after any CRA cover weld has been deposited

Table 4.124 (1/2) Requirements for PWHT and RT in ASME Sec. VIII, Div. 2 pressure vessels(21)

Materials group	P-No.	Gr. No.	Classified	Material description(1) (Examples)	Thick for PWHT(3)	PWHT holding temperature, °C (°F)(3), (8)	Full RT (22), (23)
Carbon steel or cast steel(24)	1	1	TS < 70 ksi	SA36, SA285-C SA515/516 Grades 55, 60, 65	>1.5″ (1)	595 (1100)	(12)
		2	TS > 70 ksi	SA515/516 Grade 70 SA455-1 or II	>1.5″ (1)	595 (1100)	(12)
		3	Q-T(5)	SA537-2 & 3	>1.5″ (1)	595 (1100)	(12)
		4	Q-T(5)	SA724-A & B	N/A	N/A	N/A
		4	Q-T(5)	SA724-C	>1.5″ (1)	565–620 (1050–1150)	(12)
Low alloy steel (24)	3(4)	1		C-0.5Mo (SA204-A)	>0.625″ (26)	595 (1100)	(12)
	(except	2		0.5Cr-0.5Mo (SA204-B & C)	>0.625″ (26)	595 (1100)	(12)
	SA302)	3	Q-T(5)	Mn-0.5Mo (SA533-C-1&2, SA543-Type B&C-Cl.3)	>0.625″ (26)	595 (1100)	(12), (17)
	4(4)	1		Cr ≤ 1.25, Mo ≤ 0.5 (SA-387 Grade 12, and SA/EN 10028-2 Grade 13CrMo4–5)	All (27)	650 (1200)	(12)
		2		0.75Cr-0.5Ni-Cu, etc. (SA423-1 & 2)	All (27)	650 (1200)	(12)
	5A(4)	1		2.25 to 3Cr-1Mo (SA387-21/22-1/2) (17)	All (28)	675 (1250)(29)	(12)
	5B(4)	1		5 to 9Cr-0.5 to 1Mo (SA387-5/9)	All (28)	675 (1250)(29)	(12)
	5C(4)	1	Q-T (5)	2.25Cr-1Mo-V (SA541-21-Cl.3) 3Cr-1Mo-V-Cb-Ti-B (SA541-3V)	All (28)	675 (1250)(5), (29)	(12)
	15E	1	N-T(5)	9Cr-1Mo-V/Cb (SA-387-91)	≤1/2″ > 1/2″	675 (1250)(18), (19), (20) 705 (1300)(18), (19), (20)	(12)
	9A	1		2.5Ni (SA203-A, B)	>0.625″	595 (1100)(30), (32)	(12)
	9B	1		3.5Ni (SA203-D, E)	>0.625″	595–635 (1100–1175)(30), (32)	(12)
	10A(4)	1	Q-T (5) Q-T (5)	Mn-V (SA487-1A/1B) Others (except SA487-1A/1B)	All >0.625″	595 (1100)(5), (31), (33) 595 (1100)(5), (31), (33)	(12)
	10C(4)	1		C-Mn-Si (SA612)	>1.5″ (2)	595 (1100)	(12)
	10I(4)	1		Mn-Mo-V, Mn-Cr, Mo-V alloys	All	595 (1000)	(12)

Table 4.124 (2/2) Requirements for PWHT and RT in ASME Sec. VIII, Div. 2 pressure vessels(21)

Materials group	P-No.	Gr. No.	Classified	Material description(1) (Examples)	Thick for PWHT(3)	PWHT holding temperature, °C (°F)(3), (8)	Full RT (22), (23)
Low alloy steel Ferrite steel (18) (24)	11A	1	Q-T (5)	8 to 9Ni (SA353, SA553-Type I&II, SA333-8, SA334-8)	>2″	550–585 (1025–1085)	(12)
		2	Q-T (5)	5 to 5.5Ni (SA645-A)	>2″	550–585 (1025–1085)	(12)
		4	Q-T (5)	0.2 to 0.7Ni (SA533-B/D-Cl.3)	>0.58″	540–595 (1000–1100)	(12)
		5	Q-T (5)	2 to 4Ni (SA543-Type B&C-Cl.1)	(15)	540–595 (1000–1100)	(12)
		10	Q-T (5)	2 to 4Ni (SA543-Type B&C-Cl.2)	(15)	540–595 (1000–1100)	(12)
	11B	1	Q-T (5)	Trace Cr-Mo-Zr (SA517-A/ SA592-A)	>0.58″ (25)	540–595 (1000–1100)	(12)
		2	Q-T (5)	Trace Cr-Mo-B-Ti (SA517-E/ SA592-E)	>0.58″ (25)	540–595 (1000–1100)	(12)
		3	Q-T (5)	Trace Ni-Cr-Mo-B-V (SA517-F/A592-F)	>0.58″ (25)	540–595 (1000–1100)	(12)
		4	Q-T (5)	Trace Cr-Mo-V-B-Ti (SA517-B)	>0.58″ (25)	540–595 (1000–1100)	(12)
		8	Q-T (5)	Trace Ni-Cr-Mo-B-Ti (SA517-P)	>0.58″ (25)	540–595 (1000–1100)	(12)
High alloy steel (24) (34)	6 (4), (10)	1	MSS	13Cr (403, 410)	All (9)	760 (1400)	(12)
		2	MSS	15Cr (429)	All	760 (1400)	(12)
		3	MSS	13Cr (F6a-2)	All	760 (1400)	(12)
	7 (4), (10)	1	FSS	13Cr (405, 410S)	All(11))	730 (1350)	(12)
		2	FSS	17Cr (430)	All(11)	730 (1350)	(12)
	8	1	ASS	18Cr-8Ni (304, 316, 321, 347)	(6)	(6), (14)	(12)
		2	ASS	>20Cr- > 10Ni (309, 310)	(6)	(6), (14)	(12)
	10H(4)	1	DSS	(6), (7)	(6), (7)	(6), (7)	(12)
	10I(4)	1	FSS FSS	S44635 Others (S44600, S44626, S44627)	(39), (13) (39)	(13) 730 (1350)(11)	(12)
	10K(4)	1	FSS	S44660 Others (S44800)	(6)	(6), (16) (6)	(12)
Al alloy	21–25				(40)	(40)	(12)
Cu alloys	31–35			(35)	(40)	(40)	(12)
Ni alloys	41–45			(7), (37)	(40)	(40)	(12)
Zr alloys	62			(36)	(40)	(40)	(12)
Hardfacing				(38)			

Abbreviation

TS tensile stress, *Q-T* quenched and tempered, *bc* by clients or manufacturer, *SS* stainless steel, *MSS* martensitic stainless steel, *FSS* ferritic stainless steel, *ASS* austenitic stainless steel, *DSS* duplex stainless steel, *SCC* stress corrosion cracking, *IGC* intergranular corrosion, *EGW* electrogas welding, *ESW* electroslag welding

5″ = 125 mm, 2″ = 50 mm, 1.5″ = 1½" = 38 mm, 1.25″ = 1¼" = 32 mm, 1″ = 25.4 mm, 0.94″ = 15/16″ = 24 mm, 0.75″ = 3/4″ = 19 mm, 0.625″ = 5/8″ = 16 mm, 0.58″ = 19/32″ = 15 mm, 0.5″ = 1/2″ = 13 mm, 0.38″ = 3/8″ = 10 mm, 0.25″ = 1/4″ = 6 mm, 0.18″ = 3/16″ = 5 mm, 0.13″ = 1/8″ = 3 mm, 0.09″ = 3/32″ = 2.5 mm

General Notes: source – ASME Sec. VIII, Div. 2, Tables 6.8 through 6.15 and 6.17

(a) This table is for overall PWHT requirements for PWHT of butt welds of pressure parts per P Number (P-No.): See ASME Sec. VIII, Div. 2, Table 6.8 through Table 6.15, and Table 6.17 for other weld joints. This table is not covered the PWHT requirements in EAC and low temperature service. See ASME Sec. VIII, Div. 2, Tables 6.8 through 6.16 for pipes, tubes, and fillet welds

(b) Most nonferrous metals do not require the PWHT except the materials listed in this table unless otherwise noted

(c) The thickness is based on the nominal thicknesses (t) refer to thinner of two butt-welded materials being jointed. The thickness of flange to be used to determine PWHT and RT requirements shall be the minimum [*t* or (A-B)/2] from ASME Sec. VIII, Div. 2, Fig. 4.16.1

(d) Materials required impact testing for low temperature service of ferrous metals shall be PWHT (ASME Sec. VIII, Div. 2, 3.11.8.1. (b))

(e) PWHT after repair welding: See ASME Sec. VIII, Div. 2, 6.4.5 (general), 6.7.8 (forged fabrication), and 6.8.10 (layered vessels)

(f) Heat treatment requirements for forged fabrication: See ASME Sec. VIII, Div. 2, 6.7.6

(g) Heat treatment requirements of welding for layered vessels: See ASME Sec. VIII, Div. 2, 6.8.10

(h) PWHT requirements for clad and lined weldments of vessels: See ASME Sec. VIII, Div. 2, 6.5.5

1) Vessels or the components constructed of base material with corrosion-resistant integral or weld metal overlay cladding or applied corrosion-resistant lining materials shall be PWHT per the procedure of the base metal when the base material is required to be PWHT.

2) Vessels or the components constructed of Cr stainless steel integral or weld metal overlay cladding and those lined with Cr stainless steels applied linings shall be PWHT in all thicknesses, except vessels that are integrally clad or lined with 405 SS or 410S SS and welded with an austenitic electrode or non-air-hardening Ni-Cr-Fe electrode need not be PWHT unless required by 1) above

(i) Operation (heating/cooling rates, temperature difference/variations, etc.) of PWHT: See ASME Sec. VIII, Div. 2, 6.4.4

(j) PWHT requirements for materials in low temperature services: See ASME Sec. VIII, Div. 2, 3.11.2.9.

See Fig. 2.135 in this book for compensation of impact test requirements by heat treatment [ASME Sec. VIII, Div. 2, Fig. 3.7 and 3.8]

(k) PWHT temperatures required for environmental corrosion cracking service in API, NACE, ISO, etc. may be 20–50 °C (36–90 °F) higher than the PWHT holding temperatures in this table

(l) Damage mechanisms associated with the service fluid at design conditions. Informative and nonmandatory guidance regarding metallurgical phenomena is provided in Section II, Part D, Appendix A, API RP 571, and WRC Bulletins 488/489/490

(m) WRC Bulletin 470, "Recommendations for Design of Vessels for Elevated Temperature Service," has helpful information for vessel designers
(n) Nozzles in cylindrical shells and nozzles in formed heads – stress calculations shall be in accordance with WRC 107 or WRC 297
(o) RT shall be performed after PWHT when required
(p) All WPS/PQR and P Number (P-No.) system shall comply with ASME Sec. IX and ASME Sec. VIII, Div. 2, 3.10 (Material Test Requirements) and 3.11 (Material Toughness Requirements)
(q) The vessel shall be hydrostatically tested after making the welded repair
(r) The temperature of PWHT should be less than the tempering temperature performed for the base materials (i.e., NT or Q-T) to achieve the required tensile strength and toughness unless otherwise proved the acceptable mechanical test data
(s) Heat treatment as used in ASME Sec. VIII, Div. 2 shall include all thermal treatments during fabrication at 480 °C (900 °F) and above. However, heat treatment of material is not intended to include such local heating as flame or arc cutting, preheating, welding, or heating below the critical range of tubing or pipe for bending or sizing
(t) The heat treatment requirements for test coupons (base materials, WPS/PQR, impact test, production test, clad, etc.) are not covered in this Table 4.11
(u) Table 4.124a

Table 4.124a Holding time

Materials group	$t > 25$ mm (1 in.)	$t \leq 50$ mm (2 in.)	50 mm (2 in.) $< t \leq 125$ mm (5 in.)	$t > 125$ mm (5 in.)
P-No. 1-Gr.1,2,3 P-No. 3-Gr.1,2,3	–	0.04 hr/mm (1 hr/in.), 15 min. minimum	2 hrs + 0.6 minutes/mm over 50 mm (1 hr/in. over 2″)	2 hrs + 0.6 minutes/mm over 50 mm (1 hr/in. over 2″)
P-No. 1-Gr.4	1 hr/25 mm (1 hr/in.), 30 minutes minimum [Plates-SA724-Gr.C]			
P-No. 4-Gr.1&2, P-No. 5A/5B/5C-Gr.1	–	0.04 hr/mm (1 hr/in.), 15 min. minimum[a]	0.04 hr/mm (1 hr/in.)	5 hrs + 0.6 minutes/mm over 125 mm (1 hr/in. over 5″)
P-No. 15E-Gr.1	–	0.04 hr/mm (1 hr/in.), 30 min. minimum	0.04 hr/mm (1 hr/in.), 30 min. minimum	5 hrs + 0.6 minutes/mm over 125 mm (1 hr/in. over 5″)
P-No. 6-Gr.1,2,3 P-No. 7-Gr.1,2, P-No. 8	–	0.04 hr/mm (1 hr/in.), 15 minutes minimum[a]	2 hrs + 0.6 minutes/mm over 50 mm (1 hr/in. over 2″)	2 hrs + 0.6 minutes/mm over 50 mm (1 hr/in. over 2″)
P-No. 9A/9B-Gr.1[b]	0.6 minutes/mm over 25 mm (15 minutes/in. over 1″) 1 hr min.	–	–	–
P-No. 10A-Gr.1[b]	*595 °C (1100 °F)*: 1 hr + 0.6 minutes/mm over 25 mm (15 minutes/in. over 1″) *530–560 °C (985–1040 °F)*: 0.5 hr at $t \leq 20$ mm (0.79″) for SA/NF A36-215 Gr. P440 Nj4			
P-No. 10C-Gr.1[b]	540 °C (1000 °F): 1 hr minimum +0.6 minutes/mm over 25 mm (15 minutes/in. over 1″)			
P-No. 10H-Gr.1	If performed, by liquid quenching or rapid cooling by other means			
P-No. 10I-Gr.1[b]	730 °C (1350 °F): [Class 1] 1 hr minimum +0.04 hr/mm (1 hr/in.), 15 minutes minimum [Class 2] 1 hr + 0.6 minutes/mm over 25 mm (15 minutes/in. over 1″)			
P-No. 10 K-Gr.1	If performed, the holding time should not exceed 10 minutes followed by rapid cooling			
P-No. 11A-Gr.4	0.5 hr/25 mm (0.5 hr/in.), 30 minutes minimum [Plates-SA533-Gr.B&D-Cl.3]			
P-No. 11A-Gr.5 11B-Gr.10	1 hr/25 mm (1 hr/in.), 1 hr minimum [Plates-SA543-Type B&C-Cl.1&2&3/ Forgings-SA508-Gr.4N-Cl.1&2]			
P-No. 45	If performed, by liquid quenching or rapid cooling by other means			

Notes
[a]1 hr minimum for Class 2
[b]When the heating rate is less than 30 °C/h (50 °F/hr) between 425 °C (800 °F) and the holding temperature, the additional 0.6 minutes/mm (15 minutes/in.) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 0.60 minutes/mm (15 minutes/in.) holding time is not required

(v) The exemptions from PWHT permitted in ASME Sec. VIII, Div. 2, Tables 6.8 through 6.15 are not permitted when PWHT is a service requirement as set forth in PWHT requirements for low temperature, when welding ferritic materials greater than 3 mm (0.125 in.) thick with the electron beam welding process, or when welding P-No. 3/ 4/ 5A/5B/15E/5C/6/ 7 (except for 405 SS and 410S SS) and P-No. 10 materials using the inertia and continuous drive friction welding process

Notes
(1) Min. 93 °C (200 °F) preheat for butt welding is required except SA841-Gr. A and B (C $\leq$ 0.14% and Ceq $\leq$ 0.40%) for over 32 mm (1.25 in.) to 38 mm (1.5 in.) thickness. Except for local heating, such as cutting and welding, heating of SA-841, Grades A and B above 649 °C (1,200 °F) during fabrication is prohibited
(2) Min. 93 °C (200 °F) preheat for butt welding is required for over 32 mm (1.25 in.) to 38 mm (1.5 in.) thickness
(3) PWHT is required for the following thickness of directly fired welded components:
When $t > 16$ mm (0.625 in.) for P-No.1
For all thicknesses for P-No. 3, 4, 9A, 9B, 10A, and 10C
(4) PWHT is required for the following:
; When the PWHT is required per ASME Sec. VIII, Div. 2, 3.11.2.9 (PWHT requirements in low temperature service)
; When a thickness > 3 mm (0.125 in.) with EBW process
(5) The temperature of PWHT should be less than the tempering temperature performed for the base materials (N-T or Q-T) unless otherwise proved the acceptable mechanical test data
(6) PWHT is neither required nor prohibited. Consideration should be given to the possibility of SCC and IGC and to the needs of dimension stabilization for high alloy steels and the possibility of temper embrittlement for ferritic steels

(7) PWHT is neither required nor prohibited, but PWHT for the following materials in Table 4.124b and 4.124c below shall be performed as below and followed by liquid quenching or rapid cooling by other means

Table 4.124b Heat treatment for P-No. 10H/Gr.1 (DSS)

Alloys	PWHT temperature	Alloys	PWHT temperature
J93345	Min. 1120 °C (2050 °F)	S32550	Min. 1040 °C (1900 °F)
S31200	Min. 1040 °C (1900 °F)	S32750	1025–1125 °C (1880–2060 °F)
S31260	1020–1100 °C (1870–2010 °F)	S32760	1100–1140 °C (2010–2085 °F)
S31500	975–1025 °C (1785–1875 °F)	S32900 (max.0.08%C)	940–970 °C (1725–1775 °F)
S31803/ S32205	Min. 1040 °C (1900 °F)	S32950	995–1025 °C (1825–1875 °F)
S32202	980–1080 °C (1800–1975 °F)	S39274	1050–1150 °C (1925–2100 °F)
S32304	Min. 980 °C (1800 °F)		

Table 4.124c Heat treatment for P-No. 45 (Ni alloys)

Alloys	PWHT temperature
S31266	1040–1170 °C (2085–2138 °F)

(8) See Table 4.124a for holding time

(9) PWHT is not required for 410 SS with C ≤ 0.08% and non-air-hardened ASS electrodes or non-air-hardening Ni-Cr-Fe weld deposit, provided
t ≤ 10 mm (3/8 in.), or
t is between >10 mm (3/8 in.) and ≤ 38 mm (1½ in.) with preheating, min. 230 °C (450 °F) and full RT

(10) PWHT is not required for 405 SS and 410S SS with C ≤ 0.08% and non-air-hardened ASS electrodes or non-air-hardening Ni-Cr-Fe weld deposit, provided
t ≤ 3 mm (1/8 in.), or
t is between >3 mm (1/8 in.) and ≤ 38 mm (1½ in.) with preheating, min. 230 °C (450 °F) and full RT

(11) Cooling rate shall be max. of 55 °C/hr (100 °F/hr) in the range above 650 °C (1200 °F) to prevent embrittlement

(12) See Table 5.23 in this book (or ASME Sec. VIII, Div. 2, Tables 7.2 and 7.4) for the extent of RT application per joint category, material, and thickness

(13) P-No. 10I: For alloy S44635, the rules for ferritic Cr SS shall apply, except that PWHT is neither prohibited nor required. If heat treatment is performed after forming or welding, it shall be performed at 1010 °C (1850 °F) minimum followed by rapid cooling to below 430 °C (800 °F)

(14) See Table 4.118, 4.119, 4.120, 4.138, 4.139, and 4.140 in this book for the heat treatment of ASS

(15) PWHT is neither required nor prohibited. Consideration should be given to the possibility of temper embrittlement. The cooling rate from PWHT, when used, shall not be slower than that obtained by cooling in still air

(16) P-No. 10K: For alloy S44660, the rules for ferritic Cr SS shall apply, except that PWHT is neither prohibited nor required. If heat treatment is performed after forming or welding, it shall be performed at 815 °C (1500 °F) for holding time not to exceed 10 minutes followed by rapid cooling

(17) See ASME Sec. VIII, Div. 2, 3.4.3 (Test Specimen Heat Treatment) and Fig. 2.20 (in this book) for Supplemental Requirements for Tension-CVN Impact Test Specimen After Final Heat Treatment of Cr-Mo Steels.
2.25Cr-1Mo Materials: The final PWHT temperature shall be in accordance with the requirements of this division for P-No. 5A materials, except that, for the materials listed in ASME Sec. VIII, Div. 2, Table 3.1, the permissible minimum normal holding temperature is 650 °C (1200 °F) and the holding time shall be 2.5 minutes/mm (1 hr/in.). For thicknesses over 125 mm (5 in.), the holding time shall be 5 hr plus 0.6 min for each additional mm (15 minutes for each additional inch) over 125 mm (5 in)

(18) The maximum holding temperature above is to be used if the actual chemical composition of the matching filler metal used when making the weld is unknown. If the chemical composition of the matching filler metal is known, the maximum holding temperature can be increased as follows:
a) If Ni + Mn <1.50% but ≥1.0%, the maximum PWHT temperature is 790 °C (1455 °F).
b) If Ni + Mn = >1.0% to 1.2%, the maximum PWHT temperature is 780 °C (1435 °F).
c) If the Ni + Mn content of the filler metal is greater than 1.2%, the maximum PWHT temperature shall be at least 10 °C (20 °F) below the lower critical transformation temperature (Ac1) as determined by measurement of that temperature for the specific heat (or heats) of filler metal to be used in accordance with ASTM A1033; in such case the following additional restrictions will apply:
1) The Ac1 temperature of the filler metal as measured in accordance with ASTM A1033 shall be included in the Manufacturer's Construction Records.
2) The maximum operating temperature for any vessel constructed using filler metal with a Ni + Mn content in excess of 1.2% shall be 525 °C (975 °F).
The lower transformation temperature for matching filler material is affected by alloy content, primarily the total Ni + Mn. The maximum holding temperature has been set to avoid heat treatment in the intercritical zone.
d) If multiple welds made with matching Gr. 91 filler metal in a pressure part or pressure vessel are to be postweld heat treated at the same time, the maximum PWHT temperature shall be determined based on the weld with the highest Ni + Mn content

(19) If a portion of the component is heated above the heat treatment temperature allowed above, one of the following actions shall be performed:
a) The component in its entirety must be renormalized and tempered.
b) If the maximum holding temperature in this table or (19) a) above is exceeded, but does not exceed 800 °C (1470 °F), the weld metal shall be removed and replaced.
c) The portion of the component heated above 800 °C (1470 °F) and at least 75 mm (3 in.) on either side of the overheated zone must be removed and be renormalized and tempered or replaced.
d) The allowable stress shall be that for Grade 9 material (i.e., SA-213-T9, SA-335-P9, or equivalent product specification) at the design temperature, provided that the portion of the component heated to a temperature greater than the allowed above is reheat treated within the temperature range specified above

(20) For dissimilar metal welds (i.e., welds made between a P-No.15E Gr.1 and another lower Cr ferritic, austenitic, or Ni-based steel), if the filler metal Cr content is <3.0% or if the filler metal is Ni-based or austenitic, the minimum holding temperature shall be 705 °C (1300 °F)
(21) If heat treatment is performed in this table, the forming strain (εcf) for elastic-plastic analysis in ASME Sec. VIII, Div. 2, 5.3.3 may be assumed to be zero
(22) Full RT is required for all parts of casting regardless of thickness (ASME Sec. VIII, Div. 2, 3.8.2.2)
(23) *RT for ferrous castings* – All parts of castings regardless of thickness shall be fully RT in accordance with the procedures of ASME Sec. V, Article 2. The RT shall be compared to the appropriate RT Standard listed below, and the maximum acceptable severity levels for imperfection shall be as follows:
a) For castings having radiographed thickness of less than 50 mm (2 in.), ASTM E446, Standard Reference Radiographs for Steel Castings up to 50 mm (2 in.) in Thickness, and with maximum severity levels as shown in ASME Sec. VIII, Div. 2, Table 3.9.
b) For castings having radiographed thickness from 50 to 305 mm (2–12 in.), ASTM E186, Standard Reference Radiographs for Heavy-Walled [50.8–114 mm (2–4.5 in.)] Steel Castings, or ASTM E280, Standard Reference Radiographs for Heavy-Walled [114–305 mm (4.5–12 in.)] Steel Castings, as appropriate, and with maximum severity levels as shown in ASME Sec. VIII, Div. 2, Table 3.10.
RT for nonferrous castings – All parts of castings shall be subjected to complete RT and the RT shall be compared with the radiographic standards of ASTM E272, Reference Radiographs for Inspection of High Strength Copper Base and Nickel-Copper Castings. Acceptable castings shall meet Class 1 standards, if the wall thickness is less than 25 mm (1 in.), or Class 2 standards if the wall thickness is greater than or equal to 25 mm (1 in.) as defined in the Specification
(24) Table 4.124d

Table 4.124d Alternative PWHT (lower holding temperature-longer holding time) requirements[(a)] (ASME Sec. VIII, Div. 2, Table 6.16)

Decrease in temperature between minimum specified temperature, °C (°F)	Minimum holding time[(b)] at decreased temperature, hr	Notes
30 (50)	2	–
55 (100)	4	–
85 (150)	10	(c)
110 (200)	20	(c)

Notes
[(a)]Only for CS, LAS, MSS, FSS, and some Ni alloys listed in ASME Sec. VIII, Div. 2, Tables 6.8 through 6.15
[(b)]Minimum holding time for 25 mm (1 in.) thickness or less. Add 15 minutes per in. (25 mm) or 0.6 minutes/mm of thickness for thicknesses greater than 25 mm (1 in)
[(c)]These lower PWHT temperatures permitted for P-No. 1 Gr. 1 and 2 materials, but other material groups may be also applicable per the code
Commentary Note: Some end-users' specifications indicate that Table 4.124d above should not be used for new construction

(25) The PWHT may be waived for SA-517 and SA-592 materials with 15 mm (0.56 in.) < $t \le$ 32 mm (1.25 in.) provided all of the following conditions are met:
a) A minimum preheat of 95 °C (200 °F) and a maximum interpass of 205 °C (400 °F) are used.
b) After completion of welding and without allowing the weldment to cool below the minimum preheat temperature, the temperature of the weldment is raised to a minimum of 205 °C (400 °F) and maintained at that temperature for at least 4 hr.
c) All welds are examined by NDE in accordance with the provisions of ASME Sec. VIII, Div. 1
(26) PWHT is not required for circumferential butt welds in pipe or tube where the pipe or tube has both $t \le$ 13 mm (0.5 in.) and a specified maximum carbon content ≤0.25% in ASME SA material specification
(27) PWHT is not required for circumferential butt welds in pipe or tube where the pipe or tube has all of $t \le$ 16 mm (0.625 in.), a specified maximum carbon content ≤0.15% in ASME SA material specification, and minimum preheat of 120 °C (250 °F)
(28) PWHT is not required for circumferential butt welds in pipe or tube where the pipe or tube has all of $t \le$ 16 mm (0.625 in.), a specified maximum Cr content ≤3.0%, a specified maximum carbon content ≤0.15% in ASME SA material specification, and minimum preheat of 150 °C (300 °F)
(29) When PWHT is impractical for P-No. 5A/5B/5C Gr. No. 1 materials, it is permissible to perform the PWHT at 650 °C (1200 °F) minimum provided that, for $t \le$ 50 mm (2 in.), the holding time is increased to the greater of 4 hr minimum or 9.6 minutes/mm (4 hr/in.) of thickness; for $t >$ 50 mm (2 in.), the specified holding times are multiplied by 4. The requirements in ASME Sec. VIII, Div. 2, 3.4.3 (Test Specimen Heat Treatment) must be accommodated in this reduction in PWHT
(30) PWHT is not required for circumferential butt welds in pipe or tube where the pipe or tube has all of $t \le$ 13 mm (0.5 in.), maximum OD ≤ 100 mm (4 in.), a specified maximum carbon content ≤0.15% in ASME SA material specification, and minimum preheat of 120 °C (250 °F)
(31) PWHT is not required for circumferential butt welds in pipe or tube where the pipe or tube has all of $t \le$ 13 mm (0.5 in.), a specified maximum carbon content ≤0.25% in ASME SA material specification, and minimum preheat of 95 °C (200 °F)
(32) When PWHT is impractical, it is permissible to perform the PWHT at lowest 540 °C (1000 °F) with compliance of Table 4.124d above
(33) Consideration should be given for possible embrittlement of materials containing up to 0.15%V when PWHT is performed at the minimum temperature and at lower temperatures for longer holding times per compliance of Table 4.124d above
(34) Required impact tests when thermal heat treatment for SS are performed.
Impact tests are required at the test temperature in accordance with ASME Sec. VIII, Div. 2, 3.11.4.1 but no warmer than 21 °C (70 °F) whenever thermal treatments within the temperature ranges listed for the following materials are applied.
a) ASS thermally treated between 480 °C and 900 °C (900 °F and 1650 °F), except for 304 SS, 304L SS, 316 SS, and 316L SS which are thermally treated at temperatures between 480 °C and 705 °C (900 °F and 1300 °F), are exempt from impact testing, provided the MDMT is −29 °C (−20 °F) and warmer and vessel production impact tests of the thermally treated weld metal are performed for Category A and B joints.
b) DSS thermally treated at temperatures between 315 °C and 955 °C (600 °F and 1750 °F).
c) FSS And MSS thermally treated at temperatures between 425 °C and 730 °C (800 °F and 1350 °F).
Thermal treatments of materials do not include thermal cutting
(35) If welded, castings of SB-148 (Al-Bronze Sand Castings), Alloy CDA 954 (C95400 – see Table 2.77 and Sect. 2.6.2.5 in this book) shall be heat treated after all welding at 620–640 °C (1150–1200 °F) for 1.5 hr for the 25 mm (1 in.) of cross-sectional thickness plus 0.5 hr for each additional 25 mm (1 in.) of section thickness. The material shall then be air cooled. – Note (35) is deleted in ASME Sec. VIII, Div. 1 (2019 Edition)

(36) Within 14 days after welding, all products of zirconium Grade R60705 (see Table 2.87 and Sect. 4.12.3.13 in this book) shall be heat treated at 500–610 °C (1000–1100 °F) for a minimum of 1 hr for thicknesses up to 25 mm (1 in.) plus 0.5 hr for each additional 25 mm (1 in.) of thickness. Above 425 °C (800 °F) cooling shall be done at a rate not greater than 280 °C/hr (500 °F/hr) divided by the maximum metal thickness* of the shell or head plate in inches but in no case more than 280 °C/hr (500 °F/hr). From 425 °C (800 °F), the vessel may be cooled in still air. *See Table 4.9, Note (1).

(37) PWHT of Alloy 800 (N08800), Alloy 800H (N08810), or Alloy 800HT (N08811)

a) Pressure boundary welds and welds to pressure boundaries in vessels with design temperatures above 540 °C (1000 °F) fabricated from Alloy 800, Alloy 800H, or Alloy 800HT (see Table 2.68 and Sect. 2.6.2 in this book) shall be PWHT'd. The PWHT shall consist of heating to a minimum temperature of 885 °C (1625 °F) for 1.5 hr for thicknesses up to 25 mm (1 in.) and for 1.5 hr plus 0.04 hr/mm (1 hr/in.) of thickness for thicknesses in excess of 25 mm (1 in.). Cooling and heating rates shall be by agreement between the purchaser and manufacturer. As an alternative, solution annealing in accordance with the material specification is acceptable. PWHT of tube-to-tubesheet and expansion bellows attachment welds is neither required nor prohibited.

b) Except as permitted in (c), vessels or the components that have been PWHT'd in accordance with the requirements of this paragraph shall again be PWHT'd after welded repairs have been made.

c) Weld repairs to the weld metal and HAZ in welds joining these materials may be made after the final PWHT, but prior to the final hydrostatic test, without additional PWHT. The weld repairs shall meet the requirements shown below.

1) The manufacturer shall give prior notification of the repair to the user or to his designated agent and shall not proceed until acceptance has been obtained.

2) The total repair depth shall not exceed 13 mm (0.5 in.) or 30% of the material thickness, whichever is less. The total depth of a weld repair shall be taken as the sum of the depths for repairs made from both sides of a weld at a given location.

3) After removal of the defect, the groove shall be examined. The weld repair area must also be examined using the PT.

4) The vessel shall be hydrostatically tested after making the welded repair

(38) PWHT of UNS R31233 (ULTIMET® – see Table 2.89 in this book) is required prior to cold forming when the cold-forming bend radius at the weld is less than four times the thickness of the component. PWHT shall consist of annealing at 1120 °C (2050 °F) minimum, immediately followed by water quenching

(39) PWHT is neither required nor prohibited for a thickness <13 mm (0.5 in)

(40) PWHT for nonferrous materials is not normally necessary nor desirable unless otherwise noted

Table 4.125 PWHT requirements for TS enhanced ferritic steel vessel (ASME Sec. VIII Div. 1, Table UHT-56)

Products	Spec No.	Grade or type	P-No./ Gr. No.	Nominal thickness requiring PWHT		Notes	PWHT temp., °C (°F)	Holding time	
				mm	in.			hr/in. (25 mm)	min. hr
Plate	SA-353	9Ni	11A/1	> 50	> 2		550–585 (1025–1085)	1	2
Steels	SA-517	Grade A	11B/1	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-517	Grade B	11B/4	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-517	Grade E	11B/2	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-517	Grade F	11B/3	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-517	Grade J	11B/6	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-517	Grade P	11B/8	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-533	Type B, D, Cl.3	11A/4	> 15	> 0.58	–	540–565 (1000–1050)	1/2	1/2
	SA-543	Type B, C, Cl.1	11A/5	–	–	(2)	540–565 (1000–1050)	1	1
	SA-543	Type B, C, Cl.2	11B/10	–	–	(2)	540–565 (1000–1050)	1	1
	SA-543	Type B, C, Cl.3	11A/5	–	–	(2)	540–565 (1000–1050)	1	1
	SA-553	Types I, II	11A/1	> 50	> 2		550–585 (1025–1085)	1	2
	SA-645	Grade A	11A/2	> 50	> 2		550–585 (1025–1085)	1	2
	SA-724	Grade A, B	1/4	NA	NA		NA	NA	NA
	SA-724	Grade C	1/4	> 38	> 1.5		565–620 (1050–1150)	1	1/2
Castings	SA-487	Class 4B	11A/3	> 15	> 0.58		540–565 (1000–1050)	1	1/4
	SA-487	Class 4E	11A/3	> 15	> 0.58		540–565 (1000–1050)	1	1/4
	SA-487	Class CA 6NM	6/4	> 15	> 0.58		565–620 (1050–1150)	1	1/4
Pipes and	SA-333	Grade 8	11A/1	> 50	> 2		550–585 (1025–1085)	1	2
Tubes	SA-334	Grade 8	11A/1	> 50	> 2		550–585 (1025–1085)	1	2
Forgings	SA-508	Grade 4N Cl.1	11A/5	–	–	(2)	540–565 (1000–1050)	1	1
	SA-508	Grade 4N Cl.2	11B/10	–	–	(2)	540–565 (1000–1050)	1	1
	SA-522	Type 1	11A/1	> 50	> 2		550–585 (1025–1085)	1	2
	SA-592	Grade A	11B/1	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-592	Grade E	11B/2	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4
	SA-592	Grade F	11B/3	> 15	> 0.58	(1)	540–595 (1000–1100)	1	1/4

Notes: *NA* not applicable

(1) See ASME Sec. VIII, Div. 1, UHT-82(f)

(2) PWHT is neither required nor prohibited. Consideration should be given to the possibility of temper embrittlement. The cooling rate from PWHT, when used, shall not be slower than that obtained by cooling in still air

Table 4.126 PWHT requirements for Q-T high strength steels (ASME Sec. VIII Div. 2, Table 6.17)

Product	Material	Grade of type	P-No/ Group No.	Nominal thickness requiring PWHT mm (in.)	PWHT temp. °C (°F)	Holding time, hr/25 mm (hr/in)	Minimum holding time, hr
Plate	SA-353	9Ni	11A/ 1	> 50 (2.0)	550–586 (1025–1085)	1	2
Steels	SA-517	Gr. A	11B/ 1	> 15 (0.58)	540–595 (1000–1100)	1	1/4
	SA-517	Gr. B	11B/4	> 15 (0.58)	540–595 (1000–1100)	1	1/4
	SA-517	Gr. E	11B/2	> 15 (0.58)	540–595 (1000–1100)	1	1/4
	SA-517	Gr. F	11B/3	> 15 (0.58)	540–595 (1000–1100)	1	1/4
	SA-517	Gr. J	11B/6	> 15 (0.58)	540–595 (1000–1100)	1	1/4
	SA-517	Gr. P	11B/8	> 15 (0.58)	540–595 (1000–1100)	1	1/4
	SA-533	Gr. B & D, Cl.3	11A/4	> 15 (0.58)	540–565 (1000–1050)	1/2	1/2
	SA-543	Types B & C, Cl.1	11A/5	(1)	540–565 (1000–1050)	1	1
	SA-543	Types B & C, Cl.2	11A/10	(1)	540–565 (1000–1050)	1	1
	SA-543	Types B & C, Cl.3	3/3	(Note 2)	540–565 (1000–1050)	1	1
	SA-553	Types I & II	11A/1	> 50 (2.0)	550–585 (1025–1085)	1	2
	SA-645	Gr. A	11A/2	> 50 (2.0)	550–585 (1025–1085)	1	2
	SA-724	Gr. A & B	1/4	None(2)	NA	NA	NA
	SA-724	Gr. C	1/4	> 38 (1½)	565–620 (1050–1150)	1	1/2
Pipes/ tubes	SA-333	Gr. 8	11A/1	> 50 (2.0)	550–585 (1025–1085)	1	2
	SA-334	Gr. 8	11A/1	> 50 (2.0)	550–585 (1025–1085)	1	1
Forgings	SA-372	Gr. D		See ASME Sec. VIII Div. 2, 6.7.6.3 and ASME SA-372			
	SA-372	Gr. E/F/G/H/J, Cl.70	–	See ASME Sec. VIII Div. 2, 6.7.6.3 and ASME SA-372			
	SA-372	Gr. J, Cl. 110	–	See ASME Sec. VIII Div. 2, 6.7.6.3 and ASME SA-372			
	SA-508	4N, Cl.1 & 2	11A/5 & 11B/10		540–565 (1000–1050)	1	1
	SA-522	Type 1	11A/1	> 50 (2.0)	550–585 (1025–1085)	1	2
	SA-592	Gr. A, E, F	11B/1,2,3	> 15 (0.58)	540–565 (1000–1050)	1	1/4

Notes: NA indicates not applicable
(1)PWHT is neither required nor prohibited. Consideration should be given to the possibility of temper embrittlement. The cooling rate from PWHT, when used, shall not be slower than that obtained by cooling in still air
(2)PWHT required for thickness above 22 mm (0.875 in)

Table 4.128 shows the PWHT requirements in ASME B31.1 Power Piping.

Table 4.129 shows the differences in PWHT requirements in ASME B31.3 and EN 13445-4. PWHT is not generally required for the 9% Ni steels; indeed, EN 13445-4 recommends that PWHT should be avoided. ASME B31.3, however, specifies a PWHT of 552 to 585 °C (1026 to 1085 °F) for both 9%Ni and 5%Ni alloys when thickness exceeds 51 mm (2 in.).

Table 4.127 PWHT requirements defined in ASME B31.3, Table 331.1.1 – modified

P-No. and Group No.	Holding temperature range, °C (°F)[1]	Minimum holding time at temperature for control thickness[2]	
		≤ 50 mm (2 in.)	> 50 mm (2 in.)
P 1, Gr. 1 to 3	595–650 (1100–1200)	1 hr/25 mm (1 hr/1 in.), minimum 15 minutes	2 hr + 15 minutes for additional 25 mm (1 in.) over 50 mm (2 in.)
P 3, Gr. 1 & 2	595–650 (1100–1200)		
P 4, Gr. 1 & 2	650–705 (1200–1300)		
P 5A, Gr. 1	675–760 (1250–1400)		
P 5B, Gr. 1	675–760 (1250–1400)		
P 6, Gr. 1 to 3	760–800 (1400–1475)		
P 7, Gr. 1 & 2[3]	730–775 (1350–1425)		
P 8, Gr. 1 to 4	PWHT not required unless required by WPS		
P 9A, Gr. 1 (2.25Ni steel)	595–650 (1100–1200)		
P 9B, Gr. 1 (3.5Ni steel)	595–650 (1100–1200)		
P 10H, Gr. 1 (DSS)	PWHT not required unless required by WPS. If done, see Note[4]		
P 10I, Gr. 1 (27Cr steel)[3]	730–815 (1350–1500)		
P 11A (9Ni steel)	550–585 (1025–1085[5]		
P 15E, Gr. 1 (9Cr-1Mo-V; Gr.91) See C Note 1.	730–775 (1350–1425)[6], [7]	1 hr/25 mm (1 hr/1 in.), minimum 30 minutes	*≤ 125 mm (5 in.):* 1 hr /25 mm (1 hr/ 1 in.) *> 125 mm (5 in.):* 5 hr + 15 minutes for each additional 25 mm (1 in.) over 125 mm (5 in.)
P 62 (Zr alloys)	540–595 (1000–1100)	–	[8]
All other materials	PWHT as required by WPS	In accordance with WPS	

General Notes of Table 4.127 (from B31.3 unless otherwise specified)
a. The exemptions for mandatory PWHT are defined in Table 4.127a
b. Governing thickness for PWHT (for B31.3): See Sect. 1.1.12.3 in this book

Table 4.127a (1/2) Exemptions for mandatory PWHT are defined in Table 4.127 (ASME B31.3, Table 331.1.3)

P-No., Gr. No.[a]	Control (governing) thickness[b]	Type of weld	Additional limitations required for exemption from PWHT[c] [d] [e] (tn = nominal material thickness) – See C Notes 2 & 3
P 1, all Gr.	All	All	A preheat of 95 °C (200 °F) is applied prior to welding on any tn > 25 mm (1 in.). Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
P 3, Gr. 1 & 2	≤16 mm (5/8 in.)	All	A preheat of 95 °C (200 °F) is applied prior to welding on any tn > 16 mm (5/8 in.). A specified carbon content of the base materials ≤0.25%. Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
P 4, Gr. 1	≤16 mm (5/8 in.)	Groove	Mandatory preheat has been applied. Specified carbon content of the base materials ≤0.15%. Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
	≤16 mm (5/8 in.) except the thickness of a socket weld fitting or flange need not be considered	Socket and fillet welds	Mandatory preheat has been applied. Throat thickness of the fillet weld or the socket weld ≤13 mm (1/2 in.). Specified carbon content of the pipe material ≤0.15%. tn of the pipe ≤16 mm (5/8 in.). Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
	≤16 mm (5/8 in.)	Seal welds and non-load-carrying attachments[g]	Mandatory preheat has been applied. Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
P 5A, Gr. 1	≤16 mm (5/8 in.)	Groove	Mandatory preheat has been applied. Specified carbon content of the base materials ≤0.15%. Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
	≤16 mm (5/8 in.) except the thickness of a socket weld fitting or flange need not be considered	Socket and fillet welds	Mandatory preheat has been applied. Throat thickness of the fillet weld or the socket weld ≤13 mm (1/2 in.). Specified carbon content of the pipe material ≤0.15%. tn of the pipe ≤5 mm (3/16 in.). Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
	≤16 mm (5/8 in.)	Seal welds and non-load-carrying attachments[g]	Mandatory preheat has been applied. Multiple layer welds are used when the tn > 5 mm (3/16 in.).[f]
P 5B, Gr. 1	–	–	No exemptions from PWHT.

Table 4.127a (2/2) Exemptions for mandatory PWHT are defined in Table 4.127 (ASME B31.3, Table 331.1.3)

P-No., Gr. No.[(a)]	Control (governing) thickness[(b)]	Type of weld	Additional limitations required for exemption from PWHT[(c) (d) (e)] (tn = nominal material thickness) – See C Notes 2 & 3
P 6, Gr. 1–3	All	All	Specified carbon content of the base materials ≤0.08%. tn ≤ 10 mm (3/8 in.). Weld filler metal is A-No. 8, A-No. 9, or F-No. 43 composition.[(h)]
P 7, Gr. 1	All	All	
P 7, Gr. 2	–	–	No exemptions from PWHT.
P 8, all Gr. Nos	All	All	PWHT neither required nor prohibited.
P 9A, Gr. 1	All	All	Specified carbon content of the pipe material ≤0.15%. tn ≤ 13 mm (1/2 in.). Mandatory preheat has been applied.
P 9B, Gr. 1	All	All	tn ≤ 16 mm (5/8 in.) and the WPS has been qualified using a material of equal or greater thickness than used in the production weld.
P 10H, Gr. 1	All	All	PWHT neither required nor prohibited.
P 10I, Gr. 1	All	All	PWHT neither required nor prohibited for tn ≤ 13 mm (1/2 in.).
P 11A	≤50 mm (2 in.)		–
P 15E	–	–	No exemptions from PWHT.
P 62	–	–	No exemptions from PWHT

Notes of Table 4.127a

[(a)] *If differences with the P-No. listed in Appendix A are found, the P-No. listed in ASME BPVC Section IX, Table QW/QB-422 applies*

[(b)] *The control thickness is defined in ASME B31.3, para. 331.1.3*

[(c)] *The nominal material thickness is defined in ASME B31.3, para. 331.1.3(c)*

[(d)] *No exemptions are permitted for PWHTs required by the designer or the WPS*

[(e)] *Additional exemptions for welds made in accordance with ASME B31.3, para. 328.7 may be taken for the materials addressed*

[(f)] *Single-layer or single-pass welds may be exempted from PWHT, provided the WPS has been qualified using single-pass welds with ± 10% heat input and that all other conditions for exemption are met*

[(g)] *Non-load-carrying attachments are defined as items where no pressure loads or significant mechanical loads are transmitted through the attachment to the pipe or pressure-containing material*

[(h)] *The A-Nos. and the F-Nos. are found in ASME BPVC Section IX, Tables QW-442 and QW-432, respectively*

Notes of Table 4.127 (from B31.3 unless otherwise specified)

[(1)]The holding temperature range is further defined in ASME B31.3, para. 331.1.6(c) and ASME B31.3, Table 331.1.2 (Table 4.127b Alternative PWHT Requirements for P-Nos. 1 and 3)

Table 4.127b ASME B31.3, Table 331.1.2 Alternative PWHT requirements for P-Nos. 1 and 3

Decrease in specified minimum decreased temperature, °C (°F)	Minimum holding time at decrease in specified minimum decreased temperature, hr, Note (a)
30 °C (50 °F)	2
55 °C (100 °F)	4
85 °C (150 °F), Note (b)	10
110 °C (200 °F), Note (b)	20

Notes

(a) Times shown apply to thicknesses ≤25 mm (1 in.). Add 15 minutes/25 mm (15 minutes/in.) of thickness for control thicknesses >25 mm (1 in.) (see ASME B31.3, para. 331.1.3)

(b) A decrease >55 °C (100 °F) below the minimum specified temperature is allowable only for P 1, Gr. 1 and 2 Materials

Commentary Note: Several project specifications note not to use Table 4.127b above and ASME B31.3, Table 331.1.2 for new construction. Check the project specifications if applicable

[(2)]The control thickness is defined in ASME B31.3, para. 331.1.3

[(3)]Cooling rate shall not be greater than 55 °C (100 °F)/hr in the range above 650 °C (1200 °F), after which the cooling rate shall be sufficiently rapid to prevent embrittlement

[(4)]If PWHT is performed after welding, it shall be within the following temperature ranges for the specific alloy, followed by rapid cooling: Alloys S31803 and S32205 (2205 DSS): 1020–1100 °C (1870–2010 °F) Alloy S32550 (Ferralium 255): 1040–1120 °C (1900–2050 °F) Alloy S32750 (2507 DSS): 1025–1125 °C (1880–2060 °F) All others in P-No.10H, Gr.1: 980–1040 °C (1800–1900 °F) – See Commentary Note 3 below

[(5)]Cooling rate shall be 167 to 333 °C/hr (300 to 600 °F/hr)

[(6)]The minimum PWHT holding temperature may be 720 °C (1325 °F) for the governing thicknesses ≤13 mm (0.5 in.)

[(7)]The Ni + Mn content of the filler metal shall not exceed 1.2% unless specified by the designer (user's engineer), in which case the maximum temperature to be reached during PWHT shall be the *A*1 (lower transformation or lower critical phase transformation temperature as A_{C1} in Table 4.113 in this book) of the filler metal, as determined by analysis and calculation or by test, but not exceeding 800 °C (1470 °F). If the 800 °C (1470 °F) limit was not exceeded but the *A*1 transformation temperature of the filler metal was exceeded or if the composition of the filler metal is unknown, the weld must be removed and replaced. It shall then be rewelded with compliant filler metal and subjected to a compliant PWHT. If the 800 °C (1470 °F) limit was exceeded, the weld and the entire area affected by the PWHT will be removed and, if reused, shall be renormalized and tempered prior to reinstallation

[(8)]Heat treat within 14 days after welding. Hold time shall be increased by 1.2 hr (72 minutes) for each 25 mm (1 in.) over 25 mm (1 in.) thickness. Cool to 425 °C (800 °F) at a rate ≤280 °C (500 °F)/hr

Commentary Notes (C Notes)

1. See Sect. 2.1.4.2(h) for base metal, Sect. 4.11.3.2 for welding, and Sect. 4.12.3.8 for heat treatment in this book for more detailed backgrounds of 9Cr-1Mo-V steel
2. See Table 4.127c for existing piping materials constructed in 2012 and older
3. Alternatively Table 4.123b instead of Table 4.127b may be applicable for temperature conversion.

Table 4.127c PWHT requirements in ASME B31.3, Table 331.1.1 (2012-Old Version) – Note (12)

Base metal P-No. or S-No. [Note (1)]	Weld metal analysis A-number No. [Note (2)]	Base metal group	Nominal wall thickness Note (11)		Specified min. Tensile strength base metal		Metal temperature range		Holding time			Brinell hardness [Note (4)] max.
									Nominal wall [Note (3)]		Min. time, Hr	
			mm	in.	MPa	ksi	°C	°F	Min/ mm	Hr/ in		
1	1	Carbon steel	≤20 >20	≤3/4 >3/4	All All	All All	None 593–649	None 1100–1200	– 2.4	– 1	– 1	– –
3	2, 11	Alloy steels, Cr ≤1/2%	≤20 >20 All	≤3/4 >3/4 All	≤490 All > 490	≤71 All >71	None 593–718 593–718	None 1100–1325 1100–1325	– 2.4 2.4	– 1 1	– 1 1	– 225 225
4 [Note (5)]	3	Alloy steels, 1/2% < Cr ≤ 2%	≤13 >13 All	≤1/2 >1/2 All	≤ 490 All > 490	≤71 All > 71	None 704–746 704–746	None 1300–1375 1300–1375	– 2.4 2.4	– 1 1	– 2	– 225 225
5A, 5B, 5C [Note (5)]	4, 5	Alloy steels, (2 1/4% ≤ Cr ≤ 10%)										
		≤3% Cr and ≤0.15% C	≤13	≤1/2	All	All	None	None	–	–	–	–
		≤3% Cr and ≤0.15% C	>13	>1/2	All	All	704–760	1300–1400	2.4	1	2	241
		>3% Cr or >0.15% C	All	All	All	All	704–760	1300–1400	2.4	1	2	241
6	6	MSS A 240 Gr. 429	All All	All All	All All	All All	732–788 621–663	1350–1450 1150–1225	2.4 2.4	1 1	2 2	241 241
7	7	FSS	All	All	All	All	None	None	–	–	–	–
8	8, 9	ASS	All	All	All	All	None	None	–	–	–	–
9A, 9B	10 –	Nickel alloy steels	≤20 >20	≤3/4 >3/4	All All	All All	None 593–635	None 1100–1175	– 1.2	– 1/2	– 1	– –
10[aa]	–	Cr-Cu steel	All	All	All	All	760–816 [Note (6)]	1400–1500 [Note (6)]	1.2	1/2	1/2	–
10H	–	DSS	All	All	All	All	Note (7)	Note (7)	1.2	1/2	1/2	–
101	–	27Cr steel	All	All	All	All	663–704 [Note (8)]	1225–1300 [Note (8)]	2.4	1	1	–
11A SG 1	–	8Ni, 9Ni steel	≤51 >51	≤2 >2	All All	All All	None 552–585 [Note (9)]	None 1025–1085 [Note (9)]	– 2.4	– 1	– 1	– –
11A SG 2	–	5Ni steel	>51	>2	All	All	552–585 [Note (9)]	1025–1085 [Note (9)]	2.4	1	1	–
62	–	Zr R60705	All	All	All	All	538–593 [Note (10)]	1000–1100 [Note (10)]	Note (10)	Note (10)	1	–

Notes

(1) P-Number or S-Number from ASME BPVC, Section IX, QW/QB-422

(2) A-Number from Section IX, QW-442

(3) For holding time in SI units, use min/mm (minutes per mm thick.). For US units, use hr/in. thick

(4) See para. 331.1.7

(5) See Appendix F, para. F331.1

(6) Cool as rapidly as possible after the hold period

(7) PWHT is neither required nor prohibited, but any heat treatment applied should be done as required in the material specification

(8) Cooling rate to 649 °C (1200 °F) shall be less than 56 °C (100 °F)/hr; thereafter, the cooling rate shall be fast enough to prevent embrittlement

(9) Cooling rate shall be >167 °C (300 °F)/hr to 316 °C (600 °F)

(10) Heat treat within 14 days after welding. Hold time shall be increased by 1/2 hr for each 25 mm (1 in.) over 25 mm thickness. Cool to 427 °C (800 °F) at a rate ≤278 °C (500 °F)/hr, per 25 mm (1 in.) nominal thickness, 278 °C (500 °F)/hr max. Cool in still air from 427 °C (800 °F)

(11) In the case of branch connections with reinforcing pad and/or an integral part, PWHT is required only when the thickness through the weld in any direction exceeds twice the material thickness requiring heat treatment according to ASME B31.3, Fig. 328.5.4D

(12) After cold bending and forming, heat treatment is required per above table (see B31.3, 332.4.2)

(a) For P-No. 1 to 6 materials, where the maximum calculated fiber elongation after bending or forming exceeds 50% of specified basic minimum elongation for the applicable specification, grade, and thickness. This requirement may be waived if it can be demonstrated that the selection of pipe and the choice of bending or forming process provide assurance that, in the finished condition, the most severely strained material retains at least 10% elongation

(b) For any material requiring impact testing, where the maximum calculated fiber elongation after bending or forming will exceed 5%

Commentary Notes:

[aa]P-No. 10 does not exist any more now

(bb) In addition, the current ASME B31.3 has the following specific requirements which are different form the OLD version.

Specific Requirements (ASME B31.3, 331.2)

Where warranted by experience or knowledge of service conditions, alternative methods of heat treatment or exceptions to the basic heat treatment provisions in Table 4.12.3.13a may be adopted as provided below;

(bb-1) Alternative Heat Treatment (ASME B31.3, 331.2.1)

Normalizing, or normalizing and tempering, or annealing may be applied in lieu of the required heat treatment after welding, bending, or forming, provided that the mechanical properties of any affected weld and base metal meet specification requirements after such treatment and that the substitution is approved by the designer.

(bb-2) Exceptions to Basic Requirements (ASME B31.3, 331.2.2)

The basic practices therein may require modification to suit service conditions in some cases. In such cases, the designer may specify more stringent requirements in the engineering design, including heat treatment and hardness limitations for lesser thickness, or may specify less stringent heat treatment and hardness requirements, including none.

When provisions less stringent than those in Para 331.1 (Table 4.127 in this book) are specified, the designer must demonstrate to the owner's satisfaction the adequacy of those provisions by comparable service experience, considering service temperature and its effects, frequency and intensity of thermal cycling, flexibility stress levels, probability of brittle failure, and other pertinent factors. In addition, appropriate tests shall be conducted, including WPS qualification tests.

Table 4.128 PWHT requirements in ASME B31.1, Table 132.1.1-1 modified

Base metals or P-No. and Group No.	Holding temperature range, °C (°F)[(1)]	Minimum Holding Time at Temperature for Control thickness[(2)]	
		≤50 mm (2 in.)	>50 mm (2 in.)
P 1, Gr. 1, 2, 3	595–650 (1100–1200)	1 hr/25 mm (1 hr/1 in.), minimum 15 minutes	2 hr + 15 minutes for each additional 25 mm (1 in.) over 50 mm (2 in.)
P 3, Gr. 1 & 2	595–650 (1100–1200)		
P 4, Gr. 1 & 2	650–705 (1200–1300)		
P 5A/5B, Gr. 1	675–760 (1250–1400)		
P 6, Gr. 1,2, 3	760–800 (1400–1475)		
P 7, Gr. 1 & 2[(3)]	730–775 (1350–1425)		
P 8, Gr. 1, 2, 3, 4	C Note [c.]		
P 9A, Gr. 1 (2.25Ni steel)	595–650 (1100–1200)		
P 9B, Gr. 1 (3.5Ni steel)	595–630 (1100–1175)		
P 10H, Gr. 1 (DSS)	C Note c. If PWHT'd, see Note[(4)]		
P 10I, Gr. 1, Note 3 (27Cr steel)[(3)]	730–815 (1350–1500)		
P 15E, Gr. 1 (9Cr-1Mo-V; Gr.91)[a, (5)]	730–775 (1350–1425)[(6), (7)]	1 hr/25 mm (1 hr/1 in.), minimum 30 minutes	*≤125 mm (5 in.)*: 1 hr /25 mm (1 hr/ 1 in.) *>125 mm (5 in.)*: 5 hr + 15 minutes for each additional 25 mm (1 in.) over 125 mm (5 in.)
A335-P36/ A182-F36, Gr.1 (ferritic alloy steel)	595–650 (1100–1200)	1 hr/25 mm (1 hr/1 in.), minimum 15 minutes	2 hr + 15 minutes for each additional 25 mm (1 in.) over 50 mm (2 in.)
A335-P36/ A182-F36, Gr.2 (ferritic alloy steel)[b]	540–620 (1000–1150)	1 hr/25 mm (1 hr/1 in.), minimum 30 minutes	
All other materials	PWHT as required by WPS	In accordance with WPS	

Commentary Notes (C Note)

[a] See Sect. 2.1.4.2(h) for base metal, 4.11.3(2) for welding, and 4.12.3(8) for heat treatment in this book for more detailed backgrounds of 9Cr-1Mo-V steel

[b] P/F36 are ferritic alloy steel as UNS No. K21001 (1.15Ni-0.65Cu-0.35Mo-0.0030Cb)

[c] PWHT not required unless required for WPS/PQR

Notes (from B31.1 unless otherwise specified):

(1) The permissible holding temperature range: See Table 4.128a and ASME B31.1, 132.1.1 and 132.2 for more details.Exemption of PWHT: See Table 4.128b

Table 4.128a Alternative PWHT requirements for P-Nos. 1 and 3 (ASME B31.1, Table 132.1.1-2)

Decrease in specified minimum decreased temperature, °C (°F)	Minimum holding time at decrease in specified minimum decreased temperature, hr, Note (a)
30 °C (50 °F)	2
55 °C (100 °F)	4
85 °C (150 °F), Note (b)	10
110 °C (200 °F), Note (b)	20

Notes

(a) Times shown apply to thicknesses ≤25 mm (1 in.). Add 15 minutes/25 mm (15 minutes/in.) of thickness for control thicknesses >25 mm (1 in.). See ASME B31.1, para. 132.4

(b) A decrease >55 °C (100 °F) below the minimum specified temperature is allowable only for P 1, Gr. 1 and 2 Materials

Commentary Notes: Several project specifications note not to use Table 4.128a *above and ASME B31.1, Table 132.1 for new construction. Check the project specifications if applicable*

Table 4.128b (1/2) Exemptions for mandatory PWHT are defined in ASME B31.1, Table 132.2-1

P-No., Gr. No.[a]	Control (Governing) thickness[b]	Type of weld	Additional limitations required for exemption from PWHT[c] [d] [e] (tn = Nominal Material Thickness)
P 1, all Gr.	All	All	A preheat of 95 °C (200 °F) is applied prior to welding on any tn > 25 mm (1 in.). Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
P 3, Gr. 1 & 2	≤16 mm (0.625 in.)	All	A preheat of 95 °C (200 °F) is applied prior to welding on any tn > 16 mm (0.625 in.). A specified carbon content of the base materials ≤0.25%. Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
P 4, Gr. 1	≤16 mm (0.625 in.)	Groove	Mandatory preheat has been applied. Specified carbon content of the base materials ≤0.15%. Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
	≤16 mm (0.625 in.) except the thickness of a socket weld fitting or flange need not be considered	Socket and fillet welds	Mandatory preheat has been applied. Throat thickness of the fillet weld or the socket weld ≤13 mm (1/2 in.). Specified carbon content of the pipe material ≤0.15%. tn of the pipe ≤16 mm (0.625 in.). Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
	≤16 mm (0.625 in.)	Seal welds and non-load-carrying attachments[g]	Mandatory preheat has been applied. Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
P 5A, Gr. 1	≤16 mm (0.625 in.)	Groove	Mandatory preheat has been applied. Specified carbon content of the base materials ≤0.15%. Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
	≤16 mm (0.625 in.) except the thickness of a socket weld fitting or flange need not be considered	Socket and fillet welds	Mandatory preheat has been applied. Throat thickness of the fillet weld or the socket weld ≤13 mm (0.5 in.). Specified carbon content of the pipe material ≤0.15%. tn of the pipe ≤5 mm (0.188 in.). Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
	≤16 mm (0.625 in.)	Seal welds and non-load-carrying attachments[g]	Mandatory preheat has been applied. Multiple layer welds are used when the tn > 5 mm (0.188 in.).[f]
P 5B, Gr. 1	–	–	No exemptions from PWHT.
P 6, Gr. 1-3	All	All	Specified carbon content of the base materials ≤0.08%. tn ≤ 10 mm (0.375 in.). Weld filler metal is A-No. 8, A-No. 9, or F-No. 43 composition.[h]
P 7, Gr. 1	All	All	
P 7, Gr. 2	–	–	No exemptions from PWHT for any type and thickness.
P 8, all Gr. Nos	All	All	PWHT neither required nor prohibited.
P 9A, Gr. 1	All	All	Specified carbon content of the pipe material ≤0.15%. tn ≤ 13 mm (0.5 in.). Mandatory preheat has been applied.
P 9B, Gr. 1	All	All	tn ≤ 16 mm (0.625 in.) and the WPS has been qualified using a material of equal or greater thickness than used in the production weld.
P 10H, Gr. 1	All	All	PWHT neither required nor prohibited.
P 10I, Gr. 1	All	All	PWHT neither required nor prohibited for tn ≤ 13 mm (0.5 in.).
P 15E	–	–	No exemptions from PWHT.

Notes

[a] *If differences with the P-No. listed in Appendix A are found, the P-No. listed in ASME BPVC Section IX, Table QW/QB-422 applies*

[b] *The control thickness is defined in ASME B31.1, para. 132.4.1*

[c] *The nominal material thickness is defined in ASME B31.1, para. 132.4.3*

[d] *No exemptions are permitted for PWHTs required by the designer or the WPS*

[e] *Additional exemptions for welds made in accordance with ASME B31.1, para. 127.4.9 may be taken for the materials addressed*

[f] *Single-layer or single-pass welds may be exempted from PWHT, provided the WPS has been qualified using single-pass welds with ±10% heat input and that all other conditions for exemption are met*

[g] *Non-load-carrying attachments are defined as items where no pressure loads or significant mechanical loads are transmitted through the attachment to the pipe or pressure-containing material*

[h] *The A-Nos. and the F-Nos. are found in ASME BPVC Section IX, Tables QW-442 and QW-432, respectively*

[2]The control thickness (governing thickness) is defined in ASME B31.1, para. 132.4.1

[3]Cooling rate shall not be greater than 55 °C (100 °F)/hr in the range above 650 °C (1200 °F), after which the cooling rate shall be sufficiently rapid to prevent embrittlement

[4]If the stress relieving or PWHT is performed after bending, forming, or welding, it shall be within the following temperature ranges for the specific alloy, followed by rapid cooling:Alloys S31803 and S32205 (2205 DSS): 1020–1100 °C (1870–2010 °F) Alloy S32550 (Ferralium 255): 1040–1120 °C (1900–2050 °F) Alloy S32750 (2507 DSS): 1025–1125 °C (1880–2060 °F) All others in P-No.10H, Gr.1: 980–1040 °C (1800–1900 °F) – See Commentary Note (2) below

[5]See Sect. 2.6.2.5 Casting in this book for hardness requirements for ASTM A217 Grade C12A castings after PWHT

[6]The minimum PWHT holding temperature may be 720 °C (1325 °F) for the governing thicknesses ≤13 mm (0.5 in)
[7]The Ni + Mn content of the filler metal shall not exceed 1.2% unless specified by the designer (*user's engineer*), in which case the maximum temperature to be reached during PWHT shall be the A1 (lower transformation or lower critical phase transformation temperature as A_{C1} in Table 4.113 in this book) of the filler metal, as determined by analysis and calculation or by test, but not exceeding 800 °C (1470 °F). If the 800 °C (1470 °F) was not exceeded but the *A1* transformation temperature of the filler metal was exceeded or if the composition of the filler metal is unknown, the weld must be removed and replaced. It shall then be rewelded with compliant filler metal and subjected to a compliant PWHT. If the 800 °C (1470 °F) limit was exceeded, the weld and the entire area affected by the PWHT will be removed and, if reused, shall be renormalized and tempered prior to reinstallation. See Sect. 2.1.4.2(h) for base metal, 4.11.3(2) for welding, and 4.12.3(8) for heat treatment in this book for more detailed backgrounds of 9Cr-1Mo-V steel

Commentary Notes

(1) See Sect. 2.1.4.2(h) for base metal, Sect. 4.11.3.2 for welding, and Sect. 4.12.3.8 for heat treatment in this book for more detailed backgrounds of 9Cr-1Mo-V steel

Table 4.129 PWHT requirements for cryogenic steels

	ASME B31.3		EN 13445-4	
Steel type	Thicknessmm (in.)	Temperature range, °C (°F)	Thicknessmm (in.)	Temperature range, °C (°F)
Fine-grained C/Mn steel	>19 (3/4)	593–649 (1100–1200)	>35 (1.38)	550–600 (1022–1112)
1.5%Ni	>19 (3/4)	593–635 (1100–1175)	>35 (1.38)	530–580 (986–1076)
2.5%Ni	>19 (3/4)	593–635 (1100–1175)	>35 (1.38)	530–580 (986–1076)
3.5%Ni	>19 (3/4)	593–635 (1100–1175)	>35 (1.38)	530–580 (986–1076)
5%Ni	51 (2.0)	552–585 (1026–1085)	>35 (1.38)	530–580 (986–1076)
9%Ni	51 (2.0)	552–585 (1026–1085)	All	None

4.12.3.4 Requirements for PWHT in API, AWS, WRC, BS EN Codes and Standards

(a) PWHT Requirements in API 660 (Shell and Tubes Type Heat Exchangers)
1. Machined contact surfaces, including any threaded connections, shall be suitably protected to prevent scaling or loss of finish during heat treatment.
2. PWHT of fabricated CS and LAS (max.9%Cr) steel channels and bonnets shall be performed for the following:
   – Channels and bonnets with six or more tube passes
   – Channels and bonnets whose nozzle-to-cylinder internal diameter ratios are 0.5 or greater, except where a conical reducer is used in place of the channel or bonnet
3. The purchaser shall specify if PWHT is required for weld-overlaid channels and bonnets.
4. PWHT shall be performed for all CS and LAS (maximum 9%Cr) steel floating head covers that are fabricated by welding a dished-only head into a ring flange.
5. The purchaser shall specify if PWHT of shell side or tube side components is required for process reasons.
6. For sour or wet H_2S service∗, the minimum PWHT requirements for CS construction shall be in accordance with NACE SP0472 (min. 620 °C for CS). The minimum hold time shall be in accordance with the pressure design code, or 1 hour, whichever is greater. ∗*Commentary Note: The service should be extended to all EAC which are described in this book.*
7. *Commentary notes for tube-to-tubesheet (TTT) joints: The purchaser should decide and specify the PWHT requirement for the tube-to-tubesheet weld joints, especially in EAC service. Once PWHT is required, the deformation of tubes and tube bundle should be avoided during/after PWHT. If tube expansion is applied, final rolling may be required after PWHT. For sour or wet H2S service, temper bead welding instead of PWHT may be applied if the purchaser agreed.*
8. *Commentary notes for heat treatment of tubes: The procedure used for heat treatment for TTT weld joints and U-bends shall be agreed between the purchaser and manufacturer. No fins for finned tubes should be at least 50 mm (2 in.) from the end of tubesheet when the PWHT for the TTT joints is done.*
9. Heat Treatment for U-Bends: See Sect. 4.12.3.16.

(b) PWHT Requirements in API 661 (Air-Cooled Heat Exchangers)
1. All carbon steel and low alloy chromium steel headers shall be subjected to PWHT. Welded tube-to-tubesheet (TTT) joints shall be excluded unless required by the pressure design code or specified by the purchaser.
2. Gaskets made of ferritic materials and fabricated by welding shall be fully annealed after welding.
3. For sour or wet H_2S service∗, the minimum PWHT requirements for header boxes with CS construction shall be in accordance with NACE SP0472 (min. 620 °C for CS). ∗*Commentary Note: The service should be extended to all EAC which are described in this book.*
4. Commentary notes for tube-to-tubesheet (TTT) joints: The purchaser should decide and specify the PWHT requirement for the tube-to-tubesheet weld joints, especially in EAC service. Once PWHT is required, the deformation of tubes and tube bundle should be avoided during/after PWHT. If tube expansion is applied, final rolling may be required after PWHT. For sour or wet H2S service, temper bead welding instead of PWHT may be applied if the purchaser agreed.
5. Commentary notes for heat treatment of tubes: The procedure used for heat treatment for TTT weld joints shall be agreed between the purchaser and manufacturer. No fins for finned tubes should be at least 150 mm (6 in.) from the end of header box when the PWHT for the TTT joints is done.

(c) PWHT Requirements for API Storage Tanks

Table 4.130 shows PWHT requirements in API 650 (CS welded storage tanks).

Table 4.131 shows the stress-relieving requirements with the following notes in API 620 (low pressure welded storage tanks).

API 653 (storage tanks inspection, repair, and alteration) basically suggests to avoid PWHT. Preheat and controlled deposition welding, as described in API 653, may be used in lieu of PWHT for repairs to existing nozzles where PWHT is required by API 653 or was performed in the original construction but is inadvisable or mechanically unnecessary for the repair. Prior to using any alternative method, a metallurgical review conducted by a storage tank engineer shall be performed to assess whether the proposed alternative is suitable for the application. The review shall consider the reason for the original PWHT of the equipment, susceptibility of the service to promote stress corrosion cracking, stresses in or near the weld, etc.

Table 4.132 shows the welding methods as alternatives to PWHT qualification in API 653. See API 653, 11.3.1 for Preheating Method (Impact Testing Not Required).

Table 4.130 PWHT requirements (temperature-holding time) for CS storage tanks (API 650,.5.7.4.5)

Minimum stress-relieving temperature		Holding time [hours per 25 mm (1 in.) of thickness]	See note
(°C)	(°F)		
600	1100	1	1
570	1050	2	1
540	1000	4	1
510	950	10	1,2
480 (min.)	900 (min)	20	1.2

Notes
1. For intermediate temperatures, the time of heating shall be determined by straight line interpolation
2. Stress relieving at these temperatures is not permitted for A 537 Class 2 material

Commentary Notes: PWHT in cracking environments (EAC, e.g., amine, sour water, caustic, etc.) should be carefully applied for thin wall tanks. Or may be controlled by hardness and/or temper bead welding without PWHT

Table 4.131 Stress-relieving requirements (temperature holding time) for CS storage tanks (API 620, Table 6.4)

Metal temperature, °C (°F)	Holding time, hours per in. of thickness
593 (1100)	1
621 (1050)	2
538 (1000)	3
519 (950)	5
482 (900) (minimum)	10

Notes
1. For intermediate temperatures, the heating time shall be determined by straight line interpolation
2. Stress-relieving requirements do not apply to the weld to the bottom or annular plate
3. A tank built according to the rules of this standard is not usually thermally field stress relieved after erection because its size and weight do not permit adequate support at the temperature required for stress relievingWhen a tank is not to be field stress relieved, the field welding procedure shall be one that (a) has been proven satisfactory by experience or adequate experiments and (b) will minimize locked-up residual stresses, which are thought to be one of the main causes of cracking in or adjacent to welds (see API 620, 5.25.2 for more details)
4. Tank sections that have a nominal thickness of wall plate greater than 32 mm (1.25 in.) at any nozzle or other welded attachment and nozzle necks whose thickness at any welded joint therein exceeds (D + 50)/120 shall be thermally stress relieved after welding (see API 620, 5.25.3 and 5.25.4 for more details)
5. The reinforced connection shall be completely pre-assembled into a sidewall plate. The completed assembly, including the sidewall plate that contains the connections, shall be thermally stress relieved at a temperature of 593–649 °C (1100–1200 °F) for a period of 1 hour per in. thickness of sidewall-plate thickness, td
6. See API 620, 6.18 for Thermal Stress Relief
7. See API 620, Appendix R.5.3 for PWHT

Table 4.132 Welding methods as alternatives to PWHT qualification. Thicknesses for test plates and repair grooves (API 653, Table 11-1)

Depth t of test groove welded[A]	Repair groove depth qualified	Thickness T of test coupon welded	Thickness of base metal qualified
t	$<t$	<50 mm (2 in.)	$<T$
t	$<t$	≥50 mm (2 in.)	50 mm (2 in.) to unlimited

Note: [A]The depth of the groove used for procedure qualification must be deep enough to allow removal of the required test specimen

(d) PWHT Requirements for API Centrifugal Pumps and Compressors (API 610 and API 617)

There are no specific PWHT requirements for casing except sour environment.

Commentary Notes: PWHT for all repair welds on casing in EAC environments or for all severe repair welds in other environments should be considered.

(e) PWHT-Hardness Requirements for API Valves – Flange to Body Weld
1. Steel Gate Valves — See API STD 600, Table 2
2. Gate, Globe, and Check Valves for Sizes ≤ DN 100 (NPS 4) – See API STD 602, Table B.4

(f) PWHT Requirements in BS EN 13445-4 (Unfired Pressure Vessels – Part 4. Fabrication) – See Table 4.133.

(g) PWHT Requirements in API Welding Standard (API RP582) – See Table 4.134

(h) PWHT Requirements in AWS D1.1 (Structural Welding Code), para. 3.14

Where required by the contract drawings or specifications, welded assemblies shall be stress relieved by heat treating. Final machining after stress relieving shall be considered when needed to maintain dimensional tolerances.

Once the stress relief treatment is required, it shall conform to the following requirements (Table 4.135).

Table 4.133 PWHT in BS EN 13445-4

Material group	PWHT holding temperatures, °C (°F)	Material group	PWHT holding temperatures °C (°F)
1.1	550–600 (1022–1112)	5.4 (X11CrMo9-1)	740–780 (1364–1436)
1.2 (other than 6Mo3)	550–600 (1022–1112)	6.4 (X20CrMoNiV11-1	730–770 (1346–1418)
1.2 (16Mo3)	550–620 (1022–1148)	9.1 & 9.2 (MnNi and Ni steels except X8Ni9)	530–580 (986–1076)
1.3	550–600 (1022–1112)		
5.1 (13CrMo4-5)	630–680 (1166–1256)	9.3	Normally welded with austenitic filler metal. In view of possible carbon diffusion, PWHT should be avoided
5.2 (10CrMo9-10 & 11CrMo9-10	670–720 (1238–1328)		
5.3 (X16CrMo5-1)	700–750 (1292–1382)		

Notes
1. See Table 2.101 in this book for Materials Group in BS EN Standards
2. See BS EN 13445-4, Table 10.1-1 for more details

Table 4.134 (1/2) PWHT temperature and holding time in API RP582 (Welding), Table 5 – modified

P-No.	Material type	Nominal thickness at weld, mm (in)	Service environment	Holding temperature, °C (°F)[a]	Time at holding temperature (hr)
1	Carbon steel	Per code	Per code	593–649 (1100–1200)	1 hr/in. (1 minimum)
1	Carbon steel	All	Wet H_2S	621–649 (1150–1200)	1 hr/in. (1 minimum)
1	Carbon steel	All	Caustic	621–649 (1150–1200)	1 hr/in. (1 minimum)
1	Carbon steel	All	Amine	621–649 (1150–1200)	1 hr/in. (1 minimum)
1	Carbon steel	All	Carbonates	649–677 (1200–1250)	1 hr/in. (1 minimum)
1	Carbon steel	All	HF acid	621–649 (1150–1200)	1 hr/in. (1 minimum)
1	Carbon steel	All	Deaerator	621–649 (1150–1200)	1 hr/in. (1 minimum)
1	Carbon steel	All	Ethanol	621–649 (1150–1200)	1 hr/in. (1 minimum)
3	C-1/2Mo	Per code	Per code	621–649 (1150–1200)	1 hr/in. (1 minimum)
3	C-Mn-Mo	All	All	621–649 (1150–1200)	1 hr/in. (1 minimum)
4	1Cr-1/2Mo. 1 1/4Cr-1/2Mo	All	For maximum tempering (creep)	691–718 (1275–1325)	1 hr/in. (2 minimum)
4	1Cr-1/2Mo. 1 1/4Cr-1/2Mo	All	For optimum high temperature properties (toughness)	677–704 (1250–1300)	1 hr/in. (2 minimum)
4	1Cr-1/2Mo. 1 1/4Cr-1/2Mo	All	Heavy wall pressure vessels for high pressure hydrogen service operating at or below 441 °C (825 °F)	663–691 (1225–1275)	1 hr/in. (2 minimum) refer to API-934-C for more details
5A	2 1/4Cr-1Mo	All	For maximum tempering (creep)	704–732 (1300–1350)	1 hr/in. (2 minimum)
5A	2 1/4Cr-1Mo	All	For maximum high temperature properties (toughness)	691–718 (1275–1325)	1 hr/in. (2 minimum)
5A	2 1/4Cr-1Mo	All	Heavy wall pressure vessels for high temperature, high pressure hydrogen service	677–704 (1250–1300)	1 hr/in. (2 minimum) refer to API 934-A for more details
5B	5Cr-1/2Mo	All	All	718–746 (1325–1375)	1 hr/in. (2 minimum)
5B	9Cr-1Mo	All	All	732–760 (1350–1400)	1 hr/in. (2 minimum)
5B	9Cr-1Mo-V	All	All	746–774 (1375–1425)	1 hr/in. (2 minimum)

Table 4.134 (2/2) PWHT temperature and holding time in API RP582 (Welding), Table 5 – modified

P-No.	Material type	Nominal thickness at weld, mm (in)	Service environment	Holding temperature, °C (°F)[a]	Time at holding temperature (hr)
5C	2 1/4Cr-1Mo-V	All	Heavy wall pressure vessels for high temperature, high pressure hydrogen service	691–718 (1275–1325)	8 minimum. see API 934-A for more details
6	MSS	Per code	All	Per code[b]	1 hr/in. (2 minimum)
7	FSS	Per code	All	Per code	1 hr/in. (1 minimum)
8	ASS	Per code	All	Per code[c]	Per code
9A	1½ to 2½ Ni	Per code	All	593–621 (1100–1150)	1 hr/in. (1 minimum)
9B	3 ½ Ni				
10H	DSS	Per code	All	Per code	1 hr/in. (1 minimum)
11A	8Ni, 9Ni	Per code	All	Per code	1 hr/in. (1 minimum)
45	Alloy 800, 800H, 800HT	Per code	All	Per code	Per code

Notes

[a]For quenched and tempered or normalizing and tempering materials, the PWHT holding temperature shall be at least 15 °C (25 °F) below the original tempering temperature of the base metal unless the fabricator demonstrates that mechanical properties can be achieved at a higher PWHT temperature and holding time

[b]For Type CA-15 and Type CA-15 M materials, a double tempering heat treatment is required. Initial heat treatment at 621 °C (1150 °F) minimum, followed by air cooling to ambient temperature, and second heat treatment at 621 °C (1150 °F) minimum (but lower than initial temperature) and air cooling to ambient temperature.For Type CA6NM material, a double tempering heat treatment is required. Initial heat treatment at 607–691 °C (1225–1275 °F), followed by air cooling to ambient temperature, and second heat treatment at 593–621 °C (1100–1150 °F) and air cooling to ambient temperature

[c]For 321 SS and Type 347 SS materials, postweld thermal stabilization may be specified at 871–899 °C (1600–1650 °F) for 2–4 hours

Commentary Notes

1. The holding time per code may be conservative for heavy wall (2″ and above). In this case, ASME requirements should be applied unless project (or end-user) specification noted
2. The project (or end-user) specification may require three or four cycle heat treatment for the base metal in heavy wall and/or Cr-Mo steels.Once multi-cycle heat treatment is required for the coupon of the base metal, all heat cycles with 260 °C (500 °F) and above should be considered
3. The minimum PWHT temperature in API RP582 is +28 °C (50 °F) plus that required in ASME for environment cracking services, while other API and NACE standards for environment cracking services still do not have additional temperature on the minimum PWHT temperature

Table 4.135 PWHT requirements in AWS D1.1 (CS structure welding)(1)(4)(5)(6)(7) – modified

Sequence	Requirements	Remarks
[Heating]		
From room temperature to 315 °C (600 °F)	The temperature shall not exceed 315 °C (600 °F) at the time the welded assembly is placed in the furnace.	
Above 315 °C (600 °F) to holding temperature	The heating rate in °C (°F)/hr shall not exceed 560 (400) divided by the thicker weld metal thickness, in cm (in.), but in no case more than 220 °C (400 °F)/hr. The rates of heating and cooling need not be less than 55 °C (100 °F)/hr. However, in all cases, consideration of closed chambers and complex structures may indicate reduced rates of heating and cooling to avoid structural damage due to excessive thermal gradients.	During the heating period, variations in temperature throughout the portion of the part being heated shall be no greater than 140 °C (250 °F) within any 5 m (15 ft) interval of length.
At/above holding temperature(2)(3)	After a maximum temperature of 600 °C (1100 °F) is reached on Q-T steels, or a mean temperature range between 600 °C and 650 °C (1100 °F and 1200 °F) is reached on other steels, the temperature of the assembly shall be held within the specified limits.(2) When the specified PWHT is for dimensional stability, the holding time shall be not less than the specified.(2)	During the holding period, there shall be no difference greater than 65 °C (150 °F) between the highest and lowest temperature throughout the portion of the assembly being heated.
[Cooling]		
From 315 °C (600 °F) to room temperature	Cooling shall be done in a closed furnace or cooling chamber at a rate no greater than 260 °C (500 °F) per hour divided by the maximum metal thickness of the thicker part in inches [mm], but in no case more than 260 °C (500 °F) per hour.	
Below 315 °C (600 °F)	From 315 °C (600 °F), the assembly may be cooled in still air.	

Notes: *TMCP* thermomechanical controlled processing (see Sect. 2.1.4.7), *NACT* normalizing-accelerated cooling and tempering (see Sect. 2.1.4.8), *QST* quenched and self-tempering (see para. 2.1.4.9)

(1)Historically, the AWS D1.1 PWHT requirements have been largely based on experience with ASME Sec. VIII, Div. 1 fabrication of plain carbon-manganese steels. PWHT temperature should be 600 °C (1100 °F) maximum for Q-T and QST steels and between 600 °C to 650 °C (1100 °F and 1200 °F) for other steels. See Table 4.123 and Sect. 2.6.2.1 in this book if applicable. ASTM A841 for PWHT requirements of TMCP steel.

PWHT shall be prequalified provided that it shall be approved by the responsible engineer and the following conditions shall be met.
(1-1)The specified minimum yield strength of the base metal shall not exceed 50 ksi [345 MPa]
(1-2)The base metal shall not be manufactured by Q-T, QST, or TMCP or where cold working is used to achieve higher mechanical properties (e.g., certain grades of ASTM A500 tubing)
(1-3)There shall be no requirements for notch toughness testing of the base metal, HAZ, or weld metal.
(1-4)There shall be data available demonstrating that the weld metal shall have adequate strength and ductility in the PWHT condition (e.g., as can be found in the relevant AWS A5.X filler metal specification and classification or from the filler metal manufacturer)
(2)Minimum holding time:
THK ≤ 6 mm (0.25 in.) : 15 minutes
6 mm (0.25 in.) < THK ≤ 50 mm (2 in.): 15 minutes for each 6 mm (0.25 in.) THK or fraction thereof
THK > 50 mm (2 in.): 2 hr + 15 minutes for each additional 25 mm (1 in.) THK or fraction thereof over 50 mm (2 in.)
(3)The welded assemblies may be stress relieved at lower temperatures for longer periods of time per Table 4.128a
(4)PWHT [at 620 °C (1150 °F) for a few hours] of as-rolled or normalized carbon-manganese steel and LAS (having a 50 ksi [345 MPa] or lower yield strength) does not adversely affect strength. PWHT, regardless of temperature or duration, degrades the notch toughness of Cb(Nb) or V microalloyed base metals and HAZs. Degradation varies in severity and may or may not affect the suitability for service
(5)Steels manufactured by Q-T, QST, or TMCP processing need to have the development of their PWHT based on the specific material and processing. PWHT may reduce strength and notch toughness properties for these materials. The response to PWHT is very dependent on composition. Some reports indicate that 550 °C (1025 °F) may be a more appropriate PWHT temperature for certain TMCP steels. The optimum PWHT temperature is dependent on specific composition, strength, and notch toughness requirements
(6)ASTM A710 Gr. A, precifitation-hardening Ni, Cu, Cr, Mo, or Cb (Nb) steel is susceptible to cracking in the HAZ during PWHT. Gr. B and C have not been studied. Some grades of ASTM A514/A517 are marginal for PWHT due to low ductility and possible HAZ cracking during PWHT as well as loss of strength and toughness. Some specifications place specific limits on PWHT such as ASTM A913 or "High Strength LAS Shapes of Structural Quality, produced by QST" which requires that "shapes shall not be formed and PWHT'd at temperatures exceeding 600 °C (1100 °F)." The API offshore structures specifications 2 W for TMCP steels and 2Y for Q-T steels have similar warnings regarding "Post Manufacturing Heating" which need to be considered when PWHT is contemplated
(7)Steels Not Recommended for PWHT: PWHT of weldments of ASTM A514, A517, A709 Gr. 100 (690) and 100 W (690 W) and ASTM A710 steels is not generally recommended. PWHT may be necessary for those applications where weldments shall be required to retain dimensional stability during machining or where SCC may be involved, neither condition being unique to weldments involving ASTM A514, A517, A709 Gr. 100 (690) and 100 W (690 W) and ASTM A710 steels. However, the results of notch toughness tests have shown that PWHT may actually impair weld metal and HAZ toughness, and intergranular cracking (IGC) may sometimes occur in the grain-coarsened region of the weld HAZ

4.12.3.5 Heat Treatment of Stainless Steels in Metal Handbooks and Other Resources

The main purpose of heat treatment of stainless steels is typically to remove the residual stress and/or to maintain the corrosion (IGC) resistance and demagnetized condition (only for ASS). ASTM A480 may be one of the guidelines. In the sour service, the double tempered treatments are normally required for the base metal in accordance with NACE standards. Table 4.136 shows annealing temperatures and procedures of MSS.

Tables 4.137 and 4.138 show the recommendations of the annealing treatments for FSS and ASS.

Table 4.139 shows stress relieving of ASS per operating condition and solution heat treatment of ASS. Table 4.140 shows the application guideline for thermally stabilizing heat treatment of stabilized ASS and nickel alloys.

Table 4.141 shows the applicable heat treatment of PHSS.

Table 4.136 Annealing temperatures and procedures of martensitic stainless steels (MSS) (e)

Process (subcritical) annealing (a)			Full annealing (b) (c)		Isothermal annealing (c)	
UNS No.	°C (°F)	Hardness	°C (°F)	Hardness	Procedure (d)	Hardness
S40300 S41000	650–760 (1202–1404)	82–92 HRB	830–885 (1526–1625)	75–85 HRB	Heat to 830–885 °C (1526–1625 °F) hold 6 hrs at 705 °C (1301 °F)	85 HRB
S41400	650–730 (1202–1346)	99 HRB-24 HRC	Not recommended		Not recommended	
S41600 S41623	650–760 (1202–1404)	86–92 HRB	830–885 (1526–1625)	75–85 HRB	Heat to 830–885 °C (1526–1625 °F) hold 2 hrs at 720 °C (1328 °F)	85 HRB
S42000	675–760 (1202–1404)	94–97 HRB	830–885 (1526–1625)	86–95 HRB	Heat to 830–885 °C (1526–1625 °F) hold 2 hrs at 705 °C (1301 °F)	95 HRB
S43100	620–705 (1148–1301)	99 HRB-30 HRC	Not recommended		Not recommended	
S44002	675–760 (1202–1404)	90 HRB-22 HRC	845–900 (1553–1652)	94–98 HRB	Heat to 845–900 °C (1553–1652 °F) hold 4 hrs at 690 °C (1274 °F)	98 HRB
S44003	675–760 (1202–1404)	98 HRB-23 HRC	845–900 (1553–1652)	95 HRB-20 HRC	Same as S44002	20 HRC
S44004	675–760 (1202–1404)	98 HRB-23 HRC	845–900 (1553–1652)	98 HRB-25 HRC	Same as S44002	25 HRC

Source: ASM Metal H/B, Vol. 04 series
Notes
(a) Air cooling from the annealing temperature: maximum softness is obtained by heating to temperature at high end of range
(b) Soak thoroughly at temperature within range indicated: furnace cool at 790 °C (1454 °F); continue cooling at 15–25 °C (27–45 °F)/hr to 595 °C (1103 °F); air cool to room temperature

(c) Recommended for applications in which full advantage may be taken of the rapid cooling to the transformation temperature and from it to room temperature
(d) Preheating to a temperature within the process annealing range is recommended for thin-gauge parts, heavy sections, previously hardened parts, parts with extreme variations in section or with sharp re-entrant angles, and parts that have been straightened or heavily ground or machined to avoid cracking and minimize distortion, particularly for S42000/S43100/S44002/S44003/S44004
(e) When it is exposed to wet H_2S (sour) service (ANSI/NACE MR0175/ISO 15156 and ANSI/NACE MR0103/ISO 17945), the following procedures shall be complied.
1) UNS S41000, J91150 (CA15), and J91151 (CA15M) MSS are acceptable to 22 HRC maximum provided the following three-step heat treatment is complied.
a) Austenitize and quench or air cool.
b) Temper at 621 °C (1150 °F) minimum; then air cool to ambient temperature.
c) Temper at 621 °C (1150 °F) minimum, but lower than the first tempering temperature; then air cool to ambient temperature
2) Low carbon, 12Cr-4Ni-Mo MSS, either cast UNS J91540 (CA6NM) or wrought UNS S42400 or UNS S41500 (F6NM), are acceptable to 23 HRC maximum provided the following three-step heat treatment is complied.
a) Austenitize at 1010 °C (1850 °F) minimum and air or oil quench to ambient temperature.
b) Temper at 649–691 °C (1200–1275 °F) and air cool to ambient temperature.
c) Temper at 593–621 °C (1100–1150 °F) and air cool to ambient temperature.
Variations containing alloying elements such as lead, selenium, or sulfur to improve machinability are not acceptable
3) UNS42000 shall have 22 HRC maximum and be Q-T
4) UNS41425 shall have 28 HRC maximum and be austenitized and Q-T

Table 4.137 Annealing treatments for FSS in ASM Metal H/B Vol. 4

Grade	UNS No.	Common name	Treatment temperature	
			°C	°F
Conventional ferritic grades	S40500	405	650–815	1200–1500
	S40900	409	870–900	1600–1650
	S43000	430	705–790	1300–1450
	S43020	430F	705–790	1300–1450
	S43400	434	705–790	1300–1450
	S44600	446	760–830	1400–1525
Low-interstitial ferritic grades	S43065	439	870–925	1600–1700
	S44400	444	955–1010	1750–1850
	S44626	26-1 Ti	760–955	1400–1750
	S44660	SC-1	1010–1065	1850–1950
	S43065	29-4C	1010–1065	1850–1950
	S44800	29-4-2	1010–1065	1850–1950
	S44635	26-4-4	1010–1065	1850–1950

Note: PWHT of low-interstitial FSS is generally unnecessary and frequently undesirable. Any annealing of these grades should be followed by water quenching or very rapid cooling

Table 4.138 Solution annealing temperatures for commercial ASS in ASM Metal H/B Vol. 4[(1),(2)]

UNS No.	Name	ASTM	Form	°C	°F
J93370	CD-4MCu	A743	Casting	1040 min	1900 min
J95150	CN-7 M	A743	Casting	1120 min	2050 min
N08020	20Cb-3	B464	Pipe	980–1010	1800–1850
N08024	20Mo-4	B464	Pipe	1050–1080	1925–1975
N08026	20Mo-6	B464	Pipe	1120–1205	2050–2200
N08028	Sanicro 28	B668	Tube	1080–1140	1975–2085
N08366	AL-6X	B675	Pipe	1205 min	2200 min
N08367	AL-6XN	B675	Pipe	1175 min	2150 min
N08700	JS700	B599	Plate	1090 min	2000 min
N08904	904L alloy	B677	Pipe, tube	1065–1150	1950–2100
N08925	25-6Mo	B677	Pipe, tube	1065–1150	1950–2100
S20910	22-13-5	A312	Pipe	1040 min	1900 min
S24000	18-3Mn	A312	Pipe	1040 min	1900 min
S30400	304 SS	A312	Pipe	1040 min	1900 min
S30403	304L SS	A312	Pipe	1040 min	1900 min

S30409	304H SS	A312	Pipe	1040 min	1900 min
S30451	304N SS	A312	Pipe	1040 min	1900 min
S30453	304LN SS	A312	Pipe	1040 min	1900 min
S30815	253MA	A312	Pipe	1040 min	1900 min
S30900	309 SS	A312	Pipe	1040 min	1900 min
S31000	310 SS	A312	Pipe	1040 min	1900 min
S31254	254 SMO	A312	Pipe	1150 min	2100 min
S31600	316 SS	A312	Pipe	1040 min	1900 min
S31603	316L SS	A312	Pipe	1040 min	1900 min
S31609	316H SS	A312	Pipe	1040 min	1900 min
S31651	316N SS	A312	Pipe	1040 min	1900 min
S31653	316LN SS	A312	Pipe	1040 min	1900 min
S31700	317 SS	A312	Pipe	1040 min	1900 min
S31703	317L SS	A312	Pipe	1040 min	1900 min
S31725	317LM SS	A312	Pipe	1040 min	1900 min
S31726	317L4 SS	A312	Pipe	1040 min	1900 min
S32100(3)	321 SS	A312	Pipe	1040 min	1900 min
S32109(3)	321H SS	A312	Pipe	CW 1095 min, HR 1050 min	CW 2000 min, HR 1925 min
S34700(3)	347 SS	A312	Pipe	1040 min	1900 min
S34709(3)	347H SS	A312	Pipe	CW 1095 min, HR 1050 min	CW 2000 min, HR 1925 min
S34800(3)	348 SS	A312	Pipe	1040 min	1900 min
S34809(3)	348H SS	A312	Pipe	CW 1095 min, HR 1050 min	CW 2000 min, HR 1925 min
S38100	18-18-2	A312	Pipe	1040 min	1900 min
S31200	44LN	A790	Pipe	1050–1100	1920–2010
S31260	DP-3	A790	Pipe	1020–1100	1870–2010
S31500	3RE60	A790	Pipe	980–1040	1800–1900
S31803	2205 alloy	A790	Pipe	1020–1100	1870–2010
S32304	SAF 2304	A790	Pipe	930–1040	1800–1900
S32550	Ferralium 255	A790	Pipe	1040 min	1900 min
S32950	7Mo plus	A790	Pipe	990–1025	1820–1880

Legend: *CW* cold worked/finished, *HR* hot rolled/finished
Notes
(1)Solution annealing consists of heating to temperature a cooling rapidly
(2)The indicated annealing temperatures come from ASTM standards
(3)A stabilization heat treatment for stabilized ASS after solution annealing improves resistance to intergranular corrosion (see Table 4.140, Sect. 2.1.6.3 IGC, 2.1.6.8 PTASCC and 4.12.5 stabilization heat treatment for more details)

Table 4.139 Stress relieving of ASS per operating condition (recommendation). *Consult with certified metallurgist for more detailed application

Materials	Suggested thermal treatment1)		
Service condition	304L, 316L (Low carbon)	321, 347, 318 (Stabilized)	304, 316 (Standard)
Severe stress corrosion	A, B	A, B	2)
Moderate stress corrosion	A, B, C	A, B, C	C2)
Mild stress corrosion	A, B, C, E, F	A, B, C, E, F	C, F
Remove peak stresses only	F	F	F
No stress corrosion	Not required	Not required	Not required
Intergranular corrosion	A, C3)	A, C, B3)	C
Stress relief after severe forming	A, C	A, C	C
Relief between forming operations	A, B, C	A, B, C	C3)
Structural soundness[e]	A, B, C	A, B, C	C
Dimensional stability	G	G	G

Notes: source: Handbook of SS, McGraw-Hill
1)Key to letter designations of treatments; * Holding time: 4 hours/25 mm (4 hours/in.) of thickness
A. Anneal at 573–604 °C (1063–1120 °F) and slow cool
B. Stress-relieve at 482 °C (900 °F) and slow cool
C. Anneal at 573 to 604 °C (1063 to 1120 °F) and quench

D. Stress-relieve at 482 °C (900 °F) and quench
E. Stress-relieve at 250–342 °C (482–648 °F) and slow cool
F. Stress-relieve at 250 °C (482 °F) and slow cool
G. Stress-relieve at 96–250 °C (204–482 °F) and slow cool
2)To allow the optimum stress-relieving treatment, the use of stabilized or extra low carbon grades is recommended
3)In most instances, no heat treatment is required, but where fabrication procedures may have sensitized the stainless steel, the heat treatments noted may be employed
4)Treatment A, B, or D also may be used, if followed by treatment C when forming is completed
5)Where severe fabricating stresses coupled with high service locking may cause cracking. Also, after welding heavy sections, cool rapidly

Table 4.140 Thermally stabilizing heat treatment of austenitic stainless steels and alloys – Notes 1, 2, 4, 5, 6, 7, 8, and 9

Material group	Materials	Thermally stabilizing holding temperature, °C (°F)	Holding time, hrs	Initial solution heat treatment holding temperature, °C (°F) in ASTM	Remark
ASS (Note 3)	321	843–900 (1550–1650)	2–4	Min. 1040 (1900)	Ti: 5(C + N)% to 0.70%
	321H	843–900 (1550–1650)	2–4	1050 (1925) for hot finish 1093 (2000) for cold finish	Ti: 4(C + N)% to 0.70%
	347	843–900 (1550–1650)	2–4	Min. 1040 (1900)	Nb: 10C% to 1.00
	347H	843–900 (1550–1650)	2–4	1050 (1925) for hot finish 1093 (2000) for cold finish	Nb: 8C% to 1.00
	348	843–900 (1550–1650)	2–4	Min. 1040 (1900)	Nb: 10C% to 1.00
	348H	843–900 (1550–1650)	2–4	Min. 1040 (1900)	Nb: 8C% to 1.00
	S34751 (347LN SS)	843–900 (1550–1650)	0.5 to 1	927–1010 (1700–1850)	Nb: 0.2–0.5
Nickel alloys	N08020 (alloy 20Cb-3)	Note 10		927–1010 (1700–1850) – B474 982–1010 (1800–1850) – B464	Nb: 8 × C% to 1.00
	Alloy 825	Note 10		930–980 (1700–1800)	Ti: 0.6–1.2%
	Alloy 800(H)	Note 10		Min. 1120 (2050)	Ti: 0.15–0.6%
	Alloy 625	Note 10		Min. 1093 (2000)	Nb + Ta: 3.15–4.15% Ti: ≤0.4%

Notes: (source: ASME Sec. VIII, Div. 1, ASTM standards for SS, etc.)
1. Thermally stabilized heat treatment is typically applied for Nb-, Ti-, or Ta-stabilized austenitic stainless steels and alloys which are long term exposed to 482 °C (900 °F) for stabilized ASS [or 538 °C (1000 °F) for nickel alloys above] or higher during operation (mostly) or PWHT
2. Cooling: Air cooling for thermally stabilizing heat treatment/rapid cooling for initial solution heat treatment
3. Heating: Maximum 110 °C/hour (200 °F/hour) above 649 °C (1200 °F) may be recommended. One-side heating to 900 °C (1650 °F) on thick sections may require minimum 4 hours hold time at 900 °C (1650 °F) and higher. If heat treatment done in furnace with two-side heating, no heating rate restriction may apply
4. Stabilization heat treatment for ASS is not intended in lieu of initial solution heat treatment. It is an additional requirement
5. See 4.12.5 for general application of stabilization heat treatment
6. See 2.1.6(3) for stabilization heat treatment in knife-line attack environment
7. See 2.1.6(8) for stabilization heat treatment in PTASCC (polythionic acid) environment
8. ASTM suggests that the temperature of stabilization heat treatment for ASS shall be at a temperature as agreed upon between the purchaser and vendor
9. Other stabilized ASS, such as 309Cb, 309HCb, 310Cb, 310HCb, 316Cb, etc., are not included in this table
10. Normally not required

Table 4.141 Heat treatment of precipitation hardening stainless steels (PHSS)

Metal	UNS No.	Grade or type	Heat treatment(1)								
			Solution annealing			Austenitic conditioning			Precipitation hardening		
			°C	°F	Quench	°C	°F	Quench	°C	°F	Quench
Martensitic PHSS											
PH13-8Mo	S13800	XM-13	927 ± 14	1700 ± 25	AC	–	–	–	510–538	950–1000	AC, 4 h
17–4 PH	S17400	630	1052 ± 28	1925 ± 50	AC	–	–	–	482–621	900–1150	AC, 4 h
15–5 PH	S15500	XM-12	1038 ± 14	1900 ± 25	AC	–	–	–	496–621	925–1150	AC, 4 h
Custom 450	S45000	XM-25	1038 ± 14	1900 ± 25	RC	–	–	–	482–621	900–1150	AC, 4 h
Custom 455	S45500	XM-16	830 ± 14	1525 ± 25	WQ	–	–	–	482–510	900–950	AC, 4 h
Semiaustenitic PHSS											
17–7 PH	S17700	631	1066 ± 14	1950 ± 25	AC	954 ± 8	1750 ± 15	SZC	510	950	AC, 1 h
PH15-7 Mo	S15700	632	1066 ± 14	1950 ± 25	AC	954 ± 8	1750 ± 15	SZC	510	950	AC, 1 h

17–7 PH	S17700	631	1066 ± 14	1950 ± 25	AC	760 ± 14	1400 ± 25	RC	566	1050	AC, 1 1/2 h
PH15-7 Mo	S15700	632	1066 ± 14	1950 ± 25	AC	760 ± 14	1400 ± 25	RC	566	1050	AC, 1 1/2 h
AM-350	S35000	633	1066 ± 14	1950 ± 25	RC	932 ± 14	1710 ± 25	SZC	454–538	850–1000	AC, 3 h
AM-355	S35500	634	1038 ± 14	1950 ± 25	RC	954 ± 6	1750 ± 10	SZC	454–538	850–1000	AC, 3 h
Austenitic PHSS											
A-286	S66286	660	899–982	1650–1800	RC	–	–	–	718	1325	AC, 16 h
17-10P	–	–	1121	2050	WQ	–	–	–	704	1300	AC, 24 h
HNM	–	–	1121	2050	AC	–	–	–	732	1350	AC, 16 h

Legend
*AC*air cooled, *RC* rapid cooling (air-forced cooled), *WQ* water quenching, *SZC* sub-zero cooling, *h* hours as minimum
Notes: (source: ASM Metal H/B Vol.4)
(1)SZC (sub-zero cooling): Stainless steel components can be cryogenically treated before tempering to transform retained austenite, particularly where dimensional stability is important (e.g., AISI 440C). Temperatures in the range of −75 °C (−100 °F) to −100 °C (−150 °F) are common, and deep cooling below −185 °C (−300 °F) is being used

4.12.3.6 Heat Treatments for Dissimilar Metal Weld Joints

The heat treatment holding temperature should be selected from the higher temperature required for each metal of the dissimilar metals unless otherwise specified by engineering judgment (i.e., see ASME Sec. VIII, Div. 1, UCS-56(c)) or applicable codes (i.e., see ASME Sec. VIII, Div. 1, Table UCS-56-11, Note (2)). But the temperature shall not exceed the lower LCPTT (lower critical phase transformation temperature – see Table 4.113) between two metals. Table 4.142 shows the recommended PWHT temperature for dissimilar Cr-Mo steel welds.

Table 4.142 Recommended PWHT temperature [°C (°F)] for dissimilar welds of Cr-Mo steels

Group No.	11	22	23	9	91	911	92	SS
11	690 ± 14 (1275 ± 25)	690 ± 14 (1275 ± 25)	690 ± 14 (1275 ± 25)	690 ± 14 (1275 ± 25)	Butter 690 ± 14 (1275 ± 25)	Butter 690 ± 14 (1275 ± 25)	Butter 690 ± 14 (1275 ± 25)	Butter (opt) 690 ± 14 (1275 ± 25)
22		732 ± 14 (1350 ± 25)	732 ± 14 (1350 ± 25)	732 ± 14 (1350 ± 25)	Butter 732 ± 14 (1350 ± 25)	Butter 732 ± 14 (1350 ± 25)	Butter 732 ± 14 (1350 ± 25)	Butter (opt) 732 ± 14 (1350 ± 25)
23			None	760 ± 14 (1400 ± 25)	Butter 760 ± 14 (1400 ± 25)	Butter 760 ± 14 (1400 ± 25)	Butter 760 ± 14 (1400 ± 25)[(a)]	None
9				760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	Butter (opt) 760 ± 14 (1400 ± 25)	Butter (opt) 760 ± 14 (1400 ± 25)	Butter 760 ± 14 (1400 ± 25)
91					760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)[(a)]	760 ± 14 (1400 ± 25)[(a)]	Butter 760 ± 14 (1400 ± 25)
911						760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)[(a)]	Butter 760 ± 14 (1400 ± 25)
92							760 ± 14 (1400 ± 25)	Butter 760 ± 14 (1400 ± 25)
SS								None

Source: API TR938B, EPRI 2015 Technical Report, and ESAB Technical Report-combined
General Notes
1. The objective in dissimilar welding is to maintain properties while addressing differences in the respective base metals, HAZs, and PWHT temperatures
2. Buttering and multi-step PWHT is used where PWHT required for one base metal, HAZ, or weld metal is excessive for one or more of the others
3. Where “Buffer” is shown, “Butter” the indicated base metal, perform PWHT of the butter at the temperature listed, then join the other material to the butter, and perform PWHT of the completed weldment at the second temperature
4. Grade 23 has shown tendencies towards reheat cracking from PWHT. This alloy was originally designed to be used without PWHT. Buttering may be required
5. Grade 24 typically does not require PWHT. Buttering may be required
6. Caution must be observed when selecting PWHT temperatures that will not encroach on the Ac1 of the lower temperature material
7. Opt: optional

Notes
(a)Where B9 weld metal is used for buttering or joining, 760 ± 14 °C (1400 ± 25 °F) is the optimum heat treatment temperature, provided the A_{C1} (lower critical transformation temperature) is not exceeded

4.12.3.7 ISR/DHT/Final PWHT for 2 ¼ to 3Cr-1Mo Steel Welds in Company Standards and API RP934-A/TR934-D

(a) General-ISR (intermediate stress relieving) which is done at temperature of 85–110 °C (150–200 °F) below the PWHT temperature is aimed to ensure a partial removal of the residual stresses in the weld, so as to avoid any cracking during welding. DHT which are performed at minimum temperature of 300–350 °C (570–660 °F) per steel grade is aimed to permit hydrogen to evolve from the deposited weld metal and base metal HAZ. The holding temperature tolerance range should be ±14 °C (±25 °F).

Fabrication sequence with all ISR, DHT, and final PWHT, including temperature and holding times, shall be submitted prior to material procurement.

All nondestructive examination (NDE) inspections shall also be referenced on the fabrication sequence.

The temperature and time is applicable to base material and shall include the following:

1. The maximum amount of time available for ISR and PWHT shall be established.
2. Probable times for ISR and final PWHT to fabricate the vessel shall be reported.
3. These times shall be subject to approval prior to the start of work.

ISR or DHT should be performed only after careful consideration of the metallurgical factors and possible risks. For example, the temperatures and times used for the ISR must balance the needs to reduce stress and soften the metal, with the concern of using up too much of the tempering time allowed for the steel. The DHT, if approved by purchaser, typically is used only for the non-restrained welds on conventional 2 ¼ Cr-1Mo steels, such as the shell or shell-to-head welds.

(b) Intermediate Stress Relief (ISR)

Preheat should be maintained until the piece is loaded into the furnace and ready to start the ISR. An ISR soak in a furnace should be performed at the metal temperature shown below for at least 1 hour per inch of thickness with the minimum holding time below:

(a) 2¼ to 3Cr-1 Mo steel (conventional steel): 593 °C (1100 °F), minimum 2 hours

(b) 2¼ to 3Cr-1 Mo-¼V steel (advanced steel): 650 °C (1200 °F), minimum 4 hours or 680 °C (1250 °F), minimum 2 hours

ISR typically makes a small contribution for total LMP, so that the holding time may be negligible for LMP.

(c) Dehydrogenation Heat Treatment (DHT)

The manufacturer shall make a written request for purchaser's approval to use a low temperature DHT in lieu of an ISR if needed. The manufacturer's request shall include detailed information and data concerning hydrogen controls for procurement and handling of welding consumables, hydrogen content of weld metals and HAZ(s) after the DHT, and nondestructive examination of weld joints. The purchaser may require the manufacturer to demonstrate high sensitivity ultrasonic examination procedures to detect flaws at weld joints after using a DHT.

API RP934-A (2.25 to 3Cr steels) indicates that the DHT shall be performed at a minimum metal temperature of 300 °C (570 °F) for conventional steels and 350 °C (660 °F) for advanced steels when approved by purchaser. The duration should be agreed upon between manufacturer and purchaser; however, in no case should the duration be less than 1 hour for conventional steels and 4 hours for advanced steels. For tack welds, DHT can be reduced to preheat temperatures, for a minimum 1 hour.

Some companies may specify the DHT of minimum metal temperature of 385 °C ± 14 °C (725 °F ± 25 °F) for duration of no less than 2 hours regardless of thickness. DHT typically does not affect the total LMP.

(d) Final PWHT in API RP934-A

- Conventional steels: 690 ± 14 °C (1275 ± 25 °F), holding time per ASME Sec. VIII, Div. 2, Table 6.11 and approved WPS
- Advanced steels: 705 ± 14 °C (1300 ± 25 °F), min. 8 hours holding time plus ASME Sec. VIII, Div. 2, Table 6.11 and approved WPS/PQR with required toughness and mechanical properties

4.12.3.8 Heat Treatment for Gr. 91 Material (9Cr-1Mo-V Enhanced)

(a) Dehydrogenation Heat Treatment (DHT)

If the welds are to be cooled down to ambient temperature after welding and before PWHT, a postweld bake-out may be of critical importance due to hydrogen embrittlement, especially for thick-walled components when presence of residual hydrogen is of concern. One example of postweld back-out process includes soaking the weld joint and at least 75 mm (3 in.) from the end of each side weld, at 320 °C (600 °F) for min. 20 minutes or 60 minutes for thin- and thick-walled components, respectively. Then the weldment is wrapped with insulation and allowed to slow cool below 93 °C (200 °F) to facilitate hydrogen diffusion from the weld joint. See Sect. 4.3 for hydrogen effects and requirements and Table 4.49 for hydrogen control in FCAW for more general application.

(b) Final PWHT for Maximum Holding Temperatures or Optimum Holding Temperature Ranges

The appropriate PWHT develops a sound-tempered martensitic structure. Precipitation of V/Nb-rich carbonitrides along uniform distribution of fine lath boundaries and at dislocations is the basis for superior creep rupture strength of Gr. 91 steel. Over-tempering during PWHT will result in loss of creep rupture properties, while under-tempering will lead to high weld hardness from untempered martensite.

The following requirements are to be selected partially or entirely.

1. The holding temperature: 760 ± 14 °C (1400 ± 25 °F) for utility service (e.g., power plants) and 775 ± 10 °C (1427 ± 18 °F) for process service (refinery and petrochemical process units) unless otherwise specified.

2. PWHT temperature is typically specified below A_{C1} of the filler metal by 14– 28 °C (25–50 °F). Typically, the Ac1 (LCPTT in Table 4.113) on weld metal is kept below 788 °C (1450 °F).
3. ASME Sec. VIII, Div. 1 and 2: See Tables 4.123 and 4.124, respectively, in this book.
4. EPRI 2015 recommends PWHT should be in the range of 675–770 °C (1247–1418 °F).
5. ASME Sec. I requires that
   If Ni + Mn is ≤1.0 wt% in filler metal, the maximum is 800 °C (1470 °F).
   If Ni + Mn is >1.0 but <1.2 wt% in filler metal, the maximum is 785 °C (1445 °F).
   If the Ni + Mn content of the filler material is not known, the maximum is 785 °C (1445 °F).
6. ASME B31.1 and B31.3 require that
   The Ni + Mn content of the filler metal shall not exceed 1.2% unless specified by the designer, in which case the maximum temperature to be reached during PWHT shall be the *A*1 (lower transformation or lower critical phase transformation temperature as A_{C1} (LCPTT in Table 4.113 in this book) of the filler metal, as determined by analysis and calculation or by test, but not exceeding 800 °C (1470 °F). If the 800 °C (1470 °F) limit was not exceeded but the *A*1 of the filler metal was exceeded or if the composition of the filler metal is unknown, the weld must be removed and replaced. It shall then be rewelded with compliant filler metal and subjected to a compliant PWHT. If the 800 °C (1470 °F) limit was exceeded, the weld and the entire area affected by the PWHT will be removed and, if reused, shall be renormalized and tempered prior to reinstallation.
7. API TR938-B recommends that
   The time specified in B31.1 for PWHT may be inadequate. A minimum of 2–3 hrs in the range of 750–760 °C (1382–1418 °F) is recommended, or longer for thicker sections to provide sufficient tempering.

   Also, the welding rod should have a Ni + Mn content of <1.5% to keep enough temperature gap between PWHT and A_{C1} (LCPTT in Fig. 2.27 in this book). This will ensure that the A_{C1} will be high enough so that your PWHT temperature will not exceed it. It has been shown that when the Ni + Mn of weld metal is 1.5%, the A_{C1} temperature is 780 °C (1436 °F). This is extremely close to the PWHT of 760 °C (1400 °F), and exceeding the 780 °C (1436 °F) temperature would not be uncommon; it is very possible that the A_{C1} could or would be exceeded.

   PWHT in utility services requires 760 °C ± 14 °C (1400 °F ± 25 °F) minimum, regardless of wall thickness or diameter, for at least 1 hour for wall thickness less than 13 mm (0.5 in.). For wall thickness greater than 13 mm (0.5 in.), PWHT holding time is about 2 hours. For wall thickness greater than 50 mm (2 in.), PWHT holding time is minimum 2 hours, plus 1 hour for each additional 25 mm (1 in.).

   PWHT in process services requires 775 °C ± 10 °C (1427 °F ± 18 °F), regardless of wall thickness or diameter. The holding time is typically 6 hours minimum. To avoid over-tempering and softening thin wall material [e.g., for t <12.7 mm (<0.5 in.)], shorter minimum holding time is usually established during pre-production WPQ. It is good practice to determine PWHT holding time based on testing of WPQ.

   Typical heating rate above 400 °C (750 °F) is 100–150 °C/hr (180–270 °F/hr). The cooling rate from PWHT temperature to 400 °C (750 °F) is normally controlled to 150–200 °C/hr (270–360 °F/hr) maximum. The weld is then cooled down to ambient temperature in still air.
8. Some companies required that
   In addition to code compliance, the PWHT of 9Cr-1Mo-V (P91/T91) shall be at a temperature range of 747–775 °C (1375–1425 °F). The PWHT holding time shall meet 2 hours minimum for thicknesses up to 50 mm (2 in.) and 4 hours minimum for thicknesses over 50 mm (2 in.).

4.12.3.9 PWHT for Cast Irons

PWHT may consist of either full annealing or stress relieving: when heat treatment is not applied, the welded casting is usually cooled slowly from the welding temperature to room temperature by covering it with insulating material such as lime, ground asbestos, or vermiculite.

Stress relieving at 621 °C (1150 °F) and then furnace cooling to at least 371 °C (700 °F) is recommended whenever feasible. Full annealing at 899 °C (1650 °F) is sometimes employed to produce greatest softening of the weld zone or a more complete stress relief. However, annealing lowers the as-cast tensile strength of all but the softest irons.In critical applications that require radiographic or ultrasonic inspection after heat treatment, castings often are inspected before treatment also, to save unnecessary costs if an internal defect should be present.

4.12.3.10 Heat Treatment of Nickel Based Alloys

Table 4.143 shows typical stress-relieving temperature of nickel alloys of base metal in ASTM B366. However, ASME for fabrication requires the stress relieving only for cold-formed components of some nickel alloys in accordance with ASME Sec. VIII, Div. 1, Table UNF-79.

Table 4.143 Typical stress-relieving temperature of nickel based alloys (ASTM B366)

UNS No.	Alloy	Corrosion-resistant fittings	ASME pressure fittings	Heat treatment[A,B] °C (°F)	Quench
N02200	Ni	CRN	WPN	900 to 928 (1650–1700)†	Rapid air/water
N02201	Ni, low C	CRNL	WPNL	900 to 928 (1650–1700)	Rapid air/water
N04400	Ni-Cu	CRNC[C]	WPNC[C]	900 to 928 (1650–1700)	Rapid air/water
N06002	Ni-Cr-Mo-Fe	CRHX	WPHX	1177 (2150)[D]	Rapid air/water
N06007	Ni-Cr-Fe-Mo-Cu	CRHG	WPHG	1150 to 1177 (2100–2150)	Rapid air/water
N06022	Low C-Ni-Mo-Cr	CRHC22	WPHC22	1121 (2050)[D]†	Rapid air/water
N06025	Ni-Cr-Fe	CRV602	WPV602	1204 (2200)[E]	Rapid air/water
N06030	Ni-Cr-Fe-Mo-Cu	CRHG30	WPHG30	1177 (2150)[D]	Rapid air/water
N06035	Ni-Cr-Mo	CRHG35	WPHG35	1121 (2050)	Rapid air/water
N06045	Ni-Cr-Fe	CRV45TM	WPV45TM	1177 (2150)	Rapid air/water
N06058	Low C-Ni-Cr-Mo	CR2120	WP2120	1135 (2075)	Rapid air/water
N06059	Low C-Ni-Cr-Mo	CR5923	WP5923	1121 (2050)	Rapid air/water
N06200	Low C-Ni-Cr-Mo-Cu	CRHC2000	WPHC2000	1135–1163 (2075–2125)	Rapid air/water
N06210	Low C-Ni-Cr-Mo-Ta	CRM21	WPM21	[E]	[E]
N06230	Ni-Cr-W-Mo	CRH230	WPH230	1177–1232 (2150–2250)	Rapid air/water
N10362	Low C-Ni-Mo-Cr	CRHBC1	WPHBC1	1147 (2100)[B]	Rapid air/water
N06455	Low C-Ni-Mo-Cr	CRHC4	WPHC4	1065 (1950)[D]	Rapid air/water
N06600	Ni-Cr-Fe	CRNCI	WPNCI	983–1010 (1800–1850)	Rapid air/water
N06603	Ni-Cr-Fe-Al	CR603GT	WP603GT	1189 (2175)	Rapid air/water
N06625-Gr.1	Ni-Cr-Mo-Cb	CRNCMC	WPNCMC	871 (1600)	Rapid air/water
N06625-Gr.2	Ni-Cr-Mo-Cb	CRNCMC	WPNCMC	1093 (2000)[D]†	Rapid air/water
N06686	Low C-Cr-Ni-Mo	CRIN686	WPIN686	1177 (2150)	Rapid air/water
N06219	Ni-Cr-Mo-Si	CR626Si	WP626Si	1121 (2050)†	Rapid air/water
N06985	Ni-Cr-Fe-Mo-Cu	CRHG3	WPHG3	1147–1177 (2100–2150)	Rapid air/water
N08020	Cr-Ni-Fe-Mo-Cu-Cb stabilized	CR20CB	WP20CB	927–1010 (1700–1850)	Rapid air/water
N08031	Low C-Ni-Fe-Cr-Mo-Cu	CR3127	WP3127	1189 (2175)	Rapid air/water
N08120	Ni-Cr-Fe	CRH120	WPH120	1189–1220 (2175–2225)	Rapid air/water
N08330	Ni-Fe-Cr-Si	CR330	WP330	1038 (1900)	Rapid air/water
N08367	Fe-Ni-Cr-Mo-N	CR6XN	WP6XN	1107 (2025)	Rapid air/water
N08800	Ni-Fe-Cr	CRNIC	WPNIC	983–1038 (1800–1900)[F]†	Rapid air/water
N08810	Ni-Fe-Cr	CRNIC10	WPNIC10	1147–1177 (2100–2150)[F]	Rapid air/water
N08811	Ni-Fe-Cr	CRNIC11	WPNIC11	1147–1177 (2100–2150)[F]	Rapid air/water
N08825	Ni-Fe-Cr-Mo-Cu	CRNICMC	WPNICMC	930–983 (1700–1800)[F]†	Rapid air/water
N08925	Low C-Ni-Fe-Cr-Mo-Cu	CR1925	WP1925	983–1038 (1800–1900)†	Rapid air/water
N08926	Low C-Ni-Fe-Cr-Mo-Cu-N	CR1925N	WP1925N	1177 (2150)	Rapid air/water
N10001	Ni-Mo	CRHB	WPHB	1065 (1950)[D]	Rapid air/water
N10003	Ni-Mo-Cr-Fe	CRHN	WPHN	1177 (2150)[D]	Rapid air/water
N10242	Ni-Mo-Cr-Fe	CRH242	WPH242	1050–1105 (1925–2025)	Rapid air/water
N10276	Low C-Ni-Mo-Cr	CRHC276	WPHC276	1121 (2050)[D]	Rapid air/water
N10624	Low C-Ni-Mo-Cr-Fe	CRB10	WPB10	1121 (2050)	Rapid air/water
N10629	Ni-Mo	CRVB4	WPVB4	1080 (1975)	Rapid air/water
N10665	Ni-Mo	CRHB2	WPHB2	1065 (1950)[D]	Rapid air/water
N10675	Ni-Mo	CRHB3	WPHB3	1065 (1950)[D]	Rapid air/water
N12160	Ni-Co-Cr-Si	CRH160	WPH160	1107 (2025)[D]	Rapid air/water
R20033	Low C-Cr-Ni-Fe-N	CR3033	WP3033	1121 (2050)	Rapid air/water
R30556	Ni-Fe-Cr-Co	CRH556	WPH556	1177 (2150)[D]	Rapid air/water

Notes
[A]Recommended set temperatures; different temperatures may be selected by either the purchaser or the manufacturer
[B]Set temperature, 329 °C (625 °F)
[C]Yield strength shall be 172 MPa (25,000 psi) min, for all hot-formed, annealed fittings made from WPNC material
[D]Minimum temperature
[E]Annealing temperature and quench shall be agreed upon between purchaser and manufacturer
[F]Heat treatment is highly dependent on intended service temperature – consult material manufacturer for specific heat treatments for end use temperature
†Corrected editorially

4.12.3.11 Heat Treatment of Copper Based Alloys After Fabrication

PWHT of copper and copper alloys may involve annealing, stress relieving, or precipitation hardening. The need for PWHT depends upon the base metal composition and the application of the weldment. PWHT may be required if the base metal can be strengthened by a heat treatment or if the service environment can cause SCC.

Copper alloys that include high-Zn brasses, Mn bronzes, Ni-Mn bronzes, some Al bronzes, and Ni-Ag are susceptible to SCC. Stresses induced during welding of these alloys can lead to premature failure in certain corrosive environments. These alloys may be stress relieved or annealed after welding to reduce stresses. Copper alloys that respond to precipitation hardening include some high Cu, some Cu-Al alloys, and Cu-Ni castings containing Be or Cr. If these alloys are not heat treated, the hardness in the weld area will vary as a result of aging or overaging caused by the welding heat.

Stress Relief is intended to reduce stresses from welding to relatively low values without effectively reducing mechanical properties. Stress relief is accomplished by heating the weldment to a temperature that is below the recrystallization temperature of the base metal. Typical stress-relieving temperatures for some copper alloys are given in Table 4.144. Heating time must be adequate for the entire weldment to reach temperature. The weldment is usually held for at least 1 hour at the stress relief temperature and then slowly cooled. Weldments thicker than 25 mm (1 in.) must be held for longer periods, usually for 1 hr per 25 mm (1 hour per in.) of thickness.

Table 4.144 Typical stress-relieving temperature for weldments of copper alloys

Common name	UNS No.	Temperature*, °C (°F)
Red brass	C23000	288 (550)
Admiralty brass	C44300–C44500	288 (550)
Naval brass	C46400–C46700	260 (500)
Aluminum bronze	C61400	343 (650)
Silicon bronze	C65500	343 (650)
Copper-nickel alloys	C70600–C71500	538 (1000)

Source: AWS Welding Handbook, Copper Alloys
*Heat slowly to hold at temperature for at least 1 hour

Annealing is used to reduce stresses and to homogenize weldments of hardenable copper alloys to produce a metallurgical structure that will respond to heat treatment satisfactorily. Annealing is carried out at temperatures considerably higher than those used for stress relieving, as shown in Table 4.145. Stress relaxation proceeds rapidly at the annealing temperature. Extended annealing times or annealing at the top of the temperature range can cause excessive grain growth that may reduce tensile strength and can cause other undesirable metallurgical effects.

Table 4.145 Typical annealing temperature for weldments of copper alloys

Common name	UNS No.	Temperature*, °C (°F)
Phosphor-deoxidized brass	C12200	371–649 (700–1200)
Beryllium copper	C17000, C17200	774–802 (1425–1475)
Beryllium copper	C17500	913–941 (1675–1725)
Red brass	C23000	427–732 (800–1350)
Yellow brass	C27000	427–704 (800–1300)
Muntz metal	C28000	427–593 (800–1100)
Admiralty brass	C44300–C44500	427–593 (800–1100)
Naval brass	C46400–C46700	427–593 (800–1100)
Phosphor brass	C50500–C52400	482–677 (900–1250)
Aluminum bronze	C61400	607–899 (1125–1650)
Aluminum bronze	C62500	593–649 (1100–1200)
Silicon bronze	C65100, C65500	482–704 (900–1300)
Aluminum brass	C68700	427–593 (800–1100)
90Copper-10Nickel alloys	C70600	593–816 (1100–1500)
70Copper-30Nickel alloys	C71500	649–816 (1200–1500)
Nickel silver	C74500	593–760 (1100–1400)

Source: AWS Welding Handbook, Copper Alloys
*Time at temperature: 15–30 minutes

4.12.3.12 Heat Treatment of Aluminum Based Alloys

Aluminum alloys can be greatly developed the mechanical properties by the appropriate heat treatment, such as solution heat treatment, precipitation heat treatment, and following tempering treatment.

So, the following coding system of the heat treatment is very important to handle the aluminum alloys. The temper designation follows the cast or wrought designation number with a dash, a letter, and potentially as "T" digit number, e.g., 6061-T6. The definitions for the tempers are:

- *F: As fabricated*
- *H: Strain hardened (cold worked) with or without thermal treatment*
  - H1: Strain hardened without thermal treatment
  - H2: Strain hardened and partially annealed
  - H3: Strain hardened and stabilized by low temperature heating
  - H4: Strain hardened and lacquered or painted

    Second digit (H1X, H2X, H3X, H4X): X second digit denotes the degree of strain hardening as identified by the min. Value of the ultimate tensile strength. $Y = 1, 2, 3$, or 4
    - HY2 = 1/4 hard
    - HY4 = 1/2 hard
    - HY6 = 3/4 hard
    - HY8 = full hard
    - HY9 = extra hard

    Third digit (HYXZ): Z third digit denotes a variation of a two-front digit temper $Y = 1, 2, 3$, or 4, $Z = 2, 4, 6, 8, 9$, others
    - HYX1
    - HYX6
    - HYX8

- *O: Full soft (annealed)*
- *T: Heat treated to produce stable tempers* (most common classes)
  - T1: Cooled from hot working and naturally aged (at room temperature)
  - T2: Cooled from hot working, cold worked, and naturally aged
  - T3: Solution heat treated and cold worked
  - T4: Solution heat treated and naturally aged
  - T42: Solution heat treated from annealed or F temper and naturally aged to substantially stable condition
  - T5: Cooled from hot working and artificially aged (at elevated temperature)
  - T51: Stress relieved by stretching
  - T510: No further straightening after stretching
  - T511: Minor straightening after stretching
  - T52: Stress relieved by compressing of forging
  - T54: Stress relieved by combined stretching and compressing
  - T6: Solution heat treated and artificially aged
  - T62: Solution heat treated from annealed or F temper and artificially aged
  - T7: Solution heat treated and stabilized
  - T7_2: Solution heat treated from annealed or F temper and artificially overaged to meet the mechanical properties and corrosion resistance limits of the T7_ temper
  - T8: Solution heat treated, cold worked, and artificially aged
  - T9: Solution heat treated, artificially aged, and cold worked
  - T10: Cooled from hot working, cold worked, and artificially aged
- *W: Solution heat treated only*

  Note: -W is a relatively soft intermediary designation that applies after heat treatment and before aging is completed. The -W condition can be extended at extremely low temperatures but not indefinitely and depending on the material will typically last no longer than 15 minutes at ambient temperatures.

4.12.3.13 Heat Treatment of Titanium and Zirconium Based Alloys

ASME Section VIII and II, part D indicate that heat treatment of all other titanium or zirconium alloys after welding is not mandatory, but is recommended after forming operations. For reactive metals such as titanium and zirconium, prolonged exposure at temperatures above 593 °C (1100 °F) will result in heavier surface oxide films that are not satisfactorily removed by acid pickling. It is required that a descaling treatment be employed for the removal of the thicker oxide film. In certain environments associated with pickling and annealing, as well as under actual operating conditions, absorption of hydrogen may cause embrittlement of titanium or zirconium.

In addition, oxide thickening will result from excessive annealing time and temperatures in oxidizing environments. In any heat treatment operation, reducing furnace atmospheres shall not be used. Suitable procedures are available from the manufacturers and other sources to minimize scaling and/or hydrogen pickup during the various steps associated with fabrication and heat treatment.

Titanium or zirconium weld metal in its molten state or at elevated temperature will react readily with air. Contamination during welding by oxygen, hydrogen, and nitrogen increases the weld metal hardness and decreases the ductility and notch toughness.

(a) For titanium, it is recommended that heat treatment be performed in a furnace and at a metal temperature of not less than 482 °C (900 °F) or more than 649 °C (1200 °F), with time at temperature of 1 hr. The stress-relieving heat treatment usually recommended is 482 °C (900 °F) to 593 °C (1100 °F) for 0.5 hr for Grades 1, 2, 3, and 7 and 1 hr for Grade 12. Table 4.146 shows the heat treatment temperatures for commercially pure titanium and titanium alloys in PD5500.
(b) For zirconium, PWHT is mandatory for Grade R60705 (see Section VIII, Division 1, UNF-56). Heat treatment is generally recommended after forming operations for all grades of zirconium (R60702 and R60705). It is recommended that the heat treatment be performed in a furnace and at a temperature of not less than 510 °C (950 °F) or more than 621 °C (1150 °F), for not less than 0.5 hr/in. of thickness.
(c) For titanium and zirconium equipment cladded on carbon steel, if PWHT is required, the following guidelines shall be followed:

Table 4.146 Heat treatment temperatures for commercially pure titanium and titanium alloys (PD5500)

Material grade	Stress relief		Anneal	
	Temperature, °C (°F)	Time, hr	Temperature, °C (°F)	Time, hr
1, 2, 3, 7, 11, 16, 17, 26, 27	400–500 (752–932)	0.5–2	650–700 (1202–1292)	0.5–4
9, 12, 18, 28	500–600 (932–1112)	0.5–4	700–750 (1292–1382)	0.5–4

Notes
1. Attention is drawn to the effect of heat treatment on these materials, and in particular the formation of the brittle alpha case when an oxidizing atmosphere is used
2. Heat treatment should only be carried out in argon or helium, or in a vacuum
3. Heat treatment in a reducing atmosphere results in hydrogen absorption and causes embrittlement
4. See Table 2.79 for classes of titanium and titanium alloys

– Holding temperature of 565 ± 15 °C (1050 ± 25 °F) is preferred with the longer time allowed by ASME Code.
– Between 200 °C (390 °F) and the hold temperature, the heating and cooling rates should not exceed 55 °C (100 °F) per hour.
– Others: per applicable codes.

The threshold shear stress for the interface bond should be verified by WPS/PQR with PWHT because of a large difference in coefficients of expansion between ferritic steel and titanium or zirconium.

4.12.3.14 Heat Treatment for Hot-Formed Components

For hot-formed components, complete reheat treatment in accordance with the ASTM (or ASME) materials specifications is required if the temperature of hot forming exceeds the normalizing temperature for normalized material or the tempering temperature for normalized and tempered or quenched and tempered material because hot forming normalized material at temperatures above the normalizing temperature could coarsen the grain size and reduce the CVN impact toughness. Hot-forming temperatures above the tempering temperature of normalized and tempered or quenched and tempered materials could reduce their strength below the minimum required by the ASTM (or ASME) materials specification.

4.12.3.15 PWHT Requirements in Environmentally Assisted Cracking (EAC) Services

Table 4.147 shows the PWHT requirements for CS in several industrial standards in EAC Services.

Table 4.147 PWHT requirements for CS in several industrial standards in EAC services

EAC service	Industrial standards	ERC mechanism	PWHT requirements	Remark
Amine	NACE SP0472	Alkaline SCC	635 ± 15 °C (1175 ± 25 °F) for a hold time of 1 hour for each 25 mm (1.0 in), or a fraction thereof, of metal thickness, with a minimum hold time of 1 hour.	See Para. 2.4.2(3) for the mechanism
Anhydrous Ammonia	API RP571	Alkaline SCC	PWHT is required for high TS steel.	See Para. 2.4.2 (10) for the mechanism
Carbonate	NACE SP0472	Alkaline SCC	649 to 663 °C (1200 to 1225 °F) for a hold time of 1 hour for each 25 mm (1.0 in) of thickness, with a minimum hold time of 1 hour.	See Para. 2.4.2(5) for the mechanism
	NACE Publ.34108	Alkaline SCC	Normally min. 621 °C (1150 °F).	
Caustic	NACE SP0472	Alkaline SCC	635 ± 15 °C (1175 ± 25 °F) for a hold time of 1 hour for each 25 mm (1.0 in), or a fraction thereof, of metal thickness, with a minimum hold time of 1 hour.	See Para. 2.4.2(4) for the mechanism
HF	API RP751	Hydrogen embrittlement	The PWHT temperature should be a minimum of 621 °C (1150 °F) held for 1 hour per in. of thickness, with a 1 hour minimum. PWHT at a lower temperature with a longer holding time should not be used.	See Para. 2.4.2(2) for the mechanism
HTHA	API RP941	Hydrogen attack	In order to use the CS curve with PWHT in Nelson curves, PWHT per code (i.e., ASME BPVC or piping) is required.	See Para. 2.4.3(6) for the mechanism
Sour, Wet H2S	ANSI/NACE MR0175/ ISO15156	SSC	Max. 22 HRC or PWHT at 593 °C (1100 °F min.). Note (2).	See Para. 2.4.2(1) for the mechanism
	ANSI/NACE MR0103/ ISO17945	SSC	Max. 22 HRC for base metal. NACE SP0472 for welds	Note (1)
	NACE SP0472	SSC	Max. 200 BHN for welds or cooling time control at 800–500 °C (1470–930 °F), or PWHT at 620 °C (1150 °F min.) with a minimum hold time of 1 hour. If lower PWHT temperatures or shorter times are considered necessary by the manufacturer or fabricator, because of concerns with strength or impact toughness, this shall be reviewed and agreed with the user.	See Para. 2.4.2(1) for the mechanism
	NACE Publ. 8X194	SSC	Some users specify pressure vessel plate steels with carbon >0.12 wt% to be limited to Cb ≤0.01 wt% or V ≤ 0.02 wt% with Cb + V ≤ 0.015 wt% to control HAZ hardness without PWHT. When Cb + V are present at higher levels in steels with carbon >0.12 wt%, PWHT at 635 °C (1175 °F) for 2 h minimum of welds made with low heat input is specified by some users to reduce HAZ hardness below 248 HV10. When PWHT is specified because of microalloy content in the range of 0.015 wt% < Cb + V < 0.03 wt%, a temperature of 635 ± 14 °C (1,175 ± 25 °F) for 2 h per 25 mm (1.0 in) of thickness is used by some users.	

References:
- ANSI/NACE MR0175/ISO15156: Petroleum, Petrochemical, and Natural Gas Industries — Materials for Use in H2S-Containing Environments in Oil and Gas Production
- ANSI/NACE MR0103/ISO17945: Materials Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments
- NACE SP0472: Standard Practice – Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments

- NACE Publ.8X194: Materials and Fabrication Practices for New Pressure Vessels Used in Wet H_2S Refinery Service
- API RP941: Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants
- API RP945: Avoiding Environmental Cracking in Amine Units
- API RP751: Safe Operation of Hydrofluoric Acid Alkylation Units
- NACE SP0403: Avoiding Caustic Stress Corrosion Cracking of Carbon Steel Refinery Equipment and Piping
- NACE Publ. 34108 Review and Survey of Alkaline Carbonate SCC in Refinery Sour Waters

Notes: *SSC* sulfide stress cracking, *SCC* stress corrosion cracking, *Publ.* publication (report)
(1) Most company standards require PWHT for CS equipment and hardness control for CS piping
(2) The PWHT holding temperature may be raised to meet NACE SP0472 in the short future

4.12.3.16 Stress Relieving for H/EX U-Bends

Most codes and standards state that the purchaser shall specify if heat treatment is required after bending of U-bends because of high risk of stress corrosion cracking and/or erosion. The appropriate heat treatment may be selected in Sect. 4.12.3 unless otherwise required.

Figure 4.82 shows a typical heat treatment equipment of U-bends.

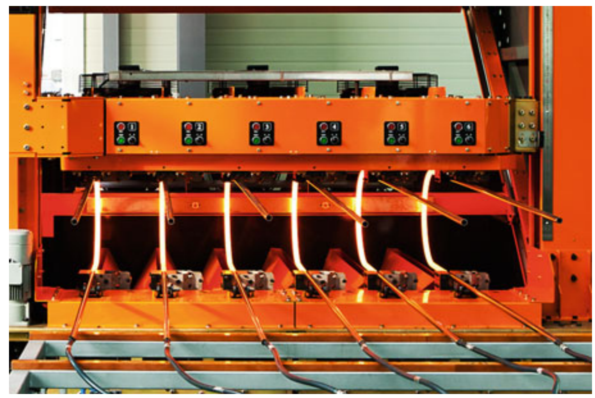


Figure 4.82 Heat treatment for U-bends

(a) API 660 (Shell and Tube Types H/EXs) Requirements for U-Bends

The purchaser shall specify if heat treatment is required after bending of U-tubes for process reasons. Unless otherwise specified by the purchaser, the following shall be subject to heat treatment per Sect. 4.12.3.1 after tube bending:

1. CS, C-Mo, and low Cr steel U-bends (C-0.5Mo through 5% Cr steels) in sour or wet H_2S service.
2. U-bends in brass alloys (e.g., per ASME SB-395/395M).
3. Unstabilized ASS with a mean radius smaller than five times the nominal outside diameter of the tube.
4. Unstabilized ASS tubing subjected to heat treatment after bending shall be supplied with 0.05% maximum carbon content or be dual certified as low carbon grade ($C \leq 0.03\%$).
5. For FSS, MSS, stabilized ASS, DSS, copper, Cu-Ni, and high Ni alloys ($Ni > 30\%$), heat treatment of U-tubes shall be applied if cold working can induce susceptibility to stress corrosion. The purchaser shall specify when heat treatment is required in such cases. See API TR 938-C (or (b) below) for guidance on heat treatment of DSS U-bends.
6. U-bend heat treatment shall be in accordance with the pressure design code. When applied, U-bend heat treatment shall be completed by electric resistance or furnace methods. Open flame heat treatment is not permitted. The procedure used for heat treatment shall be agreed between the purchaser and vendor.
7. For electric resistance or induction heating, the heat-treated portion of the U-bend shall extend at least 150 mm (6 in.) beyond the tangent point. For furnace heating, the heat treatment shall extend at least 600 mm (24 in.) beyond the tangent point.
8. When specified by the purchaser, the heat-treated portion of U-tubes shall receive a descaling treatment.
9. PWHT of fabricated CS and LAS (maximum 9%Cr) channels and bonnets shall be performed for the following:
   – Channels and bonnets with six or more tube passes
   – Channels and bonnets whose nozzle-to-cylinder internal diameter ratios are 0.5 or greater, except where a conical reducer is used in place of the channel or bonnet
10. The purchaser shall specify if PWHT is required for weld-overlaid channels and bonnets.
11. PWHT shall be performed for all CS and LAS (maximum 9%Cr) floating head covers that are fabricated by welding a dished-only head into a ring flange.
12. The purchaser shall specify if PWHT of shell side or tube side components is required for process reasons.
13. For sour or wet H_2S service, the minimum PWHT requirements for CS construction shall be in accordance with NACE SP0472. The minimum hold time shall be in accordance with the pressure design code, or 1 hour, whichever is greater.

(b) Duplex Stainless Steel (DSS) U-Bends – Sources: TEMA, API TR938-C, and ASME BPVC

U-bends formed from tube materials having low ductility, or materials which are susceptible to work hardening, may require special consideration. Outer rows of U-bends have a lower natural frequency of vibration and, therefore, are more susceptible to flow-induced vibration failures than the inner rows. Susceptibility of U-bends to damaging vibration may be reduced by optimum location of adjacent baffles in the straight tube legs and/or use of a special bend support device. Consideration may also be given to protecting the bends from flow-induced vibration by appropriately locating the shell connection and/or adjacent baffles.

H/EX U-bends are difficult to heat treat without some zone of the tubes being exposed to unacceptable temperatures, which results in impaired corrosion resistance. With furnace heat treatments, which typically only have the bends inserted into the furnace, the tangent lengths can be exposed to an unacceptable temperature. In addition, testing has shown that the properties of the U-bends without heat treatment are acceptable for refinery services down to bend radii of 1.5 times the tube diameter for super-DSS grades and at least 3.3

times the tube OD for S32205. Hence, various users have concluded that no heat treatment of U-bends should be specified, as long as there is a minimum 3.3 × OD radius for 2205 DSS (the inner row of tubes can be installed with the U-bend diagonal and with a few less tubes to accommodate this larger minimum radius).

In the cases where heat treatment of U-bends is specified, resistance or capacitance heating has been used successfully with procedures carefully designed to minimize the time of tube exposure to the 700 °C–950 °C (1300–1750 °F) range. See Sect. 2.1.6.5 for several undesirable intermetallic phases precipitated in this temperature range.

Hot bending of piping or tubes is generally done using the induction bending process, and the procedures are qualified with test bends and various essential variables. The bending temperature for 22% Cr DSS is typically in the range of 1000–1066 °C (1830–1950 °F). During induction bending, DSS pipe is purged with nitrogen or argon (0.5% maximum oxygen). Bends produced from 22% Cr DSS are solution annealed, if needed, to meet the required mechanical properties. After final heat treatment of any DSS bend, a chemical descaling and neutralization treatment is typically done. Any longitudinal welds normally receive 100% RT after bending, and the bend surface typically receives 100% PT. Dimensional and hardness testing are also performed.

The final solution heat treatment shall be in accordance with Tables 4.123a and 4.124b. After final heat treatment of any DSS bending, an acid descaling and neutralization treatment in accordance with ASTM A380 may be applied.

(c) Typical Company Standards for U-Bends
1. Cold bent tubes of CS and LAS should be stress relieved in accordance with ASME Section VIII, Div. 1, UCS-56.
2. Cold or hot bent tubes of ASS should be stress relieved by solution heat treatment.

4.12.3.17 Heat Treatment Requirements for Forged Fabrication (ASME Sec. VIII, Div. 2)

(a) PWHT for welded forging vessels should be performed as follows:
1. After all welding is completed
2. Prior to welding, followed by PWHT of the finished weld per ASME Sec. VIII, Div. 2, 6.4.2

(b) When the welding involves only minor non-pressure-retaining attachments to welded forging vessels having carbon content exceeding 0.35% but not exceeding 0.50% by ladle analysis, requirements of ASME Sec. VIII, Div. 2, 6.7.7.2 are governed.

(c) After all forging is completed, each vessel or forged part fabricated without welding shall be heat treated in accordance with the applicable material specification (i.e., normalizing or annealing).

(d) Vessels fabricated of SA-372 Q-T forging material shall be subjected to this heat treatment in accordance with the applicable material specifications after all forging and welding is completed, except for seal welding of threaded openings, which may be performed either before or after final heat treatment. See ASME Sec. VIII, Div. 1, 6.7.6 for more details.

4.12.3.18 Additional Requirements and Case Studies

(a) PWHT of DSS cladded CS
DSS shall not be used as cladding material on carbon or low alloy steel which required PWHT or SR. See below (b) and (c).

(b) PWHT of dissimilar weld joints: The PWHT of dissimilar weld joints in CS and LAS should be performed in accordance with PWHT procedure for the higher P-No material unless otherwise required by purchaser.

(c) Non-PWHT facilities (existing) from old codes and standards: A PWHT per the new industrial standards during maintenance is normally applied entirely or locally in EAC environments. A PWHT during maintenance may or may not be applicable in non-EAC environments.

4.12.4 Caution of Tempering After Normalizing or Quenching

Traditionally the tempering temperature of base metal should be higher than the stress relieving and PWHT temperature of products due to the toughness reduction.

Currently there is a new approach for heavy wall Cr-Mo steel vessel. In order to obtain the required tensile strength after multi-cycle PWHT treatment per heavy wall thickness, the tempering temperature that is slightly lower than the PWHT temperature may be acceptable if all other materials/mechanical tests successfully passed the requirements. Otherwise, the tempering temperature shall be higher (preferably at least 15 °C higher) than the PWHT temperature. Lower tempering temperature requires higher holding time to achieve the required microstructure as seen in Table 4.148.

Table 4.148 Equivalent tempering temperature and time for 2.25Cr-1Mo steel (recommended)

Temperature, °C (°F)	Time, hr
718 (1325)	2
704 (1300)	3.5
691 (1275)	7
677 (1250)	14
663 (1225)	30
649 (1200)	70
621 (1150)	300
593 (1100)	1700
566 (1050)	10,000
538 (1000)	60,000

Therefore, when purchase the heavy wall N-T or Q-T steels, the engineers have to know the target temperatures of tempering and PWHT together. Also when purchase the heavy wall N, N-T or Q-T steels to be hot formed or spinned, the engineers have to recognize the target temperatures of tempering and PWHT together as well as the temperatures of hot forming and normalizing temperature together. If the metal degradation during fabrication or operation is expected, the simulation test for the base metal shall be performed.

4.12.5 Thermally Stabilizing Heat Treatment for Stabilized Stainless Steels

The initial solution heat treatment temperature range for 321 SS and 347 SS is 1040–11,093 °C (1900–2000 °F) during 2–4 hours followed by rapid cooling. While the primary purpose of annealing is to obtain softness and high ductility, these steels may also be stress relief annealed within the carbide precipitation range 427–816 °C (800–1500 °F), without any danger of subsequent intergranular corrosion.

When fabricating ASS into equipment requiring the maximum protection against carbide precipitation obtainable through use of a stabilized grade listed in Table 4.140, it is essential to recognize that there is a difference between the stabilizing ability of Nb (Cb) and Ti. For these reasons, the degree of stabilization and of resulting protection may be less pronounced when 321 SS or 347 SS is employed.

When maximum corrosion resistance is called for, it may be necessary with 321 SS or 347 SS to employ a corrective remedy which is known as a thermally stabilizing heat treatment. The heating consists at 843–900 °C (1550–1650 °F) for 2–4 hours depending on thickness and/or heating source. This range, as seen in Fig. 4.55, is above that within which Cr-carbides are formed and is sufficiently high to cause dissociation and solution of any that may have been previously developed. The result of stabilization heat treatment is to preferentially allow the precipitation of titanium or niobium carbides (harmless) rather than chromium carbides (harmful).

See Table 4.140 (general stabilizing heat treatment), Sect. 2.1.6.3 knife-line attack environment, and 2.1.6.8 PTASCC environment for more details of stabilizing heat treatment.

This additional treatment is required less often for the Cb-stabilized 347 SS. When heat treatments are done in an oxidizing atmosphere, the oxide should be removed after annealing in a descaling solution such as a mixture of nitric (HNO_3) and hydrofluoric (HF) acids. These acids should be thoroughly rinsed off the surface after cleaning.

These alloys cannot be hardened by heat treatment.

Thermally stabilized heat treatment of ASS products may be required for high temperature [>400 °C (750 °F)] hydrocarbon service.

References: A Few Key References Are Only Introduced

1. API RP571
2. NACE SP0170
3. WRC Bulletin 421 Welding Type 347 SS, 1997
4. NACE Paper C2018-10574, 08454, 04640, 03647, 02478, 98580, 93541, 76159 and several NACE MP articles
5. Weld. Res. Suppl. 253-s, (1999)

4.12.6 Local PWHT

In general, the requirements for detailed procedures of local PWHT (Fig. 4.83) are not addressed in facility codes. However, many end-users' specifications address the cautions and applications. WRC 452 (Recommended Practices for Local Heating of Welds in Pressure Vessels) and NACE SP0472 (In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments), Appendix D are normally used for this application. The soak band is seized to ensure that the required volume of metal achieves the temperature needed to procedure the desired effect. Table 4.149 compares the preheating/interpass heating and PWHT soak bands used for the cited fabrication codes. The requirement for preheating/interpass heating an area 75 mm (3 in.) in all directions from the point of welding appears to work well and is also used by piping and structural welding codes. Note the desirability of the ASME Section III PWHT sizing approach which prevents the soak band from becoming unnecessarily large as thickness increases. In addition, the ASME Section III PWHT sizing is more desirable than either BS PD 5500 or Australia AS 1210, in that it establishes a specific size and assures attainment of the minimum temperature in the adjacent base metal to relax residual stresses present there.

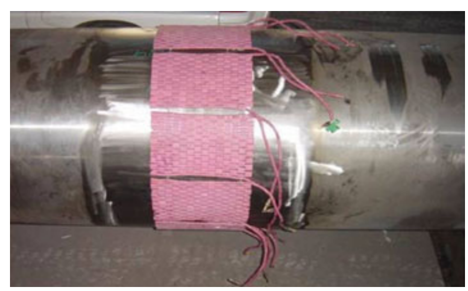


Figure 4.83 Local PWHT

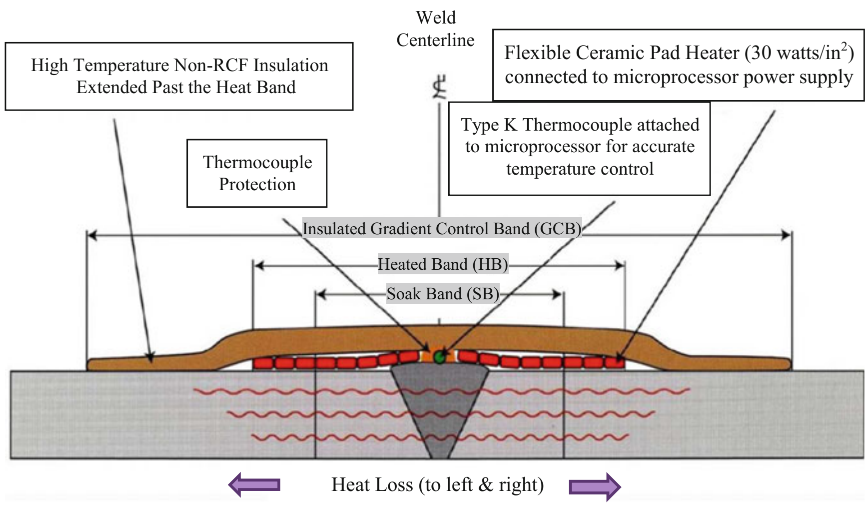
The cited fabrication codes do not provide guidance regarding sizing of the soak band for bake-out or post-heating. The soak band for bake-out should be larger than that for either preheating/interpass heating or PWHT. This is to ensure that hydrogen does not diffuse back into the weld area during welding. A reasonable approach would be to heat an area at least 152 mm (8 in.) or $3t$ (where t = wall thickness), whichever is greater, in all directions from the weld. The sizing used for PWHT appears adequate for post-heating.

Meanwhile, ASME B31.3, 331.2.5 and 331.2.6 indicates the requirements for partial heat treatment and local heat treatment as below.

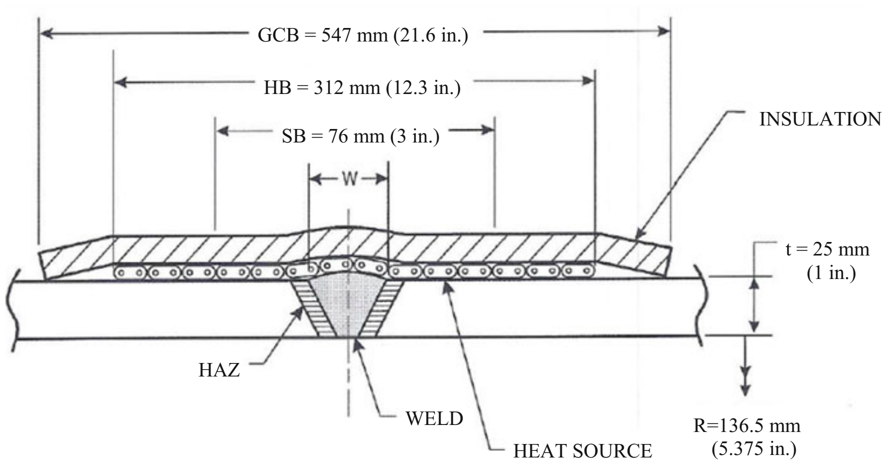
Partial Heat Treatment When an entire piping assembly to be heat treated cannot be fitted into the furnace, it is permissible to heat treat in more than one heat, provided there is at least 300 mm (1 ft) overlap between successive heats and that parts of the assembly outside the furnace are protected from harmful temperature gradients. This method may not be used for austenitizing heat treatments for ferritic materials.

Local Heat Treatment Welds may be locally PWHT'd by heating a circumferential band around the entire component with the weld located in the center of the band. The width of the band heated to the specified temperature range shall be at least three times the wall thickness at the weld of the thickest part being joined. For nozzle and attachment welds, the width of the band heated to the specified temperature range shall extend beyond the nozzle weld or attachment weld on each side at least two times the run pipe thickness and shall extend completely around the run pipe. Guidance for the placement of thermocouples on circumferential butt welds is provided in AWS D10.10, Sections 5, 6, and 8. Special consideration shall be given to the placement of thermocouples when heating welds adjacent to large heat sinks such as valves or fittings, or when joining parts of different thicknesses. No part of the materials subjected to the heat source shall exceed the lower critical temperature of the material except as permitted by ASME B31.3, 331.2.1. Particular care must be exercised when the applicable PWHT temperature is close to the material's lower critical temperature, such as for P-No. 15E materials or when materials of different P-Nos. are being joined. This method may not be used for austenitizing heat treatments.

Figure 4.84 indicates the typical band setup for local PWHT.



(a) Typical Setup



(b) Sample Setup-Local circumferential band PWHT of a Butt Weld NPS 12, 25 mm wall THK Pipe in the horizontal position (source: AWS D10.10 HB1 calculations)

Figure 4.84 Typical band setup for local PWHT. (**a**) Typical setup. (**b**) Sample setup – local circumferential band PWHT of a butt weld NPS 12, 25 mm wall. THK pipe in the horizontal position (source: AWS D10.10 HB1 calculations). (Source: AWS D10.10)

Gradient Control Band (GCB) The surface area over which insulation and/or heat source(s) are placed. It should encompass the SB, HB, and sufficient adjacent base metal such that excessive axial temperature gradients can be avoided.

Heated Band (HB) The surface area over which the heat source is applied to achieve the required temperature in the soak band and limit induced stresses in the vicinity of the weldment. It should consist of the SB plus any adjacent base metal necessary to control the temperatures within the SB and limit induced stress.

Soak Band (SB) The volume of metal which must be heated to the minimum but not exceed the maximum required temperature. As a minimum, it should consist of the weld, HAZ, and a portion of the base metal adjacent to the weld being heated.

Table 4.149 shows the comparison of the requirements for soak bands of local heat treatment (preheat, interpass, and PWHT).

Table 4.149 Comparison of requirements for soak bands

Fabrication code	Soak band size for preheat & interpass temperature control	Soak band size for PWHT	Gradient control requirement for PWHT R: internal radius of shell, *t*: nominal thickness
ASME Sec. VIII, Div. 1 Pressure vessels	All areas within 75 mm (3 in.) of the point where a weld is to be started	[Div. 1 & 2] *Shell section welds:* 2 times the shell thickness on each side of the greatest width of the weld *Nozzles or other welded attachments*: 6 times the plate thickness on either side of the nozzle or attachment weld *Pipe or tubing welds*: 3 times for Div. 1 and 6 times for Div. 2 the greatest width of the weld on each side of the weld centerline	The portion of the vessel outside of the circumferential band shall be protected so that the temperature gradient is not harmful.
ASME Sec. VIII, Div. 2 Pressure vessels			
ASME Sec. VIII, Subsection NB Pressure vessels	Not specified	Thickness of the weld or 2 inches, whichever is less, on either side of the weld face at its greatest width	The temperature of the component or item from the edge of the controlled band outwards shall be gradually diminished to avoid harmful thermal gradients.
BS PD 5500 Pressure vessels	Not specified	Weld and HAZ	The temperature at the edge of the heated band is not less than half the peak temperature. In addition, the adjacent portion of the vessel outside the heated zone shall be thermally insulated such that the temperature gradient is not harmful.
Australia AS 1210 Pressure vessels	All areas within 75 mm (3 in.) of the point where a weld is to be started	Weld metal and HAZ	The longitudinal temperature gradient shall be such that the temperature of the cylinder at a distance on each side of the weld not less than 2.5 $(Rt)^{1/2}$ shall not be less than half the heat treatment temperature.

Source: WRC 452-2000 Ed. modified
Commentary Notes
(1) See ASME B31.3, 331.2.6 for Local Heat Treatment for Process Piping
(2) See AWS D10.10 RP for Local Heating of Welds in Piping and Tubing

4.12.7 Normalizing Treatment After Fabrication of Carbon and Low Alloy Steel Equipment and Piping

Normalizing for carbon and low alloy steel is a heat-treating process that is often considered from both thermal and microstructural standpoints. In the thermal sense, normalizing is an austenitizing heating cycle followed by cooling in still or slightly agitated air. Typically, the work is heated to a temperature about 55 °C (100 °F) above the upper critical line of the iron-carbide phase diagram, that is, above Ac3 for hypoeutectoid steels and above Acm for hypereutectoid steels. To be properly classed as a normalizing treatment, the heating portion of the process must produce a homogeneous austenitic phase (fcc crystal structure), but the holding time shall be minimized to avoid grain growth, prior to cooling. See Table 4.110 and the Note (4) for normalizing temperature range.

Normally, the 1 hour/in. (25 mm) is recommended for the holding time in thin and moderate thickness. However, the holding time of 1 hour/in. (25 mm) for heavy wall of 50 mm (2 in.) and above can create some negative properties for toughness (by grain growth) as well as tensile strength (by softened) even though this value can provide a uniform temperature profile and complete through-thickness austenitization. Therefore, the holding time after completion of through-thickness austenitization should be minimized.

Metal Handbook, vol.4 suggests that:

Normalizing of carbon and low alloy steel: Heat to 870–925 °C (1600–1700 °F) and hold for a minimum of 1 h or 15–20 minutes per 25 mm (1 in.) of maximum section thickness; air cool.

For the best practice, the following procedures are recommended. Procedure 1 is preferable.

[Procedure 1]

t (holding time as minutes) = 60 minutes per 25 mm thickness (up to 50 mm)
t (holding time as minutes) = additional 15 minutes per 25 mm thickness (for 50 mm and above)

For example, for holding time calculation,

D = 50 mm ---- t = 120 minutes (2 hrs)
D = 100 mm ---- t = 150 minutes (2 hrs–30 min.)
D = 150 mm ---- t = 180 minutes (3 hrs)
D = 200 mm ---- t = 210 minutes (3 hrs–30 min.)

[Procedure 2]

t (holding time as minutes) = 60 (as a minimum) + D (diameter or thickness as mm)

For example, for holding time calculation,

D = 50 mm ---- t = 110 minutes (1 hr–50 min.)
D = 100 mm ---- t = 160 minutes (2 hrs–40 min.)
D = 150 mm ---- t = 210 minutes (3 hrs–30 min.)
D = 200 mm ---- t = 260 minutes (4 hrs–20 min.)

4.12.8 Cold and Sub-Zero Treatment

The cold and sub-zero treatment processes (Fig. 4.85) for LAS or carburized steels to obtain dimensional stability, hardness and strength, and wear resistance which are directly followed by tempering can be grouped into three broad categories, and they impact steel in the following ways:

1. Shrink of fitting reduces the diameter of a steel shaft so workers can readily assemble it with other components when cooling at −70 to −120 °C (−90 to −190 °F) until metal is cold throughout which allows tight assembly of parts. As a result, the size is temporarily changed.
2. Cold treatment at −70 to −120 °C (−90 to −190 °F) for 1 hour per about 30 mm of cross section completes the metallurgical phase transformation from retained austenite to martensite during the hardening of steels via quench and temper heat treatment. As a result, the dimension will be stable, hardness is increased, and the retained austenite is transformed to 100% martensite. However, some retained austenite may be desirable for hardened metals required some toughness, such as bearings or gears.
3. Cryo sub-zero treatment at liquid nitrogen temperatures (at −135 °C (−210 °F) and below) for above 24 hours creates conditions for the subsequent nucleation of very fine carbides in higher alloy steels. As a result, the wear resistance is improved by carbide precipitation.

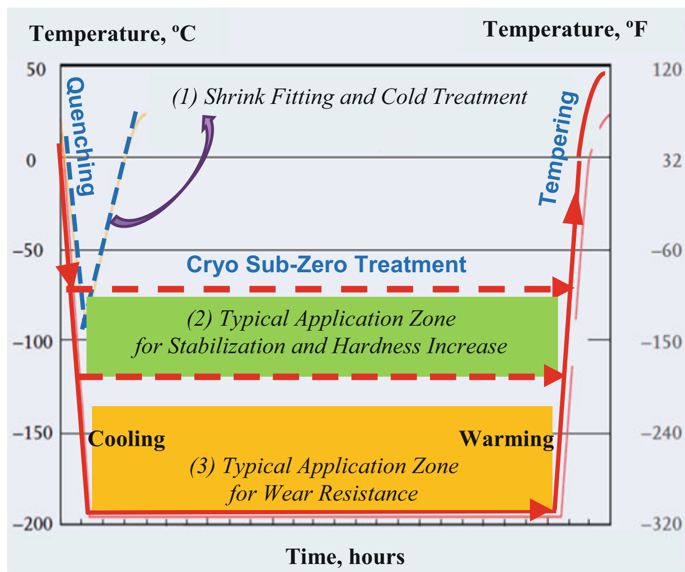


Figure 4.85 Cold and sub-zero treatment process curves

References

– ASM Metal Handbook, Vol. 4 Heat Treating
– Heat Treater's Guide: Practices and Procedures for Irons and Steels, ASM International, 1995
– T. Holm, Cryotreatment – State of the art 1997 – An Update, AGA Internal Report
– A. Stojko, M.Sc. Thesis, Sub-zero Treatment of Tool Steels, Technical University of Denmark, DTU Department of Manufacturing Engineering and Management, Sep. 24, 2001
– Torsten Holm and K.A. Orrebo, Cryogenic Applications in Metallurgy and Related Fields, AGA Internal Report
– NACE 15-5496 Electrochemical Behavior of X80 Steel in Sub-zero NS4 Solutions, 2015
– Linde, Special Edition for Sub-Zero Treatment of Steels

4.12.9 Peening

It is preformed to promote compressive residual stress and/or to reduce the residual tensile stress which is a resource of most welding crack. Normally it should be carefully applied for welds for pressure-containing equipment and piping. Figure 4.86 shows a typical needle type of peening equipment.

ASME Sec. VIII, BPVC addresses that:

Weld metal and HAZ may be peened by manual, electric, or pneumatic means when it is deemed necessary or helpful to control distortion, to relieve residual stresses, to improve fatigue life, or to improve the quality of the weld. Peening shall not be used on the 1st (root) layer of weld metal or on the finish layer of the weld metal unless the weld is subsequently PWHT'd. In no case, however, is peening to be performed in lieu of any PWHT required by ASME Sec. VIII. Controlled shot peening and other similar methods, which are intended only to enhance surface properties of the vessel or vessel parts, shall be performed after any NDE and pressure tests required by ASME Sec. VIII.

Figure 4.86 Needle type of peening equipment

However, most end-users in energy and chemical industries do not allow to use peening for new construction.

Classic Case Study 4

Failure during Pneumatic Test for the Commissioning due to Wrong Materials and Poor Inspection

Premature Failure (collapse after 12.5 years operation) of Large Bridge due to Poor Welding (Partial Penetration Welding for Butt Joint in Fatigue Environment) and Poor Inspection (1994)

Chapter 5
Test and Inspection Requirements in Codes and Standards

5.1 Overview of Test and Inspection

The test and inspection for materials, fabrication, construction, operation, and maintenance are extremely important action items to minimize the risk. They are performed at mill manufacturer's shop, lab, fabrication shop, construction field, operation plants, and maintenance shop/field. All required tests and inspections should be complied with the sound QA-QC programs and project/plant specifications and manuals as well as the applicable codes and standards.

5.1.1 Activities and Responsibilities

Table 5.1 shows the inspection and examination activities and responsibilities/duties for pressure equipment in ASME Sec. VIII, Div. 2. These inspection and examination activities and responsibilities and duties except the acceptant categories may be typically applicable for new construction of most pressure equipment and piping systems other than ASME Sec. VIII, Div. 2.

Figure 5.1 shows a pressure vessel waiting the final inspection for dimension. Figure 5.2 shows the dimension check of large-size pressure vessel head inside (concave section). The requirements of project specifications as well as applicable codes and standards for tolerance shall be complied. At the same time, NDE inspection including visual test is performed.

5.1.2 Inspection Standards in API and NACE (Other Than Onshore Equipment Standards)

API 510, Pressure Vessel Inspection Code: Maintenance, Inspection, Rating, Repair, and Alteration
API 570, Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-Service Piping Systems
API RP572, Inspection of Pressure Vessel (Towers, Drums, Reactors, H/EXs, and Condensers)
API RP573, Inspection of Fired Boilers and Heaters
API RP574, Inspection Practices for Piping System Components
API RP575, Inspection Practices of Atmospheric and Low Pressure Storage Tanks
API RP576, Inspection of Pressure Relieving Devices
API RP577, Welding Processes, Inspection, and Metallurgy
API RP578, Material Verification Program for New and Existing Alloy Piping Systems
API RP580, Risk-Based Inspection (RBI)
API RP581, Risk-Based Inspection (RBI) Technology
API RP582, RP and Supplementary Welding Guidelines for the Chemical, Oil, and Gas Industries
API Std 598, Valve Inspection and Testing
API Std 653, Tank Inspection, Repair, Alteration, and Reconstruction
API TR934H Inspection and Maintenance of Heavy Wall Reactor Vessels in HPHT Hydrogen Service
API Std 936, Refractory Installation QC-Inspection and Testing Monolithic Refractory Linings and Materials
API Std 975 (Draft), Refractory Installation QC-Inspection and Test Refractory Brick Systems and Materials
API Std 976 Refractory Installation QC-Inspection and Testing AES/RCF Fiber Linings and Materials
API Std 1631, Interior Lining and Periodic Inspection of Underground Storage Tanks
API Std 2610, Design, Construction, Operation, Maintenance, and Inspection of Terminal and Tank Facilities
API RP21, In-Service Inspection of Mooring Hardware for Floating Drilling Units provides comprehensive guidelines for inspecting catenary mooring components of floating drilling units.
API RP2X, Ultrasonic and Magnetic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Technicians contains recommendations for determining the qualifications of technicians conducting inspections of offshore structural fabrication using ultrasonic and magnetic devices. Recommendations are also given for control of inspections in a general QC program.

J. -C. Eun, *Handbook of Engineering Practice of Materials and Corrosion*,
https://doi.org/10.1007/978-3-030-36430-4_5

Table 5.1 (1/2) Inspection and examination activities and responsibilities/duties

Inspection and examination activities[4]	Time of examination	Paragraph reference in ASME Sec. VIII, Div. 2		Manufacturer's responsibilities[1]	Inspector's duties[2]
		Procedure	Acceptance criteria		
Certificate of authorization from ASME boiler and pressure vessel committee	Before start of all work	Annex 2-G, Annex 2-E	NA	Obtain the certificate and maintain QC system.	Verify the validity of certificate and that QC system is in place and being followed.
Manufacturers QC system	–	2.3.5, Annex 2-E	7-A.3.2.2	Maintain and QC system.	Verify that QC system is in place; monitor the QC system during fabrication.
Applicable drawings and documents	Before fabrication	NA	2.2.2, Part 4, Part 5	Prepare applicable design report, user design specification (if applicable), drawings, and related documents.	Verify that applicable design report, user design specification, drawings, and related documents are available.
Compliance of all materials used in the fabrication of the vessel or part including sample test coupons	Before fabrication	Part 3	Part 3, 7-A.3.2.3	Make certain that material used complies with the requirements of ASME Sec. VIII, Div. 2, part3.	Verify compliance of material with the requirements of ASME Sec. VIII, Div. 2, part 3.
Repair of material defects	Before fabrication	6.1.1.3	6.1.1.3	Make certain that material defects repaired by welding are acceptably repaired and reexamined.	Verify that material defects repaired by welding are acceptably repaired and reexamined.
Traceability of the material identification (PMI) [3]	Before/during cutting of material	3.2.7.2	NA	Make certain that the material identification numbers have been properly transferred.	Make examinations to confirm that the material identification numbers have been properly transferred.
Proper thickness and dimensional check of vessel components	Before welding	6.1.2.2, 6.1.2.7, 6.1.2.8	6.2, 7-A.3.2.4	Examine to confirm they have been properly formed to shape within tolerances.	Verify that the thickness and dimensions are within tolerances.
WPQ for welding	Before welding	6.2.2.4, Sec. IX, 6.3.4, 6.5.3, 6.5.6, 6.6.5, 6.7.7.1, 6.7.7.2, 6.8.3, 6.8.4.2	7-A.3.2.6(b), Sec. IX	Perform and maintain qualification.	Verify that all welding procedures have been qualified.
Qualification of welders and welding operators	Before welding	6.2.2.5, Sec. IX, 6.6.5.1, 6.5.6.4, 6.7.7.2, 6.8.4.3	7-A.3.2.6(b), Sec. IX	Perform and maintain qualification.	Verify that all welders and welding operators have been qualified.
Repair of material cut edge defects	During fabrication	6.1.3.1	7.4.4, 7.4.5, 7.4.6	Make certain that material edge defects repaired by welding are acceptably repaired and reexamined.	Verify that material cut edge defects repaired by welding are acceptably repaired and reexamined.
Proper fitting and cleaning of parts for welding	Before welding	6.1.3, 6.1.4, 6.1.5, 6.1.6, 6.1.2.8	7-A.3.2.4	Examine all parts to make certain they have been properly fitted/aligned and the surfaces to be joined have been cleaned for welding.	Verify that all parts have been properly fitted/aligned and the surfaces to be jointed have been cleaned for welding.
Any repairs for defects by welding	During fabrication	6.2.7	7.4.2 through 7.4.6	Make certain that weld defects are acceptably repaired and reexamined.	Verify that weld defects are acceptably repaired and reexamined.
Control for required heat treatments	During fabrication	6.4, 6.1.2.3(b), 6.1.2.3 (c), 6.1.2.4, 6.1.2.5 (b), 6.1.2.5(b), 6.5.5, 6.6.3, 6.6.6, 6.7.6, 6.8.10	7-A.3.2.5	Control to assure that all required heat treatments are performed.	Verify that the heat treatments, including PWHT have been performed properly.
Impact tests for welds as production test	After welding	3.11.8	3.11.8	Perform tests and provide records.	Verify that impact tests have been performed and that the results are acceptable.
Certification of qualification of NDE (RT, UT, PT, MT, ECT) examiners	After welding	7-A.3.2.4	7-A.3.2.6(c)	Certify that each operator meets requirements of this division.	Verify that each operator meets requirements of the division.

Table 5.1 (2/2) Inspection and examination activities and responsibilities/duties

Inspection and examination activities[4]	Time of Examination	Paragraph reference in ASME Sec. VIII, Div. 2		Manufacture's responsibilities[1]	Inspector's duties[2]
		Procedure	Acceptance criteria		
NDE	After welding	7.4, 7-A.3.2.6 (c)	2.3.1.2, 2.3.7.2, 7.4.3, 7.4.4, 7.4.5, 7.4.6, 7.4.7,	Perform examinations and provide records including retaining radiographs and UT scans.	Verify that required nondestructive examinations have been performed and that the results are acceptable.
VT	After welding	7.5.2	Table 7.6	Perform visual examinations.	Make a visual inspection of the vessel to confirm that there are no welding and dimensional defects.
Hydrostatic or pneumatic test with required inspection during such test	After fabrication	Part 8	Part 8, 7-A.3.2.7	Perform inspection and test.	Perform inspections and witnessing the hydrostatic or pneumatic tests.
Stamping and/or nameplate to the vessel	After fabrication	Annex 2-F	NA	Apply the required stamping and/or nameplate to the vessel	Verify that the required marking, including stamping, is provided and that any nameplate has been attached.
Manufacturer's data report	After fabrication	Annex 2-D	NA	Prepare, certify, and provide to the inspector for certification.	Sign the certificate of inspection.
Manufacturer's data report and records specified by this division	After delivery	Annex 2-C	NA	Maintain proper records and distribute the documentation package.	Verify that the manufacturer has maintained proper records during vessel manufacture.

ASME Sec. VIII, Div. 2, Table 7.A.1 – modified
Commentary Notes
[1]The manufacturer should have the certification of manufacturers in accordance with ASME BPVC
[2]The inspector (including authorized inspector (AI) if needed) should have the approved certification for ASME Sec. VIII, Div. 2 performance
[c]See 2.5.1 (3) for more detail. Other references may also be applicable if required, such as MSS SP-137, API RP578. ASME Sec. VIII, Div. 1, UG-77
[d]All drawings and documents should be based on the as-built and/or latest test results. Any repair history should be described in the documents

Figure 5.1 Vessel for final inspection

Figure 5.2 Dimension check of vessel head inside

API Spec 4F, Drilling and Well Servicing Structures covers the design, manufacture, and use of steel derricks, portable masts, crown block assemblies, and substructures suitable for drilling and servicing of wells. It includes stipulations for marking, inspection, standard ratings, design loading, and design specification of the equipment.

API Spec 4G, Maintenance and Use of Drilling and Well Servicing Structures covers structural repair and modification, raising line inspection, guying and guywire anchors, foundations, and low temperature operations.

API RP5A5, Field Inspection of New Casing, Tubing, and Plain-End Drill Pipe includes recommended procedures for field inspection and testing of new casing, tubing, and plain-end drill pipe.

API RP5B, Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads covers dimensions and marking requirements for API master thread gauges. Additional product threads and thread gauges, as well as instruments and methods for the inspection of threads for line pipe, round thread casing, buttress casing, and extreme-line casing connections are included.

API RP5B1, Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads covers threading, gauging, gauging practice, and inspection of threads for casing, tubing, and line pipe made under Specifications 5CT, 5D, and 5 L. It also covers gauge specifications and certification for casing, tubing, and line pipe gauges.

API RP5C6, Welding Connections to Pipe provides a standard industry practice for the shop and field welding of connectors to pipe. The technical content provides requirements for welding procedure qualifications, welder performance qualifications, materials, testing, production welding, and inspection.

API RP5C8, Care, Maintenance, and Inspection of Coiled Tubing
API RP5L7, Unprimed Internal Fusion Bonded Epoxy Coating of Line Pipe provides recommendations for materials, application, testing, and inspection of internal fusion bonded epoxy coatings on line pipe.
API RP5L8, Field Inspection of New Line Pipe covers the qualification of inspection personnel, a description of inspection methods, and apparatus calibration and standardization procedures for various inspection methods. The evaluation of imperfections and marking of inspected new line pipe are included.
API RP5UE, Ultrasonic Evaluation of Pipe Imperfections
API RP7L, Inspection, Maintenance, Repair, and Remanufacture of Drilling
API RP8B/ISO 13534, Inspection, Maintenance, Repair, and Remanufacture of Hoisting
API RP12R1, Setting, Maintenance, Inspection, Operation, and Repair of Tanks in Production Service
NACE SP0205, RP for the Design, Fabrication, and Inspection of Tanks for the Storage of Petroleum Refining Alkylation Unit Spent Sulfuric Acid at Ambient Temperatures
NACE SP0387, Metallurgical and Inspection Requirements for Cast Galvanic Anodes for Offshore Applications
NACE SP0294, Design, Fabrication, and Inspection of Tanks for the Storage of Concentrated Sulfuric Acid and Oleum at Ambient Temperatures
NACE SP0308, Inspection Methods for Corrosion Evaluation of Conventionally Reinforced Concrete Structures
NACE SP0492, Metallurgical and Inspection Requirements for Offshore Pipeline Bracelet
NACE SP0102, In-Line Inspection of Pipelines
NACE SP0274, High-Voltage Electrical Inspection of Pipeline Coatings

5.2 Destructive Examination (DE) for New Construction and Maintenance

5.2.1 Classes and Characteristics of Special DE Requirements

The applicable industrial codes, standards, and local regulations have lots of mandatory destructive examination (DE) requirements for base materials and products. In addition, the end-user's or company's specification for new construction or maintenance requires more detail application at each fabrication step as below.

1. Basic Tests for Base Metal: per the industrial materials, facility, corrosion, welding standards, and the end-user's or company's specification.
2. Simulation Tests at Mill or Shop (e.g., tensile and creep rupture with thermal hysteresis at mill/corrosion resistance, precipitation resistance, hot tensile, toughness, and several other tests at mill/mock-up test as shop) – They are normally applied per the purchaser's requirement.
3. Production Tests at Shop (per client's requirement and/or local regulations for low temperature or lethal service).

5.2.2 Mechanical Tests

See Sect. 4.2.9 for weld crack tests.

5.2.2.1 Typical Tensile Test at Atmosphere (Not Through-Thickness Test)

See Sect. 1.1.10.1(b) for more detail description (purpose, characteristics, principle test methods, results, reports, etc.).

– Test Methods: ASTM A20/370, ASTM E8, ASTM D638/882/1708, etc.
– Applicable Material Standards: Most materials except fasteners or non-tensile stress required materials

5.2.2.2 Hot Tensile Test

Hot Temperature Tensile Test of Metallic Materials are performed at hot temperature as design temperature, acceptance criteria ASME Sec. II, part D Table 1A/1B and Table U respectively unless otherwise specified in client spec.

ASTM E21 covers the procedure and equipment for the determination of tensile strength, yield strength, elongation, and reduction of area of metallic materials at elevated temperatures. The elevated-temperature tension test gives a useful estimate of the static load-carrying capacity of metals under short-time, tensile loading. Using established and conventional relationships, it can be used to give some indication of probable behavior under other simple states of stress, such as compression, shear, etc. The ductility values give a comparative measure of the capacity of different materials to deform locally without cracking and thus to accommodate a local stress concentration or overstress: however, quantitative relationships between tensile ductility and the effect of stress concentrations at elevated temperature are not universally valid. A similar comparative relationship exists between tensile ductility and strain-controlled, low-cycle fatigue life under simple states of stress. The results of these tension tests can be considered as only a questionable comparative measure of the strength and ductility for service times of thousands of hours. Therefore, the principal usefulness of the elevated-temperature tension test is to assure that the tested material is similar to reference material when other measures such as chemical composition and microstructure also show that the two materials are similar. See Sects. 2.1.4.2(c) and 2.1.4.3 in this book for more detail application of hot tensile test.

5.2.2.3 "Z" Direction Test (per Client's Requirement in Heavy Thickness or Hydrogen Service)

Through-thickness tensile test or "Z" direction tensile test is performed to evaluate mechanical properties in steel by purchaser's specific requirements. The requirement normally comes from end-user's specification when mostly the components are exposed to hydrogen, H_2S, and HF environment as well as fabricated by heavy wall. The test involves applying tensile forces on a test specimen whose axis is perpendicular to the rolled surfaces of steel plate. The primary purpose of the test is to measure resistance to lamellar tearing by determining reduction of area and ultimate tensile strength in "Z" direction. The mechanical properties in "Z" direction have very lower values compared to those in "X" (transverse for rolling direction) and "Y" (rolling direction) direction as shown in Figs. 2.122 and 2.123 in this book.

– Test Methods: ASTM A770/ C1468, EN 10164, AS 3678/ 1391, etc.

5.2.2.4 Creep and Rupture Test

See Sect. 1.3.3 in this book for more detail of creep-rupture stress.

– Test Methods: ASTM E139 (Standard Test Method for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials), etc.
– Applicable Codes and Standards: API 530/560, or others. And per purchaser's requirement in elevated temperature with design life, such as 1000/10,000/100,000 hours

5.2.2.5 Fatigue Test

See Sect. 1.3.2 in this book for more detail of fatigue stress.

– Test Methods: ASTM E466, E606, E1049, E1823 (Terminology Relating to Fatigue and Fracture Testing), etc.
– Applicable Codes and Standards: High cycle (motor-driven engineering or bridge) and low cycle (by thermal, i.e., ASME Sec. VIII, Div. 2, Appendix 5, and end-user's specification)

5.2.2.6 Shear Stress Test

A shear test is designed to apply stress to a test sample so that it experiences a sliding failure along a plane that is parallel to the forces applied. In general, shear forces cause one surface of a material to move in one direction and the other surface to move in the opposite direction so that the material is stressed in a sliding motion. Shear tests differ from other mechanicals (e.g., tension, compression, bending, creep-rupture, crushing, flare, flange test, etc.) in that the forces applied are parallel to the two contact surface, whereas in tension and compression, they are perpendicular to the contact surfaces.

See Sect. 1.1.10.1(k) in this book for more detail of shear stress.

– Test Methods: ASTM B565/B769/B831, ASTM C273, ASTM D732/D1002/D3163/D3164/D3528/D4255/D5379/D5868/D7078, ASTM E229, ASTM G146, ISO 3597/4587/12579/13445/14130, etc.
– Applicable Material Standards: ASTM B769/B831, etc.
– Applicable Codes and Standards: ASME Sec. VIII, Div. 1, UG-45 (nozzle neck), UHX 12.5, 13.5, and 14.5 (tubesheet calculation), bolting design, etc.

5.2.2.7 Disbonding Test for Clad or Weld Overlay Metal

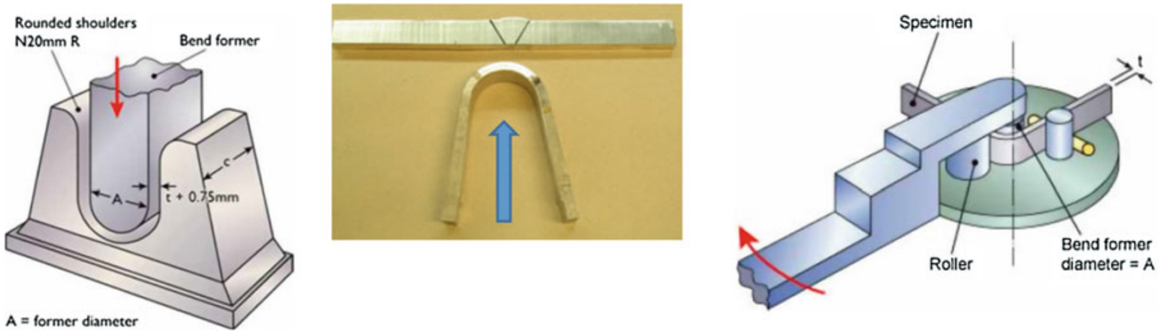
ASME Sec. VIII, Div. 1, UCL-11 requires that minimum 140 MPa (20 ksi) shear stress between clad and base metal for rolled bonded clad materials. Normally this test is not required for weld overlay and explosion-bonded clad materials unless the purchaser requires. However, API TR934-D states some cautions for disbonding of weld overlay during rapid shutdown in HPHT hydrogen service. Wide bead weld overlay surfaces (e.g., strip weld) are more susceptible to clad disbonding than narrow bead welds. The first layer of weld overlay on a backing material has a grain boundary parallel to the backing material HAZ. During PWHT there is a carbon migration from the backing material into the overlay deposit. This carbon migration weakens the grain boundary and makes it more susceptible to disbonding. A 304, 308, or 309 SS deposit is more susceptible to disbonding than a 347 or 309Cb SS deposit. Tests have shown that Cb (Nb) has a higher affinity for C than Cr and will tie the carbon up before it can deplete the Cr content.

– Test Methods for Clad or Lined Metals: ASTM A263/A264/A265 (see Sect. 2.6.2.1 in this book), ASTM B432 (copper and copper alloy clad – minimum 85 MPa (12 ksi) shear stress), ASTM B898 (reactive and refractory metal lined – minimum 138 MPa (20 ksi) shear stress), ASTM G146 (for evaluation of disbonding of bimetallic stainless alloy/steel plate for use in HPHT refinery hydrogen service), etc.
– Applicable Codes and Standards: ASME Sec. VIII, Div. 1, UCL-11 (general for pressure vessels), API RP934-A weld overlay Cr-Mo reactor material test per ASTM G146 (*variables for domain of test conditions*, thickness, max. Hydrogen partial pressure, max. Operating temperature; *test conditions of each domain*, test temperature, hydrogen partial pressure, cooling rate), etc.

5.2.2.8 Proof Tests to Establish Maximum Allowance Working Pressure

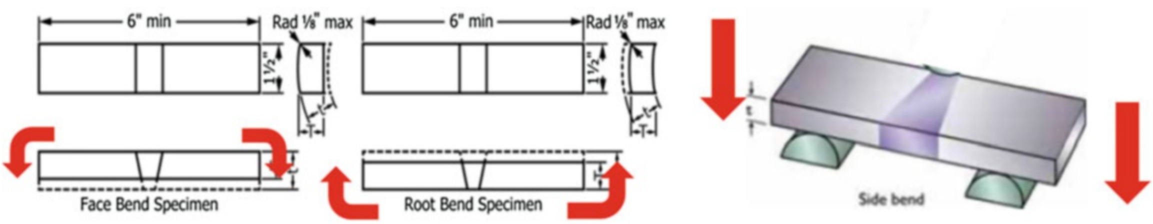
The design condition can be verified by the actual/simulation test like proof test.

– Test Methods: per codes and standards for facilities
– Applicable Codes and Standards: ASME Sec. VIII, Div. 1, UG-101, etc.



(a) Guided-Bend Test (b) Wrap-Around Bend Test

Figure 5.3 Bend test jigs (ASTM A370). (**a**) Guided bend test. (**b**) Wrap-around bend test



(a) Transverse Face- and Root Bend Test (b) Side Bend Test

Figure 5.4 Transverse face and root and side bend test (ASTM A370). (**a**) Transverse face and root bend test. (**b**) Side bend Test

5.2.2.9 Bend Test of Pipes – Figs. 5.3 and 5.4

The bend test is one method for evaluating ductility, but it cannot be considered as a quantitative means of predicting service performance in all bending operations. The severity of the bend test is primarily a function of the angle of bend of the inside diameter to which the specimen is bent and of the cross section of the specimen. These conditions are varied according to location and orientation of the test specimen and the chemical composition, tensile properties, hardness, type, and quality of the steel specified including jigs shown in Fig. 5.3. The specimen should stand being bent cold through 90° around a cylindrical mandrel, the diameter of which is 12 times the OD without developing cracks. Failure of the bend test depends upon the appearance of cracks in the area of the bend and of the nature and extent described in the product specifications.

For pipe used for coiling in sizes 2 in. and under, a bend test is made to determine its ductility and the soundness of weld. In this test, a sufficient length of full-size pipe is bent cold through 90° around a cylindrical mandrel having a diameter 12 times the nominal diameter of the pipe.

For close coiling, the pipe is bent cold through 180° around a mandrel having a diameter eight times the nominal diameter of the pipe.

ASTM A370 *states that* the specimens used are approximately 38 mm (1.5 in.) wide, at least 152 mm (6 in.) in length with the weld at the center, and are machined in accordance with Fig. 5.4a below for face and root bend tests and in accordance with Fig. 5.4b below for side bend tests. A test shall consist of a face bend specimen and a root bend specimen or two side bend specimens. A face bend test requires bending with the inside surface of the pipe against the plunger; a root bend test requires bending with the outside surface of the pipe against the plunger; and a side bend test requires bending so that one of the side surfaces becomes the convex surface of the bend specimen.

See Sect. 1.1.10.1(j) in this book for more detail of bending stress.

- Test Methods: ASTM A370/A615/A720, ASTM B490, ASTM E190/E290/E855, ASTM D522/D790/ D6272, ASME Sec. IX, ISO 9606, ISO 15614 Part 1, EN 12814–8, etc.
- Applicable Material Standards: ASTM A53/A106/A370/A615/A720, ASTM B490, etc.

5.2.2.10 Crush (as a Compression) Test (Fig. 5.5)

It is one of the compression test and typically used for nonmetallic materials (more widely) as well as metallic materials. This test is also used for assessing the quality of socket joints in small diameter ($\leq$ 90 mm) plastic pipes. The welded pipe/fitting assembly is cut in half lengthways. The pipe portion is then squeezed in a vice until the inner surfaces meet and held in this position for 10 minutes. If the weld is of good quality, there should be no evidence of cracking at the weld interface. Crush test is normally performed by the purchaser's request.

ASTM A370 states that the crush test, sometimes referred to as an upsetting test, is usually made on boiler and other pressure tubes, for evaluating ductility. The specimen is a ring cut from the tube, usually about 63.5 mm (2.5 in.) long. It is placed on end and crushed endwise by hammer or press to the distance prescribed by the applicable material specifications.

- Test Methods: ASTM C133/C497, ASTM D695/D2412, ISO 8492, etc.

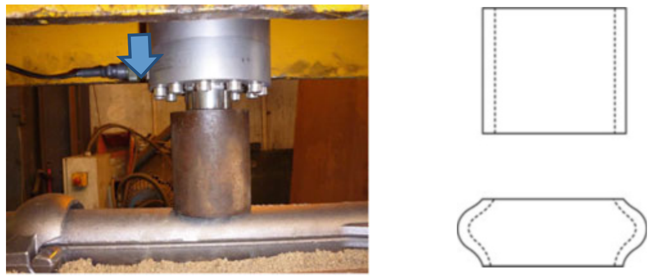


Figure 5.5 Crush test (ASTM A370)

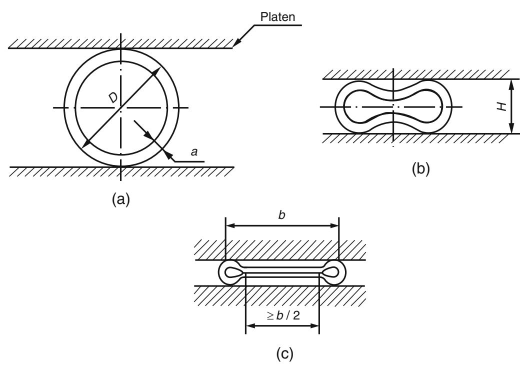


Figure 5.6 Flattening test of pipes or tubes (ASTM A370)

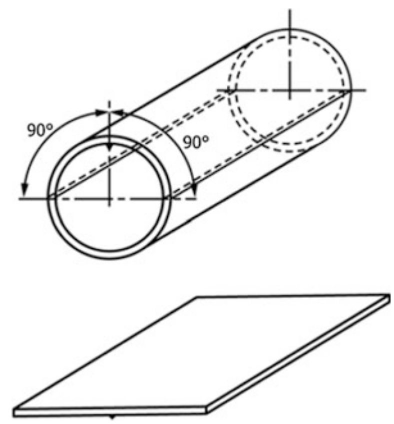


Figure 5.7 Reverse flattening test of pipes or tubes (ASTM A370)

5.2.2.11 Flattening (Reverse Flattening) Test of Pipes or Tubes (Figs. 5.6 and 5.7)

The specimen is flattened between parallel plates with the weld 90° from the direction of applied force until opposite walls of the tubing meet. Applications for this test along with the flaring test include situations where round tubing is to be formed into other shapes.

ASTM A370 states that the conventional flattening test as commonly made on specimens cut from tubular products is conducted by subjecting rings from the tube or pipe to a prescribed degree of flattening between parallel plates (Fig. 5.6 below). The severity of the flattening test is measured by the distance between the parallel plates and is varied according to the dimensions of the tube or pipe. The flattening test specimen should not be less than 63.5 mm (2.5 in.) in length and should be flattened cold to the extent required by the applicable material specifications.

ASTM A370: Reverse Flattening Test – The reverse flattening test is designed primarily for application to electric-welded tubing for the detection of lack of penetration or overlaps resulting from flash removal in the weld. The specimen consists of a length of tubing approximately 102 mm (4 in.) long which is split longitudinally 90° on each side of the weld. The sample is then opened and flattened with the weld at the point of maximum bend (Fig. 5.7 above).

– Test Methods: ASTM A370, ASTM B968, ASTM D1599, etc.
– Applicable Material Standards: ASTM A53/A106/A179/A209/A210/A213/A214/A268/A312/A334/A335/A513, etc.

5.2.2.12 Flaring Test of Pipes or Tubes (Fig. 5.8)

A370 – For certain types of pressure tubes, an alternate to the flange test is made. This test consists of driving a tapered mandrel having a slope of 1 in 10 or a 60° included angle as shown in Fig. 5.8 below into a section cut from the tube, approximately 100 mm (4 in.) in length, and thus expanding the specimen until the inside diameter has been increased to the extent required by the applicable material specifications.

The expansion of the inside and outside diameter is also dependent on standard specifications. The obtained values shall be not less than the value given that has been stated in the specification requirements.

– Test Methods: ASTM A370, etc.
– Applicable Material Standards: ASTM A179/A209/A210/A213/A214/A268/A334, etc.

5.2.2.13 Flange Test of Pipes or Tubes (Fig. 5.9)

The flange test is intended to determine the ductility of boiler tubes and their ability to withstand the operation of bending into a tubesheet.

ASTM A370 states that this test is made on a ring cut from a tube, usually not less than 100 mm (4 in.) long and consists of having a flange turned over at right angles to the body of the tube to the width required by the applicable material specifications. The flaring tool and die block shown in Fig. 5.9 are recommended for use in making this test.

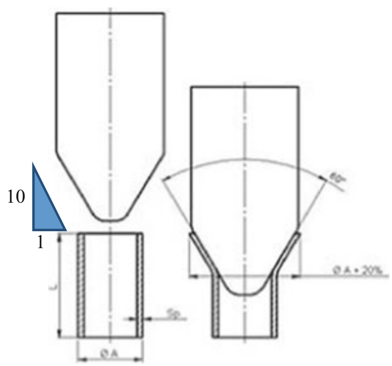


Figure 5.8 Flaring test of pipes or tubes

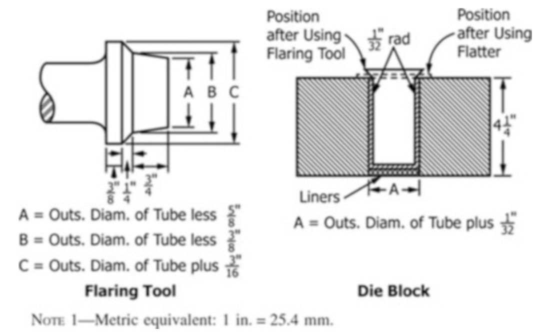


Figure 5.9 Flange test of pipes or tubes

ASTM A179 states that when specified as a substitute for the flaring test, for tubes having a wall thickness (actual mean wall) less than 10% of the outside diameter, one test shall be made on specimens from each of two tubes from each lot or fraction thereof.

– Test Methods: ASTM A370, etc.
– Applicable Material Standards: ASTM A179/A214/A268/A334, etc.

5.2.3 Toughness Tests

Impact is a very important phenomenon in governing the life of a structure. For example, pressure equipment or bridges can be catastrophically failed during operation without warning when the materials do not have enough toughness at the design temperatures or any other upset conditions. The disasters will greatly damage the human lives. For another example, in the case of aircraft, impact can take place by a bird hitting a plane while it is cruising, or during takeoff and landing the aircraft may be struck by debris that is present on the runway, and as well as other causes.

A toughness is a factor of its ability to absorb energy during plastic deformation of the material. Brittle materials have low toughness as a result of the small amount of plastic deformation that they can endure. The impact value of a material can also change with temperature. In general, the impact energy of a material is decreased at lower temperatures. The subsize of the specimen may also affect the value of the impact test because it may allow a limited impact absorbing energy due to smaller section area on fracture. The results of impact test as well as tensile strength are very sensitive per the test specimen direction as seen in Fig. 2.122. Careful selection of the direction is required per the applicable codes, standards, and specifications.

5.2.3.1 Charpy V Notch (CVN) Impact Test

ASTM A370 (Test Methods and Definitions for Mechanical Testing of Steel Products)/E23 (Notched Bar Impact Testing of Metallic Materials)/E2248 (Impact Testing of Miniaturized CVN Impact Test Specimens)/E2298 (Instrumented Impact Testing of Metallic Materials), ASME Sec. VIII, Div. 1, UCS-66, UG-84, ASME IX QW 170, API 2Z, ISO 148-1/15614/9956/9606, EN 10045, AS 1544/2205.7/2885.2/3992/3678/3679.1/3679.2/1163, DIN EN 875/10045.1, DNV P2 C2 S1, AWS series, etc.

In addition to facility codes and standards as well as company specifications, see ASME Sec. II, Part C, SFA-5.1/5.4/5.5/5.17/5.18/5.20/5.22/5.23/5.25/5.26/5.28/5.29/5.36 for impact test requirements of the welds in ASME application. See Table 5.2, Sects. 2.2.1, and 1.3.4.6 for more detail information in this book. Charpy U notch impact test is not covered in this book.

5.2.3.2 Izod Test

ASTM E23/D256 (Determining the Izod Pendulum Impact Resistance of Plastics), BS EN ISO 180 and 13,802, BS 131–1, etc. See Table 5.2 in this book for more detail.

5.2.3.3 Crack Tip Opening Displacement (CTOD) Test

E1820 (Measurement of Fracture Toughness – for measuring the three parameters of K, J, and d)/E1290 (withdrawn in 2013, incorporated into Test Method ASTM E1820), ASTM E399 (Linear Plastic Strain Fracture Toughness of Metallic Materials)/EN 10225 (weldable structural steels for fixed offshore structures), BS 7448 (Fracture Mechanics Toughness Tests), etc. See Table 5.2 in this book for more detail.

CVN impact testing enables engineers to make judgments about risks of brittle fracture occurring in steels, but a CTOD test measures a material property-fracture toughness with plastic deformation

5.2.3.4 K_{1C} Test

ASTM E399 and BS 7448 (Fracture Mechanics Toughness Tests). See Sect. 1.3.4 in this book for more detail.

Table 5.2 (1/2) Comparison of common toughness tests

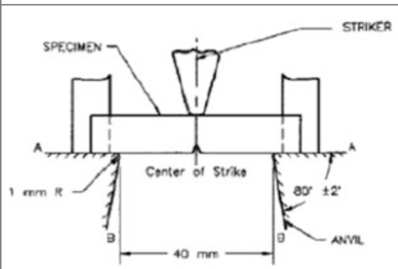
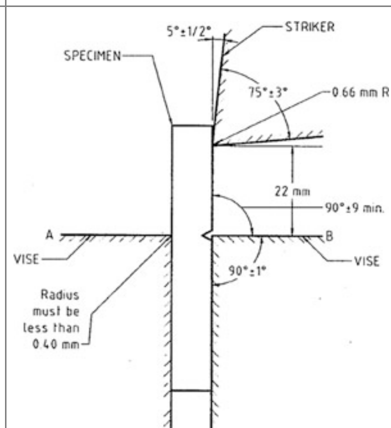
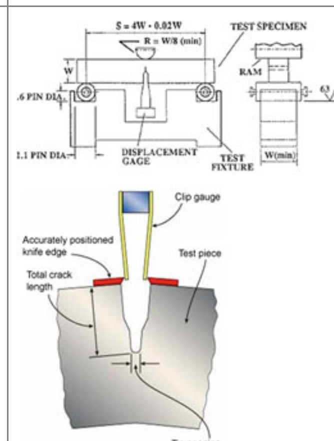
Item	CVN impact test	Izod test	CTOD test
Characteristics and purpose	Charpy V-notch impact tests show whether a metal can be classified as being either brittle or ductile. This is particularly useful for ferritic steels that show a ductile to brittle transition with decreasing temperature. A brittle metal will absorb a small amount of energy when impact tested, a tough ductile metal absorbs a large amount of energy. The appearance of a fracture surface also gives information about the type of fracture that has occurred; a brittle fracture is bright and crystalline; a ductile fracture is dull and fibrous. 3 specimens are normally used for average value.	The Izod test is has become the standard testing procedure for comparing the impact resistances of plastics or polymers. While being the standard for plastics it is also used on other materials. This is most commonly used to evaluate the relative toughness or impact toughness of materials and as such is often used in QC applications where it is a fast and economical test. It is used more as a comparative test rather than a definitive test.	CTOD is used on materials that can show some plastic deformation (propagation of a crack) before failure occurs causing the tip to stretch open. The testing material should more or less resemble the original one though dimensions can be reduced proportionally. Loading is also done so as to resemble the actual load expected. The specimen is placed on the work table and a notch is created exactly at the center. According to material used, fracture can be brittle or ductile which can be concluded from graph plotted. It is mostly used in marine and subsea facilities.
Test process	The specimen is clamped at both ends in impact test fixture. The apparatus consists of a pendulum of known mass and length that is dropped from a known height to impact a notched specimen of material. The energy transferred to the material can be inferred by comparing the difference in the height of the hammer before and after the fracture (energy absorbed by the fracture event).	The cantilever-type specimen is clamped into the pendulum impact test fixture with the notched side facing the striking edge of the pendulum. A pendulum swings on its track and strikes a notched, cantilevered plastic sample. The energy lost (required to break the sample) as the pendulum continues on its path is measured from the distance of its follow through.	The crack should be generated such that the length of defect reaches a value of about half the depth. The load applied on the specimen is generally a three-point bending load. A strain gauge is used to measure the crack opening. Crack tip plastically deforms until a critical point after which a cleavage crack is initiated which may lead to either partial or complete failure. The critical load and strain gauge measurements at the load are noted, and a graph is plotted. Note 1.
Applicable test standards	ASTM A370/E23/E2248/ E2298, API 2Z, ISO 148-1/ 15,614/ 9956/ 9606, EN 10045, AS 1544/ 2205.7/ 2885.2/ 3992/ 3678/ 3679.1/ 3679.2/ 1163, DIN EN 875/ 10045.1, DNV P2 C2 S1, etc.	ASTM E23/ D256, BS EN ISO 180 and 13,802, BS 131–1, etc.	ASTM E399/E1820, EN 10225.
Test temperature	MDMT (or DMT) or colder for pressure components. Per codes and project specification for nonpressure components/structures.	MDMT (or DMT) or colder for pressure components. Per codes and project specification for nonpressure components/structures.	Room temperature.
Lateral expansion (LE)	LE is a measure of the ductility of the specimen. When a ductile metal is broken, the test piece deforms before breaking, and material is squeezed out on the sides of the compression face. LE is particularly useful for ASS.	Not applicable.	Not applicable.
Specimen and setting for test			

Table 5.2 (2/2) Comparison of common toughness tests

	CVN impact test	Izod test	CTOD test
Assessment of test results	This absorbed energy (J or ft-lb) is a measure of a given material's notch toughness and acts as a tool to study temperature-dependent ductile-brittle transition. It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply. The ductile-brittle transition temperature (DBTT) is derived from the temperature where the energy needed to fracture the material drastically changes (transition region).	The results are expressed in energy lost per unit of thickness (such as ft·lb/in or J/cm in ASTM D256) at the notch. Alternatively, the results may be reported as energy lost per unit cross-sectional area at the notch (J/m^2 or $ft{\cdot}lb/in^2$ in ISO 180).	Crack tip opening can be calculated from the length of the crack and opening at the mouth of the notch. Examination of fractured test specimens led to the observation that the crack faces had moved apart prior to fracture, due to blunting of an initially sharp crack by plastic deformation. The degree of crack blunting increased in proportion to the toughness of the material. This observation led to the opening at the crack tip being considered as a measure of fracture toughness.

Notes
1. Four steps of CTOD
   1) Machining of the test specimen (Sample Machining)
   2) Fatiguing of the specimen within specified limits (Pre-Cracking)
   3) Breaking of the specimen under controlled conditions (Fracture)
   4) Post-analysis of the specimen and resultant data to obtain the CTOD value (Data Analysis)

5.2.3.5 J_{1C} Test

ASTM E399. ASTM E1820, ASTM E813 J_{1C} Testing (withdrawn in 1991, Merged to ASTM E1820), and BS 7448 (Fracture Mechanics Toughness Tests). See Sect. 1.3.4 in this book for more detail.

5.2.3.6 K-R Curve Determination Test (for Determination of the Resistance to Fracture of Metallic Materials Under Mode I Loading at Static Rates)

ASTM E561

5.2.3.7 J–R Curve Test

ASTM E1820, ASTM E1737 (withdrawn in 1996, Merged to ASTM E1820)

5.2.3.8 Determination of Reference Temperature

To, for Ferritic Steels in the Transition Range (cleavage toughness KJC Test) – ASTM E1921

5.2.3.9 Critical Crack-Tip-Opening Angle (CTOA) or Crack Opening Displacement (COD)

ASTM E2472

5.2.3.10 Drop Weight Test (DWT)

(ASTM E208 Drop Weight Test to Determine Nil Ductility Transition Temperature and E436 Drop Weight Tear Tests of Ferritic Steels and API RP5L3) – It is a material characterization test aimed at avoiding brittle fracture and ensuring crack arrest mainly in pipelines (seamless or welded). ASME Sec. VIII, Div. 2, 3.11.3.3 states that:

(a) When the MDMT is colder than −29 °C (−20 °F), drop weight tests as defined by ASTM E208 (Conducting Drop Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels) shall be made on all materials listed in ASME Sec. VIII, Div. 2, Table 3-A.2 (Q-T High Strength Steels), with the following exceptions:
   1. SA-522 for any MDMT;
   2. SA-353 and SA-553 when the temperature is not colder than −196 °C (−320 °F);
   3. SA-645 Grade A when the temperature is not colder than −170 °C (−275 °F).

(b) Number of Tests for Plates – For plates 16 mm (5/8 in.) thick and greater, one drop weight test (two specimens) shall be made for each plate in the as-heat-treated condition (see ASME Sec. VIII, Div. 2, 3.11.3.3).

(c) Number of Tests for Forgings and Castings – For forgings and castings of all thicknesses, one drop weight test (two specimens) shall be made for each heat in any one heat treatment lot. The sampling procedure shall comply with the requirements of ASTM E208. Specimen locations for forgings shall be the same as specified in SA-350 for location of impact test specimens (SA-350, paragraph 7.2.3).

(d) Required Test Results – Each of the two test specimens shall meet the "no-break" criterion, as defined by ASTM E208, at the test temperature.

5.2.3.11 Dynamic Tear Test

ASTM E604

5.2.3.12 Measurement of Fatigue Crack Growth Rates

ASTM E647

5.3 General Classification of Nondestructive Examination (NDE)

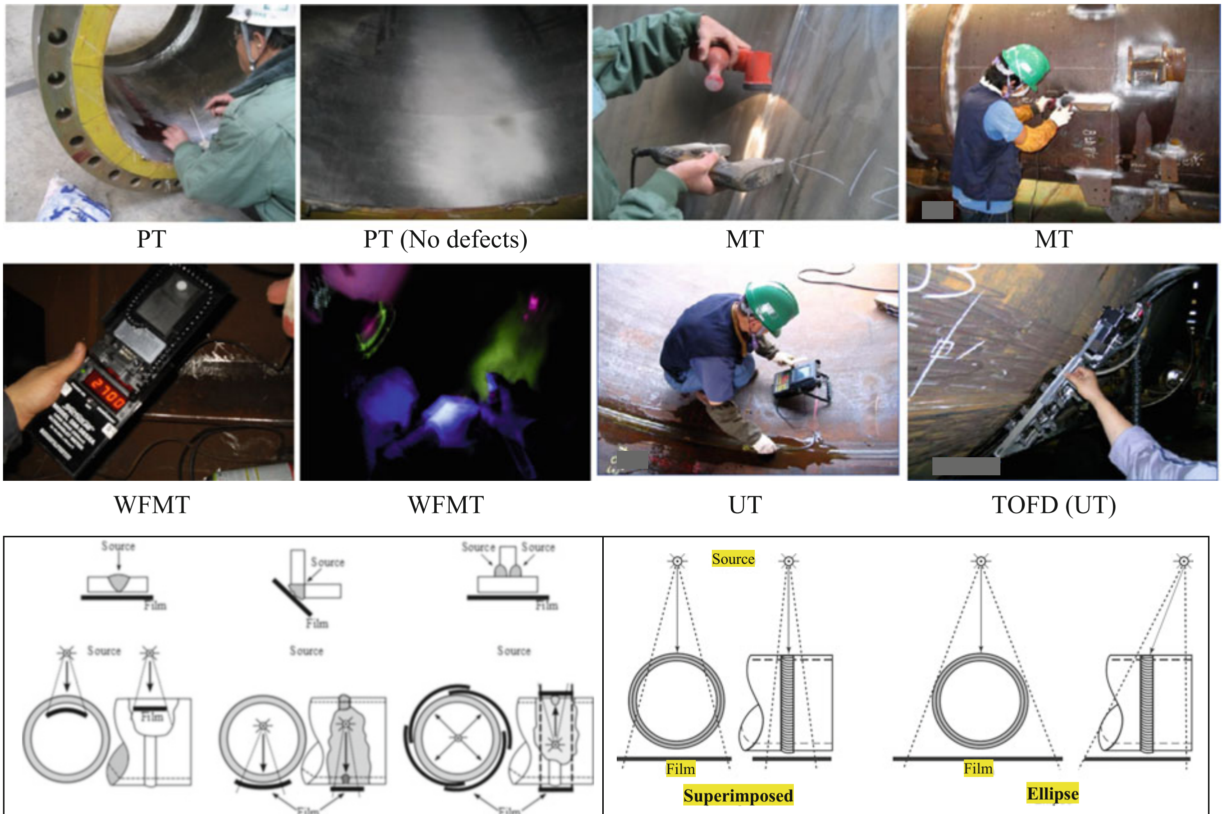
5.3.1 Classes of NDE: Advantage and Disadvantage See Table 5.3

This section is for introduction of several NDE methods and procedures. The NDE is applicable for base metal as well as production (on fabrication and operation). The benefits for production are very remarkable because the tests do not require detrimental results of the metal. Table 5.3 and Fig. 5.10 show the summary and figures of NDE methods for evaluating welds and base metal. Table 5.4 indicates the capacities of NDE detection per imperfection. See Sect. 2.5.1.3 for procedure of PMI and traceability and Sect. 5.4.1 for hardness test as a nondestructive test.

Table 5.3 Overview of NDE methods for evaluating welds and base metal[4]

Method	Defects detected	Advantages	Limitations
Visual[1] (VT)	Misalignment, undercut, overlap, surface cracks, craters, surface porosity, excessive reinforcement, under fill, arc strikes, poor workmanship	Basic prior to all other methods Inexpensive No major equipment needed Very effective	Can't see subsurface defects.
Liquid Penetrant[2] (PT)	Defects open to the surface; cracks, porosity, laps	Low cost Portable Results easily interpreted	Defect must be open to surface. Surface films may prevent detection of defects (parts must be cleaned before/after inspection). Application temperature; 4–52 °C (40–125 °F). Min. 10 °C (50 °F) preferable.
Magnetic Particle[3] (MT)	Slightly subsurface (by DC)/surface (by AC) defects; cracks, porosity, laps, inclusions	Low cost Fast Portable Indicates slightly subsurface (max. 3 mm) defects	Magnetic materials only available. (no austenite) Alignment of magnetic field is critical (should test in two directions about 90 degrees apart). Parts must be cleaned before inspection. Depends on wet, dry, and particle manufacturer's recommendations.
Radiography (X-ray or gamma, γ ray) (RT)	Internal and surface defects; crack, porosity, lack of fusion, incomplete penetration, burn-through, slag, undercut, and excessive penetration	Film gives a permanent record of inspection Portable Detects subsurface defects and inside pitting pattern. Geometry variation does not affect direction of radiation beam	Radiation hazard – Source decay. Trained operators needed. Depth of defect not indicated – Linear defect may be missed. Defects of certain orientations may not be detected. Access needed to at least two sides of the part. Detectable thickness is limited compared to UT.
Ultrasonic (UT)	Internal and surface defects; cracks, porosity, lack of fusion, burn-through, slag, undercut, and incomplete penetration with shape and direction	Most sensitive to cracks Test results known immediately Portable/automation possible Depth of defect is indicated Permanent record available	Limited to detect surface defects. Couplant & special probes required. Calibration block needed. Clean surface condition required. Trained operators required. UT is required all plate 4 in. (102 mm) and over in ASME sec. VIII, div. 2 AM-203.
Eddy current (EC)	Surface & subsurface crack depth as well as seams, alloy content, heat treatment variations, wall & coating thickness, conductivity and permeability	No couplant required No probe contact required Permanent record available Low cost and high speed	Conductive material only available. Shallow depth of penetration.
Acoustic emission (AE)	Crack initiation and growth rate Int. cracking in welds during cooling, boiling or cavitation Friction or wear Plastic deformation Phase transformations	Remote and continuous surveillance Permanent record and portable Dynamic (rather than static) detection of cracks Triangulation techniques to locate flaws	Transducers must be placed on part surface highly ductile materials yield low amplitude emissions. Part must be stressed or operating test system noise need to be filtered out.
Infrared thermography	Hot spots, heat transfer temperature ranges, temperature monitoring, CUI, liquid level, and electrical assemblies	Permanent record available Thermal picture provides Remote sensing Portable	Expensive. Reference standard required. Limited to thick section.

Notes
(1)Mirrors or bore scopes used for looking at hidden undersides of welds
(2)All materials. Fluorescent penetrants can be used for added sensitivity
(3)Fluorescent particles can be used for added sensitivity
(4)See API RP577 for more detail information



RT- Single Wall Techniques (source: API RP577, Figure 33)

RT- Double Wall Techniques (source: API RP577, Figure 34)

Figure 5.10 Several NDEs

Table 5.4 (1/2) Imperfection vs. type of NDE methods

Imperfection	Surface(1)		Subsurface(2)		Volumetric(3)				
	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT
Service-induced imperfections									
Abrasive Wear (localized)(5)	●	□	□	. . .	●	□	□	. . .	□
Baffle Wear (H/EXs)(5)	●	. . .	. . .	□	. . .	. . .	. . .	. . .	. . .
Corrosion-Assisted Fatigue Cracks (6)	Δ	□	●	. . .	Δ	●	. . .	●	. . .
Corrosion – crevice	●	. . .	. . .	. . .	. . .	. . .	. . .	. . .	Δ
– General/uniform	. . .	. . .	. . .	Δ	□	. . .	□	. . .	●
– Pitting	●	●	Δ	. . .	●	Δ	Δ	□	Δ
– Selective(7)	●	●	Δ	. . .	. . .	. . .	. . .	. . .	Δ
Creep (primary)(4)	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Erosion(5)	●	. . .	. . .	. . .	●	Δ	□	. . .	□
Fatigue Cracks(6)	Δ	●	●	□	□	●	. . .	●	. . .
Fretting (H/EX tubing)(5)	□	. . .	. . .	□	. . .	. . .	. . .	. . .	□
Hot (Solidification) Cracking(8)	. . .	□	□	. . .	□	Δ	. . .	□	
Hydrogen-induced cracking (HIC)(9)	. . .	□	□	. . .	Δ	□	. . .	□	. . .
Intergranular stress-corrosion cracks (IGSCC)(10)	. . .	. . .	. . .	. . .	. . .	Δ	. . .	. . .	. . .
SCC (Transgranular) & SSC(11)	Δ	□	●	Δ	□	□	. . .	□	. . .
Welding imperfections									
Burn-Through(12)	●	. . .	. . .	. . .	●	□	. . .	. . .	Δ
Cracks	Δ	●	●	□	□	●	Δ	●	. . .
Excessive/inadequate reinforcement	●	. . .	. . .	. . .	●	□	Δ	. . .	Δ
Inclusions (slag/tungsten)	. . .	. . .	□	□	●	□	Δ	Δ	. . .
Incomplete fusion	□	. . .	□	□	□	●	□	□	. . .

Table 5.4 (2/2) Imperfection vs. type of NDE methods

	Surface[1]		Subsurface[2]		Volumetric[3]				
Imperfection	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT
Incomplete penetration	□	●	●	□	●	●	□	□	...
Misalignment[13]	●	...	...	...	●	□	...	...	...
Overlap	□	●	●	Δ	...	Δ	...	...	...
Porosity	●	●	Δ	...	●	□	Δ	Δ	...
Root concavity	●	...	...	...	●	□	Δ	Δ	Δ
Undercut	●	□	□	Δ	●	□	Δ	Δ	...
Product form imperfections[15]									
Bursts (forgings)	Δ	●	●	□	□	□	□	●	...
Cold shuts (castings)	Δ	●	●	Δ	●	□	□	Δ	...
Cracks (all product forms)	Δ	●	●	□	□	□	Δ	●	
Hot tear (castings)	Δ	●	●	□	□	□	Δ	Δ	...
Inclusions (all product forms)	...	...	□	□	●	□	Δ	Δ	...
Lamination (plate, pipe)[14]	Δ	□	□	...	...	Δ	●	Δ	●
Laps (forgings)	Δ	●	●	Δ	□	...	Δ	Δ	...
Porosity (castings)	●	●	Δ	...	●	Δ	Δ	Δ	...
Seams (Bar, pipe)	Δ	●	●	□	Δ	□	□	Δ	...

ASME Sec. V, Table A-110 – modified
Legend: *AE* acoustic emission, *UTA* ultrasonic angle beam, *ET* electromagnetic (Eddy Current), *UTS* ultrasonic straight beam, *(WF) MT* (wet fluorescent) magnetic particle, *UTT* ultrasonic thickness measurement, *PT* liquid penetrant, *RT* radiography, *VT* visual
● All or most standard techniques well detect this imperfection under all or most conditions. --- Not applicable
□ One or more standard technique(s) will detect this imperfection under certain conditions
Δ Special techniques, conditions, and/or personnel qualifications are required to detect this imperfection
General Notes: See Table 2.143 for In-Line Inspection (ILI).
This table lists imperfections and NDE methods that are capable of detecting them. It must be kept in mind that this table is very general in nature. Many factors influence the detectability of imperfections. This table assumes that only qualified personnel are performing NDE and good conditions exist to permit examination (good access, surface conditions, cleanliness, etc.). See API RP577 for discontinuities on weld
Notes
(1) Methods capable of detecting imperfections that are open to the surface only
(2) Methods capable of detecting imperfections that are either open to the surface or slightly subsurface (max. 3 mm)
(3) Methods capable of detecting imperfections that may be located anywhere within the examined volume
(4) Various NDE methods are capable of detecting tertiary (third stage) creep, and some, particularly using special techniques, are capable of detecting secondary (second stage) creep. There are various descriptions/definitions for the stages of creep, and a particular description/definition will not be applicable to all materials and product forms. See Sects. 1.3.3 and 5.2.2.4 in this book
Commentary Notes: See Sect. 5.3 in this book for more detail guidelines, procedures, and requirements of NDE
(5) Erosion: See Sect. 2.4.5, Tables 2.124(9), and 2.138(6) and (7) in this book
(6) Fatigue crack: See Fig. 1.30, Sects. 2.4.2.11 and 5.2.3.12 in this book
(7) Selective: See Tables 2.79, 2.124(13), and 2.138(15) in this book
(8) Hot crack: See Table 2.39 Note (4), Sects. 2.1.4.3, 2.1.5.5(d), 2.1.6.1, 2.3.7, 4.2.7, 4.2.8, 4.11.6.3, and 4.11.9.2 in this book
(9) HIC: See Sect. 2.4.2.1 in this book
(10) IGSCC: See Sects. 2.1.6.3 and 2.4.2.3 in this book
(11) SSC: See Sect. 2.4.2.1 in this book
(12) Burn-through: See Sects. 4.6.3, 4.6.4, and 4.6.5 and Table 4.44 in this book
(13) Misalignment (offset): See Table 4.39 and Table 5.11 in this book
(14) Lamination: See Sect. 4.6.5(3) and Table 5.5 in this book
(15) For steel castings: See MSS SP-55

5.3.2 Characteristics and Applicable References of NDE

See ASTM E1316 for terminology for NDE.

5.3.2.1 NDE for Measurement of Defects in Metal and Welds

Tables 5.5, 5.6, 5.7, and 5.8 show the general characteristics and applicable standards of several NDE. See Table 5.23 for detail procedures and acceptance categories of several NDE required in industrial codes and standards.

Table 5.5 General characteristics of MT and PT

Applications	Advantage	Remarks
MT (magnetic particle)		
For locating surface and subsurface defects that are not too deep (max. 3 mm or 1/8 in.) – Slightly subsurface defects (by DC)/surface defects (by AC)/crack length Minimum detectable flaw length on the metal surface: 1.5 mm (1/16 in.) for dry MT and 0.75 mm (1/32 in.) for WFMT approximately. Technique employs either electric coils wound around the part or prods to create a magnetic field. A magnetic powder applied to the surface will show defects as local magnetic fields. The nature of the defects will be revealed by the way the powder is attracted.	1. Useful for the inspection of nozzle and manhole welds for which RT would be difficult at best and most often impossible 2. Reveals small surface defects that cannot be detected by RT 3. Useful in weld repair to assure removal of defect before rewelding 4. Can be used to detect laminations at plate edges 5. Useful for CS, LAS, MSS, FSS, DSS, etc.	1. Useful only for magnetic material (not for austenitic structures) 2. Not suitable for defects parallel to magnetic field 3. Training needed to evaluate visual indications of defects 4. Prod methods of testing may require the surface of a machined or smooth part 5. See Table 5.23 for applicable codes & standards for pressure containing components and notes below
PT (liquid penetrant)		
For locating surface defects A liquid dye penetrant is applied to a dry, clean surface and allowed to soak long enough to penetrate any surface defects (cracks or pits). After a time interval up to an hour, the excess penetrant is wiped off and a thin coating of developer applied. The penetrant entrapped in a defect will be drawn to the surface by the developer, and the defect will be indicated by the contrast between the color of the penetrant and that of the developer.	1. Applicable for magnetic and nonmagnetic materials 2. Useful for the inspection of nozzle and manhole welds when radiography is impossible 3. Easy to apply, accurate, fast, and low cost 4. Useful for all metals including austenitic metals	1. Detects only defects that are open to the surface 2. Not practical on rough surface 3. Take care in applying dye penetrant to ensure that excessive amounts of vapors are not inhaled 4. See Table 5.23 for applicable codes & standards for pressure containing components and notes below

References: See Notes for Table 5.6

Table 5.6 General characteristics of wet fluorescent MT (WFMT)

Applications	Advantage	Remarks
A highly sensitive MT powder, 14A fluorescent mag particles are engineered to locate very fine discontinuities in critical parts and applications. Defects show clearly under black light. For leak test, penetrant is applied to one side, and the other side is examined under black light for indications of glow. Normally applied to the weld joints with high crack susceptibility, oil & gas (EAC environments), aerospace, subsea industries.	*Increases indication detection* • Find smaller, finer indications in critical applications using the highly sensitive, strong ferromagnetic 14A particles • Optimized particle size and shape help particles move freely to stick to a wide variety of discontinuities with less particle clumping *Minimizes inspection time* • Clear, bright fluorescent indications form quickly due to the highly fluorescent, highly mobile particles • Minimal background fluorescence help indications stand out more, so inspectors need to spend less time examining each part *Improve inspection consistency and reliability* • Maintain magnetic particle system performance over greater periods of time, thanks to the highly durable, easily dispersed 14A particles • Reduced particle clumping helps maintain particle concentration in the suspension bath for dependable inspections	• Can be suspended in water or petroleum distillate (oil) vehicle • High sensitivity (higher by White Background and Black Oxide) • Excellent fluorescent contrast • Excellent particle mobility • Optimized particle size and shape distribution • Durable particles • Easily dispersed • Available in a variety of different formats See Fig. 5.10 for the image

References for Tables 5.5 and 5.6 *(Other than ASME BPVC; See* Table 5.23 *for more detail)*
– ASTM A275/A 275 M Test Method for MT of Steel Forgings
– ASTM A456 Specification for MT of Large Crankshaft Forgings
– ASTM E543 Practice Standard Specification for Evaluating Agencies Performing NDT
– ASTM E709 Guide for MT (Dry and Wet)
– ASTM E1316 Terminology for NDE
– ASTM E1444 SP for MT (Dry and Wet)
– ASTM E 2297 Standard Guide for Use of UV-A and Visible Light Sources and Meters Used in the Liquid Penetrant and MT
– ASTM E165 Standard Practice for PT for General Industry
– ASTM E1417 Standard Practice for PT
– EN 1330–7 NDT – Terminology – Part 7: Terms used in MT
– EN 1369 Founding – MT
– EN 10228–1 NDT of steel forgings – Part 1: MT
– EN 1371 Founding – PT – Part 1: Sand, gravity die, and low pressure die castings, Part 2: Investment castings
– EN 2002–16 Aerospace Series, Metallic Materials; Test Methods – Part 16: NDT-PT
– EN 10228–2 NDT of Steel Forgings – Part 2: PT

– ISO 3059 NDT – PT and MT – Viewing Conditions
– ISO 9934 NDT – MT – Part 1/2/3: General principles/ Detection media/ Equipment
– ISO 10893-5 NDT of Steel Tubes. MT of seamless and welded ferromagnetic steel tubes for the detection of surface imperfections
– ISO 17638 NDT of Welds – MT
– ISO 23278 NDT of Welds – MT of Welds – Acceptance Levels
– ISO 3452 NDT-PT, Part 1, General principles, Part 2, Testing of penetrant materials, Part 3, Reference test blocks, Part 4, Equipment, Part 5, PT at temperatures higher than 50 °C, Part 6, PT at temperatures lower than 10 °C
– ISO 10893-4 NDT of Steel Tubes. PT of seamless and welded steel tubes for the detection of surface imperfections
– ISO 12706 NDT-PT – Vocabulary
– ISO 23277 NDT-PT of Welds – Acceptance Levels
– CSA W59 Welded Steel Construction-Canada
– A-A-59230 Fluid, MT, Suspension-USA Military
– MIL-STD-271 Requirements of NDT Methods
– MIL-STD-2132 NDE Requirements for Special Applications
– SAE AMS 3040 MT, Nonfluorescent, Dry Method
– SAE AMS 3041 MT, Nonfluorescent, Wet Method (WFMT), Oil Vehicle, Ready-To-Use
– SAE AMS 3042 MT, Nonfluorescent, Wet Method (WFMT), Dry Powder
– SAE AMS 3043 MT, Nonfluorescent, Wet Method (WFMT), Oil Vehicle, Aerosol Packaged
– SAE AMS 3044 MT, Fluorescent, Wet Method (WFMT), Dry Powder
– SAE AMS 3045 MT, Fluorescent, Wet Method (WFMT), Oil Vehicle, Ready-To-Use
– SAE AMS 3046 MT, Fluorescent, Wet Method (WFMT), Oil Vehicle, Aerosol Packaged5
– SAE AMS 5062 Steel, Low Carbon Bars, Forgings, Tubing, Sheet, Strip, and Plate 0.25 Carbon, Maximum
– SAE AMS 5355 Investment Castings
– SAE AMS I-83387 Inspection Process, Magnetic Rubber
– SAE AMS-STD-2175 Castings, Classification, and Inspection of
; AS 4792 Water Conditioning Agents for Aqueous MT
; AS 5282 Tool Steel Ring Standard for Magnetic Particle Inspection
; AS5371 Reference Standards Notched Shims for Magnetic Particle Inspection

Table 5.7 Characteristics of *X*-ray and γ-ray of RT

Applications	Advantage	Remarks
X-ray RT		
For examination of internal soundness of welds, castings, forgings, and plate material	1. Sources: X-ray 2. Gives shaper definition and greater contrast for thickness up to 3 inch. (150 kV: ≤ 30 mm for carbon steels, ≤ 80 mm for aluminum, 300 kV: ≤ 40–75 mm for carbon steels, ≤ 50 mm for copper alloys) 3. Gives a graphic and permanent record indicating size and nature of defects 4. Offers established standards of interpretation of guidance 5. Radiation source can be turned off when not in use	1. Protective precautions necessary to protect personnel in surrounding area 2. Trained technicians required to take and interpret film
γ-Ray RT		
For examination of internal soundness of welds, castings, forgings, and plate material	1. Sources: Ir-192, Cobalt-60, Selelum-75 2. More suitable for heavy thicknesses (Ir-192: 6–63 mm, Co-60: ≤ 228 mm, max. 127 mm preferable, Se-75: ≤ 19 mm for carbon steels) 3. Portable equipment 4. Source holder permits use through small openings 5. Lower initial cost 6. Requires no cooling mechanism 7. Gives a graphic and permanent record 8. No tube replacement	1. Government license may be required for possession and use of isotopes 2. Proactive precautions necessary 3. Sensitivity is not as high as X-ray testing, and person not properly trained in interpreting film may underestimate seriousness of a defect 4. Energy cannot be adjusted, so isotope must be chosen to meet sensitivity requirements and thickness of material 5. Special test room may be required

References (Other than ASME BPVC; See Table 5.23 *for more detail)*
– ASTM E 94, *Standard Guide for RT*
– ASTM E 155, *Standard Reference RT Aluminum and Magnesium Castings*
– ASTM E 592, *Standard Guide to Obtainable ASTM Equivalent Penetrameter Sensitivity for Radiography of Steel Plates 1/4 to 2 in. [6 to 51 mm] Thick with X-Rays and 1 to 6 in. [25 to 152 mm] Thick with Cobalt-60*
– ASTM E 747, *SP for Design, Manufacture, and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology*
– ASTM E 801, *SP for Controlling Quality of RT of Electronic Devices*
– ASTM E 1030, *TM for RT of Metallic Castings*
– ASTM E 1032, *TM for RT of Weldments*
– ASTM 1161, *SP for RT of Semiconductors and Electronic Components*
– ASTM E 1648, *Standard Reference RT of Aluminum Fusion Welds*
– ASTM E 1735, *TM for Determining Relative Image Quality of Industrial RT Film Exposed to X-Radiation from 4 to 25 MeV*

– ASTM E 1815, *TM for Classification of Film Systems for Industrial RT*
– ASTM E 1817, *SP for Controlling Quality of RT by Using Representative Quality Indicators (RQIs)*
– ASTM E 2104, *SP for RT of Advanced Aero and Turbine Materials and Components*
– API 1104, *Welding of Pipelines and Related Facilities: 11.1 RT Methods*
– EN 444, *NDT – general principles for the radiographic examination of metallic materials using X-rays and gamma, γ-rays*
– EN 462: *NDT – image quality of radiographs*
– EN 584, *NDT – industrial radiographic film*
– EN 1330–3, *NDT – Terminology – Part 3: Terms used in industrial RT*
– EN 2002–21, *Aerospace series – Metallic Materials; Test Methods – Part 21: RT of castings*
– EN 10246–10, *NDT– Part 10: RT of weld seam of automatic fusion arc welded steel tubes for the detection of imperfections*
– EN 12517–1, *NDT of welds – Part 1: Evaluation of welded joints in steel, Ni, Ti, and their alloys by RT, Acceptance levels*
– EN 12517–2, *NDT of welds – Part 2: Evaluation of welded joints in aluminum and its alloys by RT, Acceptance levels*
– EN 12679, *NDT – Determination of the size of industrial radiographic sources – Radiographic method*
– EN 12681, *Founding – RT*
– EN 13068, *NDT – RT*
– EN 14096, *NDT – Qualification of RT film digitization systems*
– EN 14784, *NDT – Industrial computed RT with storage phosphor imaging plates*
– ISO 4993, *Steel and iron castings – RT*
– ISO 5579, *NDT – RT of metallic materials by X- and gamma, γ-rays – Basic rules*
– ISO 10675-1, *NDT of welds – Acceptance levels for RT – Part 1: Steel, nickel, titanium, and their alloys*
– ISO 11699, *NDT – Industrial RT films*
– ISO 14096, *NDT – Qualification of r RT film digitization systems*
– ISO 17636 *NDT of welds. Radiographic testing. X- and gamma, γ--ray techniques with film and digital detectors*
– ISO 19232, *NDT – Image quality of radiographs*

Table 5.8 Characteristics of UT(1),(2)

Applications	Advantage	Remarks
For detecting defects in welds and plate material and for gauging thickness of plate high-frequency sound impulses are transmitted through a search unit, usually a quartz crystal. This search unit is held in intimate contact with the part being tested, using an intermediary such as oil or glycerin to exclude air. The sound waves pass through the part being tested and are reflected from the opposite side or from a defect. The time of travel shows the defect on a cathode-ray tube or scope. This scope can also measure depth of crack or defect.	1. Portable equipment. 2. Access from one side of part being tested is possible. 3. Reveals small root cracks and defects not indicated by radiographic film, especially in thick-walled vessels. 4. Thickness measurements are rapidly made. 5. Good for detection of laminated plates. 6. Can be used in nuclear vessels, where induced radiation eliminates the use of radiography. 7. Remote inspection can be made in hostile environment. 8. Can be used to determine whether use or corrosion has affected the thickness of vessel walls and piping.	1. Training required for interpretation of visual indications of defects. 2. Rough surfaces must be made smooth if crystal is to make contact with part. 3. Photographs must be taken to provide permanent records. 4. Ultrasonic test methods when required (see code appendix 12). 5. Not very effective on welds with backing rings. ∗ tolerance of electronic micrometer: ± 2 μm (or 0.0001 in.).

References (Other than ASME BPVC; See Table 5.23 *for more detail)*
(1)Conventional UT Techniques
– ASTM A388 SP for UT of Steel Forgings
– ASTM A531 Practice for UT of Turbine-Generator Steel Retaining Rings
– ASTM A578 Standard Specification for Straight-Beam UT of Rolled Steel Plates for Special Application
– ASTM A745 Practice for UT of Austenitic Steel Forgings
– ASTM A788 Specification for Steel Forgings, General Requirements
– ASTM B548 TM Ultrasonic Inspection of Aluminum Alloy Plate for Pressure Vessels
– ASTM E164 Practice for Contact Ultrasonic Testing of Weldments
– ASTM E213 SP for UT of Metal Pipe and Tubing
– ASTM E273 SP for UT of Longitudinal Welded Pipe and Tubing
– ASTM E317 Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Instruments and Systems Without the Use of Electronic Measurement Instruments
– ASTM E543 Specification for Agencies Performing NDT
– ASTM E587 Practice for Ultrasonic Angle-Beam Contact Testing
– ASTM E797 SP for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method
– ASTM E1065 Guide for Evaluating Characteristics of Ultrasonic Search Units
– ASTM E2192 Guide for Planar Flaw Height Sizing by Ultrasonics
– AWS B1.10 NDE of Welds
(2)Special/Advanced UT Techniques
– AUT-Automated Ultrasonic C-Scan Corrosion Mapping System with Several UT Techniques (See Table 5.15 for more detail)
– TOFD (Time of Flight Diffraction) – ASTM E2373, ASME Code Case 2235-xx (See Table 5.23 in this book)
– PAUT (Phased Array UT) – ASTM E2491 Guide for Evaluating Performance Characteristics of Phased-Array Ultrasonic Testing Instruments and Systems, ASTM E2700 (Standard Practice for Contact Ultrasonic Testing of Welds Using Phased Arrays)

5.3.2.2 NDE for Measurement of Metal Thickness

(a) UT Mapping or AUT (Automated UT)
Ultrasonic wall thickness measurement can be performed by mechanized scanners. Such scanners use encoders to track the UT transducer's position and wall thickness measurements. The wall thickness measurements are illustrated as a map (C-Scan Plot View) using coordinates of the UT probe position and wall thickness illustrated in color. Using mechanized UT scanners on elevated and freezing surface temperatures can be challenging. See Table 5.14 and 5.17 for more detail.

(b) Guided Wave UT (GWUT)
There are several types of Guided Wave UT methods available. In some cases, detection of anomalies up to 46 m (150 ft) away from the UT sensor ring can be achieved. Guided Wave UT sensors must have direct contact with the pipe. If piping is insulated, a small area must be stripped of insulation to attach the sensors. Guided Wave UT is affected by coating condition, OD surface scale, numbers of elbows and welds, etc. Inspection surface temperatures are limited for some Guided Wave UT equipment. Given the uniform nature of corrosion, GWUT inspection techniques are not recommended because GWUT relies on sudden volumetric changes to provide an indication (reflection). This method is primarily used to detect welds for PMI and low silicon inspection programs.

(c) Pulsed Eddy Current (PEC)
There are several types of these tools available under a number of different trade names. All of them essentially work by producing an Eddy Current field and measuring perturbations in the field to derive a wall thickness. Some companies apply the PEC tool more for screening than for precise measurements and then follow up with other techniques like UT straight beam or profile RT. Similar to RT scanners, an advantage is that insulation does not need to be removed in order to perform this inspection.

(d) Real-Time Radiographic Testing Scanners
These have a display and a crawler mechanism to move a source along while displaying the inspection image in real time, that is, without the need for developing film as in conventional RT. Wall thicknesses can be measured with reasonable accuracy. This method is particularly beneficial for detecting localized corrosion. The primary limitation pertains to access constraints in congested parts of piping systems. An advantage is that insulation does not need to be removed in order to perform this inspection. Lower power hand-held devices can also be effective for measuring the local wall thickness.

(e) Smart Pigging
There are several types of pigs that can be used to measure wall thickness of piping, pipelines, and heater tubes. Such pigs travel through the tube while taking continuous UT thickness readings. Tubes typically need to be cleaned prior to the inspection and there are limitations on bend radius.

5.3.2.3 NDE for Measurement of Coating Thickness

See ASME SD-7091 (ASTM D7091) Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Nonferrous Metals.

5.3.2.4 NDE Personnel Qualification and Certifications

The following qualification and certification standards are normally applied in US business.

– ASNT Practice SNT-TC-1A Personnel Qualification and Certification in Nondestructive Testing
– ANSI/ASNT-CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel
– MIL-STD-410 Nondestructive Testing Personnel Qualification and Certification

5.3.3 RT Requirements in ASME

5.3.3.1 RT Requirements in ASME Sec. VIII

Table 5.9 shows RT requirements in ASME Sec. VIII, Div. 1. See Tables 4.123 and 4.124 in this book for more detail (per material and thickness) in ASME Sec. VIII, Div. 1 and Div. 2, respectively.

See Table 5.4 for more detail application related with several imperfections.

Table 5.10 shows the acceptability per defect type for full RT and spot RT in ASME Section VIII, Div. 1.

5.3.3.2 RT Requirements in ASME B31.3

Table 5.11 shows the acceptability per defect type for full RT and spot RT in ASME B31.3.

5.3.3.3 Marking Requirements for RT in in ASME Sec. VIII, Div. 1 (Table 5.12)

Table 5.9 RT requirements and related paragraphs in ASME Sec. VIII, Div. 1

Full RT [(1)]		Spot RT	
Requirement	Paragraph	Requirement	Paragraph
Full RT for all joints over 32 mm (1.25 in.) for CS (required radiographing on lesser thickness)	UW-11(a)(2), UCS-57, Table UCS-57	General recommendations	UW-11(b)
Circumferential butt joints of nozzles and communicating chambers with diameter not exceeding 254 mm (10 in.) or with thickness not exceeding 29 mm (1.125 in.) do not require RT	UW-11(a)(4)	Spot-RT required for higher weld joint efficiencies	UW-12, UW-52 Table UW-12
Vessels containing lethal substances must be fully radiographed	UW-11(a)(1), UW-2	Minimum number of spots	UW-52(b)
Efficiency of fully radiographed joints	UW-12, Table UW-12	Minimum length of spot RT: 150 mm (6 in.)	UW-52(c)
Radiographic acceptance standards	UW-51	Surface weld buildup	UW-42
Surface weld buildup	UW-42, UCS-56(f)(5)	If cladding is included in computing required thickness, spot radiograph is mandatory	UCL-23(c)
Carbon and low alloy steel materials	UCS-57, UCS-19	Vessels having 15 m (50 ft) or less of main seams require one spot examination; larger vessels require one spot for each 15 m (50 ft) of welding	UW-52(b)(1)
High alloy steel materials	UHA-33	Additional spots may be selected to examine welding of each welder or welding operator	UW-52(b)(2)
Clad-plate materials	UCL-35	Repair welding defects in material; forgings	UF-37, UCD-78
Nonferrous materials	UNF-57, UNF-91	General requirements for castings	UG-24
Ferritic steel whose tensile properties have been enhanced by heat treatment	UHT-57	Low temperature vessels	ULT-57
Layered vessel inner shells and heads	ULW-51	High alloy steel vessels	UHA-33
Welded joints in layers of layered vessels	ULW-52(d)	Ferritic steel whose tensile properties have been enhanced by heat treatment	UHT-57
Butt welded joints in layered vessels	ULW-54	Joints welded with austenitic chromium-nickel steel	UCL-35, UCL-36
Low temperature vessels	ULT-57	Repair welds in layered construction	ULW-57, ULW-51

Notes
[(1)]See Table 4.123 for more detail and various metals

Table 5.10 Acceptability of full RT in ASME Section VIII, Div. 1

Type of Defect	Full RT		Spot RT
Cracks	Not allowed – UW 51(b)(1)		Not allowed – UW 52(c)(1)
Incomplete penetration	Not allowed – UW 51(b)(1)		Not allowed – UW 52(c)(1)
Incomplete fusion	Not allowed – UW 51(b)(1)		Not allowed – UW 52(c)(1)
Burn-through	Not covered – UW 51(b)(1) (see incomplete penetration)		Not covered – UW 52(c)(1) (see incomplete penetration)
Internal concavity	Not covered		Not covered
Undercut at root pass or cap pass	Not covered		Not covered
Slag inclusions, elongated, except at noted	*Thickness* <3/4″ (19 mm) 3/4–2–1/4″(19~57.2 mm) >2–1/4″ (57.2 mm) *T* = weld thickness	*Max. Slag length* 1/4″ (6.4 mm) total 1/3 length of T” 3/4″ (19 mm) UW 51(b)(2)	Maximum length of 2/3 T, where T is the thickness of material, with 3/4″ (19 mm) maximum Maximum total length of T in 6 T weld length The length < 1/4″ (6.4 mm); acceptable for any T. – UW 52(c)(2)
Porosity	See App. IV figures for allowable pore density. Maximum pore dimension 1/4 T or 5/32″ (4 mm), whichever is less, except pores separated by 1″ may be 1/3 T or 1/4″ (6.4 mm), or 3/8″ (9.5 mm) for T > 2, where T = weld thickness. (Sec. VIII, Div.1, App. 4)		Rounded indications are not a factor in the acceptability of welds not required to be fully radiographed – UW 52(c)(3)
Root penetration	Same as weld reinforcement – UW-35(d)		Same as weld reinforcement – UW-35(d)
Accumulation of discontinuities	Not covered		Not covered
	Additional requirements		
Max. misalignment tolerance	See Table 4.7 maximum misalignment tolerance of weld joints		
Max. reinforcement thickness on butt welds	See Table 4.8 maximum reinforcement thickness of weld joints		

Table 5.11 Simplified acceptability of full and spot RT in ASME B31.3 [(1)(2)(3)(4)]

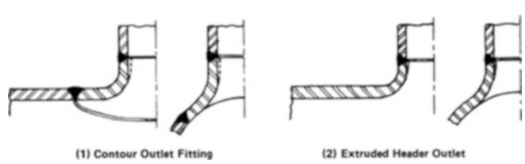
Type of Defect	Full RT	Spot RT
Cracks	Not allowed	Not allowed
Incomplete penetration at root pass	Not allowed	Maximum depth of 0.8 mm (1/32 in.) or 20% of wall thickness, whichever is less. Max. Length 38 mm (1.5 in.) in 152 mm (6 in.) of weld
Incomplete fusion due to high-low fit-up	Not allowed	Maximum depth of 0.8 mm (1/32 in.) or 20% of wall thickness, whichever is less. Max. Length 38 mm (1.5 in.) in 152 mm (6 in.) of weld
Incomplete fusion at root pass	Not allowed	Not allowed
Lack of fusion at side wall or cold lap	Not allowed	Not allowed
Burn-through	(See incomplete penetration)	(See incomplete penetration)
Concave root surface (suckback)	Shall not reduce weld thickness to less than thinner material	Shall not reduce weld thickness to less than thickness
Undercutting	Not allowed	Lesser of 0.8 mm (1/32 in.) or 1/4 Tw, where Tw = weld thickness
Slag inclusion of elongated indication	Max. length 1/3 Tw max. width 2.4 mm (3/32 in.) Max. total length shall not exceed Tw In any 12 Tw length of weld	Max. length 2 Tw, max. width 3.2 mm (1/8 in.) Max. total length shall not exceed 4 Tw In any 152 mm (6 in.) length of weld
Accumulation of discontinuities	See ASME Sec. VIII, Div. 1, App.4	Tw $\leq$ 6.4 mm (1/4 in.), see ASME Sec. VIII, Div. 1, App. 4 Tw > 6.4 mm (1/4 in.), 1.5 $\times$ ASME Sec. VIII, Div. 1, App. 4
Accumulation of discontinuities	Not covered	Not covered
Surface porosity of slag inclusions	Not allowed for Tw, 4.8 mm (3/16 in.) or less	Not allowed for Tw, 4.8 mm (3/16 in.) or less
Additional requirements		
Weld reinforcement or protrusion	Wall thickness, mm (inch) $\leq$6.4 ($\leq$1/4) Over 6.4~12.7 (1/4 ~ 1/2) Over 12.7~25.4 (1/2 ~ 1) >25.4 (>1)	Max thickness, mm (inch) 1.6 (1/16) 3.2 (1/8) 4.0 (5/32) 4.8 (3/16)
Misalignment	Maximum internal misalignment determined by WPS & engineering design	Maximum internal misalignment determined by WPS & engineering design

Notes: *Tw* wall thickness

[(1)]See ASME B31.3, Table 341.3.2 for more detail in acceptance categories per service (M fluid, severe cyclic, and D fluid)

[(2)]In Elevated Temperature Fluid Service, all longitudinal or spiral (helical seam) welds in P No. 4 or P No. 5 series materials shall be examined by 100% RT or 100% UT

[(3)]All circumferential butt and miter groove welds and all fabricated branch connection welds comparable to those shown below shall be examined by 100% RT per ASME B31.3, para. 344.5, or (if specified in the engineering design) by 100% UT per ASME B31.3, para. 344.6



[(4)]*Closure Welds.* The final weld connecting piping systems or components that have been successfully tested per ASME B31.3, para. 345 need not be leak tested provided the weld is examined in-process per ASME B31.3, para. 344.7 and passes with 100% RT per ASME B31.3, para. 344.5 or 100% UT per ASME B31.3, para. 344.6

5.3.4 MT and PT Requirements in ASME Sec. VIII, Div. 1

Table 5.13 shows MT and PT requirements in ASME Sec. VIII, Div. 1. See Table 5.4 for more detail application related with several imperfections.

5.3.5 UT Techniques and Requirements in Codes and Standards

Table 5.14 shows Pulse-Echo UT techniques and applicable standards as conventional UT.

Table 5.12 Summary for RT marking requirements in ASME Sec. VIII, Div. 1 (see Notes)

Item	Sub-item	RT 1 (Full)	RT 2	RT 3 (Spot)	RT 4	RT (100%)	No RT
Vessel design data box	ASME Sec. VIII Div.1 paragraph	UW-12(a)	UW-12(d)	UW-12(b)	UW-12(d)	UW-12(a)	UW-12(c)
	Radiography	RT-1 full	RT-2 UW-11 (a)(5)(b) Full for LS Spot for CR	RT-3 spot	RT-4 spot	RT-1100% (including all butt welds)	None
	LS Joint Eff.	1.0	1.0	0.85	0.85	1.0	0.70
	CS Joint Eff.	1.0	1.0	0.85	0.85	1.0	0.70
Design calculation	Shell LS	Full	Full	Spot	Spot	Full	None
	Shell CS	Full	Modified spot	Spot	Spot, UW-12(b)	Full	None
	Head – single piece	None (no seams in heads)					
	Head – multi-segments	Full	Full	Spot	Spot	Full	None
	Head to shell seam	Full	Modified spot	Spot	Modified spot	Full	None
Vessel notes or ITP (additional)		None	None	None	Each head to shell seam per UW-11(a)(5)(b), J.E = 1.0. All other LS & CS per UW-11(b) as required by code.	None	None
Weld detail		Replace "RT #" callouts in the NDE section of the LA & CS details with "RT 1"	Replace "RT #" callouts in the NDE section of the LS & CS details with "RT 2"	Replace "RT #" callouts in the NDE section of the LA & CS details with "RT 3"	Replace "RT #" callouts in the NDE section of the LS & CS details with "see note ##" this note should cross reference to the corresponding vessel notes.	Replace "RT #" callouts in the NDE section of the LS & CS and flange to nozzle neck details with "RT 1." UT in category D may be applicable.	Replace "RT #" callouts in the NDE section of the LS & CS details with "NONE"

Abbreviation: *LS* longitudinal seam, *CS* circumferential seam, *ITP* inspection and test plan, *Eff.* efficiency
Notes [ASME Section VIII, Div. 1, UG-116(e)]

1. "RT 1" when all pressure-retaining butt welds, other than Joint Category B and C butt welds associated with nozzles and communicating chambers that neither exceed NPS 10 (DN 250) nor 11/8 in. (29 mm) wall thickness [except as required by UHT-57(a)], satisfy the full radiography requirements of UW-11(a) for their full length; full radiography of the above exempted Category B and C butt welds, if performed, may be recorded on the Manufacturer's Data Report
2. "RT 2" when the complete vessel satisfies the requirements of UW-11(a)(5) and when the spot radiography requirements of UW-11(a)(5)(-b) have been applied
3. "RT 3" when the complete vessel satisfies the spot radiography requirements of UW-11(b)
4. "RT 4" when only part of the complete vessel has satisfied the radiographic requirements of UW-11(a) or where none of the markings "RT 1," "RT 2," or "RT 3" are applicable

Table 5.13 MT and PT requirements in ASME Sec. VIII, Div. 1

Requirements$^{(1)}$	Paragraph
When vessel is to be pneumatically tested, welds around openings and attachment welds of throat thickness greater than 1/4″ must be given a magnetic particle or liquid penetrant examination for ferromagnetic materials (liquid penetrant for nonmagnetic materials)	UW-50
Liquid penetrant examination must be made on all austenitic Cr-Ni alloy steel welds in which shell thickness is over 3/4 in and on all thicknesses of 36% nickel steel welds. Examinations shall be made after heat treatment if heat treatment is given	UHA-34
Heat-treated enhanced materials used for vessels; all welds must be given a magnetic particle examination after hydrotesting. Liquid penetrant is an acceptable alternative	UHT-57
Pressure part welded to a plate thicker than 1/2″ to form a corner joint must be examined by magnetic particle or liquid penetrant method	UG-93, UW-13 Fig. UW-13.2
Layered vessels	ULW-56
Low temperature vessel construction; all attachment welds and joints not radiographically examined shall be given a liquid penetrant examination	ULT-57
Qualification of personnel: Magnetic particle (MT) Liquid penetrant (PT)	Appendix 6 Appendix 8

Notes
$^{(1)}$MT and PT: See Table 5.4 for more detail application

Table 5.14 Pulse-Echo UT techniques and applicable standards

ASME code case	Characteristics	Remark
System	Two types of waves, the longitudinal waves[1] (faster) and the transverse waves[2] for most materials	Heavy wall Cr-Mo steel vessel: API RP934-A, Table A.2 lists the recommended steps and rejection criteria for PE shear wave UT. Manual PE shear wave UT guideline for identifying transverse reheat cracks. Coupling & Reference object necessary. Result depends on experience.
Advantages	Determinable position and height of defect as well as surface cracks and thickness Size of defect compared to reference object determinable Accessibility only on one side necessary Automated testing possible. Technique is fast, multifunctional, and flexible	
Displays	*A-scan* (shows the time, representing the depth of the specimen, on the X-axis and the amplitude on the Y-axis), *B-scan* (two-dimensional display with different bright fields. The brightness indicates the amplitude of the wave.), and *C-scan* (two-dimensional display with different bright fields. The brightness shows all echoes within a certain range of depth, usually between front and back echoes indicating defects.)	
Targets for application	For heavy wall, – Category D joint of pressure vessels, Used to characterize indications found by TOFD	
Applicable standards	ASTM E797 measuring thickness by manual ultrasonic pulse-Echo contact method ASTM E317 SP for evaluating performance characteristics of ultrasonic pulse-Echo testing instruments and systems without the use of electronic measurement instruments ASTM E1685 SP for measuring the change in length of fasteners using the ultrasonic pulse-Echo technique	

Notes
[1]Straight Beam (used longitudinal-wave) – Ultrasonic Straight Beam (UTS): For thickness, <51 mm (2 in.), the 1/4-thickness reflector may not be resolved. If this is the case, drill another hole at 1/2 thickness and use the 1/2- and 3/4-thickness reflectors for correction. See Table 5.4 for more detail application
[2]Angle Beam (used shear-wave) – Ultrasonic Angle Beam (UTA): May be determined by means of side-drilled hole reflectors at 1/4 and 3/4 of the thickness. The 1/2-thickness depth to a side-drilled hole may be added to the standardization or used alone at thicknesses, <25.4 mm (1 in.). See Table 5.4 for more detail application

Table 5.15 shows the requirements and history of UT (PAUT or TOFD) in lieu of RT in ASME BPVC. Tables 5.16 and 5.17 show the characteristics of Phased Array UT (PAUT)/Time of Flight Diffraction (TOFD) and Automated UT (AUT) techniques, respectively.

Table 5.15 UT[1] in lieu of RT in ASME BPVC[2]

ASME Code Case	Code	Approved Date	Contents
2235	Sec. VIII, Div. 1 & 2	Jan. 1, 1995	For 4″ thickness and over, the case approved UT in lieu of RT including acceptance criteria for indications and was considered a breakthrough in the philosophy of NDE.
2235–1	Sec. VIII, Div. 1 & 2	Sep. 23, 1999	Applicable for 4″ thickness and over
2235–2	Sec. VIII, Div. 1 & 2	Sep. 23, 1999	Applicable by TOFD (time of flight diffraction) for 1/2″ thickness and over.
2235–3	Sec. I Sec. VIII Div. 1 & 2	Jan. 1, 1998	Also, applicable for ASME sec. I (power plant).
2235–4	Sec. VIII Div. 1, UW-(a), Div. 2, Table AF-241.1 Sec. I, PW-11	Nov. 30, 2001	More detail instruction with condition and Limitations are specified.
2235–5	Sec. VIII, Div. 1, UW-1 (a) Div. 2, Table AF-241.1 Sec. I, PW-11	Nov. 30, 2002	The revised detail instruction with condition and Limitations will be specified.
2235–6	Sec. VIII, Div. 1 & 2	May 21, 2003	The revised detail instruction with condition and limitations will be specified.
2235–9	Sec. I; Sec. VIII, Div. 1 and 2; and Sec. XII	Oct. 11, 2005	Question: A weld is subjected to UT examinations in lieu of RT under the provisions of Code Case 2235–9. During the examination, indications characterized as plate segregates that have become reflective after fabrication, as discussed in ASME Sec. V, Article 4, T-481, are found. Are these indications considered "indications of geometric origin subject to handling under the rules of subparagraph (i)(2) of the Code Case? Reply: Yes. Extended to Sec. I and XII.
2235–10	Sec. I; Sec. VIII, Div. 1 and 2; and Sec. XII	Mar. 21, 2012	Added case studies.
2235–13	Sec. I and Sec. XII	Jul. 9, 2014	Q-A when radiography is required in accordance with Section I, PW-11, and Section XII, TE-230.1. UT to be performed using a "device employing automatic computer based data acquisition."

Notes
[1]See Table 5.16 Phased Array UT (PAUT) and Time of Flight Diffraction (TOFD) below
[2]See ASME Sec. VIII, Div. 2, 7.5.5 for Div. 2 pressure vessel

Table 5.16 Phased Array UT (PAUT) [1] and Time of Flight Diffraction (TOFD) techniques

ASME code case	Characteristics		Remark
	PAUT	TOFD UT	
System & characteristics	Typically consist of a transducer assembly from 16 to as many as 256 small individual elements that can each be pulsed separately. These may be arranged in a strip (linear array), a ring (annular array), a circular matrix (circular array), or a more complex shape. Requires appropriate angles, 50% beam overlap and < 5% data drop-out for encoded scanning	OD and ID visible. Defects (excellent PoD) detectable in middle (dead zone of max. 3 mm at outer surface). May be difficult to interpret (require skilled and trained operators)	No documented experience to detect reheat cracking. Calibration before using is required.
Advantages	Rapidly produce the images in a few seconds for most materials Useful for mapping components at appropriate angles	Rapid (and relatively low cost) inspections	
Displays	*A-scan* (reflections from one position, shows echoes from two side-drilled holes), *B-scan* (showing a cross-sectional profile through one vertical slice, and then relative hole depth), *C-scan* (a two-dimensional presentation of data displayed as a top or planar view), and *S-scan* (a two-dimensional cross-sectional view derived from a series of A-scans)		
Targets for application	Weld inspection, bond testing, thickness profiling (corrosion monitoring & mapping), in-service cracks-discontinuities-flaws detection, rolling stock inspection (wheels and axles)		
Applicable standards	ASTM E2700 SP for *Contact UT of Welds Using PA* ASTM E2491 *Evaluating Characteristics of PAUT Instruments/Systems* EN 16018, ISO/WD 13588 NDT of welds – Use of (Semi-)automated PA Technology ASME Sec. V Article 4, MA IV – Manual using linear arrays ASME Sec. V (2019 Ed.) Appendix E, E-474 PAUT	ASTM E2373 standard practice for use of TOFD technique ASME Sec. V, Article 4, MA-III API RP2X RP for UT and MT of offshore structure	
	ASME BPVC Code Case 2235-xx and ASME B31.1 Code Case 168 UT in Lieu of RT ASME BPVC code case N-659 UT in lieu of RT for sec. III ASME BPVC code N-713 UT in lieu of RT for sec. XI ASME B31.3 code case 179 use of ultrasonic examination in lieu of radiography for B31.1 applications in materials 1/2 in. And less in wall thickness ASME sec. V article 4, MA V - Using E & S-scan linear scanning, para. E-474, and non-mandatory appendix P API 620/650 app. U UT in lieu of RT ASME B31.1 code case 189 & ASME B31.3 code case 181-x use of alternative UT acceptance criteria AASME B31.12 code case 186 use of alternative UT acceptance criteria		

Notes: *PoD* probability of detection

[1]FMC/TFM per EN 16018 or ASME Sec. V (2019 Ed.): Can be used as an examination technique involving the combination of classic FMC data acquisition and TFM data reconstruction

- Full Matrix Capture (FMC) – FMC specific data acquisition process using ultrasonic array probes where each element in an array is successively used as the transmitter, while all elements are used as receivers for each transmitted pulse
- Total Focusing Method (TFM) – A method of image reconstruction where the value of each constituent datum of the image results from focused ultrasound. Electronic focusing which consists of adapting the receiving delay laws to focus at many points which form a grid, after a single pulse which generates a large and/or divergent ultrasonic beam

5.3.6 NDE for OCTG and Offshore Structures (API)

Tables 5.18, 5.19, 5.20, 5.21, and 5.22 show the NDE requirements in API for OCTG and Offshore industries.

5.3.7 Summary of General Requirements and Acceptance Criteria of NDE in Codes and Specification

Table 5.23 shows the summary of general requirements of NDE in ASME, AWS, and ASTM.

ASME Sec. VIII, Div. 2, Part 7 (Inspection and Examination Requirements) is based on the materials group in ISO/TR 15608 Material Group (see Sect. 2.1.11).

Table 5.17 Automated UT (AUT) techniques

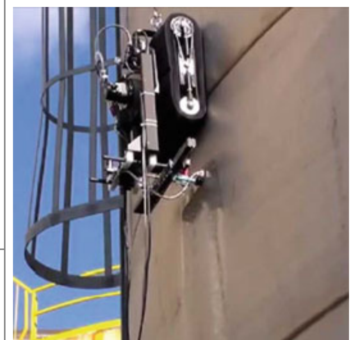
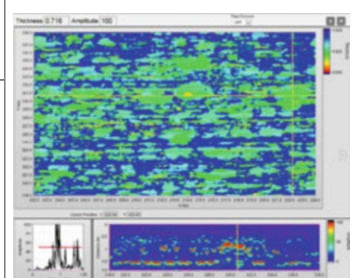
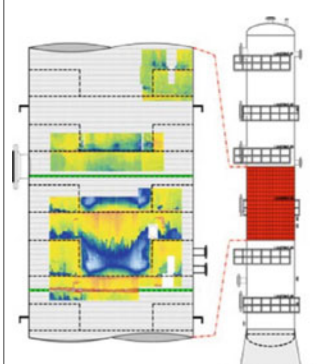
ASME Code Case	Characteristics	Remark
Application	• Technologies employed include TOFD, pulse-Echo, corrosion mapping, and phased Array • The data collected is then displayed in color in multiple A–D-scan images. *A-scan*: the signal amplitude is shown as a vertical excursion from the horizontal sweep time trace *B- & D-scan*: two-dimensional views of cross-sectional planes through the test object on different axis. This imaging is helpful in distinguishing mid-wall inclusions such as laminations and blistering, from back-wall discontinuities like erosion and corrosion *C-scan*: two-dimensional plan view of the object. Indication of depth is color coded to provide the image with qualities, which resemble a topographical map viewed from the inspecting surface. Very good for wall thickness measurement	
Advantages	• High productivity compared to conventional UT techniques • Highly reproducible technique • Computer-controlled data acquisition • Data is stored for future comparison or audit • Data is gathered with weld positional information • 3D image presentation of all defects • Rapid large area inspection using automated scanners • Better ability than manual ultrasonic testing to distinguish flaw signals from geometric signals • Good ability to trend flaws for growth by comparing to previous inspection results	
Applicable subject materials	• All ferrous metals • Nonferrous materials capable of supporting ultrasound • Nonmetals: HDPE (high-density polyethylene) and other plastic materials capable of supporting ultrasound/certain layered materials, plastics, and ceramics	
Limitations	• Scan areas on test material must be accessible to scanner(s) with no immediate obstructions to scan areas • The scan surface must be in a clean condition; thin wall paints and other coatings are acceptable if no disbonding, flaking, or other anomalies are present • Coarse-grained materials can present problems for ultrasonic techniques • Nonferrous materials need to have alternative methods of securing the scanner to the material surface	
Targets for application	• *Corrosion mapping* – Inspect large areas with mechanized scanners – Accurate information on amount and location of corrosion – Capable of detecting large and small diameter pitting, corrosion, erosion in piping, pressure vessels, tanks, and flange raised faces. • *Weld/crack inspection(in-service and new pressure vessels)* – Perform rastering shear wave weld inspection – TOFD weld inspection – Phased Array weld inspection – Able to inspect long weld seams with multiple files – Short range inspection on butt-welded annular plates • *HTHA, HIC, SOHIC, and laminar crack∗ inspection* – Detection and sizing of hydrogen damage (HTHA) – Accurately map out laminar cracking over large areas – Detection of stepwise cracking – Detection and sizing of SOHIC cracking in the HAZ • *Cladding inspection* – Perform inspection from the OD surface – Detect cladding disbondments – Inspection for cladding failures and associated base metal degradation (e.g., Coker and FCC units) • *High temperature inspection* – Mount scanners on specialized tracks/possible to inspect materials up to 300 °C (572 °F). May be able to perform techniques at higher temperatures per the techniques	 * API 5 L: For sour service, individual laminations and/or lamination densities exceeding the acceptance limits for sour service given in API 5 L, Table K.1.
Applicable standards	– ASTM E1961 mechanized ultrasonic examination of girth welds – API 1104 Welding of Pipelines and Related Facilities – ISO 13847 Welding of Pipelines for Petroleum and Natural Gas Industries – CSA Z662 oil and gas pipeline industries – DNV OS F101 submarine pipeline systems Pipes and Tubes: API 5 L, ASTM A53, DIN 2440, BS 1387, Deutsche SEP 1917 (NDT of Resistance Welded Pipes of Ferritic Steels)	Mostly applied to pipelines and piping. Some paragraphs indicate the requirements or acceptance categories of AUT.

Table 5.18 Summary of NDE methods for seamless pipe, coupling stock, and body of welded pipe

Grade	Visual inspection (see API 5CT, 10.14)	Wall thickness determination	UT inspection	Flux leakage inspection	Eddy Current inspection	MT inspection[a]
Pipe and accessory materials						
H40, J55, K55	R	N	N	N	N	N
N80 (all types), L80, R95	R	R	A	A	A	A
P110	R	R	A	A	A	NA
C90, T95, C110, Q125	R	R	C	B	B	B
Coupling stock						
H40, J55, K55, N80 type 1	R	NA	N	N	N	N
N80 (all types), L80, R95, P110, C90, T95, C110, Q125	R	R	A	A	A	A

Source: API spec 5CT Steel pipes for use as casting and tubing for wells
N not required, *R* required, *NA* not applicable, *A* one method or any combination of methods shall be used, *B* at least one method shall be used in addition to ultrasonic inspection to inspect the outside surface, C = ultrasonic inspection shall be used to inspect the outside and inside surfaces
Notes
[a]MPI (MT-magnetic particle inspection) is permitted for end-area inspection. MPI is permitted for pipe-body outside-surface inspection in combination with other methods of pipe body inspection. MPI is permitted for coupling stock outside surface inspection. Coupling stock receiving full-length MPI does not require full-length wall thickness verification; however, mechanical wall thickness measurement of each end is required

Table 5.19 Acceptance (inspection) levels for seamless pipe, coupling stock, and body of welded pipe

Materials Parts & Grades		External Imperfection		Internal Imperfection	
		Longitudinal	Transverse	Longitudinal	Transverse
Pipe body with accessory materials					
N80 Type 1		L3	–	L3	–
N80Q, L80, R95		L4	–	L4	–
P110 to A.9 (SR16)		L4	L4	L4	L4
P110		L2	L2	L2	L2
P110 to A.9 (SR16) and A.3 (SR2)		L2	L2	L2	L2
C90, T95, C110, Q125	UT	L2	L2	L2	L2
	2nd method	L2	L2	–	–
Coupling stock					
All grades except C110		L2	L2	N	N
C110		L2	L2	L3	L3
Weld seam					
P110, Q125		L2	N	L2	N
All other grades		L3	N	L3	N
All other grades to A.3 (SR2)		L2	N	L2	N

Source: API spec 5CT casting and tubing
N = not required; $L\chi$ acceptance (inspection) level; - Not Applicable, Indication of Each Level: See Table 5.20

Table 5.20 Artificial reference indicators for seamless pipe, coupling stock, and body of welded pipe

Acceptance (inspection) level	Notch depth[a]	Notch length at full depth	Notch width	Radially drilled hole diameter[b]
	max. %	max. mm	max. mm	max. mm
L2	5	50	1	1.6
L3	10	50	1	3.2
L4	12.5	50	1	3.2

Source: API spec 5CT casting and tubing
[a]Depth as a percent of specified wall thickness. The depth tolerance shall be ±15% of the calculated notch depth with a minimum notch depth of 0.3 mm ±0.05 mm
[b]Drilled hole diameter (through the pipe wall) shall be based on the drill bit size

Table 5.21 Recommended minimum extent of NDE inspection

Parts	Case	Extent, %	Method
Structural tubulars	Longitudinal weld seam (L)	10(1)	UT or RT
	Circumferential weld seam (C)	100	UT or RT
	Intersection of L & C	100	UT or RT
Tubular joints	Major brace-to-chord welds	100	UT
	Major brace-to-brace welds	100	UT
Misc. bracing	Conductor guides	10(1)	UT (or MT) (2)
	Secondary bracing and subassemblies, i.e., splash zone and/or mudline secondary bracing, boat landings, etc.	10(1)	UT (or MT) (2)
	Attachment weld connecting secondary bracing/subassemblies to main members	100	UT or MT
Deck members	All primary full penetration welds	100	UT or RT
	All partial penetration welds	100	Visual(3)
	All fillet welds	100	Visual(3)

Source: API RP 2A-WSD-2002, Planning, Designing, and Constructing Fixed Offshore Platforms

Notes

(1)Partial inspection should be conducted as 10% of each piece, not 100% of the number of pieces: Partial inspection should include a minimum of three segments randomly selected unless specific problems are known or suspected to exist. All suspect areas (e.g., areas of tack welds) shall be included in the areas to be inspected. If unacceptable flaws are found from such 10% inspection, additional inspection should be performed until the extent of rejects has been determined and the cause corrected

(2)Depending upon design requirements and if specified in the plans and specifications, MT may be an acceptable inspection method

(3)May include MT and/or PT

Table 5.22 Recommended extent of NDE inspection: reused structure

Case	Extent	Method
Jacket primary tubulars		
Longitudinal weld seams (L)	(a)	UT or MT
Circumferential weld seams (C)	(a)	UT or MT
Intersection of L & C	(a)	UT or MT
Tubular joints		
Major brace-to-chord welds	(b)	MT
Major brace-to-brace stub welds	(b)	MT
Deck members and connections		
Truss bracing members	10%*	UT or MT
Truss chord members	10%*	UT or MT
Plate girder members	10%*	UT or MT
Connections to deck legs	25%*	UT or MT
Crane pedestal connections	100%	UT or MT
Cantilever deck connections	100%	UT or MT
Survival/safety equipment connections	100%	UT or MT
Misc. jacket/deck members and connections		
Nonredundant bracing and subassemblies, i.e., lifting eyes, lifting bracing, sole conductor guide framing level above mudline, etc.	100%	UT or MT
Attachment welds connecting nonredundant bracing/subassemblies to main members	100%	UT or MT
Redundant bracing and subassemblies, i.e., multi-level conductor guide framing, secondary splash zone and mudline bracing, boat landings, etc.	10%	Visual**
Attachment welds connecting redundant bracing/subassemblies to main members	10%	Visual**
Piling		
Longitudinal weld seams (L)	10%	UT or RT
Circumferential weld seams (C)	10%	UT or RT
Intersection of L & C	10%	UT or RT
Filed splices	100%	UT or RT

Source: API RP 2A-WSD-2002, Planning, Designing, and Constructing Fixed Offshore Platforms

Notes

*Partial inspection should be conducted as percentage of each piece, not 100% of percentage of the number of pieces

**Limited to inspection of completed weld; may include MT and or PT

Extend Notes

(a) Extent of inspection for these welds should be determined by comparing the design loadings and stresses (including removal and reinstallation loads and stresses) for the new site with those to which the welds have previously been designed for and/or exposed. Where new design loadings are less than or equal to initial design or actual loadings, then the extent of inspection, if any, should be determined based on NDE documentation or the results of the initial spot survey per API 5CT, Section 15.2.3.5b.Where new design loadings are significantly greater than initial design or actual loadings, or when comparison based on initial design or actual loadings is not possible, a minimum of one (1) bracing member and one (1) jacket leg spanning between each level should be inspected. Additional inspection per API 5CT, Section 15.2.3.5b, should be performed where in-service damage is known of or suspected

(b) All damage-prone connections should be inspected. Damage-prone connections are defined in API 5CT, Section 15.2.3.4. Where NDE inspection of these connections reveals significant defects, additional inspection of other connections should also be performed.For tubular connections, a minimum of one (1) brace to chord connection at each level and X brace connection between levels, as applicable, should be inspected.For tubular connections not having Class A steel in the heavy wall joint cans, both UT and MT should be performed

Table 5.23 (1/6) General requirements of NDE in codes and specification – ASME, AWS, ASTM – Notes 1, 2, 3

NDE	Codes/STD	Scope and procedures	Acceptance criteria
VT (visual test)	ASME Sec. V, Art. 9	VT examination – general requirements (written procedure, personnel requirements, physical requirements, equipment, examination technique-direct, remote, translucent, evaluation, documentation, and record maintenance)	
	ASME Sec. VIII, Div.2,	Para 7.5.2.1 & 7.5.2.3	Para 7.5.2.2 and Table 7.6
		Para. 3.7.2(a) for bolts, studs, and nuts	Para. 3.7.2(a)
		Para 3.8.3.1(a) for nonferrous casting	Para 3.8.3.1(a)
	ASME B 31.3, Chapter VI	Para 344.2; examination per Sec. V, Art.9	Table 341.3.2
	AWS B 1.10 guide for NDE of welds	Section 3.1: VT methods; "Section 3.1, 3.2, 3.3, 3.4, 4.3" and Table 5.16 are not from this book, but from the industrial codes/standards.	
	AWS B 1.11	Guide for VT of welds	
PT (dye penetration test)	ASME Sec. V, Art. 6 and 24 ASME/ ASTM; SD-129 SD-516 SD-808 SD-1552 SE-165	**[Art. 6]** PT – General requirements (written procedure, equipment, surface condition, contamination control, drying after PT, test temperature/time, examination, calibration, evaluation, development, interpretation, documentation, and recording of indications) mandatory appendix 1, 2, & 3 **[Art. 24]** STD guide for PT SD-129 TM for sulfur in petroleum products (general bomb methods) SD-516 TM for sulfate ion in water SD-808 TM for chlorine in new and used petroleum products (bomb methods) SD-1552 TM for sulfate in petroleum products (high temperature method) SE-165 TM for liquid penetrant examination	See the acceptance category/level in each ASME/ ASTM.
	ASME Sec. VIII, Div.1, App.8	Para 8-2, 8-3 Para 8-5: Repair requirements	Para 8-4; free from relevant linear indications; relevant rounded indications, >4.8 mm (3/16″); four or more relevant rounded indications in a line separated by 1.6 mm (1/16″) or less.
	ASME Sec. VIII, Div.2, Tables 7.2 & 7.4 Para. 7.5.7	Tables 7.2 and 7.4: Extend of PT application scope per joint category and material Para. 7.5.7.1 general requirements and procedure To meet ASME sec. V, article 6 except below. (a) A complete set of records, as described in ASME sec. V, article 6, T-691 and T-692, shall be retained by the manufacturer until the Manufacturer's data report and signed by the inspector. (b) Personnel performing ASME sec. VIII, div. 2 shall be per para 7.3 (qualification of inspector) by PT level II or III personnel. (c) PT exam shall be performed by the manufacturer to be per the requirements of ASME sec. V, T-150. See note 4 below for more detail.	Para. 7.5.7.2 (same as MT category) See note 5 below for more detail.

Table 5.23 (2/6) General requirements of NDE in codes and specification – ASME, AWS, ASTM – Notes 1, 2, 3

NDE	Codes/STD	Scope and procedures	Acceptance criteria
PT (dye penetration test)	ASME Sec. VIII, Div.2, Forgings	Para 3.6.4	Para 3.6.4
	ASME Sec. VIII Div.2, castings	Para 3.8.2.2(e) for ferrous and Para 3.8.3.1(a) for nonferrous	Para 3.8.2.2(e) and 3.8.3.1(a)
	ASME Sec. VIII Div.2, castings	For repair welding, Para 3.8.2.3(b) for ferrous and Para 3.8.3.2(a) for nonferrous	Para 3.8.2.3(b) and 3.8.3.2(a) & (b)
	ASME Sec. VIII Div.2, bolts, studs, and nuts	Para 3.7.2(b)	Para 3.7.2(b)
	ASME B 31..3 Chapter VI	Para 344.4; examination per Sec. V, Art.6	Para 344.4.2
	AWS B 1.10 guide for NDE of welds	Section 3.2: PT methods	
MT (magnetic test)	ASME Sec. V Art. 7 and 25 ASME/ASTM; SE-709 SE-1186	**[Art. 7]** MT – general requirements (written procedure, equipment, surface condition, prod technique, longitudinal/circular/multidirectional magnetization technique, yoke technique-direct, calibration, examination, evaluation, documentation, and recording of indications) **[Art. 25]** STD guide for MT SE-709 standard guide for MT SE-1186 TM for nondestructive measurement of dry film thickness of nonmagnetic coatings applied to a Ferrous Base	See the acceptance category/level in each ASME/ASTM.
	ASME Sec. VIII Div.1, App.6	Para 6-2, 6-3 Para 6-5: Repair requirements	Para 6-4; free from relevant linear indications; relevant rounded indications, >4.8 mm (3/16″); four or more relevant rounded indications in a line separated by 1.6 mm (1/16″) or less.
	ASME Sec. VIII Div.2, Tables 7.2/7.4 Para. 7.5.6	Tables 7.2 and 7.4: Extend of MT application scope per joint category and material Para. 7.5.6.1 general requirements and procedure To meet ASME Sec. V, Article 7 except below: (a) A complete set of records, as described in ASME Sec. V, Article 7, T-791 and T-792 shall be retained by the manufacturer until the Manufacturer's data report, and signed by the inspector (b) Personnel performing by ASME Sec. VIII, Div.2 shall be per para 7.3 (qualification of inspector). Evaluation of MT by MT Level II or III personnel (c) MT shall be performed in accordance with a written procedure, certified by the manufacturer to be per the requirements of ASME Sec. V, Article 7, T-150 See Note 4 below for more detail	Para. 7.5.6.2 (same as PT category) See note 5 below for more detail.
	ASME Sec. VIII Div.2, castings	Para 3.8.2.2(d) for ferrous	Para 3.8.2.2(d)
	ASME Sec. VIII Div.2, castings	For repair welding, Para 3.8.2.3(b) for ferrous	Para 3.8.2.3(b)
	ASME Sec. VIII Div.2, bolts, studs, and nuts	Para 3.7.2(b)	Para 3.7.2(b)
	ASME B 31.3 Chapter VI	Para 344.3; examination per Sec. V, Art.7	Para 344.3.2
	AWS B 1.10 guide for NDE of welds	Section 3.3: MT methods	

Table 5.23 (3/6) General requirements of NDE in codes and specification – ASME, AWS, ASTM – Notes 1, 2, 3

NDE	Codes/STD	Scope and procedures	Acceptance criteria
RT (radiographic test)	ASME Sec. V Art. 2 and 22 ASME/ASTM; SE-94 SE-747 SE-999 SE-1025 SE-1030 SE-1114 SE-1165 SE-1255 SE-1416	**[Art. 2]** RT – general requirements (procedure, surface preparation, backscatter radiation, system of identification, monitoring density limitations of RT, equipment, materials, calibration, examination technique, select/use/sensitivity of IQI, evaluation, radiographic density, and documentation) **[Art. 22]** STD guide for RT SE-94 standard guide for RT SE-747 standard practice for design, manufacture, and materials grouping classification of wire IQI used for RT SE-999 standard guide for controlling the quality of industrial radiographic film processing SE-1025 standard practice for design, manufacture, and materials grouping classification of hole-type IQI used for RT SE-1030 TM for RT of metallic castings SE-1114 TM for determining the focal size of Ir 192 industrial radiographic sources SE-1165 TM for measurement of focal spots of industrial X-ray tubes by pinhole imaging SE-1255 standard practice for RT SE-1416 TM for RT of weldments SE-1416 standard practice for determining contrast sensitivity in RT	See the acceptance category/level in each ASME/ ASTM. [Alternative] BS-EN-ISO 10675-1
	ASME Sec. VIII Div.1 UW-51/52 & App.4 t = thickness	[UW-51] (a) SNT-TC-1A (or ACCP or CP-189) shall be used (b) Other examination per Sec. V, Art. 2 (c) Repair: UW-38 (d) UT in lieu of RT	**[UW-51]** (a) Crack, LF, or IP. (b) Indications exceed the reference level amplitude and have lengths which exceed: 6.4 mm (¼″) for $t \leq$ (19 mm (3/4″); 1/3 t for 19 mm (¾″) $< t \leq$ 57.2 mm (2 ¼″); 19 mm (¾″) for $t >$ 57.2 mm (2 ¼″). (c) any group of aligned indications that have an aggregate length greater 1/12 t, except when the distance between the successive imperfections, >6 L where L is the length of the longest imperfection in the group. (d) Rounded indications > acceptance criteria in app. 4. **[App. 4]** rounded indication charts; acceptance standard for RT-determined rounded indications in welds. See Sect. 4.3.
	ASME Sec. VIII Div.2, Tables 7.2/7.3/7.4 Para. 7.5.3	Tables 7.2 and 7.4: Extend of RT application scope per joint category and material Table 7.3: Selection of RT for full penetration joints per shell thickness and joint category Para 7.5.3.1 general requirements and procedure (see note 6 below)	Para 7.5.3.2 (see note 7 below) *(a)* Linear indications *(b)* Rounded indications Table 7.7 (examples) Tables 7.8 to 7.11 flaw acceptance criteria for welds
	ASME Sec. VIII Div.2, castings	Para 3.8.2.2(b) for ferrous and Para 3.8.3.1(b) for nonferrous	Para 3.8.2.2(b) and 3.8.3.1(b)
	ASME Sec. VIII Div.2, castings	For repair welding, Para 3.8.2.3(b) for ferrous and Para 3.8.3.2(a) for nonferrous	Para 3.8.2.3(b) and 3.8.3.2(b)
	ASME B 31.3 Chapter VI	Para 344.5; examination per Sec. V, Art.2 Para 344.5.2 extent of RT – 100% RT – girth and miter groove weld/ branch connection weld to Fig 328.5.4E – Random RT – girth and miter groove welds – Spot RT	Table 341.3.2
	AWS B 1.10 guide for NDE of welds	Section 3.4: RT methods	

Table 5.23 (4/6) General requirements of NDE in codes and specification – Notes 1, 2, 3

NDE	Codes/STD	Scope and procedures	Acceptance criteria
UT (ultrasonic test)	ASME Sec. V, Art. 4, 5, 14 and 23 ASME/ASTM; SA-388/388 M SA-435/435 M SA-577/577 M SA-578/578 M SA-609/609 M SA-745/745 M SB-548 SE-213 SE-273 SE-797/SE-797 M SE-2491	See T-150 for procedure – general **[Art. 4]** UT – general requirements for written procedure, equipment, surface conditions, examination techniques, longitudinal/circular/multidirectional magnetization techniques, yoke technique-direct, calibration, examination, evaluation, documentation, and recording of indications **[Art. 5]** UT examination methods for materials [Art. 23] STD practice/specification/method/guide for UT SA-388/388 M UT of heavy steel forgings SA-435/435 M straight-beam UT of steel plates SA-577/577 M angle-beam UT of steel plates SA-578/578 M straight-beam UT of plain and clad steel plates for special applications SA-609/609 M casings, CS, LAS, and MSS, UT thereof SA-745/745 M UT of austenitic steel forgings SB-548 UT inspection of Al-alloy plate for pressure vessels SE-213 UT of metal pipe and tubing SE-273 UT of the weld zone of welded pipe and tubing SE-797/SE-797 M measuring thickness by manual ultrasonic pulse-Echo contact method SE-2491 evaluating performance characteristics of phased-Array UT instruments and systems ASME SE-2700 contact UT of welds using phased arrays	See the acceptance category/level in each ASME/ASTM. ASME Sec. V, Art 14, Appendix II, Tables II-1434-1 & II-1434–2
	ASME Sec. VIII Div.1, App. 12	Para 9-300, 310 Para 9-330: Repair requirements	Para 12-3; unacceptable if exceeds the following: (a) Cracks, LF, or IP regardless of length (b) Indications exceed the reference level amplitude and have lengths which exceed: 6.4 mm (¼″) for t ≤ (19 mm (3/4″); 1/3 t for 19 mm (¾″) < t ≤ 57.2 mm (2 ¼″); 19 mm (¾″) for t > 57.2 mm (2 ¼″).
	ASME Sec. VIII Div.2, Tables 7.2/7.3/7.4 Para. 7.5.4	Tables 7.2 and 7.4: Extend of UT application scope per joint category and material Table 7.3: Selection of UT for full penetration joints per shell thickness and joint category Para 7.5.4.1 general requirements and procedure (or see note 8 below)	See sec VIII, div. 2, para 7.5.4.2 (or see note 9 below)
	ASME Sec. VIII Div.2, plates, forgings, bolts	Para 3.6.2 for plates	Para 3.6.2
		Para 3.6.3 for forgings	Para 3.6.3
		Para 3.7.2(C) & (d) bolts, studs, and nuts	Para 3.7.2(C) & (d)
	ASME Sec. VIII Div.2, castings	Para 3.8.2.2(c) for ferrous and Para 3.8.3.1(c) for nonferrous	Para 3.8.2.2(c) and 3.8.3.1(c)
		For repair welds, Para 3.8.2.3(b) for ferrous, and Para 3.8.3.1 (c) for nonferrous	Para 3.8.2.2(c) and 3.8.3.2(b)
	B 31.3 Chapter VI	Para 344.6; examination per Sec. V, Art.5 except 344.6.1 (a) & (b)	Para 344.6.2: Unacceptable if exceeds the following: (a) 6.4 mm (¼″) for t ≤ 19 mm (3/4″) (b) t/3 for 19 mm (¾″) < t ≤ 57.2 mm (2 1/4″) (c) 19 mm (¾″) for t > 57.2 mm (2 ¼″)
	AWS B 1.10 NDE of welds	Section 3.5: UT methods	
	ASME SA-578 for rolled plate (solid or clad), t ≥ 10 mm (3/8″)	Procedure: See Para 5 Recording: See Para 6	See note 10 below. Stringent level: C > B > A
	ASME SA-435 for fully killed carbon and alloy plate, t ≥ 12.5 mm (1/2″)	Procedure: See ASME SA-435, Para 5	1. Any discontinuity indication causing a total loss of back reflection which cannot be contained within a circle, the diameter of which is 75 mm (3 in.) or 1/2 plate thickness, whichever is greater, is unacceptable. 2. The manufacturer reserves the right to discuss unacceptable UT-tested plates with the purchaser with the object of possible repair of the ultrasonically indicated defect before rejection of the plate.

Table 5.23 (5/6) General requirements of NDE in codes and specification – Notes 1, 2, 3

NDE	Codes/STD	Scope and procedures	Acceptance criteria
UT (ultrasonic test)	ASME SA-388 for forging	Per the procedures for the contact, pulse-echo ultrasonic examination of steel forgings by the straight and angle-beam techniques	See Note 11 below.
	; ASME Sec. VIII Div.2, Para. 7.5.5 UT in lieu of RT *TOFD* ASME Sec. V, Art.4. MA III ASME Code Case 2235–10 API RP934-A *PAUT* See Table 5.16.	TOFD (time of flight diffraction) – This is an affective fully computerized inspection method for the detection and sizing of flaws of welds with accuracy never achieved before. With the TOFD techniques which apply diffraction signals instead of reflection signals, type, location, geometry, or orientation of the anomalies is in most cases irrelevant for detection and sizing. In the TOFD technique, a transmitter and a receiver are placed on equal distances of the weld focused at the same location in the weld ASTM E2373 use of the ultrasonic time of flight diffraction (TOFD) technique ASME Code Case 2235 Use of UT in Lieu of RT, Sec. I, VIII, Div. 1 & 2 API RP934-A, A.5.1 for Cr-Mo Heavy Wall vessel application	ASME Sec. VIII, Div. 2, 7.5.5.3. Code Case 2235-latest
ECT (Eddy current test)	ASME Sec. V Art. 8 and 26 ASME/ASTM; SE-243	**[Art. 8]** ECT – general requirements (performance, personnel, procedure, equipment, calibration, examination, evaluation, and documentation) **[Art. 26]** STD guide for ECT SE-243 standard practice for electromagnetic examination (ECT) of copper and copper alloy tubes	See the acceptance category/level in each ASME/ASTM.
	ASME SEC. VIII, Div.2	ASME Sec VIII, Div. 2, para 7.5.8	All surfaces examined shall be free of relevant ET surface flaw indications.
AE (acoustic emission)	ASME Sec. V, Art. 12, 13, and 29 ASME/ASTM; SE-650/650 M SE-976 SE-1067/1067 M SE-1118/1118 M SE-1139 SE-1211/1211 M SE-1419	**[Art. 12]** AE exam of metallic vessels during pressure testing **[Art. 13]** continuous acoustic emission monitoring of pressure boundary components **[Art. 29]** STD guide for AE SE-650 guide for mounting piezoelectric AE sensors SE-750 practice for characterizing AE instrumentation SE-976 determining the reproducibility of AE sensor response SE-1067 AE exam of FRP tanks/vessels SE-1118 AE of RTRP (reinforced thermosetting resin pipe) SE-1139 for continuous monitoring from metal pressure boundaries SE-1211 for leak detection and location using surface-mounted AE sensors SE-1419 for examination of seamless, gas-filled pressure vessel using AE ASTM E543 specification for agencies performing NDE ASTM E569 practice for AE monitoring of structures during controlled stimulation ASTM E2374 guide for AE system performance verification AIA NAS-410 certification and qualification of NDT personnel SNT-TC-1A recommended practice for NDT personnel qualification and certification ANSI/ASNT CP-189 ASNT standard for qualification and certification of NDT personnel	See the acceptance category/level in each ASME/ASTM.
LT (leak test)	ASME Sec. V Art 10	**[Art. 10]** LT – general requirements (procedure, equipment, cleanliness, opening, temperature, pressure limits, examination, gauge calibration, evaluation, documentation, and recording)	
	ASME B 31.3 Chapter VI	[Para 345] Para 345.1 – Required LT Para 345.2 – General requirements for LT Para 345.3 – Preparation for LT Para 345.4 – Hydrostatic LT Para 345.5 – Pneumatic LT Para 345.6 – Hydrostatic-pneumatic LT Para 345.7 – Initial service LT Para 345.8 – Sensitive LT Para 345.9 – Alternative LT	
	AWS B 1.10 guide for NDE of welds	Para 3.7: LT methods	
ACFM	ASTM	E2261 standard practice for examination of welds using the alternating current field measurement (ACFM) technique	

Table 5.23 (6/6) General requirements of NDE in codes and specification – Notes 1, 2 3

NDE	Codes/STD	Scope and procedures	Acceptance criteria
TIR (thermal/ infrared test)	ASTM	E1256 TM for radiation thermometers (single waveband type) E307 TM for normal spectral emittance at elevated temperatures E639 standard method for measuring Total-radiance temperature of heated surfaces using a radiation pyrometer E1213 TM for min. Resolvable temperature difference for thermal imaging systems E1965 standard specification for infrared thermometers for intermittent determination of patient temperature E1213 TM for min. Resolvable temperature difference for thermal imaging systems (MRTD) E1311 TM for min. Detectable temperature difference for thermal imaging systems (MDTD) E1543 TM for noise equivalent temperature difference of thermal imaging systems (NETD) E1862 TM for measuring and compensating for reflected temperature using infrared imaging radiometers E1933 TM for measuring and compensating for emissivity using infrared imaging radiometers E1934 standard guide for examining electrical and mechanical equipment with infrared thermography	See the acceptance category/level in each ASME/ASTM.
NRDM	ASTM E1496; TM for neutron radiographic dimensional measurements (NRDM)	A technique for extracting quantitative dimensional information on an object from its neutron radiograph. The technique is based on the identification of changes in film density caused by material changes where a corresponding discontinuity in film density exists. This test method is designed to be used with neutron radiographs made with a well-collimated beam. The film densities in the vicinity of the edge must be in the linear portion of the density versus exposure curve. The accuracy of this test method may be affected adversely in installations with high-angular-divergence neutron beams or with large object-to-film distances	

*All paragraphs, figures, and tables specified in this table come from the individual codes/standard unless otherwise noted

Legend

SNT-TC-1A: Personnel Qualification and Certification in Nondestructive Testing

CP-189: Published by the American Society for Nondestructive Testing, Inc.

Tw: thickness of welded part

ACFM: Alternating Current Field Measurement (Theory: same as MT)

Notes: *t* wall thickness, *Art* article, *TM* standard test method

1. All NDEs are for weld joints unless otherwise specified (e.g., forging, plates, bolts, etc.)
2. See SNT-TC-1A for the detail of ASNT level and applicable NDE test
   ASTM E1316 for terminology for NDE
   ASME Sec. V, Art. 1, Table 1–100 for capacities of imperfection detecting per type of various NDEs
   Minimum NDT Operator Qualification; *ASNT Level I*
3. Valve, ASME B16.34

Appendix I – RT	Appendix III – PT
I-1 RT procedure	I-1 PT procedure
I-2 acceptance standards	I-2 acceptance standards
Appendix II – MT	Appendix IV – UT
I-1 MT procedure	I-1 UT procedure
I-2 acceptance standards	I-2 acceptance standards

4. Procedures for PT and MT (ASME Sec. VIII, Div. 2, 7.5.7.1 and 7.5.6.1, respectively)
   An indication of an imperfection may be larger than the imperfection that causes it; however, the size of the indication is the basis for acceptance evaluation. Only indications with major dimensions greater than 1.5 mm (1/16 in.) shall be considered relevant:
   (1) A linear indication is one having a length greater than three times the width (L > 3 W)
   (2) A rounded indication is one of circular or elliptical shape with a length equal to or less than three times its width
   (3) Any questionable or doubtful indications shall be reexamined to determine whether or not they are relevant
5. Acceptance Categories for PT and MT (ASME Sec. VIII, Div. 2, 7.5.7.2 and 7.5.6.2, respectively)
   (a) All surfaces to be free of:
      (1) Relevant linear indications
      (2) Relevant rounded indications greater than 5 mm (3/16 in)
      (3) Four or more relevant rounded indications in a line separated by 1.5 mm (1/16 in.) or less, edge-to-edge
   (b) Crack-like indications detected, irrespective of surface conditions, are unacceptable

6. Procedure of RT for Pressure Vessel, ASME Sec. VIII, Div. 2, 7.5.3.1
   To meet ASME Sec. V, Article 2 except below:
   (a) A complete set of radiographs and records, as described in ASME Sec. V, Article 2, T-291 and T-292 shall be retained by the manufacturer per ASME Sec. V, Article 2, Sect. 2.3.5 (manufacturer's construction records)
   (b) Personnel performing ASME Sec. VIII, Div. 2 shall be qualified and certified per para 7.3 (qualification of inspector)
   (c) Evaluation of radiographs shall only be performed by RT Level II or III personnel
   (d) Demonstration of density and Image Quality Indicator (IQI) image requirements on production or technique radiographs shall be considered satisfactory evidence of compliance with Article 2 of Section V
   (e) Final acceptance of radiographs shall be based on the ability to see the prescribed hole (IQI) image and the specified hole or the designated wire of a wire IQI
   (f) Ultrasonic examination of SAW welds in 2 1/4 Cr–1Mo–1/4 V vessels per para 7.5.4.1(e) is required
7. Acceptance Criteria of RT for Pressure Vessel, ASME Sec. VIII, Div. 2, 7.5.3.2
   (a) Linear Indications
      (1) Terminology
      Thickness (t) – the thickness of the weld excluding any allowable reinforcement. For a butt weld joining two members having different thicknesses at the weld, t is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the fillet throat shall be included in the calculation of t
      (2) Acceptance/Rejection Criteria
         (−a) Any crack or zone of incomplete fusion or lack of penetration
         (−b) Any other linear indication that has a length greater than:
            (−1) 6 mm (1/4 in.) for t less than or equal to 19 mm (3/4 in)
            (−2) t/3 for t greater than 19 mm (3/4 in.) and less than or equal to 57 mm (2 1/4 in)
            (−3) 19 mm (3/4 in.) for t greater than 57 mm (2 1/4 in)
         (−c) Any group of indications in line that has an aggregate length greater than t in a length of *12t* except when the distance between the successive imperfections exceeds *6L* where *L* is the length of the longest imperfection in the group
         (−d) Internal root weld conditions are acceptable when the density or image brightness change as indicated in the radiograph is not abrupt. Linear indications on the radiograph at either edge of such conditions shall be evaluated in accordance with the other sections of this paragraph
   (b) Rounded Indications
      (1) Terminology
         (−a) Rounded Indications – indications with a maximum length of three times the width or less on the radiograph are defined as rounded indications. These indications may be circular, elliptical, conical, or irregular in shape and may have tails. When evaluating the size of an indication, the tail shall be included
         (−b) Aligned Indications – a sequence of four or more rounded indications shall be considered to be aligned when they touch a line parallel to the length of the weld drawn through the center of the two outer rounded indications
         (−c) Thickness (t) – the thickness of the weld, excluding any allowable reinforcement. For a butt weld joining two members having different thicknesses at the weld, t is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the fillet throat shall be included in the calculation of t
      (2) Acceptance Criteria
         (−a) Rounded Indication Charts – relevant rounded indications characterized as imperfections shall not exceed those shown in ASME Sec. VIII, Div. 2, Figures 7.5 through 7.10, which illustrate various types of assorted, randomly dispersed and clustered rounded indications for different weld thicknesses greater than 3 mm (1/8 in.). The charts for each thickness range represent full-scale 150 mm (6 in.) radiographs and shall not be enlarged or reduced. The distributions shown are not necessarily the patterns that may appear on the radiograph but are typical of the concentration and size of indications permitted
         (−b) Relevant Indications – only those rounded indications that exceed the following dimensions shall be considered relevant and compared to the acceptance charts for disposition
            (−1) for t less than 3 mm (1/8 in)
            (−2) 0.4 mm (1/64 in.) for t greater than or equal to 3 mm (1/8 in.) and less than or equal to 6 mm (1/4 in)
            (−3) 0.8 mm (1/32 in.) for t greater than 6 mm (1/4 in.) and less than or equal to 50 mm (2 in)
            (−4) 1.5 mm (1/16 in.) for t greater than 50 mm (2 in)
            (−5) Maximum Size of Rounded Indication – the maximum permissible size of any indication shall be *t/4* or 4 mm (5/32 in.), whichever is smaller; except that an isolated indication separated from an adjacent indication by 25 mm (1 in.) or more may be *t/3*, or 6 mm (1/4 in.), whichever is less. For t > 50 mm (2 in.), the maximum permissible size of an isolated indication shall be increased to 10 mm (3/8 in)
            (−6) Aligned Rounded Indications – aligned rounded indications are acceptable when the summation of the diameters of the indications is less than t in a length of 12t. The length of groups of aligned rounded indications and the spacing between the groups shall meet the requirements of ASME Sec. VIII, Div. 2, Figure 7.4
            (−7) Clustered Indications – the illustrations for clustered indications show up to four times as many indications in a local area, as that shown in the illustrations for random indications. The length of an acceptable cluster shall not exceed the lesser of 25 mm (1 in.) or 2t. Where more than one cluster is present, the sum of the lengths of the clusters shall not exceed 25 mm (1 in.) in a 150 mm (6 in.) length weld
            (−8) Weld Thickness t Less Than 3 mm (1/8 in.) – for t less than 3 mm (1/8 in.), the maximum number of rounded indications shall not exceed 12 in., a 150 mm (6 in.) length of weld. A proportionally fewer number of indications shall be permitted in welds less than 150 mm (6 in.) in length
         (−c) Image Density – density or image brightness within the image of the indication may vary and is not a criterion for acceptance or rejection
         (−d) Spacing – the distance between adjacent rounded indications is not a factor in determining acceptance or rejection, except as required for isolated indications or groups of aligned indications
8. Procedure and Acceptance of UT for Pressure Vessel: See ASME Sec. VIII, Div. 2, 7.5.4.1 and ASME Sec. V, Article 4 except below

(a) A complete set of records, as described in ASME Sec. V, Article 4, T-491 and T-492, for each vessel or vessel part shall be retained by the manufacturer in accordance with ASME Sec. VIII, Div. 2, 2-C.3. In addition, a record of repaired areas shall be noted as well as the results of the reexamination of the repaired areas. The manufacturer shall also maintain a record from uncorrected areas having responses that exceed 50% of the reference level. This record shall locate each area, the response level, the dimensions, the depth below the surface, and the classification
(b) Personnel performing and evaluating ultrasonic examinations required by this Division shall be qualified and certified in accordance with ASME Sec. VIII, Div. 2, 7.3
(c) Flaw evaluations shall only be performed by UT Level II or III personnel
(d) Ultrasonic examination shall be performed in accordance with a written procedure certified by the manufacturer to be in accordance with the requirements of ASME Sec. V, Article 1, T-150
(e) SAW welds in 2.25Cr–1Mo–0.25V vessels require ultrasonic examination using specialized techniques beyond those required by this Division (see ASME Sec. VIII, Div. 2, 2.2.2.2 Additional Requirements). API RP 934-A, Annex A (Guideline for Inspection for Transverse Reheat Cracking of 2.25Cr-1Mo-V steel Reactors) may be used as a guide in the selection of the examination specifics

9. Acceptance Criteria of UT for Pressure Vessel, ASME Sec. VIII, Div. 2, 7.5.4.2
(a) Imperfections that are interpreted to be cracks, lack of fusion, or incomplete penetration are unacceptable regardless of length
(b) All other linear-type imperfections are unacceptable if the amplitude exceeds the reference level and the length of the imperfection exceeds the following:
(1) 6 mm (1/4 in.) for t less than 19 mm (3/4 in.)*
(2) t/3 for t greater than or equal to 19 mm (3/4 in.) and less than or equal to 57 mm (2–1/4 in)
(3) 19 mm (3/4 in.) for t greater than 57 mm (2–1/4 in.)*(recommendation) to apply the environmentally assisted corrosion service

10. ASTM SA578 Rolled Plate: Unacceptable if It Exceeds the Following; But Acceptance Level B Should Apply Unless Otherwise Agreed to by Purchaser. (): Former Level Grade
Acceptance Standard-Level A (II)
Any area where one or more discontinuities produce a continuous total loss of back reflection accompanied by continuous indications on the same plane (within 5% of plate thickness) that cannot be encompassed within a circle whose diameter is 76 mm (3 in.) or 1/2 of the plate thickness, whichever is greater, is unacceptable
Acceptance Standard-Level B (I)
Level A plus two or discontinuities smaller than described in level A unless separated by a min. Distance equal to the greatest diameter of the larger discontinuity or unless they may be collectively encompassed by the circle described in Level A
Acceptance Standard-Level C (III)
Any area where one or more discontinuities produce a continuous total loss of back reflection accompanied by continuous indications on the same plane (within 5% of plate thickness) that cannot be encompassed within a 25.4 mm (1 in.) diameter circle is unacceptable

11. Acceptance of UT for ForgingAcceptance quality levels shall be established between purchaser and manufacturer on the basis of one or more of the following criteria
(a) Straight-Beam Examination:
a-1 No indications larger than some percentage of the reference back reflection
a-2 No indications equal to or larger than the indication received form the flat-bottom hole in a specific reference block or blocks
a-3 No areas showing loss of back reflection larger than some percentage of the reference back reflection
a-4 No indications per a-1 or a-2 coupled with some loss of resultant back reflection per a-3
a-5 No indications exceeding the reference level specified in the DGS (Distance Gain-Size) method
(b) Angle-Beam Examination – No indications exceeding a stated percentage of the reflection from a reference notch or of the amplitude reference line

5.4 Functional Classification of NDE/NDT

5.4.1 Hardness Test and Requirements

5.4.1.1 Types of Hardness Tests

The hardness test which is measured into the material surface with a fixed load (dead weight) is one of the nondestructive tests, while the tensile test which is to measure the strength property through the thickness of the specimen is destructive test. Figure 5.11 shows a schematic outline of essential features of hardness testing. Table 5.24 described the comparison characteristics of several standard test methods, such as Brinell, Vickers, and Rockwell C.

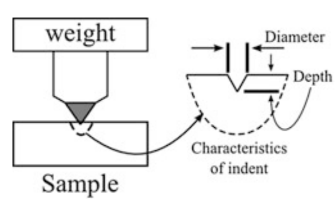
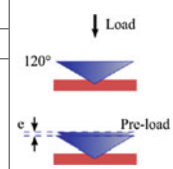
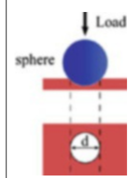
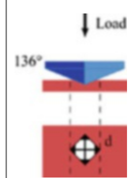


Figure 5.11 Schematic outline of essential features of hardness tests

5.4.1.2 Hardness Tests for Metallic Materials per Codes and Standards

(a) Types of hardness test
- Macro and micro tests (by end-user's specification, code, and standard for environmental cracking services)
- Metallic and nonmetallic material tests
- Conventional test methods – Brinell, Vickers, Rockwell, Superficial, Knoop, Shore Scleroscope, and Leeb

Table 5.24 Comparison of indentation hardness tests for metal

Hardness test	Weight	Indenter	Measure	Use	Remark
Rockwell A	60 kg	120° diamond cone	Depth	Hardened surface hardness	
Rockwell B	100 kg	1/16 in. ball	Depth	Soft hardness	
Rockwell C	150 kg	120° diamond cone	Depth	Medium to high hardness	
Brinell	500 ~ 3000 kg	Large ball (10 mm)	Diameter	Soft to medium hardness	
Vickers	10 ~ 120 kg	136° diamond pyramid, DPH, or Knoop	Diagonal length	Soft to high hardness	
Microhardness	0.001 ~ 1 kg	120° diamond cone	Diagonal length	Micro constituents	

Source: standards in Sect. 5.4.1.2(b)

– Potable hardness tests: (ASTM E110) Brinell testers (several brand testers), Rockwell testers (several brand testers), (others) ultrasonic and dynamic hardness testers

(b) Standards for hardness test methods and requirements: TM = test methods, RP = recommended practice

– ASTM A370 TM and Definitions for Mechanical Testing of Steel Products Included Conversion Table
– ASTM A833 TM for Indentation Hardness of Metallic Materials by Comparison Hardness Testers
– ASTM A956 and DIN 50156–1 TM for Leeb (Former Equotip) Hardness Testing of Steel Products
– ASTM A1038 Portable Hardness Testing by Ultrasonic Contact Impedance Method
– ASTM B277 TM for Hardness Testing of Electrical Contact Materials
– ASTM B294 TM for Hardness Testing of Cemented Carbides
– ASTM B578 TM for Microhardness of Electroplated Coatings
– ASTM B647 TM for Indentation Hardness of Aluminum Alloys by Means of a Webster Hardness Gauge
– ASTM B648 TM for Indentation Hardness of Aluminum Alloys by Means of a Barcol Impressor
– ASTM C661 TM for Indentation Hardness of Elastomeric-Type Sealants by Means of a Durometer
– ASTM C730 TM for Knoop Indentation Hardness of Glass
– ASTM C748 TM for Rockwell Hardness of Fine-Grained Graphite Materials
– ASTM C805 TM for Rebound Number of Hardened Concrete
– ASTM C849 TM for Knoop Indentation Hardness of Ceramic Whitewares
– ASTM C886 TM for Scleroscope Hardness Testing of Fine-Grained Carbon and Graphite Materials
– ASTM C1326 TM for Knoop Indentation Hardness of Advanced Ceramics
– ASTM C1327 TM for Vickers Indentation Hardness of Advanced Materials
– ASTM D785 TM for Rockwell Hardness of Plastics and Electrical Insulating Materials
– ASTM D1415 TM for Rubber Property-International Hardness
– ASTM D1474 TM for Indentation Hardness of Organic Coatings
– ASTM D2240 TM for Rubber Property-Durometer Hardness
– ASTM D2583 TM for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
– ASTM D3363 TM for Film Hardness by Pencil Test (Coating)
– ASTM D5230 TM for Carbon Black-Automated Individual Pellet Hardness
– ASTM E10 and ISO 6506-1 TM for Brinell Hardness of Metallic Materials
– ASTM E18 and ISO 6508-1 TM for Rockwell Hardness of Metallic Materials
– ASTM E92 and ISO 6507-1 TM for Vickers Hardness
– ASTM E103 TM for Indentation Hardness of Organic Coatings
– ASTM E110 Hardness Testing Potable

– ASTM E140 Hardness Conversion Table Among Brinell, Vickers, Rockwell, Superficial, Knoop, and Scleroscope for Non-austenitic Steel, Austenitic Steel, Ni-Based Alloys, Copper Alloys, Alloyed White Irons, and Wrought Aluminum Products – See Fig. 5.12 in this book for DSS
– ASTM E384 TM for Micro-Indentation Hardness of Materials
– ASTM E1268 Annex Conversion from Knoop Test (HK) to HRC for Steels/from Carbon Content to HRC for As-Quenched Steels
– ASTM F1957 TM for Composite Foam Hardness-Durometer Hardness
– API RP582 Welding Guidelines for the Chemical, Oil, and Gas Industries
– API STD 1104 Welding of Pipelines and Related Facilities
– API RP945 Avoiding Environmental Cracking in Amine Units
– API RP751 Safe Operation of HF Acid Alkylation Units
– API RBI Standards 570, 571, 572, 574, 579, 580, etc.
– ANSI/NACE MR0175/ISO15156 Wet H2S (Sour) Service-Upstream and Midstream
– ANSI/NACE MR0103/ISO17945 Wet H2S (Sour) Service-Downstream
– NACE SP0472 In-Service Environmental Cracking of CS Weldments
– AWS D1.1 Structural Welding Code-Steel

(c) Record hardness results and location (e.g., weld metal, HAZ, and base metal)
When specified by the purchaser, the hardness test results shall be recorded in the PQR. PQR hardness testing is required where the purchaser requires production hardness testing for environmental cracking or other services as specified by the purchaser.

ASTM E140 does not address the hardness conversion for DSS. So, API TR938-C has developed the hardness conversion curve for DSS in Fig. 5.12.

Fig. 5.13 shows the possible offset in Rockwell hardness measurement values that could be obtained for the diamond indenter scales by varying the applied preliminary forces and total forces within the ASTM tolerances (a) and the ISO tolerances (b).

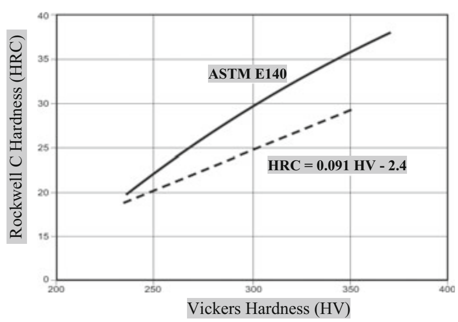


Figure 5.12 Comparison of hardness data between ferrous steel (non-austenitic steel: real line from ASTM E140) and DSS (dot line). (Source: API TR938-C)

1. For PQR in Non-environment Cracking Service
Fig. 5.14 shows the locations of Vickers Hardness Indentations on weldments in API RP582. Normally the hardness testing should be performed after any required PWHT. Readings in the HAZ shall be conducted if specified by the applicable code (e.g., ASME B31.3) or standard.
2. For PQR in Environment Cracking Service (Especially for Sour Service)
Figs. 5.15, 5.16, 5.17, 5.18, and 5.19 show the locations and survey methods of Vickers and Rockwell Hardness Indentations on weldments in NACE MR0175/ISO15156. Normally the hardness testing should be performed after any required PWHT.
3. Measurement on Products
Figure 5.20 shows the hardness testing overview for products.

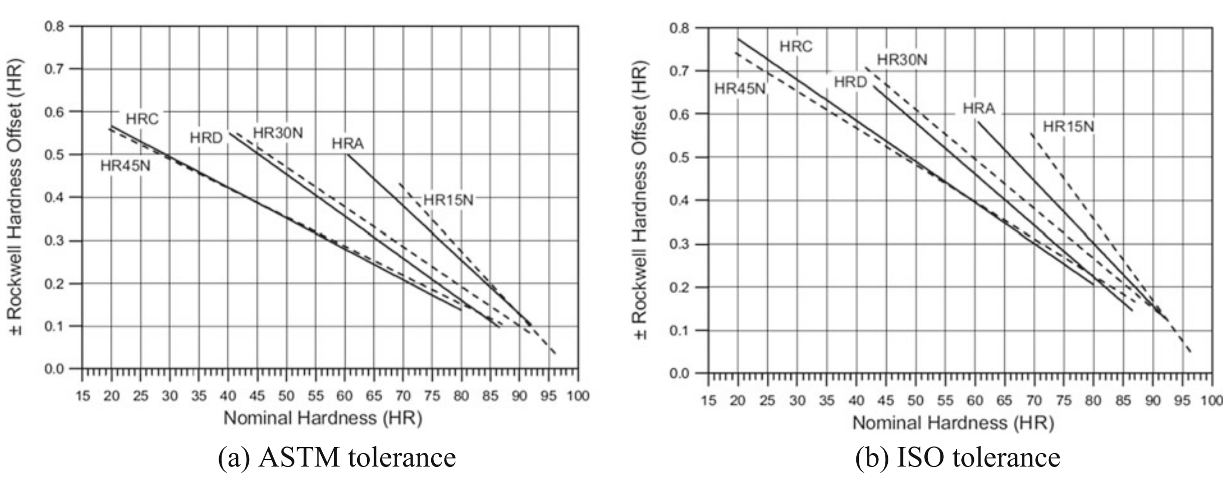


Figure 5.13 Possible offset in Rockwell hardness measurement values in ASTM/ISO tolerance (NIST publication, 2013). (**a**) ASTM tolerance. (**b**) ISO tolerance

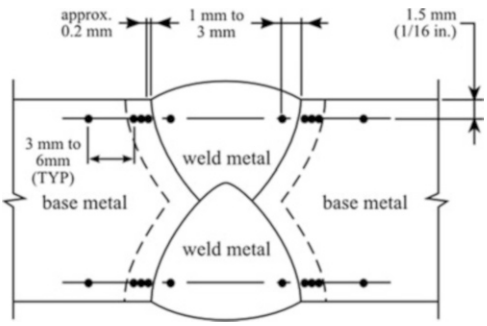


Figure 5.14 Locations of Vickers Hardness Indentations. (Source: API RP582). Note: HV10 measurement for HAZ requires 0.04 in. (1 mm) minimum spacing between indentations. In some cases, it is acceptable that hardness measurement location is off-the line in order to satisfy the minimum spacing requirements

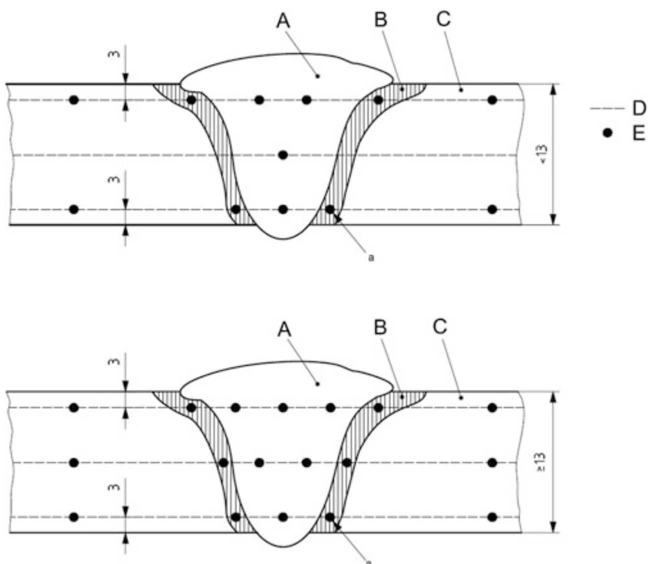


Figure 5.16 Butt-weld survey method for Rockwell Hardness Measurement (dimensions: mm). (Source: NACE MR0175/ISO15156, Part 2). *Key:* A weld. B weld HAZ (visible after etching). C parent metal. D lines of survey. E hardness impressions: Impressions in the weld HAZ should be located within 2 mm of the fusion boundary

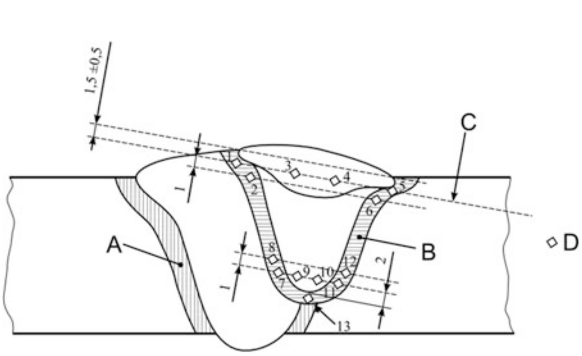


Figure 5.18 Repair and partial penetration welds survey method for Vickers Hardness Measurement (dimensions: mm). (Source: NACE MR0175/ISO15156, Part 2). *Key*: A original weld HAZ. B repair-weld HAZ. C parallel lines of survey. D hardness impressions: Impressions in the HAZ should be located as close as possible to the fusion boundary. The top line of survey should be positioned so that the HAZ impressions coincide with the HAZ of the final run or change in profile of the cap of fusion line associated with the final run

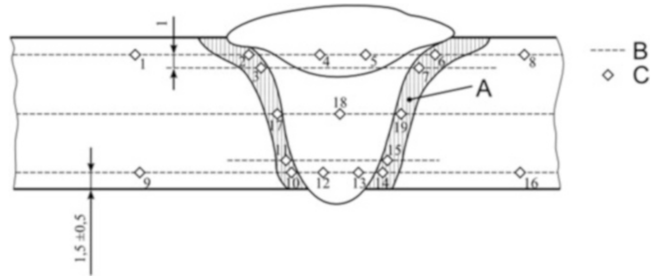


Figure 5.15 Butt-weld survey method for Vickers Hardness Measurement (dimensions: mm). (Source: NACE MR0175/ISO15156, Part 2). *Key:* A weld HAZ (visible after etching). B lines of survey. C hardness impressions: Impressions 2, 3, 6, 7, 10, 11, 14, 15, 17, and 19 should be entirely within the HAZ and located as close as possible to the fusion boundary between the weld metal and the HAZ. The top line of survey should be positioned so that impressions 2 and 6 coincide with the HAZ of the final run or change of profile of the fusion line associated with the final run

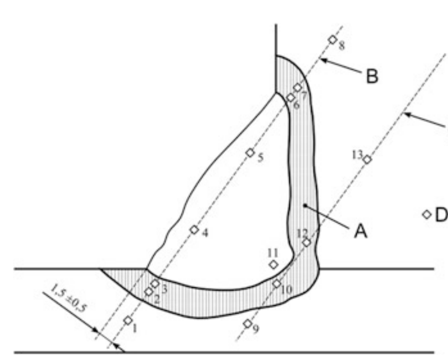


Figure 5.17 Fillet-weld survey method for Vickers Hardness Measurement (dimensions: mm). (Source: NACE MR0175/ISO15156, Part 2). *Key:* A weld HAZ (visible after etching). B line of survey. C line of survey, parallel to line B and passing through the fusion boundary between the weld metal and the HAZ at the throat. D hardness impressions: Impressions 3, 6, 10, and 12 should be entirely within the HAZ and located as close as possible to the fusion boundary between the weld metal and the HAZ

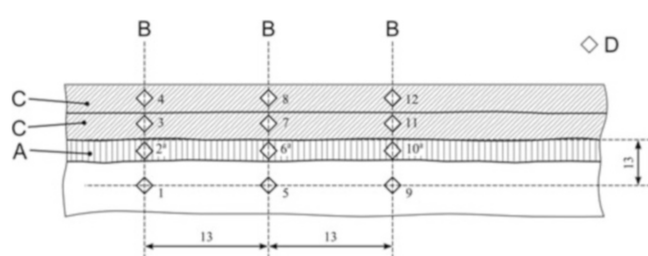


Figure 5.19 Weld-overlay survey method for Vickers Hardness Measurement (dimensions: mm). (Source: NACE MR0175/ISO15156, Part 2). *Key:* **A** weld HAZ (visible after etching). **B** lines of hardness survey indentations 1 to 12. **C** layer of weld overlay (visible after etching). **D** hardness impressions. The Rockwell C hardness measurement method may be used subject to the requirements of NACE MR0175/ISO 15156, Part 2, 7.3.3.2. HRC hardness impressions in the HAZ shall be located within 2 mm of the fusion boundary. [a]Using the Vickers or Rockwell 15 N measurement methods, hardness impressions 2, 6, and 10 should be entirely within the HAZ and located as close as possible to, but no more than 1 mm from, the fusion boundary between the weld overlay and HAZ

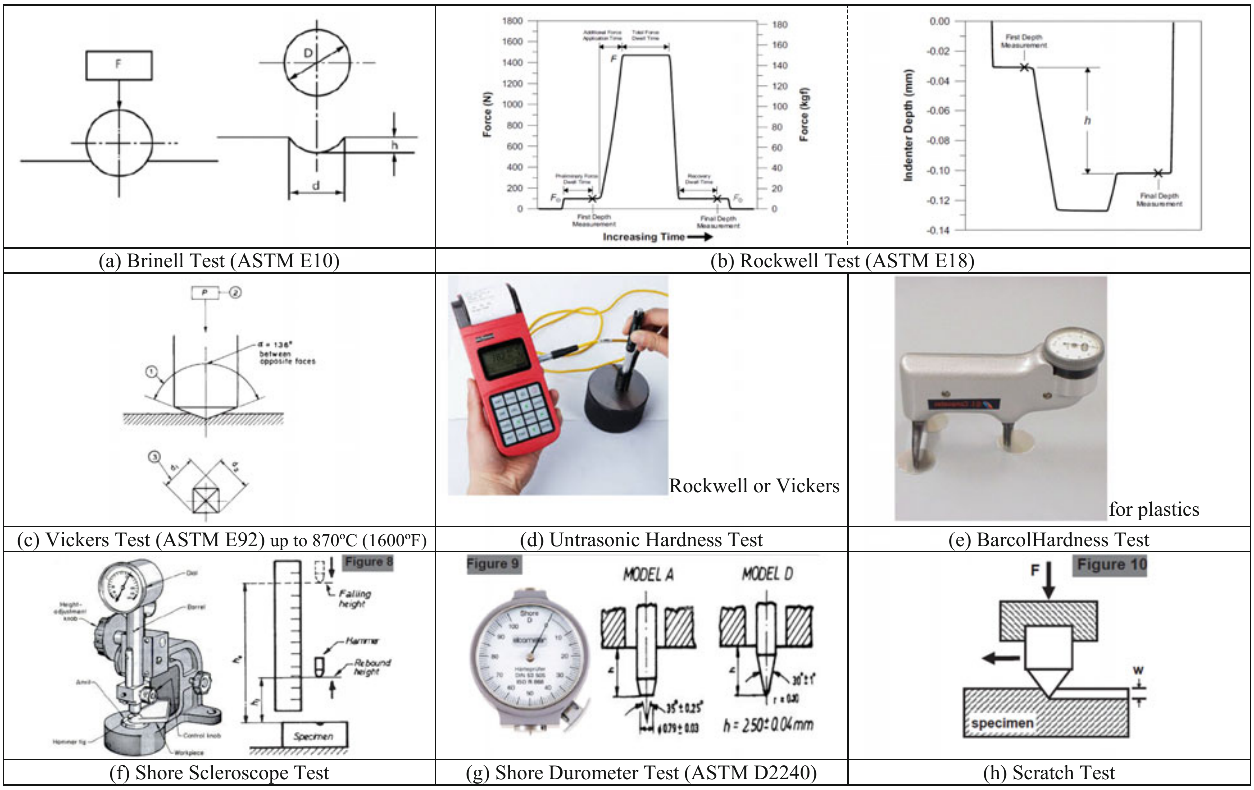


Figure 5.20 Various hardness testing – overview. (**a**) Brinell Test (ASTM E10). (**b**) Rockwell Test (ASTM E18). (**c**) Vickers Test (ASTM E92) up to 870 °C (1600 °F). (**d**) Ultrasonic Hardness Test. (**e**) Barcol Hardness Test. (**f**) Shore Scleroscope Test. (**g**) Shore Durometer Test (ASTM D2240). (**h**) Scratch Test

Table 5.25 Required hardness values in oil and gas industries (typical for general services)

	Brinell hardness (HBW)		Vickers (10 kg) hardness	
Materials	Minimum	Maximum	Minimum	Maximum
P no.1	130	200	130	248
P no. 3 & 4	145	215	145	248
P no. 5A, 5B (5Cr), 6, 7	160	235	160	248
P no 5B (9Cr), 15E (9Cr modified), 5C	160	248	160	300
P no. 6 (12Cr)		237		248

Notes: *HBW* hardness of Brinell by Wolfram (Tungsten)
1. Above table is typically applied to non-corrosive service in most plants. However the required values for P. No.1, 3, and 4 may be somewhat excessive requirements. Many end-users want to use the hardness values in API RP582
2. The difference between any hardness measurements shall not exceed 30 BHN
3. See Table 5.26 for sour service requirements

Table 5.26 Required hardness values of materials in wet H_2S (sour) services (1)(2)

Alloy steel (P no.)	Maximum hardness	Alloy steel (P no.)	Maximum hardness
3 and 4	225 HBW	8	22 HRC (237 HBW)
5A	235 HBW	10A, 10B, 10C, and 10F	225 HBW
5B except grade 91, 911 (C12A)	235 HBW	10H	28 HRC
15E - grade 91, 911 (C12A)	248 HBW	11	225 HBW
5C, 6 and 7	235 HBW		

ANSI/NACE MR0103/ISO 17945 Materials Resistant to SSC in Corrosive Petroleum Refinery
Notes
(1)NACE SP0472 (200 HBW for Weld Deposit/248 HV10 for HAZ) should be applied for P. No. 1 welds
(2)ANSI/NACE MR0175/ISO 15156 (Oil and Gas Upstream) specifies more classified requirements per component/part, material type/class, service condition, etc.

Tables 5.25, 5.26, 5.27, 5.28, 5.29, 5.30, 5.31, and 5.32 show the hardness requirements of several materials in codes and standards. Typically the hardness requirements for all pressure components are controlled by maximum values or hardness ranges except hardfacing parts.

Figure 5.21 shows the approximate comparison of hardness scale of several materials.

Table 5.27 Hardness values of several materials

Alloy steel	Maximum hardness	Alloy steel	Maximum hardness
Carbon steel	200 HBW	2.25Cr-1Mo	241 HBW
C-0.5Mo	225 HBW	5,7,9 Cr-Mo	241 HBW
1.25Cr-0.5Mo	225 HBW	12Cr	241 HBW

API RP577 Welding Inspection and Metallurgy

Table 5.28 Hardness values of several materials

Alloy steel	API RP934-A Max. hardness	Alloy steel	API RP934-C Max. hardness
2.25Cr-1Mo 3Cr-1Mo	225 HBW	1.25Cr-0.5Mo	225 HBW
2.25Cr-1Mo-0.25 V 3Cr-1Mo-0.25 V	235 HBW		

API RP934A/C Cr-Mo Vessels

Table 5.29 Hardness values of materials in Cr-Mo steels

Alloy steel	Max. hardness
CS	225 HBW
LAS ($\leq$ 2% Cr)	225 HBW
LAS (2% $<$ Cr $\leq$ 9%), MSS, FSS	240 HBW

API RP660 Shell and Tube Type H/EX

Table 5.30 Hardness values of materials in Cr-Mo steels

Alloy steel	Max. hardness
CS to 1.25Cr-0.5Mo	20 HRC
>1.25Cr-Mo & 11/13/17Cr	22 HRC

API 661 Air Coolers

Table 5.31 Hardness values of materials in Cr-Mo steels

Alloy steel (P no.)	Max. hardness
1, 3, 4	225 HBW
5B gr. 1	241 HBW
5A and 5C	225 HBW
6, 7	241 HBW

API 582 Welding Guidelines for the Chemical, Oil, and Gas Industries

5.4.1.3 Hardness Test for Nonmetals

Tables 5.33, 5.34, 5.35, 5.36, and 5.37 and Figs. 5.22, 5.23, and 5.24 show Shore Durometer (Rubber) Hardness Tests and Conversion. See ASTM D2583 for indentation hardness of rigid plastics and composite materials.

Table 5.32 Maximum hardness for ring gaskets(3),(4)

Ring gasket material	Maximum hardness(2)		Remark
	Brinell	Rockwell "B" scale	
Soft iron (1)	90	56	B16.20, MSS SP 65 & API 6A
Low carbon steel	120	68	B16.20, MSS SP 65 & API 6A
4–6 chrome ½ Mo	130	72	B16.20, MSS SP 65
Type 410	170	86	B16.20, MSS SP 65
Type 304	160	83	B16.20, MSS SP 65 & API 6A
Type 316	160	83	B16.20, MSS SP 65 & API 6A
Type 347	160	83	B16.20, MSS SP 65 & API 6A
Alloy 825 (N08825)		92	API 6A

Notes

(1)May be low carbon steel, not to exceed maximum hardness of 90 Brinell — 56 Rockwell "B"

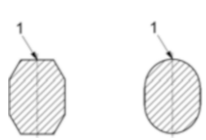
(2)The flange face contacted by ring gasket may have at least 15 BHN higher than that of the actual hardness of ring gasket. API Spec 6A specifies the hardness test location (No.1) for ring joint as below figures

(3)ASME B16.20, MSS SP 65, API Spec 6A/ISO 10423, etc.

(4)See Sect. 3.2.6 for gasket selection

(5)See each standard for the marking symbol requirements

(6)There are several premature failure (crack) case studies for RTJ (ring type joint-octagonal or oval type below) flanges of equipment and piping, while there are no remarkable failure reports for RF flanges used at the similar pressure in high pressure hydrocarbon processing. So, API technical committees want to recommend RF (raised face)-type flange instead of RTJ flange in high pressure environment if the design calculation is acceptable



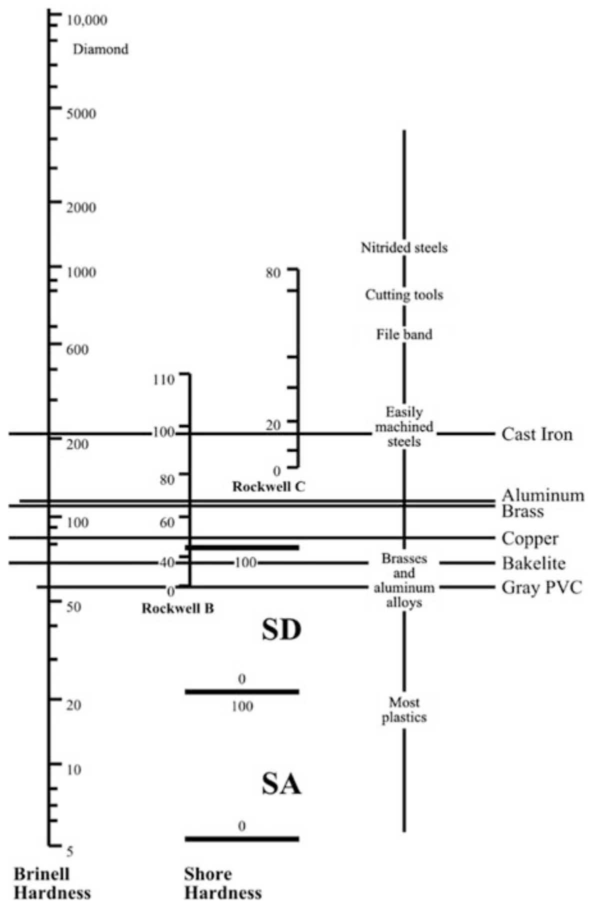


Figure 5.21 Approximate comparison of hardness scale of several materials. (Source: Matweb.com-Matweb report, 2012)

Table 5.33 Type 1 precision: type A durometer method – ASTM D2240

Material	Average level	Within laboratories			Between laboratories		
		Sr[A]	r[B]	(r)[C]	SR[D]	R[E]	(R)[F]
1	51.4	0.646	1.83	3.56	1.56	4.41	8.59
2	65.3	0.878	2.48	3.81	2.21	6.06	9.27
3	68.0	0.433	1.23	1.90	2.28	6.45	9.49
Pooled values	61.6	0.677	1.92	3.11	2.018	5.72	9.28

Notes
[A]*Sr* = repeatability standard deviation, measurement units
[B]*r* = repeatability = 2.83 × *Sr*, measurement units
[C](*r*) = repeatability, relative, (i.e., in percent)
[D]*SR* = reproducibility standard deviation, measurement units
[E]*R* = reproducibility = 2.83 × *SR*, measurement units
[F](*R*) = reproducibility)

Table 5.34 Type 1 precision: type D durometer method – ASTM D2240

Material	Average lever	Within laboratories			Between laboratories		
		Sr[A]	r[B]	(r)[C]	SR[D]	R[E]	(R)[F]
1	42.6	0.316	0.894	2.10	2.82	7.98	18.7
2	54.5	0.791	2.24	4.11	3.54	10.0	18.4
3	82.3	1.01	2.86	3.47	3.54	10.0	12.2
Pooled values	59.8	0.762	2.16	3.61	3.32	9.40	15.7

Notes:
[A]*Sr* = repeatability standard deviation, measurement units
[B]*r* = repeatability = 2.83 × *Sr*, measurement units
[C](*r*) = repeatability, relative, (i.e., in percent)
[D]*SR* = reproducibility standard deviation, measurement units
[E]*R* = reproducibility = 2.83 × *SR*, measurement units
[F](*R*) = reproducibility)

Table 5.35 Type 1 precision: type M durometer method – ASTM D2240

Material	Within laboratories				Between laboratories		
	Mean	Sr[A]	r[B]	(r)[C]	SR[D]	R[E]	(R)[F]
1	31.8	1.26	3.58	11.24	3.76	10.63	33.41
2	40.8	1.14	3.23	7.90	2.47	7.00	17.13
3	54.0	0.975	2.76	5.11	2.38	6.73	12.46
4	62.8	0.782	2.21	3.52	2.24	6.34	10.10
5	70.9	0.709	2.01	2.83	0.974	2.76	3.89
6	80.6	1.696	4.77	5.92	1.61	4.56	5.65
7	87.7	1.15	3.25	3.71	2.63	7.45	8.50
8	32.4	0.947	2.68	8,26	3.64	10.29	31.73
9	41.8	0.797	2.26	5.40	2.23	6.31	15.11
10	53.3	0.669	1.89	3.55	2.29	6.49	12.17
11	63.2	0.485	1.37	2.17	2.19	6.20	9.80
12	69.6	0.737	2.09	3.00	0.99	2.80	4.02
13	78.3	0.784	2.22	2.84	1.04	2.94	3.75
14	87.6	1.121	3.17	3.62	2.65	7.49	8.55
15	34.1	0.85	2.40	7.05	1.84	5.20	15.25
16	42.3	0.635	1.80	4.25	1.20	3.39	8.01
17	54.6	0.56	1.59	2.90	2.15	6.09	11.15
18	62.9	1.12	3.17	5.04	1.47	4.16	6.61
19	70.3	0.689	1.95	2.77	0.944	2.67	3.80
20	81.7	0.483	1.37	1.67	1.10	3.10	3.80
21	97.9	0.879	2.49	2.83	2.07	5.86	6.67
Average	61.4						
Pooled values		0.924	2.62	4.26	2.146	6.07	9.89

Notes
[A]Sr = repeatability standard deviation, measurement units
[B]r = repeatability = 2.83 × Sr, measurement units
[C](r) = repeatability, relative, (i.e., in percent)
[D]SR = reproducibility standard deviation, measurement units
[E]R = reproducibility = 2.83 × SR, measurement units
[F](R) = reproducibility, relative, (i.e., in percent)

Table 5.36 Durometer selection: typical uses (Notes 1, 2, and 3)

Type (scale)	Typical examples of materials tested	Durometer hardness (typical uses)
A	Soft vulcanized rubber, natural rubber, nitriles, thermoplastic elastomers, flexible polyacrylics and thermosets, wax, felt, and leathers	20-90A
B	Moderately hard rubber, thermoplastic elastomers, paper products, and fibrous materials	Above 90A and below 20 D
C	Medium-hard rubber, thermoplastic elastomers, medium-hard plastics, and thermoplastics	Above 90 B and below 20D
D	Hard rubber, thermoplastic elastomers, harder plastics, and rigid thermoplastics	Above 90A
DO	Moderately hard rubber, thermoplastic elastomers, and very dense textile windings	Above 90C and below 20D
M	Thin, irregularly shaped rubber, thermoplastic elastomer, and plastic specimens	20–85 A
O	Soft rubber, thermoplastic elastomers, very soft plastics and thermoplastics, medium-density textile windings	Below 20 DO
OO	Extremely soft rubber, thermoplastic elastomers, sponge, extremely soft plastics and thermoplastics, foams, low-density textile windings, human and animal tissue	Below 20 O
CF	Composite foam materials, such as amusement ride safety cushions, vehicle seats, dashboards, headrests, armrests, and door panels	See test Method F 1957

Notes: Durometer selection guide
1. The durometer selection guide is designed to assist in the selection of the proper durometer type for various applications
2. It is generally recognized that durometer hardness determination below 20 and above 90 are unreliable. It is recommended that the next lower or higher type (scale) be used
3. It is also recommended that, whenever possible, an operating stand be employed in performing durometer hardness tests

Table 5.37 Shore durometer (rubber) hardness conversion – ASTM D2240

Indicated value	Type A, B, E, O	Type C, D, DO	Type M	Type OO, OOO	Type OOO-S
0	0.55	0	0.324	0.203	0.167
10	1.3	4.445	0.368	0.294	0.343
20	2.05	8.89	0.412	0.385	0.520
30	2.8	13.335	0.456	0.476	0.696
40	3.55	17.78	0.5	0.566	0.873
50	4.3	22.225	0.544	0.657	1.049
60	5.05	26.67	0.589	0.748	1.226
70	5.8	31.115	0.633	0.839	1.402
80	6.55	35.56	0.677	0.93	1.579
90	7.3	40.005	0.721	1.02	1.755
100	8.05	44.45	0.765	1.111	1.932
N/durometer unit	0.075	0.445	0.0044	0.00908	0.01765
Spring calibration tolerance	± 0.075 N	± 0.4445 N	± 0.0176 N	± 0.0182 N	± 0.0353 N

Durometer spring force calibration *(1)* – all values are in N
Note *(1)* Refer to ASTM D2240, 5.1.1.3 for the Type *xR* designation (*Presser Foot*–flat circular)

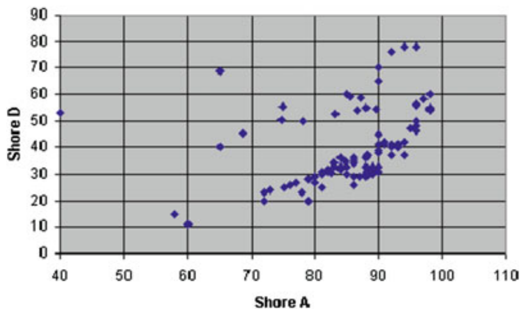


Figure 5.22 Comparison of shore A and shore D. (Source: Matweb.com – Matweb report, 2012)

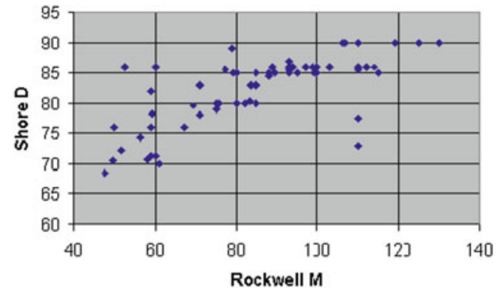


Figure 5.23 Comparison of shore D and Rockwell M. (Source: Matweb.com – Matweb report, 2012)

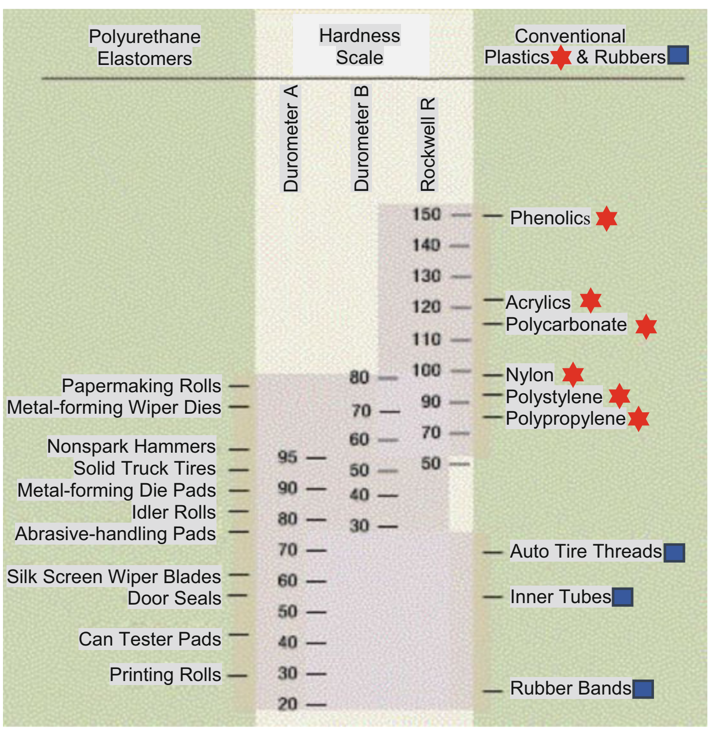


Figure 5.24 Comparison of several nonmetallic materials. (Source: Matweb.com – Matweb report, 2012)

5.4.2 Metallurgy Analysis

1. Micro Structure Analysis – ASTM E407
2. Macro Structure Analysis – ASTM E340 and E381
3. Sulfur Print (Baumann Print) Test – ASTM E1180
4. Temper Embrittlement Test (Step Cooling Test) – API RP934A and User's Specification
5. Molybdenum Checking on 304 SS (no Mo) and 316 SS (2–3% Mo) – ASTM STP 550, PMI, and XRD

5.4.3 Inspection of H/EX Tubes

There are several inspection methods as below. Figure 5.25 shows simplified corrosion types on tubes of H/EX. See Table 2.138 for more detail corrosion mechanisms and remedy and Table 5.40 for NDT methods.

5.4.3.1 IRIS (Internal Rotary Inspection System)

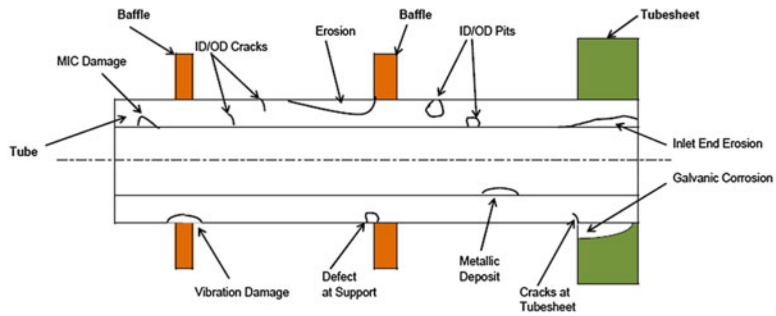
IRIS consists of a high-frequency ultrasonic immersion probe inside a rotating test head used to examine tubes for internal/external corrosion or erosion damage. It can accurately measure remaining wall thickness in most instances. The characteristics are below:

– Inspection, typically 70–100 tubes per shift
– Can test all of the tube (straight lengths only)
– Applicable to most materials
– Accurate wall thickness measurement
– Sensitivity – 1.5 mm diameter, 5% loss (variable with tube size/cleanliness)
– Not affected by baffle plate/tubesheet
– Tube has to be flooded
– Bore surface has to be very clean
– Cannot detect cracks
– Requires 110/240 volt power supply and potable water supplies

5.4.3.2 ECT (Eddy Current Testing)

This is an electromagnetic technique for the rapid inspection of nonferromagnetic tubes and is capable of detecting internal and external defects. An Eddy Current field is induced in the tube under test, and defects present will influence the characteristics of this field. The characteristics are below:

– High detectability for all nonferromagnetic materials
– Inspection, typically 500–1000 tubes per shift



Type of Tube Defects	Characteristics and Causes
ID/OD Pitting :	This is the most common form of damage in copper alloy tubing
ID/OD Cracks :	Cracking can be present in any tube material (by corrosion and vibration)
Erosion Inside:	Caused by increased flow rate due to fouling
Inlet End Erosion:	Caused by turbulent flow and high velocity at the Tube Inlet
Vibration Damage:	Occurs between supports (wearing and crack)
Cracks at Tubesheet:	Caused by high stresses
Defect at support:	Pitting or crack due to crevice or wearing
MIC:	At untreated water/stagnant flow on stream and shutdown
Metallic Deposits:	Produce signals that can be miscalled as defects
Dew Point Corrosion:	Dew point corrosion at the border line of liquid and vapor
Under Deposit Corrosion:	Deposit and stagnant flow

Figure 5.25 Typical corrosion types occurred on tubes

- Computerized analysis
- Can be used as a standalone technique
- Cleanliness is less critical than for IRIS
- Bends can be tested using special probes
- Cracking is detectable
- Less accurate than IRIS
- Can only be applied to nonferromagnetic tubes
- Reference tube of same size and specification as tubes under test required
- May require IRIS backup for critical applications
- Defects close to the tubesheet are difficult to detect
- Requires 110/240 volt power supply

5.4.3.3 RFECT (Remote Field Eddy Current Testing)

This is an electromagnetic technique for the inspection of ferromagnetic tubes. The technique is based on measuring the amplitude and phase lag of the remote Eddy Current field. The technique has good detection and measurement capability for general thinning, but sensitivity to pit-type defects can be more limited. The characteristics are below:

- Inspection, typically 500 tubes per shift
- Equally sensitive to ID and OD defects
- Computerized analysis
- Good for general wall losses
- Phase plane analysis allows estimation of wall loss
- Cleanliness not critical
- Sensitivity to pitting can be limited (material and tube size dependent)
- Speeds typically from 0.1 to 0.5 m/s
- Faster than IRIS but slower than other electromagnetic methods
- Requires 110/240 volt power supply

The data in Table 5.38 show high detectability of ECT for nonferromagnetic materials and high detectability of IRIS for carbon steel.

Nonferromagnetic materials, such as stainless steel, titanium, brass, Cu-Ni alloys, and Inconel, should be inspected by Eddy Current Testing. ECT has high detectability and high inspection speed for nonferromagnetic materials.

Ferromagnetic materials, such as carbon steel, can be inspected by IRIS or RFECT. IRIS should be used when small pits can be expected. When the damage does not include small pits and is mainly general wall loss, then IRIS or RFECT can be used. IRIS will be more accurate but slow and require significant cleaning. RFECT will be fast and require minimal cleaning. RFECT works very well for inspection of feedwater heater tubes in power plants where the damage is general wall loss. In case of carbon steel tubes with aluminum fins, IRIS should be the preferred technique.

Table 5.38 Comparison of flaw detection performance by material – only reference

Materials	ECT	IRIS
Stainless steel	91%	28%
Titanium	98%	68%
Admiralty Brass	92%	Not tested
90Cu-10Ni	91%	Not tested
Carbon steel	67% (as RFECT)	83%

Source: MTI report, 2003

Table 5.39 Comparison of flaw detection performance by defect type – only reference

Defect type	ECT	IRIS	
Pitting	90%	67%	
Cracks	93%	Not applicable	
Thinning/wear	80%	55%	
Support wear	93%	93%	
Large volume flaw	88%	72%	
Small volume flaw	90%	67%	

Source: MTI report, 2003

The data in Table 5.39 shows high detectability of ECT for small defects such as cracks, pits, etc., and also clearly shows that while IRIS is a good tool for detecting tube thinning and wear, it fails to detect common damage types in nonferromagnetic materials. IRIS will fail to detect cracks in SS, brass, Hastelloy, and Inconel; MIC damage in stainless steel; pin holes in titanium, etc.

5.4.3.4 DINSEARCH™ (Magnetic Bias)

This is an electromagnetic technique for the rapid inspection of ferromagnetic tubes and is capable of detecting internal and external defects. Conventional Eddy Current techniques cannot be applied to ferromagnetic tubes due to their high magnetic permeability that results in low field penetration and high noise levels. This technique relies on partial magnetic saturation of the tube using electromagnets. The presence of defects in the tube causes variations in magnetic flux density that are detected using Eddy Current sensors. The technique can provide an indication of tube condition, but wall loss measurement capability is very limited. The characteristics are below:

- Inspection, typically 500–1000 tubes per shift
- Ferromagnetic materials can be inspected
- Cleanliness is less critical than for IRIS
- Poor wall thickness measurement capability
- Calibration tube required
- IRIS backup is essential in most cases
- To be used as a screening tool only
- Will not detect generally thinned tubes
- Requires 110/240 volt power supply

5.4.4 *Specific Test and Inspection*

Table 5.40 shows the typical NDT methods and the capabilities according to flaw types and sizing in H/EX tubing.

Table 5.40 NDT methods and the capabilities according to flaw types and sizing in H/EX tubing

Defect/Tech	ECT	ECA	FSECT	IRIS	RFT	RFA	NFT	NFA	MFL(4)	MFLA	PSEC
ID general wall loss	B	A	B(1)	A	B(2)	B	A	A	B	B	B
OD general wall loss	B	A	B	A	B	B	D	C	B	B	B
ID pitting	B	A	B	C	B	B	B	A	B	A	C
OD pitting	B	B	B	B	C	C	D	D	C	A	C
ID grooving	A	B	A	A	A	A	A	A	A	A	A
Galvanic corrosion	B	A	C	B	B	B	D	C	B	A(3)	B
ID erosion	B	A	B	A	A	A	A	A	A	A	B
OD erosion/impingement	B	A	B	A	A	A	D	D	B	A(3)	C
Cracking (Circ.)(5)	C	A	C	C	C	C	C	A	B	B	C
Cracking (axial)	C	A	C	D	C	C	C	A	C	A	C
OD baffle wear (fretting)(5)	A	A	A	A	B	B	C	C	A	A	C
Vibration damage (tube/tube, tube/shell) (5)	B	A	B	A	C	C	C	C	C	B	B
Metallurgical changes (titanium Hydrite)	B	A	B	D	C	C	C	C	C	A	C
Metallurgical changes (Dealloying)	B	A	D	D	C	C	C	C	C	C	C

General Notes: Source – API RP586-Section 1 for H/EX Tubing Inspection. 500 series, 600 series. Appendix B-3

a. Individual sensor arrays provide independent circumferential position and extend flaws in a C-scan data image. Greater flaw sizing of isolated flaws and circumferential cracking (if applicable)

Abbreviations: *ECT* Eddy Current testing, *ECA* Eddy Current array, *FSECT* full saturation Eddy Current testing, *IRIS* internally rotating inspection system, *RFT* remote field testing, *RFA* remote field array, *NFT* near field testing, *NFA* near field array, *MFL* magnetic flux leakage, *MFA* magnetic flux leakage array, *PSEC* partial saturation Eddy Current

Notes

(1)Less effective for ID wall loss in CS

(2)Defects >20% ID wall loss

(3)Preferred for subtracting CS support responses

Commentary Notes: (4)Effective for thickness measurement of the storage tank bottom plate through UT technique. (5) Only for reference

Legend

NDT method flaw detection rank	Descriptions
A: Highly effective	The best flaw sizing option
B: Effective	A commonly used flaw sizing option
C: Less effective	The least capable flaw sizing option
D: Not effective	Not recommended unless a proven application within ranks A–C

5.4.4.1 Measurement of Thickness on Stream – Fig. 5.26

The TML (thickness measurement locations) and the windows should be selected at the design stage of the facilities. The historical records should be the primary consideration to select the TML. Also, consideration should be given to the type of component (e.g., straight run pipe, elbow, tee, or reducer) and its orientation which are susceptible to internal and external corrosion and erosion. The external corrosion are greatly related with CUI (see API RP583 and NACE SP0198). In particular, corrosion mechanisms that are accelerated by increased shear-velocity effects will have an increased impact on the outside of bends or reducers. Consideration should be given to ensure a variety of components are selected for monitoring, as well as certain susceptible areas, such as turbulent regions, phase separation areas, water pockets, or deadlegs. See Sect. 5.3.2.2 for thickness measurement techniques with UT.

5.4.4.2 Inspection for CUI on Stream

The most susceptible areas of CUI may be the lowest points as well as the end of the insulation. Some experience indicates the smaller piping are more susceptible to CUI than large bore piping. See Sect. 2.4.2.13 for more detail information for CUI. The following are the most common current techniques to measure the CUI:

- Guided Wave Examination Method (GWT) (See API RP583 and Fig. 5.27)
- X-Ray (Profile Radiography) (See API RP583)
- X-Ray (Film Density Radiography) (See API RP583)
- X-Ray (Radiometric Profiling)
- X-Ray (Real-Time Radiography Examination Method)
- X-Ray (Computed and Digital Radiography – CR and DR)
- Pulsed Eddy Current Method
- Neutron Backscatter Examination Method
- Thermal/Infrared Imaging Examination Method (See Fig. 5.28)
- Crawling Robet System (for storage tanks and vertical type pressure vessels)

Figure 5.26 UT sensors installed in the piping. (Source: Inspectioneering Journal, p1–6, Jan./Feb. 2016)

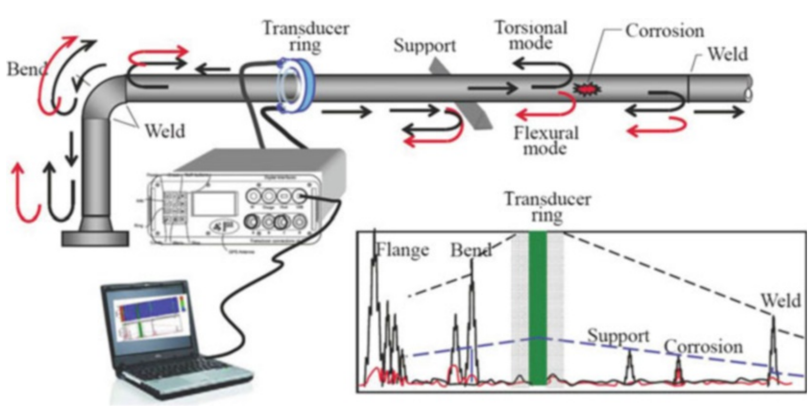


Figure 5.27 Schematic of Guided Wave Examination Method (source: NACE paper 13-2570)

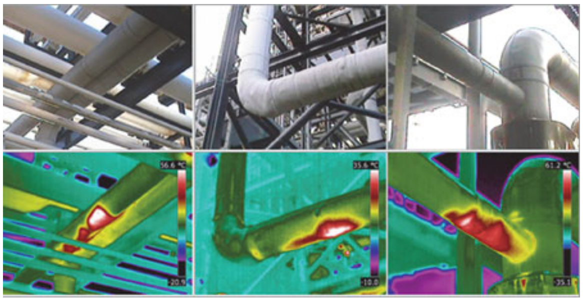


Figure 5.28 Thermal/infrared imaging examination method. (Source: API RP583)

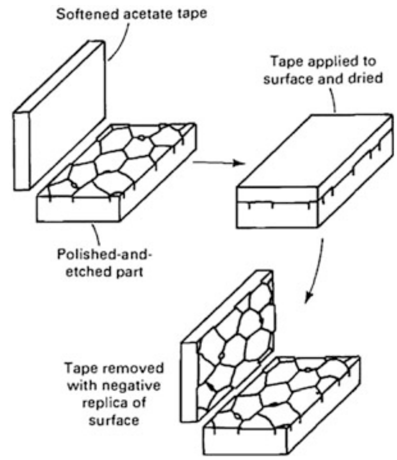


Figure 5.29 Schematic of the plastic replica technique. (Source: ASM Metal Handbook, Vol. 17, Replication Microscopy Techniques)

5.4.4.3 Inspection for Hot Spot on Stream

In case of most common practice, the failure of refractory lining or heat tracing control as well as deposit of coke may create the hot spot of the metal surfaces. The thermal/infrared imaging examination method in Fig. 5.28 is the most common current technique to detect the hot spot on the surfaces of equipment, piping, heaters, and boilers. This method has the following characteristics:

– Rapid method to detect damaged or wet insulation
– Noninvasive, noncontact method that does not require direct access to the insulated surface (i.e., can be done from ground level without scaffolding)
– Easy-to-use method to highlight areas requiring inspection follow-up

5.4.4.4 Replica Tests (Fig. 5.29)

Replication is a nondestructive sampling procedure which records and preserves the topography/microstructures of a metallography specimen as a negative relief on a plastic film when the actual testing material cannot be relocated to a lab and/or sampled in field. The microstructural replica can be examined using a light microscope (LM) or scanning electron microscope (SEM) for subsequent analysis. Specimens examined in the SEM are vacuum coated with vaporized carbon or a suitable metal to provide contrast and conductivity. The convenience of the replication process makes it suitable for obtaining microstructures from field locations for subsequent examination and analysis in a lab. The proper preparation of the test surface and of the replica itself is of paramount importance and must receive careful attention.

Because of the diversity of metallographic equipment available and the wide range of environments in which replication is conducted, the preparation of replicas of high quality should be viewed as a skilled process for which there exists a variety of techniques that achieve satisfactory results. All replicas are normally prepared in accordance with the replication technique outlined in ASTM E1351. Table 5.41 shows the comparison of several replica techniques and materials.

IRIS (Internal Rotary Inspection System), LOTIS®, etc. for Tube Internal Surfaces and Smart Pigging, InVista®, etc. for Pipe/Pipeline Internal Surfaces may be used instead of relica test.

5.4.4.5 Scooping Tests (Fig. 5.30)

A using subsize specimens (boat sample) cut from small scoop samples of the existing fixed facilities in support of remaining life assessments may be used for mechanical tests, hardness test, toughness tests, corrosion test, and fatigue tests. Once all test results are acceptable, the scooped areas should be deposited and recovered completely by welding before the reuse.

Table 5.41 Comparison of replica techniques and materials

Types	Advantage	Disadvantage
Surface replicas		
Acetate	Excellent resolution	Coating required
Acrylic	Direct viewing	Adhesion
Rubber	Easy removal	Resolution
Extraction replicas		
Direct stripped plastic	Easy preparation	Particle retention
Positive carbon	Excellent particle retention with two-stage etching	Coating required
Direct carbon	Excellent resolution	Not applicable to in situ studies

Source: ASM Metal Handbook, Vol. 17, Replication Microscopy Techniques

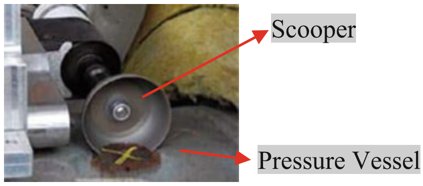


Figure 5.30 Scooping test

Figure 5.31 Hoop and axial strain gauge installed on a coke drum

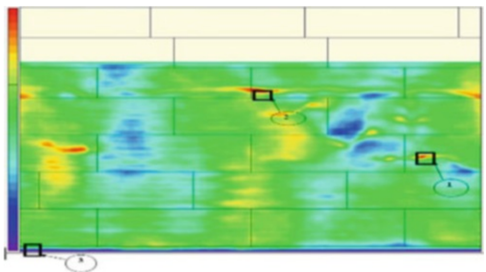


Figure 5.32 Strain gauge locations and the records

5.4.4.6 Continuous Measurement of Strain Gauges

Figures 5.31 and 5.32 show the strain gauges which are uniaxial resistive element sensors attached to the outer wall of a coke drum. As they are stretched or shortened, their resistance changes, and the Wheatstone Bridge circuitry converts this to an output voltage which can be scaled as micro-strain. A data logger records these signals, as well as associated temperature. Because of the hazardous conditions of coke drum service, all sensor leads from the data logger must be protected with intrinsically safe electronic barriers to prevent sparking at the vessel. If only a few cycles are to be recorded in conjunction with AE monitoring, the system is usually allowed to operate with Hot Work Permitting requiring regular testing for combustible gas.

Strain gauge measurements at a single location will be influenced by local conditions as well as global conditions. Variations can create unusually large stress due to local hot or cold spot zones created by water channeling between the solidified coke mass and the vessel wall. This local activity combined with local bulge geometry produces variations in principal stress associated with hoop and axial directions. Some cycles can produce tensions and others compression of either component. When one principal stress is tension and the other compression, biaxial shear develops with a stress intensity greater than either principal stress.

Low cycle fatigue is a function of the cyclic range of the stress intensity.

Consequently, measurement of only one component such as the axial strain can mislead the interpretation of the cycle severity. Both hoop and axial strain measurements should be measured, corrected for temperature, calculated as principal stress, and combined as stress intensity. When a significant number of cycles are recorded, the variation of stress at a location can be represented as a histogram with high and low stress occurrences represented as the extremes of the histogram.

5.5 Hydrostatic (Hydrotest), Pneumatic, Vacuum, and Cryogenic Tests

This section is for introduction of conventional test methods for hydrostatic (hydrotest), pneumatic, vacuum, and cryogenic tests of the pressure components in oil and gas industries. See Sect. 1.3.6 for MPT (minimum pressurizing temperature).

5.5.1 Principle Concept of Hydrostatic and Pneumatic Tests (Table 5.42)

5.5.2 Requirements for Hydrostatic and Pneumatic Tests

5.5.2.1 Characteristics and Comparison of Hydrostatic and Pneumatic Test (Table 5.43)

5.5.2.2 Hydrotest

(a) Maximum Hydrotest Pressure (Recommendation for Safety)
    The test pressure shall not exceed the maximum test pressure for any vessel, pump, valve, or other components in the system under test. A check shall be made to verify that the stress due to pressure at the bottom of vertical runs does not exceed either of the following:
    1. 90% of SMYS except 50–60% SMYS for ASTM A999 (General Requirements for Pipe Materials)
    2. ASTM B16.5 (1988 or earlier for flanges and fittings)
(b) Hydrotest Procedure (Recommendation for Safety) – See Fig. 5.33.
(c) Failure Case Studies of Hydrotest
    Figure 5.33 shows a typical hydrotest process.

Table 5.42 Types of pressure and leak test for pressure components in energy industries

Test method	Purpose	Test fluids	Remark
Proof-pressure test (or hydrostatic test)	To prove no-permanent deformation (mainly) and no-leakage	Mainly water or suitable nontoxic liquid. Codes also allow to use gases as a pneumatic test for low pressure applications and vessels having low volumetric capacity.	For pressure vessels, pipe materials, and pipelines
Hydrostatic leak test	To prove no-permanent deformation and no-leakage (mainly)	Water or nonflammable and nontoxic liquid	For piping and fittings
Pneumatic leak test	Leak test to prove no-leakage or the permitted leakage Special application for telltale hole*: Lower test pressure is applied for leak detection	Nonflammable and nontoxic gases, such as air, nitrogen, helium, or any permitted gas	For piping and pressure vessels *see Sect. 3.3.3 in this book
Hydrostatic-pneumatic leak test	A combination hydrostatic-pneumatic leak test	Requirements to be per hydrostatic leak test (pressure) and pneumatic test (fluids)	For piping
Initial service leak test	If the hydrotest and pneumatic test are not available, this test only for nonflammable and nontoxic service may be applied at end-user's option	Actual service	For piping
Bubble test	This method consists of pressurizing the component (e.g., expansion joints) and watching for escaping bubbles. A stream of bubbles originating from any isolated point shall be interpreted as a leakage. Standards designate the maximum permitted leakage rate (e.g., ASME B31.3: Max. 0.001 ml/sec). Also, applicable for leakage test of tank bottom plate	The test component (e.g., expansion joints) usually charged with dry air or N2 gas Or submerging it into a water (or detecting liquid) tank	Sensitive leak test See ASME Sec. V, Article 10, Appendix I or others

General Notes: The test pressure is related with allowable stresses, MAWP, DP, or required pressure per standard
The test fluid temperature shall be maintained to avoid brittle failure during testing

Table 5.43 (1/3) General comparison and the requirements of hydrostatic and pneumatic test

Item	Hydrotest	Pneumatic/Leak test	Remark
Purpose	Pressure test to prove no-permanent deformation and no-leakage.	Leak test to prove no leakage or permitted leakage. Also has a function to detect very fine leak paths which may not be found in hydrostatic test.	
Limitation for application	Mostly for moderate and high pressure applications.	Mostly for low pressure applications and vessels having low volumetric capacity.	
Test media	Water or suitable nontoxic liquid (flash point ≥39 °C (102 °F) for flammable fluids). Test media used is not compressible by pressure application.	Air, N_2, Ar, and He (nontoxic & nonflammable) are used for pneumatic test. Test media used is compressible by pressure application. *10	
Energy stored per unit volume	Energy stored per unit volume of water under pressure is very negligible.	Energy stored per unit volume of compressed air is very high.	At the same test pressure
What is proved?	To prove the strength of equipment.	Mainly to prove the leak test on equipment which have already proved their strength by hydrotest. However, ASME codes also allow to apply a pneumatic test in lieu of hydrostatic test for low pressure applications & vessels having low volumetric capacity.	
After test	Needs dry cleaning after test to eliminate moisture especially for services which are reactive to moisture/fluids.	Easy to clean after testing.	
Pressure relief	Pressure relief valves are recommended to control sudden increase in pressure during testing.	Pressure relief valves should ensure no overpressurization during pneumatic test.	
Safety distance	Needs less safety distance to cordon off from man entry during testing.	Needs large area to be cordoned off during testing as accidental release of pressure travels long distance due to high energy stored.	
Damage of facility failure	Low.	High due to large amount of stored energy.	
Test weight of equipment	Weight of equipment with test medium as water is high, hence special attention (foundation, supports, drain, etc.) should be considered.	Weight of equipment with test medium as air is comparatively less.	
Coating, painting, and lining prior to hydrotest	*22for ASME BPVC.	*23for ASME BPVC.	

Table 5.43 (2/3) General comparison and the requirements of hydrostatic and pneumatic test

Item	Hydrotest	Pneumatic/Leak test	Remark
Cautions before testing	Needs verification and examination of joints and connections before testing.	Needs very careful and specific checking of weld joints (opening and attachments) thoroughly before testing (see ASME Sec. VIII, Div. 1, UW–50 for more detail.).	
Personnel skill	Skilled and semiskilled personnel can carry out test.	Needs involvement of senior experienced staff to monitor test.	
Recommended volume	Recommended where large volumes are to be tested at the same time (e.g., pipelines).	If pipe lines are tested, it should be done with small segmental lengths at a time.	
Magnitude of damage	Damages due to failures are less Compared to failures in pneumatic testing.	Damages due to failure in testing are very huge and extensive.	
Others	It is a regular practice and safe procedure and can be followed in any work site.	Needs special attention and safety precautions.	Others
Min. hydrotest Pressure pipe ASTM A999	Each length (random) to be tested per A999. $P = 2S_T/D$ or $S = PD/2\,t$	Alternative test: Nondestructive electric test per the A999.	For bulk pipe materials
Min. hydrotest Pressure Sec. VIII, Div. 1 *General*	1.3 × MAWP × S_T/S [*2] [UG-99 [*1 *3 *13]]	1.1 × MAWP × S_T/S [*3] [UG-100 [*14]] except enameled vessels. The NDE[*12] shall be performed per UW-50.	Detected by strain (deformation) and cracking (fracture) as well as leaking.
Min. test pressure & holding time Sec. VIII, Div. 1	1.4 × D.P at 65 °C (150 °F) for minimum 15 minutes holding [ULT-99 [*13]].	1.2 × D.P at 65 °C (150 °F) for minimum 15 minutes holding [ULT-100 [*14]].	Materials having higher allowable stresses at low temperature.
Min. Test pressure Sec. VIII, Div. 1 *Cast Iron*	[UCI-99 [*13]] standard 2.0 × MAWP for MAWP>30 psi 2.5 × MAWP (bur max.60 psi) for MAWP<30 psi	–	STD hydrotest
Test to destruction Sec. VIII, Div. 1 *Cast Iron*	[UCI-101] MAWP to destruction $P_R = \frac{P_B}{6.67} \times \frac{(\text{SMTS})}{(\text{avg.T.S of test specimen})}$	–	P_B = destruction test pressure P_R = MAWP at operating temperature
Min. Test pressure Sec. VIII, Div. 1 *Cast ductile Iron*	2.0 × MAWP × S_T/S [*2] [UCD-99 [*13]]	–	
Test to destruction Sec. VIII, Div. 1 *Cast ductile Iron*	[UCD-101] MAWP to destruction $P_R = \frac{P_B f}{5} \times \frac{(\text{SMTS})}{(\text{avg.T.S of test specimen})}$ f = casting quality factor as defined in UG-24, which applies only to identical cast ductile iron vessels put into service	–	P_B = destruction test pressure P_R = MAWP at operating temperature
Min. Test pressure Sec. VIII, Div. 2 General	$P_T = \gamma$ min MAWP or $\gamma_{ST/S}$·MAWP (S_T/S) [*13 *20] [Sec. VIII, Div. 2, 8.2] [*21]	$P_T = \gamma$ min MAWP or $\gamma_{ST/S}$·MAWP (S_T/S) [*14 *20]	Dew point control required [Sec. VIII, Div. 2, 8.3]
Min. Test pressure Sec. VIII, Div. 3 General	1.25 × D.P × S_T/S [KT-3 [*8 *13]]	–	See code para. KT-312 for the upper limit for the test pressure
Min. Test pressure Sec. VIII, Div. 3 CRPV prototype	1.25 × D.P or 1.5 × service or working pressure, whichever greater [KT-3 [*8 *13]]		
Min. Test pressure Sec. I Boilers (general)	1.5 × MAWP at ambient, min. 20 °C (70 °F) and max. 50 °C (120 °F) [PG-99] [*9]	1.25 × D.P [PG-73.5.1]	See PW-54 for welding and NDE before/after hydrotest
Min. Test pressure Sec. I Miniature boilers	1.5 × MAWP at ambient, min. 15 °C (60 °F) provided shell thickness is <10 mm or 300 series SS or SA-53-E/S, SA-106, SA-516, SA-105, SA-234 [PMB-21]	–	
Min. Test pressure Sec. I electric boilers	Same as PG-99 or PMB-21 [PEB-17]	–	
Min. Hydrostatic-leak test pressure B31.3 [*4 *5] *Process piping*	1.5[**] × D.P × S_T/S (but S_T/S < 6.5) for min. 10 minutes [[**] 1.25 for high pressure piping in chap. IX]	1.1 × D.P [*6 *7] (max. 1.33 × D.P)	Detected by leaking mainly at flanges gasket face, welds, fitting, bends, etc.
Min. Hydrostatic-leak test B31.1 *Power piping*	1.5 × D.P × S_T/S for min. 10 minutes; not exceeding the maximum allowable test pressure of any non-isolated components	1.2 to1.5 × D.P for min. 10 minutes	Detected by leaking mainly at flanges gasket face, welds, fitting, bend parts, etc.

Table 5.43 (3/3) General comparison and the requirements of hydrostatic and pneumatic test

Item	Hydrotest	Pneumatic/Leak Test	Remark
Min. Hydrostatic-leak test B31.8 *Gas transmission and distribution piping*	1.25 × MAOP for installed pipeline system, 1.4 × MAOP for offshore platform piping and offshore pipeline risers	–	Holding time: min. 2 hours for piping*19 for transportation of line pipe
Test procedure API RP1110 Pressure testing of steel pipelines	General test procedure	–	For transportation of gas, petroleum gas, hazardous liquids, highly volatile liquids or CO_2
Min. Test pressure API RP1111 Offshore (pipelines, flowlines, flowline risers, gas lines)	$Pt \leq fd\ fe\ ft\ Pb$ $Pd \leq 0.80\ Pt$ $Pa \leq 0.90\ Pt$ ∗15, ∗16	–	For production and transportation of hydrocarbon liquids, gases, and mixtures of these hydrocarbons with water
Min. Test pressure API RP14E offshore production platform pipelines	Same as ASME B31.3 except below *17	Same as ASME B31.3 except below *18	
Min. Test pressure API 560 *9	1.5 × D.P × S_T/S_m	430 kPag (60 psig) or 15% of MAWP, whichever is less, for min. 15 minutes∗	∗A bubble surfactant shall be applied to weld seams to aid visual leak detection
Min. Test pressure API 620, 7.18 Appendix Q.8	@ smaller pressure of 2psig or 50% D.P in the vapor space above water level	@ 1.25 × D.P in the vapor space above water level (for 1 hour holding)	@ 15 psig for repads Min. 3 psig for vacuum test of bottom plates
Min. Test pressure API 610 *Centrifugal Pumps*	1.5 × MAWP	–	To be leak-free to the max. Operation conditions.
Testing for mass-produced pressure vessels	ASME Sec. VIII, Div. 1, Appendix 35–7	ASME Sec. VIII, Div. 1, appendix 35–6 *11	
RBI standards (inspection, repair, alteration, etc.) for existing facilities	API RP572 (pressure vessels), RP570 (piping in-service), RP574 (piping), RP575 (tanks), RP573 (boiler/heaters), RP576 (PRD), and ASME PCC-2 (repair of pressure equipment and piping) – They have some alternative pressure tests with different test fluids and/or no-pressure test with several other requirements		

Abbreviations: *D* OD, *t* specified wall thickness, *D.P* design pressure, *MAWP* maximum allowable working pressure, *MAOP* maximum allowable operating pressure, *MOP* maximum operating pressure, S_T stress value at test temperature of the material, *S* stress value at design temperature of the material, S_m stress value of the material at max. Metal temperature, P_R (Test Pressure) = MAWP at operating temperatures listed in Table UCI-23 of ASME Sec. VIII, Div. 1, P_B destruction test pressure, *(MS)TS* (minimum specified) tensile strength, *CRPV* Composite Reinforced Pressure Vessels, P_T minimum hydrotest pressure

Notes: Each code may have some more exceptional conditions, so find them for more detail

*1 See ASME Sec. VIII, Div. 1, 27–4 for glass-lined vessels

*2 A pneumatic test prescribed in this paragraph may be used in lieu of the standard hydrotest prescribed in code UG-99 for vessels:
- *(1)* That are so designed and/or supported that they cannot safely be filled with water
- *(2)* Not readily dried, that are to be used in services where traces of the testing liquid cannot be tolerated and the parts of which have, where possible, been previously tested by hydrostatic pressure to the pressure required in ASME Sec. VIII, Div. 1, UG-99

*3 See ASME Sec. VIII, Div. 1, Appendix 35–7 for hydrotest for mass-produced pressure vessels
See ASME Sec. VIII, Div. 1, Appendix 35–6 for pneumatic testing for mass-produced pressure vessels

*4 Where the owner considers both hydrostatic and pneumatic leak testing impracticable, Alternative Leak Test may be used if both of the following conditions apply:
- *(1)* A hydrotest would damage linings or internal insulation or contaminate a process which would be hazardous, corrosive, or inoperative in the presence of moisture or would present the danger of brittle fracture due to low metal temperature during the test
- *(2)* A pneumatic test would present an undue hazard of possible release of energy stored in the system or would present the danger of brittle fracture due to low metal temperature during the test

*5 Any other leak tests in ASME B31.3:
- Para 345.2.1 Preliminary Pneumatic Test – A preliminary test using air at no more than 170 kPag (25 psig) pressure may be made prior to hydrotesting to locate major leaks
- Para. 345.2.2(a) A leak test shall be maintained for at least 10 min, and all joints and connections shall be examined for leaks. The test pressure may be reduced, but not less than the design pressure
- Para. 345.6 Hydrostatic-Pneumatic Leak Test
- Para. 345.7 Initial Service Leak Test
- Para. 345.8 Sensitive Leak Test
- Para. 345.9 Alternative Leak Test

*6 The pressure that would produce a nominal pressure stress or longitudinal stress in excess of 90% of the YS of any component at the test temperature

*7 See ASME B31.3, para. 345.6 for combination hydrotest-pneumatic leak test

*8 Combination for exemption of hydrostatic criterion (ASME Sec. VIII, Div. z3, Table KD-230.3)

Ratio of hydrotest pressure to design pressure	Ration of YS/TS
1.25	≥0.72
1.30	≥0.76
1.35	≥0.82
1.40	≥0.88

*[9] The maximum test pressure shall be limited to the extent that the weakest component SHALL NOT be stressed beyond 90% of the material's yield strength at ambient temperature. If hydrotesting or pneumatic pressure testing of pressure parts is not considered practical, by agreement between the purchaser and the vendor, 100% radiography shall be performed on all welds and pneumatic leak testing shall be performed using air or a nontoxic, nonflammable gas

*[10] Air or gas is hazardous when used as a testing medium. It is therefore recommended that the vessel be tested in such a manner as to ensure personnel safety from a release of the total internal energy of the vessel. See also ASME PCC-2, Article 5.1, Appendix III "Safe Distance Calculations for Pneumatic Pressure Test" and Appendix II "Stored Energy Calculations for Pneumatic Pressure Test"

*[11] ASME Sec. VIII, Div. 1, Appendix 35–6 for pneumatic testing for mass-produced pressure vessels:

(a) The MAWP to be stamped on the vessel SHALL NOT exceed 3.5 MPag (500 psig)

(b) Materials used for pressure-retaining portions of the vessel, and for nonpressure parts attached to pressure parts by welds having a throat thickness greater than 6 mm (1/4 in.), shall be restricted to those listed in the notes of ASME Sec. VIII, Div. 1, Fig. UCS-66

(c) The following thickness limitations apply:

(1) For butt joints, the nominal thickness at the thickest welded joint SHALL NOT exceed 13 mm (1/2 inch)

(2) For corner joints or lap welds, the thinner of the two parts joined SHALL NOT exceed 13 mm (1/2 inch)

(3) ASME B16.5 ferritic steel flanges used at design metal temperatures ≥ -29 °C (-20 °F) may be used without thickness limitation

(d) The minimum metal temperature during the pneumatic test shall be maintained at least 17 °C (30 °F) above that given on ASME Sec. VIII, Div. 1, Fig. UCS-66 for the governing material classification and thickness combination in ASME Sec. VIII, Div. 1, UCS-66(a)

(e) ASME Sec. VIII, Div. 1, UW-50 NDE requirements are not applicable for mass-produced pressure vessels

(f) The pneumatic test pressure shall be at least equal to 1.3 times the maximum allowable working pressure to be stamped on the vessel, multiplied by the lowest ratio (for the materials of which the vessel is constructed) of the stress value *S* for the test temperature of the vessel to the stress value *S* for the design temperature (see ASME Sec. VIII, Div. 1, UG-21).In no case shall the pneumatic test pressure exceed 1.3 times the basis for calculated test pressure as defined in ASME Sec. VIII, Div. 1, MA 3, section 2 by more than 10%. The pressure in the vessel shall be gradually increased to not more than one-half of the test pressure. Thereafter, the test pressure shall be increased in steps of approximately one-tenth of the test pressure until the required test pressure has been reached. Then the pressure shall be reduced to a value equal to the test pressure divided by 1.3 and held for a sufficient time to permit inspection of the vessel. This inspection may be performed as a separate test. The visual inspection of the vessel at the required test pressure divided by 1.3 may be waived provided:

(1) A suitable gas leak test is applied

(2) Substitution of the gas leak test is by agreement reached between manufacturer and inspector

(3) All welded seams that will be hidden by assembly are given a visual examination for workmanship prior to assembly

*[12] The full length of the following welds shall be examined before the pneumatic test is performed, for the purpose of detecting cracks:

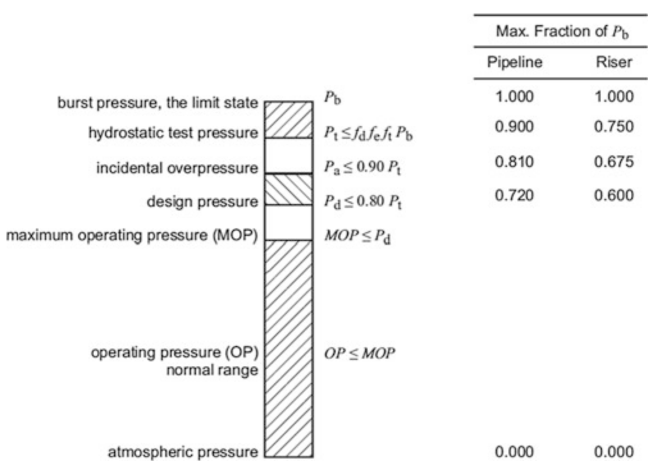
(a) All welds around openings

(b) All attachment welds, including welds attaching nonpressure parts to pressure parts, having a throat thickness greater than 6 mm (1/4 in)

*[13] To be maintained at least 17 °C (30 °F) above the MDMT, but need not exceed 48 °C (120 °F), to minimize the risk of brittle fracture

*[14] To be maintained at least 17 °C (30 °F) above the MDMT to minimize the risk of brittle fracture

*[15] Pressure level relations of offshore pipelines and risers (API RP1111, Fig. 2)



Where:

Pa = incidental overpressure (internal minus external pressure), in N/mm2 (psi)

Pb = specified minimum burst pressure of pipe, in N/mm2 (psi)

Pd = design pressure of the pipeline, (internal minus external pressure) in N/mm2 (psi)

Pt = hydrotest pressure (internal minus external pressure), in N/mm2 (psi)

f_d *= internal pressure (burst) design factor[0.90 for pipelines; 0.75 for pipeline risers]*

f_e *= weld joint factor, longitudinal or spiral seam welds [see ASME B31.4 or ASME B31.8]*

f_t *= temperature derating factor [as specified in ASME B31.8 [1.0 for temperatures less than 121 °C (250 °F)]*

*[16] Test-pressure levels

(a) pipeline: All parts of an offshore pipeline designed according to API RP1111 should be subjected to an after-construction strength test of not less than 125% of the pipeline MOP (max. Operating pressure)

(b) Flowlines and flowline risers should be subjected to hydrotest of 125% of the MOP or 111% of shut-in pressure (may result from closure of a valve at the production facility without closing the valves at the tree, manifold, or down hole safety valve. The condition may also occur due to leakage of these same valves or due to plugging of the flowline. The shut-in pressure condition should be considered unless an overpressure protection device or system is installed (refer to API RP14C).) whichever is greater

(c) Gas lines regulated under 49 *Code of Federal Regulations* Part 192 require riser sections physically connected to a platform to be tested to 150% of MOP. Regulatory agencies have indicated that SCRs connected to floating production systems can be considered an extension of the connecting pipeline, and thus for gas lines regulated under 49 *Code of Federal Regulations* Part 192, the SCR up to its hangoff point only needs to be tested to 125% of MOP

*[17]Isolation

(a) When a system is to be tested, the following equipment should be isolated:

(1) Pumps, turbines, and compressors

(2) Rupture discs and relief valves

(3) Rotameters and displacement meters

(b) The following equipment should be tested to design pressure and then isolated:

(1) Indicating pressure gauges, when the test pressure will exceed the scale range

(2) External float-type level shutdown devices and controllers, when the float is not rated for the test pressure. The float should be subjected to design pressure; and then the float chamber should be isolated from the system

(c) Check valves should be held open and block, and bleed ball valves should be in the one-half open position during testing

*[18]Test procedure

(a) The test pressure should be 1.1 times the maximum design pressure, or 689 kPag (100 psig), whichever is the lesser. To guard against brittle fracture hazards, the minimum metal temperature for all components during the test should be 16 °C (60 °F)

(b) Pressure should be gradually increased to not more than 179 kPag (26 psig), and held until all joints have been inspected for leaks with soap solution. If no leaks are found, the pressure should be increased in increments of approximately 15 psi until the final test pressure is reached. The pressure should then be reduced to 90% of test pressure, and held for a sufficient length of time to permit inspection of all joints, welds, and connections with soap solution

*[19]Any line pipe to be transported by railroad, inland waterway, or by marine transportation, shall be loaded and transported in accordance with API RP5L1 or API RP5LW. Where it is not possible to establish that pipe was loaded and transported in accordance with the above referenced recommended practice, the pipe shall be hydrostatically tested for at least 2 hours to at least 1.25 times the MAOP if installed in a Class 1 location; or to at least 1.5 times the MAOP if installed in a Class 2, 3, or 4 location. [See ASME B31.8, 840.2.2 for definition of each location class]

*[20]*For vacuum designed vessels,* the internal test pressure SHALL NOT be less than 1.43 times the difference between normal atmospheric pressure and the minimum design internal absolute pressure

β = elastic–plastic load (design) factor, 3.0 for Class 1 vessels and 2.4 for Class 2 vessels

β_T = test condition load factor for hydrostatic or pneumatic test and for Class 1 or Class 2 construction (see below Table)

γmin = minimum test condition load factor for hydrostatic or pneumatic test and for Class 1 or Class 2 construction (see below Table)

$\gamma S_T/S$ = test condition load factor considering the ratio of the allowable stress at the test condition to the allowable stress at the design condition for hydrostatic or pneumatic test and for Class 1 or Class 2 construction (see below Table)

	Pressure test factor, β_T		Minimum test condition load, γmin		Test condition load factor considering the ratio of the allowable stress, $\gamma S_T/S$	
Class	Hydrotest	Pneumatic test	Hydrotest	Pneumatic test	Hydrotest	Pneumatic test
1 & 2	0.95	0.8	1.5 β_T	1.5 β_T	1.25	1.15

*[21]A hydrostatic test based on a calculated pressure may be used by agreement between the user and the manufacturer. The hydrostatic test pressure at the top of the vessel shall be the minimum of the test pressures calculated by multiplying the basis for the calculated test pressure for each pressure element by 1.43 and reducing this value by the hydrostatic head on that element

*[22]For painting, coating, and lining prior to hydrotest (pressure test) in ASME Sec. VIII, Div. 1, UG-99:

(a) Unless permitted by the user or his designated agent, pressure-retaining welds of vessels (including casting vessels) SHALL NOT be painted or otherwise coated either internally or externally prior to the hydrotest

(b) When painting or coating prior to the hydrostatic test is permitted, or when internal linings are to be applied, the pressure-retaining welds shall first be leak tested per ASME Sec. V, Article 10. Such a test may be waived with the approval of the user or his designated agent

(c) Vessels for lethal service [see Sect. 1.1.11.2 in this book] SHALL NOT be painted or otherwise coated or lined either internally or externally prior to the hydrostatic pressure test

(d) The requirements given in above *(1)* and *(2)* do not apply to glass-lined vessels; see ASME Sec. VIII, Div. 1, 27–4

*[23]For painting, coating, and lining prior to pneumatic test in ASME Sec. VIII, Div. 1, UG-100

(a) Unless permitted by the user or his designated agent, pressure-retaining welds of vessels SHALL NOT be painted or otherwise coated either internally or externally prior to the pneumatic pressure test

(b) When painting or coating prior to the pneumatic test is permitted, or when internal linings are to be applied, the pressure-retaining welds shall first be leak tested per ASME Sec. V, Article 10. Such a test may be waived with the approval of the user or his designated agent

(c) Vessels for lethal service [see Sect. 1.1.11.2 in this book] SHALL NOT be painted or otherwise coated or lined either internally or externally prior to the pneumatic pressure test

Other Standards for Leak Testing:

EN 1593, Nondestructive testing – Leak testing – Bubble emission techniques

EN 1779, Nondestructive testing – Leak testing – Criteria for method and technique selection

EN 13184, Nondestructive testing – Leak testing – Pressure change method

EN 13185, Nondestructive testing – Leak testing – Tracer gas method

EN 1593, Bubble emission technique

EN 13185 Tracer gas method

EN 13184 Pressure change method

ASME Sec. VIII, Div. 2 states that the test pressure shall be gradually increased to 50% of test pressure (Fig. 5.33). At 50% of test pressure, a hold period (5–10 minutes is generally adequate) is recommended while the system is inspected for leaks and deformation. From the hold point at 50% of test pressure to the final test pressure, pressure should then be increased in increments of 1/tenth of test pressure with a hold period at the end of each increment. Some companies apply the pressuring rate of 100 psi/minute or less unless high pressure systems may utilize a higher rate when approved by end-user or representative.

Figure 5.34 shows failure during hydrotest in pressure vessel manufacturing shop. The root cause may come from a violation of the requirements of ASME Sec. VIII, Div. 1, UG-99 (g) as below and/or unqualified material (i.e., low toughness/ no impact tested).

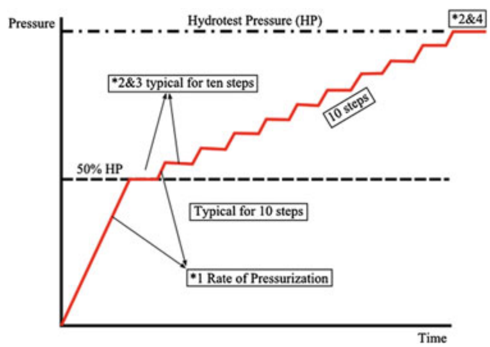


Figure 5.33 Pressurizing steps for hydrotest. *Notes**1 $\leq$ 100 psi/minute, but pressure changes faster than 10 psi/minute can introduce localized stresses in excess of the average stresses calculated. (typically $\leq$10 psi/minute in API RP1110 steel pipeline pressure testing). *2 Inspect the leaks and deformation. *3 10 steps after 50%HP: Each increase shall have 5–10 minutes holding time at the end of each increment if applied. (See ASME Sec. VIII, Div. 2, 8.3.4). *4 Holding time at HP: 15–30 minutes unless otherwise specified in the applicable codes and standards. *General Notes*: If ambient temperature is below 16 °C (60 °F), rate of pressurization should be held to 1/2 the allowable pressurization rate for each step given above

UG-99 (h): It is recommended that the metal temperature during hydrotest be maintained at least 17 °C (30 °F) above the MDMT, but need not exceed 48 °C (120 °F), to minimize the risk of brittle fracture. [See UG-20 and General Note (6) to Fig. UCS-66.2.] The test pressure shall not be applied until the vessel and its contents are at about the same temperature. If the test temperature exceeds 48 °C (120 °F), it is recommended that inspection of the vessel required by (g) above be delayed until the temperature is reduced to 48 °C (120 °F) or less.

Figure 5.35 shows longitudinal brittle fracture failure during hydrostatic leak test of pipe spool. The root cause was to using unqualified pipe material.

(d) Holding Time

See Table 5.44 for the requirements in several codes and standards.

(e) Hydrotest Requirements for Raw Materials

The raw materials, such as pipes, tubes, and fittings have individual hydrotest requirements. See below.

- ASTM A234 for Piping Fittings of Wrought Carbon Steel and Alloy Steel for Moderate and High Temperature Service
- ASTM A403 for Wrought ASS Piping Fittings
- ASTM A420 for Piping Fittings of Wrought Carbon Steel and Alloy Steel for Low Temperature Service

Figure 5.34 Failure during hydrotest in pressure vessel manufacturing shop

Figure 5.35 Failure during hydrostatic leak test of pipe spool. (Source: Hanging H Co.)

Table 5.44 Holding time[(1)] of hydrotest

Code and standards	Class of test/Paragraph	Applications/Requirements	Minimum time at full pressure
ASME sec. VIII, div. 1	ULT-100	Low temperature service	15 minutes
ASME B31.1	Hydrostatic (para. 137.4.5)	All joints and connections	10 minutes
ASME B31.3	Leak (para. 345.2.2)	All joints and connections	10 minutes
ASME B31.4	Hydrostatic (para. 437.4.1)	All joints and connections	4 hours
ASME B31.8	Hydrostatic (para. A847.4)	All joints and connections	2 hours for prefabricated piping 8 hours for pipeline
ASME B16.5	Hydrostatic (para.8.2.4)	Fitting size, NPS ≤ 2”	1 hour
		Fitting size, 2 ½” ≤ NPS ≤ 8”	2 hours
		Fitting size, NPS ≥ 10”	3 hours
API 560 & 661	Hydrostatic		1 hour
API 5 L	Hydrostatic (para.10.2.6)	D ≤ 457 mm (18 inch)	5 seconds
		D > 457 mm (18 inch)	10 seconds
API 5CT	Hydrostatic (for leaks and seats) – para 10.12.1		5 seconds

Note [(1)]Maximum Time: not specified

Table 5.45 Hydrostatic body test pressure of wellhead and Christmas tree equipment (API 6A, Table 31)

Working pressure rating		End and outlet connections											
		Nominal size of flange, mm (in)				Line-pipe and tubing threads		Casing threads, mm (in)					
		≤ 346 (13 5/8)		≥ 425 (16 3/4)				114.3–273.1 (4 1/2–10 3/4)		298.5–339.7 (11 3/4–13 3/8)		406.5–508 (16–20)	
MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)
13.8	2	27.6	4	20.7	3	27.6	4	27.6	4	27.6	4	15.5	2.25
20.7	3	41.5	6	31.0	4.5	41.5	6	41.5	6	31.0	4.5	–	–
34.5	5	51.7	7.5	51.7	7.5	51.7	7.5	51.7	7.5	–	–	–	–
69.0	10	103.5	15	103.5	15	103.5	15	–	–	–	–	–	–
103.5	15	155.0	22.5	155.0	22.5	–	–	–	–	–	–	–	–
138.0	20	207.0	30	–	–	–	–	–	–	–	–	–	–

- ASTM A450 for Carbon and Low Alloy Steel Tubes
- ASTM A530 for Specialized Carbon and Alloys Steel Pipes
- ASTM A815 Wrought FSS, DSS, MSS Piping Fittings
- ASTM A861 High Silicon Iron Pipes and Fittings
- ASTM A985 for Steel Investment Castings-Pressure Containing Parts
- ASTM A999 for Alloy and Stainless Steel Pipes
- ASTM B361 Factory-Made Wrought Aluminum and Aluminum-Alloy Welding Fittings
- ASTM B363 Seamless and Welded Unalloyed Titanium and Titanium Alloy Welding Fittings
- ASTM B366 Factory-Made Wrought Nickel and Nickel Alloy Fittings
- ASTM B462 for Forged or Rolled Nickel Alloy Pipe Flanges, Forged Fittings, and Valves and Parts for Corrosive High Temperature Service
- ASTM B824 for Copper Alloy Castings
- ASTM B829 for Nickel and Nickel Alloys Seamless Pipes and Tubes
- ASTM B775 for Nickel and Nickel Alloys Welded Pipes
- ASTM B751 for Nickel and Nickel Alloys Welded Tubes

(f) Hydrotest Requirements of Wellhead and Christmas Tree Equipment (API 6A)

Table 5.45 shows the minimum hydrotest pressure for wellhead and Christmas tree equipment.

(g) Hydrotest Requirements of Casing and Tubing Steel Pipes (API 5CT)

1. Hydrotest pressure for plain-end pipe

The hydrotest pressures for plain-end pipe are calculated using the outside diameter, wall thickness, and yield strengths and using Eq. 5.1:

$$p = 2 \times f \times YS\mathrm{m} \times t/D \qquad \text{(Eq. 5.1)}$$

where

p: the minimum hydrotest pressure, expressed in MPa
D: the specified outside diameter, expressed in mm
YSm: the yield strength, expressed in MPa

Table 5.46 Hydrostatic body test pressure of casing and tubing steel pipes (API 5CT, G.9.1)

Material grade	Label 1	Standard test		Alternative test	
		f	Max. pressure, MPa	*f*	Max. pressure, MPa
H40, J55, K55	<10 3/4	0.8	69.0	–	–
	≥10 3/4	0.6	69.0	0.8	69.0
M65, N80-type 1, N80Q, R95, L80, T95	All sizes	0.8	69.0	–	–
C110, P110, Q125	All sizes	0.8	69.0	0.8	No max.

t: the specified wall thickness, expressed in mm
f: a factor based on the size and grade of the pipe
0.6 for grades H40, J55, and K55 larger than label 1: 9–5/8
0.8 for all other grades and sizes

Table 5.46 shows the minimum hydrotest pressure for casing and tubing steel pipes. The calculated hydrotest pressures for plain-end pipe were rounded to the nearest 0.5 MPa up to a maximum of 69.0 MPa.

2. Hydrotest pressure for couplings (API 5CT and TR 5C3)
   The SI values for the maximum hydrotest pressures for couplings were calculated (not converted) using Eq. 5.2 (taken from API TR 5C3 Technical Report on Equations and Calculations for Casing, Tubing, and Line Pipe Used as Casing or Tubing and Performance Properties Tables for Casing and Tubing):

$$p_{\mathrm{m}} = 0.8 \times YS_{\mathrm{m}} \times (W_{\mathrm{m}} - d1_{\mathrm{m}})/W_{\mathrm{m}} \tag{Eq. 5.2}$$

   where:
   pm is the hydrotest pressure, expressed in MPa
   Wm is the outside diameter of the coupling, expressed in mm
   YSm is the yield strength, expressed in MPa
   d1m is the diameter, expressed in mm, at the root of the coupling thread at the plane of the end of the pipe in the power-tight position
   The calculated SI values for the maximum hydrotest pressures for couplings were rounded to the nearest 0.5 Mpa
3. Internal pressure leak resistance at E1 or E7 plane (API 5CT and TR 5C3)
   The SI values for internal pressure leak resistance at the E1 plane of round thread connections and at the E7 plane of buttress thread casing were calculated (not converted) using Eq. 5.3 (taken from API TR 5C3):

$$p_{\mathrm{LRm}} = E \times \tau \times N \times P \times \left[W_{\mathrm{m}}{}^{2} - E\mathrm{s}^{2}\right] / \left[2 \times E\mathrm{s} \times W\mathrm{m}^{2}\right] \tag{Eq. 5.3}$$

   where:
   pLRm is the internal pressure leak resistance at the E1 or E7 plane, expressed in MPa
   Wm is the outside diameter of the coupling, expressed in mm
   E is the modulus of elasticity, 207,000 MPa
   Es is the pitch diameter at the seal, expressed in mm
   E1 for round threads
   E7 for buttress threads
   N is the number of power turns
   P is the thread pitch, expressed in inches per thread
   τ is the thread taper, expressed in inches per inch
   The calculated SI values for internal pressure leak resistance limits were rounded to the nearest 0.5 MPa.
4. Hydrotest pressure for threaded and coupled pipe
   The hydrotest pressure for threaded and coupled pipe is the lowest pressure of:
   – The hydrotest pressure for plain-end pipe
   – The maximum hydrotest pressure for couplings
   – The internal pressure leak resistance

(h) Maximum allowable leakage rates for valves: See API 598, Table 6 for maximum allowable leakage rates for closure tests.

5.5.2.3 Pneumatic Test

(a) Purpose and Application of Pneumatic Test
   The following characteristics and application may be considered before the test at the initial design stage:
   – It is a well-known fact that as water cannot be compressed (Boyles law), the energy stored in a vessel under hydrostatic pressure is very less as compared to that of vessel under same pressure with air. This stored potential energy gets converted to kinetic energy at the time of rupture and that is what makes pneumatic test very dangerous.
   – It may be an alternative method of pressure test in lieu of hydrotest, allowed by codes at certain conditions, by using air or any other gas as test media.

– It is mostly recommended only for equipment already tested and proved safe by hydrostatic pressure test.
– Preferably done only for low pressure applications and vessels having low volumetric capacity.
– The test pressure is always less compared to hydrotest pressure. (pneumatic test pressure is 1.1 times of design pressure, whereas hydrotest pressure is 1.3 times of design pressure in ASME Sec. VIII, Div. 1)
– Leakages are identified by soap water application on weld joints and not by observing the pressure gauge.

(b) New requirements (2019) for welded pressure vessels before the test in ASME Sec. VIII, Div. 1, UW-50:
1. The full length of the following welds shall be examined by appropriate NDE before the pneumatic test is performed, for the purpose of detecting cracks:
(a) All welds around openings
(b) All attachment welds having a throat thickness greater than 6 mm (1/4 in.), including welds attaching nonpressure parts to pressure parts
2. The weld joint examination requirements given in *(1)* above may be waived when the MAWP of the vessel is no greater than 3.5 MPa (500 psi) and the following applicable requirement is met:
(a) For Part UCS materials, the governing thickness as defined in UCS-66(a) shall be limited to a maximum governing thickness of 13 mm (1/2 in.) for materials assigned to Curve A and 25 mm (1 in.) for materials assigned to Curve B, C, or D in Figure UCS-66.
(b) For 304, 304 L, 316, 316 L, 321, and 347 SS in Part UHA, the maximum nominal material thickness shall be 19 mm (3/4 in.).
(c) For aluminum, aluminum alloy 3000 series, aluminum alloy 5000 series, and aluminum alloy 6061-T6 in Part UNF, the maximum nominal material thickness shall be 25 mm (1 in.).

(c) Risks of Pneumatic Test

The definition of risk is to occur injury, asset loss, construction schedule impact, reputation loss, etc. The following may be major factors of the risks:
1. Air/gas used for pneumatic test is compressible to large extent and has very high potential energy stored when compressed.
2. Any minor leak path can lead to a rupture and blast within no time releasing total energy with an impact of sudden explosion.
3. Time gap between identifying a leakage and failure is very small making it almost impossible to take remedial action.
4. Damages associated with failure are uncontrollable and huge.
5. The overpressure that accompanies failure of an equipment/piping/pipeline system causes harm that is a function of the magnitude and the duration of the shock wave. Typical damage from overpressures is listed below:
   - 0.04 psig: Very loud noise [143 dB], sonic boom glass failure
   - 0.10 psig: Breakage of small windows under strain
   - 0.15 psig: Typical glass pressure-induced failure
   - 0.30 psig: 10% of windows broken
   - 0.4 psig: Limited minor structural damage to buildings
   - 0.5–1 psig: Glass shattering with body penetrating velocities
     – 0.50 psig: Windows shattered, minor damage to house structures
     – 0.7 psig: Minor damage to house structures/upper limit for reversible effects on humans
   - 1 psig: Partial damage of house structures; made uninhabitable
   - 1 psig: 95% eardrum protection with ear plugs
   - 1 psig: People knocked down with potential of significant resulting injuries
   - 2.0 psig: Partial collapse of walls and roofs of houses
   - 2.4 psig: Eardrum rupture
   - 2.5 psig: Threshold for significant human lethality
   - 3.0 psig: Steel frame building distorted and pulled away from foundation

   Therefore, the minimum safe exclusion distance (SED) in this report is defined here as a zone within a radius beyond which the overpressure from rupture of the testing system under test will not exceed 0.5 psig (0.0345 barg).

(d) Precautions as Mandatory Requirements to Minimize the Risks

The following precautions should be considered for pneumatic test:
1. When performing a pneumatic test, particular care shall be taken to avoid brittle fracture given the potential hazards of the energy stored in the compressed gas. Therefore, the decision to perform a pneumatic test shall be considered during the design of equipment/piping/pipeline so that the minimum design temperature/coincident pressure conditions for all pressure-boundary components, including any reduction in temperature and to a coincident reduction in pressure of the service fluid as the design pressure is released (auto-refrigeration), are considered when selecting the materials of construction. The MAT (minimum allowable temperature) will be lower than the MDMT (minimum design metal temperature) under the consideration of stress ratio due to auto-refrigeration (depressurization), up to -104 °C (-155 °F) as a minimum. However, care must be taken to prevent this cooling from increasing the risk of brittle fracture. Typically, blowdown rate is controlled to a low enough rate to prevent the formation of ice near the vent.
2. Comprehensive testing and safety procedures must be formalized and implemented, and documentation must be maintained certifying that all personnel involved in the testing activities have attended training sessions in which the project procedures have been reviewed. Safety procedures should include requirements that test personnel shelter to the maximum extent possible behind either heavy equipment or barricades during the tests.

3. Test procedures must clearly define the points in time during the test when test personnel are permitted to leave sheltered areas and enter the exclusion zone. Prior to proving the system at the full pneumatic test pressure, it is suggested that personnel enter the exclusion zone only when the circumferential stress in the equipment/piping/pipeline is no greater than 50% of the specified minimum yield strength (SMYS) of the equipment/piping/pipeline materials in the test system and only after prescribed holding times at such pressures. When the system test pressure results in circumferential stresses that exceed 50% SMYS, test personnel should enter the exclusion zone only after the test system has first been proven for the prescribed time period at full test pressure. Test personnel should *never* enter the exclusion zone when the test pressure exceeds the equipment/piping/pipeline system design pressure.
4. Formalized checklists must be utilized to document that pretest preparations have been completed.
5. Schedule tests at optimum times to ensure safety. The risk of injury resulting from a test system failure can be dramatically reduced by testing at night or on weekends when fewer personnel are on (and possibly off) site.
6. Materials must be procured only from manufacturers that have been determined to adhere to suitable, documented QC and production processes.
7. Materials received must be carefully checked to ensure compliance with material specifications. The material impact-tested shall be reviewed through laboratory test reports.
8. The project PMI (positive material identification) specification shall be used including carbon and low alloy steels which are to be impact tested for equipment, piping, and pipeline.
9. Pressure design calculations for both operating and test pressures must be documented and checked for all equipment/piping/pipeline systems.
10. The use of nondestructive examination (NDE) must be maximized to ensure the quality of all welded joints in the system. All pressure containing welded joints shall be 100% UT or RT tested.
11. The intended use of "golden welds" (i.e., welds that are not proven by pressure testing) to join sections of pretested equipment/piping/pipeline must be carefully reviewed to ensure guaranteed quality of the weld joints.
12. Vessels may be painted or coated either internally or externally and may be lined internally, prior to pressure testing. However, the application of paints, coatings, and linings is not permitted prior to hydrotest if the vessel is to contain fluids of such a nature that a very small amount mixed or unmixed with air is dangerous to life. The user is cautioned that the application of paints, coatings, or linings may mask leaks that would otherwise be detected during the pressure test.
13. Test Fluids

    Any pressurizing medium used in pneumatic testing shall be nonflammable and nontoxic. When compressed air is used for a pressure test, the following should be considered:
    - Use only clean, dry, oil-free air meeting the requirements of Class 1, 2, or 3 air per ISO 8573-1.
    - The dew point of the air should be between −20 °C and − 70 °C (−4 °F to −94 °F).
    - Verification that there is no hydrocarbon contamination or other organic residue within the vessel since this could result in the formation of an explosive mixture.
14. Prior to testing, test equipment shall be examined to ensure that it is tight and all filling lines and other appurtenances that should not be subjected to the test pressure have been disconnected or isolated by valves or other suitable means.
15. The limits of each test system must be clearly defined in test package documentation, and the methods of isolation (test blinds, etc.) must be well defined. Test blind designs must be checked to ensure suitability for the system test pressures. The proposed design of test systems must be checked by Bechtel inspector.
16. The metal temperature during a pneumatic test shall be maintained at least 17 °C (30 °F) above the minimum design metal temperature (MDMT) to minimize the risk of brittle fracture.
17. The test pressure shall not be applied until the equipment/piping/pipeline and the test fluid are at about the same temperature.
18. The pneumatic test in lieu of hydrotest shall be monitored by acoustic emission examination in accordance with ASME Section V, Article 12. In any case, the maximum pneumatic test pressure shall be in the safety zone (PV $\leq$ 50,000 psig.ft3) in Fig. 5.36.
19. The combined pressure test (hydrotest plus pneumatic test), such as pneumatic test containing water, is not acceptable.
20. Test pressure shall be gradually increased until one-half of the test pressure is reached after which the test pressure shall be increased in steps of approximately one-tenth of the test pressure until the test pressure has been reached in the same procedure as Fig. 5.33. The pressure shall then be reduced to a value not less than the MAWP or design pressure for leakage.
21. In addition, safe exclusion distance and stored energy shall be calculated and complied with the following paragraphs.

(e) Stored Energy Calculations for Pneumatic Pressure Test (ASME PCC-2, Article 5.1)

The intents of stored energy calculation are to define the safe exclusion distance from the tested facilities and to evaluate the risk.

The stored energy of the equipment/piping/pipeline system should be calculated and converted to equivalent kilograms (pounds) of TNT (Trinitrotoluene) using the following equations:

$$E = \int V \cdot dP = [1/(k-1)] \times Pat \times V\left[1 - (Pa/Pat)^{\{(k-1)/k\}}\right] \quad \text{(Eq. 5.4)}$$

where:

E = stored energy, J (ft-lb)

k = ratio of specific heat for the test fluid = Cv (constant volume)/Cp (constant pressure) = 1.4 for air or N_2

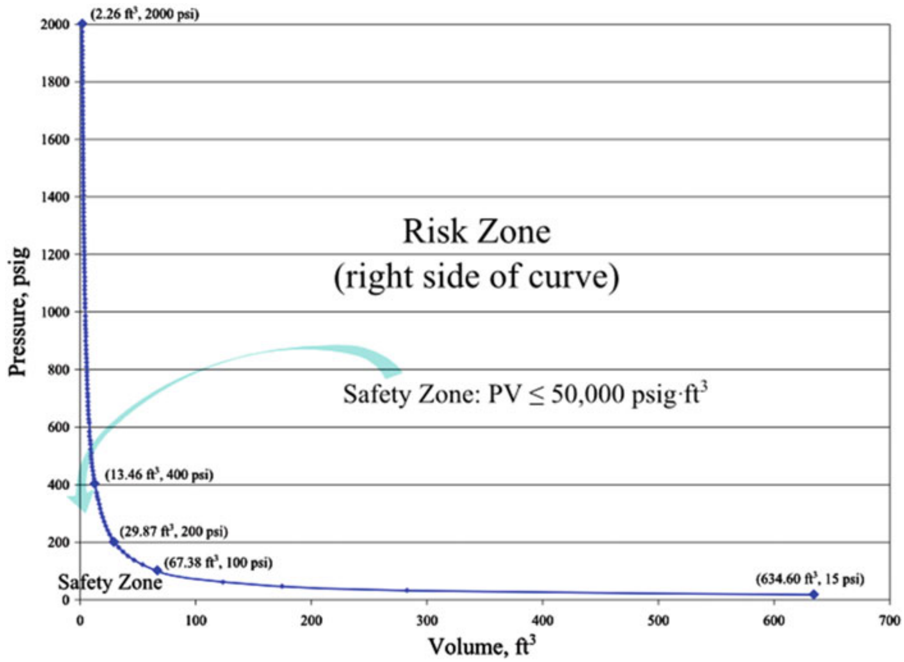


Figure 5.36 Limitation (combination by pressure x volume) of pneumatic test

Pa = absolute atmospheric pressure, 101 kPa (14.7 psia) = P_2
Pat = absolute test pressure, Pa (psia) = P_1
V = total volume under test pressure, m^3 (ft^3)
Example
What is the stored energy in 42 NPS pipe (0.5 "THK), 36 feet length, and pressurized to 7.5 psig (P = P1 = Pa = 7.5 + 14.5 = 22 psia)? V = 3.14/4 × $(41)^2$ × 36 × 12 = 570,062 $inch^3$
k = ratio of specific heat for the test fluid (Cp/Cv) = 1.4 for air
Pneumatic Test
From Eq. 5.4:

$$E = \frac{P_1 \cdot V_1}{K-1} \cdot K \cdot \left[\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} - 1\right]$$

$$= (22 \times 570,062)/(1.4-1) \times 1.4 \times \left[(14.7/22)^{(1.4-1)/1.4} - 1\right]$$

$$= 294,815 \text{ lb} - \text{ft}$$

$$\text{TNT} = \frac{E}{4\,266\,920}\,(\text{kg}) \text{ or } [\text{E} = \text{J}] \quad \text{(Eq. 5.5a)}$$

$$\text{TNT} = \frac{E}{1,488,617}\,(\text{lb})\,[\text{E} = \text{ft-lb}] \quad \text{(Eq. 5.5b)}$$

From Eq. 5.5b:
TNT = 294,815/1,488,617 = 0.198 lb
This power is equivalent that an SUV traveling at 42 mph [68 kph] has this amount of energy.
6. Safe Exclusion Distance (SED) During Pneumatic Test (ASME PCC-2, Article 5.1)
If the test will result in hoop stresses above 72% of SMYS or is above 50% pneumatic test pressure, the minimum SED as below shall be complied with:
SED ≥ 100 ft for $E \leq$ 100,000,000 ft-lb (or 30 m for $E \leq$ 135,500,000 J)
SED ≥ 200 ft for 100,000,000 < $E \leq$ 200,000,000 ft-lb (or 60 m for 135,500,000 < $E \leq$ 271,000,000 J)
When E is higher than 271,000,000 J (200,000,000 ft-lb), see ASME PCC-2, Article 5.1, formula (III-1).

(f) Acceptance Categories of Pneumatic Test Results [ASME Sec. VIII, Div. 2, 8.3.5]

1. Following the reduction of the test pressure to the level indicated in ASME Sec. VIII, Div. 2, 8.3.4(c), a visual examination for leakage shall be made. The inspector shall witness this examination. Except for leakage that might occur at temporary test closures

(a) Failure and Initiation Points in LNG Tank (b) Failure and Initiation Points in Cold Box

Figure 5.37 Failure and initiation points during pneumatic test in LNG tank terminal and cold box. (**a**) Failure and initiation points in LNG tank. (**b**) Failure and initiation points in cold box

for those openings intended for welded connections, leakage is not allowed at the time of the required visual inspection. Leakage from temporary seals shall be directed away so as to avoid masking leaks from other joints. Visual examination of the vessel may be waived provided:
- A suitable gas leak test is applied; see ASME Sec. VIII, Div. 2, 8.4.2.
- Substitution of the gas leak test is by agreement between the manufacturer and inspector.
- All welded seams that will be hidden by assembly are given a visual examination for workmanship prior to assembly.

2. Any leaks that are present, except for that leakage that may occur at temporary test closures for those openings intended for welded connections, shall be corrected, and the vessel shall be retested.
3. The inspector shall reserve the right to reject the vessel if there are any visible signs of permanent distortion.

(g) Failure Case Studies of Pneumatic Test

Figure 5.37 shows failure during pneumatic test in LNG Tank Terminal. The explosion occurred during pneumatic testing of a NPS 36 inch diameter, 600 m long line segment that had been laid out in an S shape. Target test pressure was 15.6 MPa (2262 psi), but as the system pressure reached 12.3 MPa (1784 psi), a flange at the end of the test section ruptured. The photo clearly shows a "clean" break. The root cause may be a violation of the requirements of ASME Sec. VIII, Div. 1, UG-100 as below. Also, the calculation for stored energy and safe distance (to consider blast wave distance as well as fragment throw distance) is a key to preparing a safe test package that minimizes the risk to equipment and personnel.

1. The metal temperature during pneumatic test shall be maintained at least 17 °C (30 °F) above the MDMT to minimize the risk of brittle fracture. [See UG-20 and General Note (6) to Fig. UCS-66.2.]
2. The pressure in the vessel shall be gradually increased to not more than one-half of the test pressure.

Thereafter, the test pressure shall be increased in steps of approximately one-tenth of the test pressure until the required test pressure has been reached. Then the pressure shall be reduced to a value equal to the test pressure divided by 1.1 and held for a sufficient time to permit inspection of the vessel.

Figure 5.37 shows brittle fracture failure during nitrogen pneumatic test of LNG tank terminal and cold box. The root cause was to using unqualified flange material.

Figure 5.38 shows brittle fracture failure during nitrogen pressure test of gas compressor package. The root cause was to using unqualified pipe material.

(h) References

1. ABSA AB-522 Standard Pneumatic Test Procedure Requirements, Edition 2
2. ASME PCC-2 Repair of Pressure Equipment and Piping
3. ASME Sec. I/VIII, B31.3/31.1/31.8
4. API RP1110/ RP1111/ RP14E/ 560/ 650/ 620/ 610
5. V. Edwards et al., Methods for Evaluating and Reducing the Risks of Pneumatic Pressure Testing of Vessels and Piping, Precautions in Pneumatic Pressure Testing, 2010
6. V. Edwards et al., Evaluating and Reducing the Risks of Pneumatic Pressure Testing, Chemical Engineering, Feb. 2011

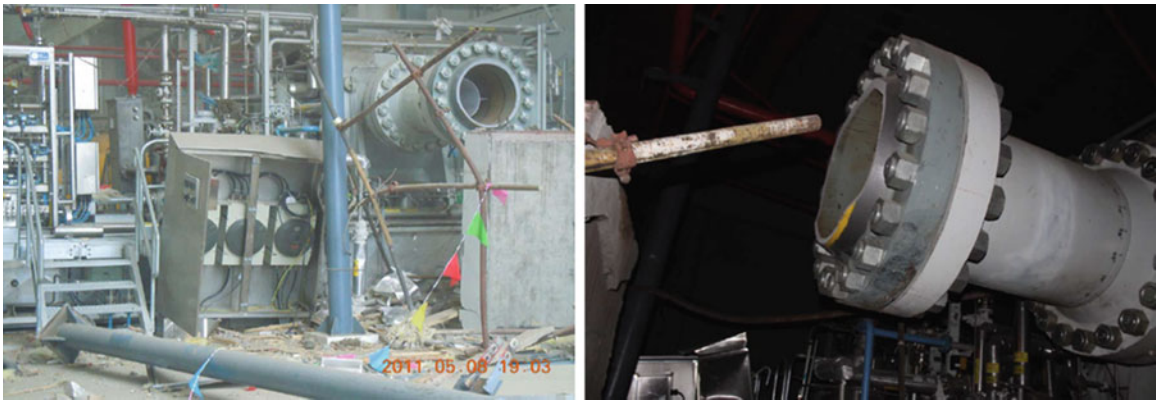


Figure 5.38 Failure during nitrogen pressure test in LNG tank terminal

5.5.3 Vacuum Test

5.5.3.1 Vacuum Test of Equipment Designed as Dewar Flask or Vacuum Pressure

The highly qualified vacuum facilities with liquefied service are required the vacuum test to confirm the maintaining of required vacuum pressure because of different dew point at day and night and/or a leakage. Normally 12–24 hour test is required as a minimum.

Also, the vacuum condition (test with negative pressure) can be used for the detection of some weld joints (e.g., large size storage tank bottom plates) which cannot be effectively tested by NDE.

5.5.3.2 Vacuum Test of Double Wall Container Designed as Dewar Flask/Boil-off Test

If the volume between the walls is filled with gas molecules at atmospheric pressure, the heat transfer across the volume is basically by the heat being exchanged between hotter and colder molecules as they collide with one another. If the molecules are removed with a vacuum pump, the number of molecular collisions drop in proportion to the pressure which can be thought of as the molecular population per unit volume. As the gas is pumped out, the thermal conductivity between the walls will fall off quickly until a pressure corresponding to molecular flow conditions is achieved.

Molecular flow is defined as a statistical condition where a gas molecule, in normal motion, will strike a wall before it strikes another molecule. Below this pressure, usually about 10 millitorr or so, changes in thermal conductivity with lower pressure still occur due to fewer molecules, but the changes occur at a lower rate. This explains, for example, why thermal conductivity vacuum gauges such as thermocouple or Pirani gauges have a useful limit only slightly below 1 millitorr.

The basic simplicity of using a vacuum space as a high performance insulator is often overshadowed by the complexity of achieving and maintaining a good vacuum level. It looks like a fairly simple exercise in vacuum technology, but there are several practical problems. The vacuum levels necessary will usually require both a roughing pump and a high-vacuum pump. Even though an oil-sealed mechanical pump can easily produce a vacuum of 10 millitorr, which is often considered adequate for some liquid nitrogen dewars, the pumping speed of mechanical pumps drops to near zero at these pressures. At higher pressures, the gas load is atmospheric gases that pump away relatively easily, but water vapor, desorbing from the walls, becomes the major component of the gas load at lower pressures.

A high -vacuum pump is required to provide enough low pressure pumping speed to deal with the desorbed water vapor. In fact, a much lower pressure than 10 millitorr is required in most dewars at the termination of the pumpdown cycle. This is especially true with liquid helium dewars. The degree of vacuum, then, is proportional to the boiling point of the cryogen. A lower boiling point requires a lower heat load, and that means a better vacuum to provide adequate insulation for an acceptable holding time.

Although a dewar is sometimes pumped continually by a high-vacuum pump, it is more common to isolate the vacuum space from the pumping system. This is usually done by a permanent "tip-off" formed by heat sealing a glass tube or pinching off a copper tube.

5.5.3.3 Vacuum Test of Tank Bottom Plate Designed as Vacuum Pressure (API 650 Tank)

Vacuum testing for the weld joints on the topside of the bottom plate is performed to detect any leaks using a testing box. During testing, illumination shall be adequate for proper evaluation and interpretation of the test. The open bottom shall be sealed against the tank surface by a suitable gasket. Connections, valves, lighting, and gauges, as required, shall be provided. A soap film solution or commercial leak detection solution, applicable to the conditions, shall be used.

The following procedure shall require:

(a) Performing a visual examination of the bottom and welds prior to performing the vacuum-box test
(b) Verifying the condition of the vacuum box and its gasket seals
(c) Verifying that there is no quick bubble or spitting response to large leaks
(d) Applying the film solution to a dry area, such that the area is thoroughly wetted and a minimum generation of application bubbles occurs

Also, the following requirements should be satisfied [1 in. Hg = 0.491153 lbf/in^2 = 25.4 torr]:

(a) A partial vacuum of 21 kPa (3 lbf/in^2 = 6 in. Hg = 152 torr) to 35 kPa (5 lbf/in^2 = 10 in. Hg) gauge shall be used for the test. If specified by the purchaser, a second partial vacuum test of 56 kPa (8 lbf/in^2, 16 in. Hg) to 70 kPa (10 lbf/in^2, 20 in. Hg) shall be performed for the detection of very small leaks.
(b) The manufacturer shall determine that each vacuum-box operator meets the following requirements:
  (i) Has vision (with correction, if necessary) to be able to read a Jaeger Type 2 standard chart at a distance of not less than 300 mm (12 in.). Operators shall be checked annually to ensure that they meet this requirement
  (ii) Is competent in the technique of the vacuum-box testing, including performing the examination and interpreting and evaluating the results; however, where the examination method consists of more than one operation, the operator performing only a portion of the test need only be qualified for that portion the operator performs.
(c) The vacuum-box test shall have at least 50 mm (2 in.) overlap of previously viewed surface on each application.
(d) The metal surface temperature limits shall be between 4 °C (40 °F) and 52 °C (125 °F), unless the film solution is proven to work at temperatures outside these limits, either by testing or manufacturer's
  (iii) recommendations.
(e) A minimum light intensity of 1000 Lux (100 fc) at the point of examination is required during the application of the examination and evaluation for leaks.
(f) The vacuum shall be maintained for the greater of either at least 5 seconds or the time required to view the area under test.
(g) The presence of a through-thickness leak indicated by continuous formation or growth of a bubble(s) or foam, produced by air passing through the thickness, is unacceptable. The presence of a large opening leak, indicated by a quick bursting bubble or spitting response at the initial setting of the vacuum box, is unacceptable. Leaks shall be repaired and retested.
(h) A record or report of the test including a statement addressing temperature and light intensity shall be completed and furnished to the purchaser upon request.
(i) As an alternate to vacuum-box testing, a suitable tracer gas and compatible detector can be used to test the integrity of welded bottom joints for their entire length. Where tracer gas testing is employed as an alternate to vacuum-box testing, it shall meet the following requirements:
  (i) Tracer gas testing shall be performed in accordance with a written procedure which has been reviewed and approved by the purchaser and which shall address as a minimum: the type of equipment used, surface cleanliness, type of tracer gas, test pressure, soil permeability, soil moisture content, satisfactory verification of the extent of tracer gas permeation, and the method or technique to be used including scanning rate and probe standoff distance.
  (ii) The technique shall be capable of detecting leakage of 1×10^{-4} Pa m^3/s (1×10^{-3} std cm^3/s) or smaller.
  (iii) The test system parameters (detector, gas, and system pressure, i.e., level of pressure under bottom) shall be calibrated by placing the appropriate calibrated capillary leak, which will leak at a rate consistent with (ii) above, in a temporary or permanent fitting in the tank bottom away from the tracer gas pressurizing point. Alternatively, by agreement between the purchaser and the manufacturer, the calibrated leak may be placed in a separate fitting pressurized in accordance with the system parameters.
  (iv) While testing for leaks in the welded bottom joints, system parameters shall be unchanged from those used during calibration.

5.5.4 Gas/Bubble Test

The gas test at room temperature may be acceptable if no sustained bubbles are observed. If leakage is observed, the rate should be less than the permitted rates measured at atmospheric pressure, during specified pressure-hold periods per the applicable codes/standards. Table 5.47 shows the comparison of valve shell test time-minimum in several standards. Table 5.48 shows gas leakage acceptance criteria for wellhead and Christmas tree equipment. See API 598, Table 6 for maximum allowable leakage rates for closure tests of valves.

5.5.5 Requirements for Hydrotest/Rinsing Water Quality

5.5.5.1 Types and Characteristics of Hydrotest Water

Freshwater is generally obtained from rivers, lakes, streams, or comparatively shallow water sands. The salinity is low (much lower than seawater) usually less than 2000 ppm. Organic content and bacteria content depend widely on water source.

Brackish water may have high salinity and very high number of bacteria.

Table 5.47 Comparison of valve shell test time-minimum (minutes)

	API 598 and ISO 10434				
Size NPS (DN)	Check	Other	EN 12266–1	ISO 5208	ISO 14313 (API 16D)
≤2 (50)	1.0	0.25	0.25	0.25	2.0
2 1/2 to 6 (65–150)	1.0	1.0	1.0	1.0	5.0
8–12 (200–300)	1.0	2.0	3.0	3.0	5.0
≥14 (350)	2.0	5.0	3.0	3.0	15.0 / 3.0

Table 5.48 Room temperature gas leakage acceptance criteria

Equipment	Seal type	Allowance leakage
Valves, gate, and plug	Through-bore	$30 cm^3$/min/25.4 mm of nominal bore size
	Stem seal	$60 cm^3/h$
	Static (bonnet seal, end connection)	$20 cm^3/h$
Valve and check	Through-bore	$5 cm^3$/min/25.4 mm of nominal bore size
	Stem seal	$60 cm^3/h$
	Static (bonnet seal, end connection)	$20 cm^3/h$
Chokes	Dynamic (stem seal)	$60 cm^3/h$
	Static (bonnet seal, end connection)	$20 cm^3/h$
Actuators	All actuator fluid retaining seals	$60 cm^3/h$
Hangers	Annular pack-off or bottom casing/tubing pack-off	$10 cm^3$/min/25.4 mm of tubing/casing size
Tubing-head adapter, other end connections, fluid sampling devices, closures according this international standard	External closure	$20 cm^3/h$

Source: API 6A, Table F.1 wellhead and Christmas tree equipment

Potable water (municipal drinking water) is used for human consumption and must meet certain criteria on chemical composition and bacteria content. The salinity is low; normally total dissolved solids (TDS) are lower than 500 ppm. It is the cleanest water from the point of view of bacteria content.

Chlorine may be present in potable water. The presence of chlorine can be detrimental to different materials depending on the chlorine concentration in water.

It should not be assumed that no bacteria are present in potable water (the requirement is that they should be not of the type that causes human disease), but the time of exposure to this type of water may be much longer than with other types of water without having microbiological induced corrosion (MIC) problems. Currently several companies have their own specifications for hydrotest water QC. The control may require additional cost and prolonged hydrotest period.

5.5.5.2 Requirements Before Hydrotest

Before hydrotesting, the equipment should be cleaned of loose construction debris, dirt, grease, and mill scale, and all other foreign materials should be removed from the surfaces that will come in contact with the water. The cleaning should be done first by mechanically removing as much foreign material as possible and then following this by a passive chemical cleaning flush if it is deemed necessary.

5.5.5.3 Chloride Limitation for Hydrotest/Rinsing Water

Table 5.49 shows the chloride limitations for hydrotest/rinsing water in industrial codes and standards.

Table 5.49 Limitation for hydrotest/rinsing water

Codes and STD	Paragraph	Limitation	Remark
API 560 (fired heater)	14.5.1.3	Max. 50 ppm chloride for ASS	Hydrotest water
API RP57 (inspection for fired boiler and heater)	8.4.1	Max. 50 ppm chloride for ASS	Hydrotest water
API 650 (storage tank)	S.4.10.1	Max. 50 ppm chloride for SS	Hydrotest water
API 650 (storage tank)	S.4.9.2	Max. 200 ppm chloride at T < 40 °C (104 °F) Max. 100 ppm chloride at 40 °C (104 °F) < T < 65 °C (149 °F)	Rinsing water for cleaning/ pickling
API 661 (air cooled H/EX)	10.3.3	Max. 50 ppm chloride for ASS or Ni-cu alloys	Hydrotest water
API 660 (Shell & Tube H/EX)	10.3.4	Max. 50 ppm chloride for ASS	Hydrotest water
API 610 (centrifugal pumps)	8.3.2.8	Max. 50 ppm chloride for ASS	Hydrotest water
ASME B31.1 (power piping)	IV-3.4	Use deionized water, high purity, Steam condensate, or potable water[(1)] for SS	Hydrotest water
API 602 (gate, globe, and check valves)	B.7.3	Max. 100 ppm chloride for ASS	Hydrotest water
API 598 (Valve Inspection & Testing)	5.6.4	Max. 100 ppm chloride for ASS	Hydrotest water
API 6D (pipeline valves)	11.1	Max. 30 ppm chloride for ASS & DSS	Hydrotest water
BS 6364 (Valves for Cryogenic Service)	8.1.1	Max. 30 ppm chloride for SS	Hydrotest water

Notes

[(1)]Potable water in this context follows US practice, with 250 ppm maximum chloride content, sanitized with chlorine or ozone

5.5.5.4 Protection per Water Source and Materials (Table 5.50)

Table 5.50 Protection per water source and materials[(6)] – only for reference

MOC	Water source	Filtration[(1)]	Biocide[(2)]	Oxygen[(3)] scavenger	Corrosion inhibitor[(4)]
Carbon steels	Seawater[(7)]	Yes	Yes	Yes	No[(5)]
	River/Lake water	Yes	Yes	Yes	No[(5)]
	Potable water	No	Yes	Yes	No[(5)]
Stainless steels	Seawater[(7)]	Yes	Yes	Yes	No[(5)]
	River/Lake water	Yes	Yes	Yes	No[(5)]
	Potable water	No	Yes	Yes	No[(5)]
Plastics	Seawater[(7)]	Yes	Maybe	No	No
	River/Lake water	Yes	Maybe	No	No
	Potable water	No	No	No	No

Notes
[(1)] Filtration (up to 75 microns of any particle)
[(2)] Biocides (glutaraldehyde or THPS – tetrakis(hydroxymethyl)phosphonium sulfate) injection at an approved chemical vendor's suggested dosage
[(3)] Oxygen scavenger (ammonium bisulfide) injection at an approved chemical vendor's suggested dosage
[(4)] Corrosion inhibitor determined with consultation of the end-user and the approved chemical vendor
[(5)] May be used if water will be contained for several years or presence of rust is undesirable
[(6)] The drain, drying, and cleaning procedure after hydrotest shall be approved by the end-user
[(7)] The temporary cathodic protection (CP) may be required. The procedure including anode installation mapping shall be approved by the end-user

5.5.5.5 Quality Control of Hydrotest Water for Corrosion Prevention

(a) General Phenomena of Different bacteria in the water may cause the corrosion of metallic materials by formation of biofilm. Under the biofilm, the environment changes due to the metabolism of bacteria, and the corrosivity may become quite different from the bulk of the solution. The biofilm is a layer formed by bacteria of different types and other biological material that effectively protects the bacteria from chemical and/or physical agents that may be present in the water. Once the film is created, it is very resistant to biocides and very difficult to remove. It is good practice and generally more beneficial to avoid the formation of biofilms than to remove them once they are formed.

At longer exposures (low velocity) and/or higher temperature, the bulk water chemical composition may change as well and then may increase corrosion of the facilities.

In microbiological induced corrosion (MIC), the following two types can be distinguished as the ones that have the greatest impact:

- Sulfate-reducing bacteria (SRB)
- Acid-producing bacteria (APB)

SRBs produce H_2S (as the product of their metabolism) that may cause one or more of the several corrosion forms induced by this chemical species (including SCC – stress corrosion cracking). The severity and type of corrosion depend on the concentration of H_2S and the type of metallic material.

APBs release aggressive organic (acetic, succinic, isobutyric, etc.) and/or inorganic acids (sulfuric), and corrosion occurs beneath the colonies formed by these bacteria. The corrosion process may continue during the service life of the equipment and the consequences may become evident after a long period of service. This makes this form of corrosion particularly dangerous.

The type of hydrotest water is selected by the water source availability, volume of water necessary, and criticality of the tested equipment.

(b) Requirements for Hydrotest Water Quality

Table 5.51 shows the basic requirements for the water quality before hydrotest.

(c) Chemical Treatment

If the water does not meet the requirements in Table 5.51, the use of dosage may be necessary.

(d) Treatment After Hydrotest

In addition to the water QC in Table 5.51, the following should be continuously performed:

1. After the hydrotest, the water should be removed from the equipment as soon as possible, but not exceed a few days (max. 7 days) unless otherwise approved. Exposure time includes the filling, testing, dewatering, and the time until fully dried.
2. After testing, rinsing, or flushing, low point drains and vents should be opened shortly. Tilting of equipment may be required to assure complete draining if possible.
3. As soon as drained (and rinsing if required), the system or component should be completely dried with compressed air. The compressed air should be dry and clean (oil-free and no contamination by foreign materials) and have a dew point of -40 °C (-40 °F) or lower. Dry air should be introduced into each section until the discharged air has a dew point less than -20 °C (-4 °F).
4. The drying operation should be completed within 5 days after dewatering unless otherwise approved.
5. Once the tested system has been thoroughly dried, every effort should be expended to ensure and periodically verify that water (condensation, rain, etc.) has not been reintroduced into the system or component.

Table 5.51 Water quality for hydrotest (recommendation)

Test parameter	Values/Ranges (all ppm: by weight)
Chlorides	Max. 50 ppm for austenitic stainless steels Max. 100 ppm for other metals
pH	6.5–9
Sulfate (SO_4^{-2}, HSO_4^-: H_2SO_4)	≤10 ppm preferable, max. 42 ppm
Dissolved oxygen	≤10 ppb for stainless steel or nickel alloys ≤50 ppb for carbon and low alloy steels
Fatty acids	≤14 ppm
Ammonium	≤3 ppm
Bacteria (SRB, APB, etc.)	"Insignificant" or "very low" activity
Total suspended solids (TSS)	Max. 20 ppm as a monthly average(1)
Turbidity	<1 nephelometric turbidity unit (NTU)
Total organic matter	≤4 ppm
Sulfides (S^{-2}, HS^-: H_2S)	Nil
Particle size	≤50 μm(2)
Temperature	≤50 °C(3)

Notes

(1)As a minimum, water shall be filtered to remove particles of 25 μm and larger. Special filtration may be required where the water contains considerable total organic compounds and turbidity

(2)Bacteria can hide under sediment and therefore can be protected from the biocide and inhibitor. If this were to occur, the bacteria could multiply and cause corrosion

(3)The temperatures of the water, pipe, and equipment under test shall be kept below 50 °C for austenitic stainless steel to avoid stress corrosion cracking, crevice corrosion, and pitting. For carbon and low alloy steels, the test water temperature shall be such that the minimum metal temperature during the hydrotest is maintained at least 17 °C above the MDMT (minimum design metal temperature) to ensure brittle fracture does not occur

5.5.5.6 Hydrotest with Seawater

The following cautions and preventions should be considered for the hydrotest seawater:

– Seawater should be drawn from as deep as possible (approximately 150 m (500 ft)) to minimize the oxygen content and sediment content. If this is not practical, extra care is needed with the filtration and scavenging of the water.
– The seawater inlet should be well off the ocean floor to minimize the possibility of picking up dirt and debris.
– Temporary CP installation (all procedure including anode installation mapping shall be approved by purchaser before the contract agreement).
– Filtration (max. 75 μm of seawater).
– Biocides (glutaraldehyde or THPS – tetrakis(hydroxymethyl)phosphonium sulfate) injection at an approved chemical vendor's suggested dosage.
– Oxygen scavenger (ammonium bisulfide) injection at an approved chemical vendor's suggested dosage
– Corrosion inhibitor, if need, should be consulted with the chemical vendor.
– Drain, drying, and cleaning procedure after hydrotest.

References

– Australian Standard AS 4809

5.5.6 Cryogenic Leakage Test of Valves

The valve can be readily leaked at cryogenic temperature compared to room or elevated temperature because of high contraction of each component. So, this test is very important typically for cryogenic valves. Normally two types of leakage test are applied, such as internal test for seat and external test for body. The cryogenic test is typically performed at −196 °C (−320 °F) in liquid nitrogen (most common), −150 °C (−240 °F) or warmer with liquefied or gaseous nitrogen, or − 79 °C (−240 °F) or warmer with dry ice (CO_2). The permitted leakage rate should not exceed 100 mm^3/s/DN (all valves except 200 mm^3/s/DN for check valves) or 50 ppm/10 seconds unless otherwise required. DN = metric valve size.

References

– MSS SP-134/ BS 6364 Cryogenic Valves
– ISO/FDIS 10497 Valve Tests
– BS-EN 1626 Cryogenic Vessels-Valves/1473 Installation and Equipment for LNG
– API 607/ NFPA 55 Fire Test

Useful Websites

1. Code Design Guides and Case Track
   http://www.becht.com/Process%20Power/Presentations/New%20ASME%20Codes/newasme_files/frame.htm
   http://www.absa.ca/ [ABSA]
   http://cstools.asme.org/CodeCases.cfm [ASME Code Cases]
   https://secure.asme.org/cfforum2000/index.cfm [ASME Code Forum]
   http://www.cenorm.be/catweb/cwen.htm [European Standards]
   http://bsonline.techindex.co.uk/BSI2/Dir1/SitePage.asp?LS=&PgID=0002 [BS Standard Online Search]
   http://www.eng-tips.com [Q & A for All Engineering Issues]
   http://www.software.rockwell.com/forum/rslogix/messageview.cfm?catid=9&threadid=6853 [Tank Forum]
   http://www.steamforum.com/index.htm [Steam Boiler Forum]
2. Cost of Equipment and Materials
   http://www.matche.com/EquipCost/index.htm
3. Unit Conversion and Simple Formulas Calculation
   http://www.ex.ac.uk/cimt/dictunit/dictunit.htm#prefixes [Unit and Their Conversion]
   http://joshmadison.com/software/convert/ [Unit Conversion]
   http://www.engineersedge.com/Design_Data.shtml [Design Calculation Formulas for Diverse Engineering, Conversion and Definition]
   http://member.nifty.ne.jp/yurioka/p01/p01.html [Ceq, Pcm]
   http://www.industri.no/e-weld/eng/?ID=13&Side=Hjelp [Ceq, Pcm]
   http://www.gordonengland.co.uk/hardness/index.htm [Hardness Tests and Their Conversion]
4. Mechanical Engineering Software and Sample Strength Calculation
   http://www.engineering-software.com/me/ [Mechanical Engineering Software]
   http://www.xcalcs.com/ [WRC 297/ Sec. VIII Div.1 Appendix 2, 24, Y/ API 650/ BS 5500/ Sec. VI PG-27, 29/ EN 13445-3/ Beams/ Volume]
   http://www.mecaconsulting.com/taillug.htm [Lifting/Tailing Lug Calculation Program]
   http://www.coade.com/cgi-local/ultimatebb.cgi?ubb=forum;f=3 [COADE Discussion Forum]
   http://www.codeware.com/download.html [Codeware Download]
5. Manufacturing and Inspection
   http://www.apvma.com/members.htm [Alberta, Canada]
   http://www.aws.org/cgi-bin/mwf/forum_show.pl [AWS Forum]
   http://www.ukwelder.com/forum//index.php?showforum=7 [UK Welder Technical Forum]
   http://www.nationalboard.org/Nbic/Interpretations/2001.html [NBIC Interpretation]
6. Others
   http://www.gordonengland.co.uk/hardness/index.html [Impact Tests]
   http://www.nidi.org/index.cfm/ci_id/45/la_id/1.htm [NiDI Technical Literature
   http://www.stainless-steel-world.net/ [Stainless Steels Journal and Literature]
   http://www.forengineers.org/cgi-bin/wrcbulletin/bulletin.pl [WRC Bulletins Search]

General References: Other Than Codes and Standards

1. Bruce E. Ball and Will J. Carter, CASTI Guidebook to ASME Section VIII Div.1 – Pressure Vessel, 2002
2. Robert Chuse and Bryce E. Carson, Pressure Vessels-The ASME Code Simplified, McGraw-Hill, Inc.1993
3. Eugene F. Megyesy, Pressure Vessel Handbook, PVHP, Inc. 8th Edition
4. Henry H. Bednar, Pressure Vessel Design Handbook, VNR company, 1981
5. Anthony L. Kohan, Pressure Vessel Systems, McGraw-Hill, Inc.1987
6. Warren C. Young, Roark's Formulas for Stress and Strain, McGraw-Hill, Inc. 6th Edition
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8. Dennis R. Moss, Pressure Vessel Design Manual, GPC, 1987
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12. A.J. Heinze, Pressure Vessel Design for Process Engineers, Hydrocarbon Processing, May 1979
13. Manual of Steel Structure, AISI, 8th Edition
14. D. Pecker and I.M. Bernstein, Handbook of Stainless Steels, McGraw-Hill, Inc.,1987
15. G. E. Dieter, Mechanical Metallurgy, 3rd edition, McGraw-Hill, Inc.
16. Specifications, Manuals, and Case Studies of Various Projects

Appendix

J. -C. Eun, *Handbook of Engineering Practice of Materials and Corrosion*,
https://doi.org/10.1007/978-3-030-36430-4

A.1 Temperature Conversion Tables (See Table 1.79 for the Conversion Used in ASME Sec. VIII).

°C = 5/9 (°F - 32), °F = 9/5 (°C) + 32, 0°K = −273.19 °C, **Δ°C = 5/9 Δ °F, Δ °F = 9/5 Δ °C**

Table A.1 (1/2) Temperature conversion table (°F → °C)

°C		°F	°C		°F	°C		°F	°C		°F	°C		°F
-273	-459.4		-17.8	**0**	32	10.0	50	122.0	38	**100**	212	260	**500**	932
-268	-450		-17.2	1	33.8	10.6	51	123.8	43	110	230	266	510	950
-262	-440		-16.7	2	35.6	11.1	52	125.6	49	120	248	271	520	968
-257	-430		-16.1	3	37.4	11.7	53	127.4	54	130	266	277	530	986
-251	-420		-15.6	4	39.2	12.2	54	129.2	60	140	284	282	540	1004
-246	-410		-15.0	5	41.0	12.8	55	131.0	66	150	302	288	550	1022
-240	**-400**		-14.4	6	42.8	13.3	56	132.8	71	160	320	293	560	1040
-234	-390		-13.9	7	44.6	13.9	57	134.6	77	170	338	299	570	1058
-229	-380		-13.3	8	46.4	14.4	58	136.4	82	180	356	304	580	1076
-223	-370		-12.8	9	48.2	15.0	59	138.2	88	190	374	310	590	1094
-218	-360		-12.2	10	50.0	15.6	60	140.0	93	**200**	392	316	**600**	1112
-212	-350		-11.7	11	51.8	16.1	61	141.8	99	210	410	321	610	1130
-207	-340		-11.1	12	53.6	16.7	62	143.6	100	212	413.6	327	620	1148
-201	-330		-10.6	13	55.4	17.2	63	145.4	104	220	428	332	630	1166
-196	-320		-10.0	14	57.2	17.8	64	147.2	110	230	446	338	640	1184
-190	-310		-9.4	15	59.0	18.3	65	149.0	116	240	464	343	650	1202
-184	**-300**		-8.9	16	60.8	18.9	66	150.8	121	250	482	349	660	1220
-179	-290		-8.3	17	62.6	19.4	67	152.6	127	260	500	354	670	1238
-173	-280		-7.8	18	64.4	20.0	68	154.4	132	270	518	360	680	1256
-169	-273	-459.4	-7.2	19	66.2	20.6	69	156.2	138	280	536	366	690	1274
-168	-270	-454	-6.7	20	68.0	21.1	70	158.0	143	290	554	371	**700**	1292
-162	-260	-436	-6.1	21	69.8	21.7	71	159.8	149	**300**	572	377	710	1310
-157	-250	-418	-5.6	22	71.6	22.2	72	161.6	154	310	590	382	720	1328
-151	-240	-400	-5.0	23	73.4	22.8	73	163.4	160	320	608	388	730	1346
-146	-230	-328	-4.4	24	75.2	23.3	74	165.2	166	330	626	393	740	1364
-140	-220	-364	-3.9	25	77.0	23.9	75	167.0	171	340	644	399	750	1382
-134	-210	-346	-3.3	26	78.8	24.4	76	168.8	177	350	662	404	760	1400
-129	**-200**	-328	-2.8	27	80.6	25.0	77	170.6	182	360	680	410	770	1418
-123	-190	-310	-2.2	28	82.4	25.6	78	172.4	188	370	698	416	780	1436
-118	-180	-292	-1.7	29	84.2	26.1	79	174.2	193	380	716	421	790	1454
-112	-170	-274	-1.1	30	86.0	26.7	80	176.0	199	390	734	427	**800**	1472
-107	-160	-256	-0.6	31	87.8	27.2	81	177.8	204	**400**	752	432	810	1490
-101	-150	-238	0.0	32	89.6	27.8	82	179.6	210	410	770	438	820	1508
-96	-140	-220	0.6	33	91.4	28.3	83	181.4	216	420	788	443	830	1526
-90	-130	-202	1.1	34	93.2	28.9	84	183.2	221	430	806	449	840	1544
-84	-120	-184	1.7	35	95.0	29.4	85	185.0	227	440	824	454	850	1562
-76	-110	-166	2.2	36	96.8	30.0	86	186.8	232	450	842	460	860	1580
-73	**-100**	-148	2.8	37	98.6	30.6	87	188.6	238	460	860	466	870	1598
-68	-90	-130	3.3	38	100.4	31.1	88	190.4	243	470	878	471	880	1616
-62	-80	-112	3.9	39	102.2	31.7	89	192.2	249	480	896	477	890	1634
-57	-70	-94	4.4	40	104.0	32.2	90	194.0	254	490	914	482	**900**	1652
-51	-60	-76	5.0	41	105.8	32.8	91	195.8				488	910	1670
-46	-50	-58	5.6	42	107.6	33.2	92	197.6				493	920	1688
-40	-40	-40	6.1	43	109.4	33.9	93	199.4				499	930	1706
-34	-30	-22	6.7	44	111.2	34.4	94	201.2				504	940	1724
-29	-20	-4	7.2	45	113.0	35.0	95	203.0				510	950	1742
-23	-10	14	7.8	46	114.8	35.6	96	204.8				516	960	1760
-17.8	0	32	8.3	47	116.6	36.1	97	206.6				521	970	1778
			8.9	48	118.4	36.7	98	208.4				527	980	1796
			9.4	49	120.2	37.2	99	210.2				532	990	1814
						37.8	**100**	212.0				538	**1000**	1832

°C = 5/9 (°F - 32), °F = 9/5 (°C) + 32, 0°K = −273.19 °C, **Δ°C = 5/9 Δ °F, Δ °F = 9/5 Δ °C**

Table A.1 (2/2) Temperature conversion table (°C ↔ °F)

°C		°F	°C		°F	°C		°F	°C		°F
538	**1000**	1832	816	**1500**	2732	1093	2000	3632	1371	**2500**	4532
543	1010	1850	821	1510	2750	1099	2010	3650	1377	2510	4550
549	1020	1868	827	1520	2768	1104	2020	3668	1382	2520	4568
554	1030	1886	832	1530	2786	1110	2030	3680	1388	2530	4586
560	1040	1904	838	1540	2804	1116	2040	3704	1393	2540	4604
566	1050	1922	843	1550	2822	1121	2050	3722	1399	2550	4622
571	1060	1940	849	1560	2840	1127	2060	3740	1404	2560	4640
577	1070	1958	854	1570	2858	1132	2070	3758	1410	2570	4658
582	1080	1976	860	1580	2876	1138	2080	3776	1416	2580	4676
588	1090	1994	866	1590	2894	1143	2090	3794	1421	2590	4694
593	**1100**	2012	871	**1600**	2912	1149	**2100**	3812	1427	**2600**	4712
599	1110	2030	877	1610	2930	1154	2110	3830	1432	2610	4730
604	1120	2048	882	1620	2948	1160	2120	3848	1438	2620	4748
610	1130	2066	888	1630	2966	1166	2130	3866	1443	2630	4766
616	1140	2084	893	1640	2984	1171	2140	3884	1449	2640	4784
621	1150	2102	899	1650	3002	1177	2150	3902	1454	2650	4802
627	1160	2120	904	1660	3020	1182	2160	3920	1460	2660	4820
632	1170	2138	910	1670	3038	1188	2170	3938	1466	2670	4838
638	1180	2156	916	1680	3056	1193	2180	3956	1471	2680	4856
643	1190	2174	921	1690	3074	1199	2190	3974	1477	2690	4874
649	**1200**	2192	927	**1700**	3092	1204	**2200**	3992	1482	**2700**	4892
654	1210	2210	932	1710	3110	1210	2210	4010	1488	2710	4910
660	1220	2228	938	1720	3128	1216	2220	4028	1493	2720	4928
666	1230	2246	943	1730	3146	1221	2230	4046	1499	2730	4946
671	1240	2264	949	1740	3164	1227	2240	4064	1504	2740	4964
677	1250	2282	954	1750	3182	1232	2250	4082	1510	2750	4982
682	1260	2300	960	1760	3200	1238	2260	4100	1516	2760	5000
688	1270	2318	966	1770	3218	1243	2270	4118	1521	2770	5018
693	1280	2336	971	1780	3236	1249	2280	4136	1527	2780	5036
699	1290	2354	977	1790	3254	1254	2290	4154	1532	2790	5054
704	**1300**	2372	982	**1800**	3272	1260	**2300**	4172	1538	**2800**	5072
710	1310	2390	988	1810	3290	1266	2310	4190	1543	2810	5090
716	1320	2408	993	1820	3308	1271	2320	4208	1549	2820	5108
721	1330	2426	999	1830	3326	1277	2330	4226	1554	2830	5126
727	1340	2444	1004	1840	3344	1282	2340	4244	1560	2840	5144
732	1350	2460	1010	1850	3362	1288	2350	4262	1566	2850	5162
738	1360	2480	1016	1860	3380	1293	2360	4280	1571	2860	5180
743	1370	2498	1021	1870	3398	1299	2370	4298	1577	2870	5198
749	1380	2516	1027	1880	4316	1304	2380	4316	1582	2880	5216
754	1390	2534	1032	1890	3434	1310	2390	4334	1588	2890	5234
760	**1400**	2552	1038	**1900**	3452	1316	**2400**	4352	1593	**2900**	5252
766	1410	2570	1043	1910	3470	1321	2410	4370	1599	2910	5270
771	1420	2588	1049	1920	3488	1327	2410	4388	1604	2920	5288
777	1430	2606	1054	1930	3506	1332	2430	4406	1610	2930	5306
782	1440	2624	1060	1940	3524	1338	2440	4424	1616	2940	5324
788	1450	2642	1066	1950	3542	1343	2450	4442	1621	2950	5342
793	1460	2660	1071	1960	3560	1349	2460	4460	1627	2960	5360
799	1470	2678	1077	1970	3578	1354	2470	4478	1632	2970	5378
804	1480	2696	1082	1980	3596	1360	2480	4496	1638	2980	5396
810	1490	2714	1088	1990	3614	1366	2490	4514	1643	2990	5414
			1093	**2000**	3632				1649	**3000**	5432

A.2 Hardness Conversion Tables

Table A.2a (1/2) Hardness conversion table for non-austenitic steels (Vickers, DPH-Hv10 to others)

Equivalent Hardness Values													T.S. (approx)	T.S. (approx)
Vickers Hv10 (HV)	Brinell Φ10 mm, 3000 kgf			Rockwell				Rockwell Special Scale			Shore Sclero-scope	Vickers Hv10 (HV)	ksi	MPa
	STD (HBW)	Hultgren	WC (HBW)	A scale 60 kgf (HRA)	B sclae 100 kgf Φ 1/16" (HRB)	C scale 150 kgf (HRC)	D scale 100 kgf (HRD)	15-N scale 15 kgf (HR 15-N)	30-N scale 30 kgf (HR 30-N)	45-N scale 45 kgf (HR 45-N)				
940	-	-	-	85.6	-	68.0		93.2	84.4	75.4	97	940	-	-
920	-	-	-	85.3	-	67.5		93.0	84.0	74.8	96	920	-	-
900	-	-	-	85.0	-	67.0		92.9	83.6	74.2	95	900	-	-
880	-	-	767	84.7	-	66.4		92.7	83.1	73.6	93	880	-	-
860	-	-	757	84.4	-	65.9		92.5	82.7	73.1	92	860	-	-
840	-	-	745	84.1	-	65.3	-	92.3	82.2	72.2	91	840	-	-
820	-	-	733	83.8	-	64.7	-	92.1	81.7	71.8	90	820	-	-
800	-	-	722	83.4	-	64.0	-	91.8	81.1	71.0	88	800	-	-
780	-	-	710	83.0	-	63.3	-	91.5	80.4	70.2	87	780	-	-
760	-	-	698	82.6	-	62.5	-	91.2	79.7	69.4	86	760	-	-
740	-	-	684	82.2	-	61.8	-	91.0	79.1	68.6	84	740	-	-
720	-	-	670	81.8	-	61.0	-	90.7	78.4	67.7	83	720	-	-
700	-	615	656	81.3	-	60.1	-	90.3	77.6	66.7	81	700	-	-
690	-	610	647	81.1	-	59.7	-	90.1	77.2	66.2	-	690	-	-
680	-	603	638	80.8	-	59.2	-	89.3	76.8	65.7	80	680	329	2268
670	-	597	630	80.6	-	58.8	-	89.7	76.4	65.3	-	670	324	2234
660	-	590	620	80.3	-	58.3	-	89.5	75.9	64.7	79	660	319	2200
650	-	585	611	80.0	-	57.8	-	89.2	75.5	64.1	-	650	314	2165
640	-	578	601	79.8	-	57.3	-	89.0	75.1	63.5	77	640	309	2131
630	-	571	591	79.5	-	56.8	32.9	88.8	74.6	63.0	-	630	304	2096
620	-	564	582	79.2	-	56.3	32.4	88.5	74.2	62.4	75	620	299	2062
610	-	557	573	78.6	-	55.7	31.9	88.2	73.6	61.7	-	620	294	2027
600	-	550	564	78.8	-	55.2	31.4	88.0	73.2	61.2	74	600	289	1993
590	-	542	554	78.4	-	54.7	30.9	87.8	72.7	60.5	-	590	284	1958
580	-	535	545	78.0	-	54.1	30.4	87.5	72.1	59.9	72	580	279	1924
570	-	527	535	77.8	-	53.6	29.9	87.2	71.7	59.3	-	570	274	1889
560	-	519	525	77.4	-	53.0	29.4	86.9	71.2	58.6	71	560	269	1855
550	505	512	512	77.0	-	52.3	29.9	86.6	70.5	57.8	-	550	264	1820
540	496	503	507	76.7	-	51.7	28.4	86.3	70.0	57.0	69	540	260	1793
530	488	495	497	76.4	-	51.1	279	86.0	69.5	56.2	-	550	254	1751
520	480	487	488	76.1	-	50.5	274	85.7	69.0	55.6	67	520	250	1724
510	473	479	479	75.7	-	49.8	269	85.4	68.3	54.7	-	510	244	1683
500	465	471	471	75.3	-	49.1	264	85.0	67.7	53.9	66	500	240	1655
490	456	460	460	74.9	-	48.4	260	84.7	67.1	53.1	-	490	234	1613
480	448	452	452	74.5	-	47.7	254	84.3	66.4	52.2	64	480	230	1586
470	441	442	442	74.1	-	46.9	250	83.9	65.7	51.3	-	470	228	1572
460	433	433	433	73.6	-	46.1	244	83.6	64.9	50.4	62	460	223	1538
450	425	425	425	73.3	-	45.3	240	83.2	64.3	49.4	-	450	217	1496
440	415	415	415	72.8	-	44.5	234	82.8	63.5	48.4	59	440	212	1462
430	405	405	405	72.3	-	43.6	230	82.3	62.7	47.4	-	430	205	1413
420	397	397	397	71.8	-	42.7	224	81.8	61.9	46.4	57	420	199	1372
410	388	388	388	71.4	-	41.8	220	81.4	61.1	45.3	-	410	193	1331
400	379	379	379	70.8	-	40.8	214	81.0	60.2	44.1	55	400	187	1289
390	369	369	369	70.3	-	39.8	210	80.3	59.3	42.9	-	390	181	1248
380	360	360	360	69.8	(110.0)	38.8	204	79.8	58.4	41.7	52	380	175	1207
370	350	350	350	69.2	-	37.7	200	79.2	57.4	40.4	-	370	170	1172
360	341	341	341	68.7	(109.0)	36.6	195	78.6	56.4	39.1	50	360	164	1131
350	331	331	331	68.1	-	35.5	190	78.0	55.4	37.8	-	350	159	1096
340	322	322	322	67.6	(108.0)	34.4	185	77.4	54.4	36.5	47	340	155	1069
330	313	313	313	67.0	-	33.3	180	76.8	53.6	35.2	-	330	150	1034
320	303	303	303	66.4	(107.0)	32.2	175	76.2	52.3	33.9	45	320	146	1007
310	294	294	294	65.8	-	31.0	170	75.6	51.3	32.5	-	310	142	979
300	284	284	284	65.2	(105.5)	29.8	166	74.9	50.2	31.1	42	300	138	951
295	280	280	280	64.8	-	29.2	161	74.6	49.7	30.4	-	295	136	938
290	275	275	275	64.5	(104.5)	28.5	156	74.2	49.0	29.5	41	290	133	917
285	270	270	270	64.2	-	27.8	151	73.8	48.4	28.7	-	285	131	903
280	265	265	265	63.8	(103.5)	27.1	146	73.4	47.8	27.9	40	280	129	889
275	261	261	251	63.5	-	26.4	141	73.0	47.2	27.1	-	275	127	876
270	256	256	256	63.1	(102.0)	25.6	139	72.6	46.4	26.2	38	270	124	855
265	252	252	252	61.7	-	24.8	136	72.1	45.7	25.2	-	265	122	841

Notes: source: ASTM E140 – extended
WC = tungsten carbide, HBS = BHN = HBW; see ASTM E140 for HRE, HRF, HRG, HRK, HR 15 T/30-T/45-T scales for Ni alloys
See ASTM E140 for hardness conversion of ASS and brass
See Fig. 5.12 in this book for DSS

Table A.2a (2/2) Hardness conversion table (Vickers, DPH-Hv10 to others)

Equivalent Hardness Values													T.S. (approx)	T.S. (approx)
Vickers Hv10 (HV)	Brinell Φ10 mm, 3000 kgf			Rockwell				Rockwell Special Scale			Shore Sclero-scope	Vickers Hv10 (HV)	ksi	MPa
	STD (HBS)	Hultgren	WC (HBW)	A scale 60 kgf (HRA)	B sclae 100 kgf Φ 1/16” (HRB)	C scale 150 kgf (HRC)	D scale 100 kgf (HRD)	15-N scale 15 kgf (HR 15-N)	30-N scale 30 kgf (HR 30-N)	45-N scale 45 kgf (HR 45-N)				
260	247	247	247	62.4	260	24.0	43.1	71.6	45.0	24.3	37	260	120	827
255	243	243	243	62.0	255	23.1	42.2	71.1	44.2	23.2	-	255	117	807
250	238	238	238	61.6	250	22.2	41.7	70.6	43.4	22.2	36	250	115	793
245	233	233	233	61.2	245	21.3	41.1	70.1	42.5	21.1	-	245	113	770
240	228	228	228	60.7	240	20.3	40.3	69.6	41.7	19.9	34	240	111	765
230	219	219	219	-	230	(18.0)	-	-	-	-	33	230	106	731
220	209	209	209	-	220	(15.7)	-	-	-	-	32	220	101	696
210	200	200	200	-	210	(13.4)	-	-	-	-	30	210	97	669
200	190	190	190	-	200	(11.0)	-	-	-	-	29	200	92	634
190	181	181	181	-	190	(8.5)	-	-	-	-	28	190	86	607
180	171	171	171	-	180	(6.0)	-	-	-	-	26	180	84	579
170	162	162	162	-	170	(3.0)	-	-	-	-	25	170	79	545
160	152	152	152	-	160	(0.0)	-	-	-	-	24	160	75	517
150	143	143	143	-	150	-	-	-	-	-	22	150	71	490
140	133	133	133	-	140	-	-	-	-	-	21	140	66	455
130	124	124	124	-	130	-	-	-	-	-	20	130	62	427
120	114	114	114	-	120	-	-	-	-	-	-	120	57	393
110	105	105	105	-	110	-	-	-	-	-	-	110	-	-
100	95	95	95	-	100	-	-	-	-	-	-	100	-	-
95	90	90	90	-	95	-	-	-	-	-	-	95	-	-
90	86	86	86	-	90	-	-	-	-	-	-	90	-	-
85	81	81	81	-	85	-	-	-	-	-	-	85	-	-

Notes: source: ASTM E140 – extended
WC = tungsten carbide, HBS = BHN = HBW; see ASTM E140 for HRE, HRF, HRG, HRK, HR 15T/30-T/45-T scales for Ni alloys
See ASTM E140 for hardness conversion of ASS and brass
See Fig. 5.12 in this book for DSS

Table A.2b (1/2) Hardness conversion table (Brinell to Others)

Equivalent Hardness Values														T.S. (approx)	T.S. (approx)
Brinell Dent Diameter mm	Brinell Φ10 mm, 3000 kgf			Vickers Hv10 (HV)	Rockwell				Rockwell Special Scale			Shore Sclero-scope	Brinnel Dent Diameter mm	ksi	MPa
	STD (HBS)	Hultgren	WC (HBW)		A scale 60 kgf (HRA)	Dent Diameter	C scale 150 kgf (HRC)	D scale 100 kgf (HRD)	15-N scale 15 kgf (HR 15-N)	30-N scale 30 kgf (HR 30-N)	45-N scale 45 kgf (HR 45-N)				
-	-	-	-	940	85.6	-	68.0	76.9	93.2	84.4	75.7	97	-	-	-
-	-	-	-	920	85.3	-	67.5	76.5	93.0	84.0	74.8	96	-	-	-
-	-	-	-	900	85.0	-	67.0	76.1	92.9	83.6	74.2	95	-	-	-
-	-	-	767	880	84.7	-	66.4	75.7	92.7	83.1	73.6	93	-	-	-
-	-	-	757	860	84.4	-	65.9	75.3	92.5	82.7	73.1	92	-	-	-
2.25	-	-	745	840	84.1	-	65.3	74.8	92.2	82.2	72.2	91	2.25	-	-
-	-	-	733	820	83.8	-	64.7	74.3	92.1	81.7	71.8	90	-	-	-
-	-	-	722	800	83.4	-	64.0	73.8	91.8	81.1	71.0	88	-	-	-
2.30	-	-	712	-	-	-	-	-	-	-	-	-	2.30	-	-
-	-	-	710	780	83.0	-	63.3	73.3	91.5	80.4	70.2	87	-	-	-
-	-	-	698	760	82.6	-	62.5	72.6	91.2	79.7	69.4	86	-	-	-
-	-	-	684	740	82.2	-	61.8	72.1	91.0	79.1	68.6	-	-	-	-
2.35	-	-	682	737	82.2	-	61.7	72.0	91.0	79.0	68.5	84	2.35	-	-
-	-	-	670	720	81.8	-	61.0	71.5	90.7	78.4	67.7	83	-	-	-
-	-	-	656	700	81.3	-	60.1	70.8	90.3	77.6	66.7	-	-	-	-
2.40	-	-	653	697	81.2	-	60.0	70.7	90.2	77.5	66.5	81	2.40	-	-
-	-	-	647	690	81.1	-	59.7	70.5	90.1	77.2	66.2	-	-	-	-
-	-	-	638	680	80.8	-	59.2	70.1	89.8	76.8	65.7	80	-	329	2268
-	-	-	630	670	80.6	-	58.8	69.8	89.7	75.4	65.3	-	-	324	2234
2.45	-	-	627	667	80.5	-	58.7	69.7	89.6	76.3	65.1	79	2.45	323	2227
2.50	-	601	-	677	80.7	-	59.1	70.7	89.8	76.8	65.7	-	2.50	328	2262
	-	-	601	640	79.8	-	57.3	68.7	89.0	75.1	63.5	77		309	2131
2.55	--	578	-	640	79.8	-	57.3	68.7	89.0	75.1	63.5	-	2.55	309	2131
	-	-	578	615	79.1	-	56.0	67.7	88.4	73.9	62.1	75		297	2048
2.60	-	555	-	607	78.8	-	55.6	67.4	88.1	73.5	61.6	-	2.60	293	2020
	-	-	555	591	78.4	-	54.7	66.7	87.8	72.7	60.6	73		285	1965
2.65	-	534	-	579	78.0	-	54.0	66.1	87.5	72.0	59.8	-	2.65	279	1924
	-	-	534	569	77.8	-	53.5	65.8	87.2	71.6	59.2	71		274	1889
2.70	-	514	-	553	77.1	-	52.5	65.0	86.7	70.7	58.0	-	2.70	266	1834
	-	-	514	547	76.9	-	52.1	64.7	86.5	70.3	57.6	70		263	1813
	495	-	-	539	76.7	-	51.6	64.3	86.3	69.9	56.9	-		259	1786
2.75	-	495	-	530	76.4	-	51.1	63.9	86.0	69.5	56.2	-	2.75	254	1751
	-	-	495	528	76.3	-	51.0	63.8	85.9	69.4	56.1	68		253	1744
	477	-	-	516	75.9	-	50.3	63.2	85.6	68.7	55.2	-		247	1703
2.80	-	477	-	508	75.6	-	49.6	62.7	85.3	68.2	54.5	-	2.80	243	1675
	-	-	477	508	75.6	-	49.6	62.7	85.3	68.2	54.5	66		243	1675
	461	-	-	495	75.1	-	48.8	61.9	84.9	67.4	53.5	-		237	1634
2.85	-	461	-	491	74.9	-	48.5	61.7	84.7	67.2	53.2	-	2.85	235	1620
	-	-	461	491	74.9	-	48.5	61.7	84.7	67.2	53.2	65		235	1620
	444	-	-	474	74.3	-	47.2	61.0	84.1	66.0	51.7	-		226	1558
2.90	-	444	-	472	74.2	-	47.1	60.8	84.0	65.8	51.5	-	2.90	225	1551
	-	-	444	472	74.2	-	47.1	60.8	84.0	65.8	51.5	63		225	1551
2.95	429	429	429	455	73.4		45.7	59.7	83.4	64.6	49.9	61	2.95	217	1496
3.00	415	415	415	440	72.8	-	44.5	58.8	82.8	63.5	48.4	59	3.00	210	1448
3.05	401	401	401	425	72.0		43.1	57.8	82.0	62.3	46.9	58	3.05	202	1393
3.10	388	388	388	410	71.4	-	41.8	56.8	81.4	61.1	45.3	56	3.10	195	1345
3.15	375	375	375	396	70.6	-	40.4	55.7	80.6	59.9	43.0	54	3.15	188	1296
3.20	363	363	363	383	70.0	-	39.1	54.6	80.0	58.7	42.0	52	3.20	182	1255
3.25	352	352	352	372	69.3	(110.0)	37.9	53.8	79.3	57.6	40.5	51	3.25	176	1214
3.30	341	341	341	360	68.7	(109.0)	36.6	52.8	78.6	56.4	39.1	50	3.30	170	1172
3.35	331	330	330	350	68.1	(108.5)	35.5	51.9	78.0	55.4	37.8	48	3.35	166	1145
3.40	321	321	321	339	67.5	(108.0)	34.3	51.0	77.3	54.3	36.4	47	3.40	160	1103
3.45	311	311	311	328	66.9	(107.5)	33.1	50.0	76.7	53.3	34.4	46	3.45	155	1069
3.50	302	302	302	319	66.3	(107.0)	32.1	49.3	76.1	52.2	33.8	45	3.50	150	1034
3.55	293	293	293	309	65.7	(106.0)	30.9	48.3	75.5	51.2	32.4	43	3.55	145	1000
3.60	285	285	285	301	65.3	(105.5)	29.9	47.6	75.0	50.3	31.2	-	3.60	141	971
3.65	277	277	277	292	64.6	(104.5)	28.8	46.7	74.4	49.3	29.9	41	3.65	137	945
3.70	269	269	269	284	64.1	(104.0)	27.6	45.9	73.7	48.3	28.5	40	3.70	133	917
3.75	262	262	262	276	63.6	(103.0)	26.6	45.0	73.1	47.3	27.5	39	3.75	129	889
3.80	255	255	255	269	63.0	(102.0)	25.4	44.2	72.5	46.2	26.0	38	3.80	126	869
3.85	248	248	248	261	62.5	(101.0)	24.2	43.2	71.7	45.1	24.5	37	3.85	122	841
3.90	241	241	241	253	61.8	100.0	22.8	42.0	70.9	43.9	22.8	36	3.90	118	814
3.95	235	235	235	247	61.4	99.0	21.7	41.4	70.3	42.9	21.5	35	3.95	115	793
4.00	229	229	229	241	60.8	98.2	20.5	40.5	69.7	41.9	20.1	34	4.00	111	765
4.05	223	223	223	234	-	97.3	(18.5)	-	-	-	-	-	4.05	-	-

Source: ASTM E140 – extended

Table A.2b (2/2) Hardness conversion table (Brinell to Others)

Equivalent Hardness Values															T.S. (approx) ksi	T.S. (approx) MPa
Brinell Dent Diameter mm	Brinell Φ10 mm, 3000 kgf			Vickers Hv10 (HV)	Rockwell				Rockwell Special Scale			Shore Sclero -scope	Brinnel Dent Diameter mm			
	STD (HBS)	Hultgren	WC (HBW)		A scale 60 kgf (HRA)	B sclae 100 kgf Φ 1/16" (HRB)	C scale 150 kgf (HRC)	D scale 100 kgf (HRD)	15-N scale 15 kgf (HR 15-N)	30-N scale 30 kgf (HR 30-N)	45-N scale 45 kgf (HR 45-N)					
4.10	217	217	217	228	-	96.4	(17.5)	-	-	-	-	33	4.10	105	724
4.15	212	212	212	222	-	95.5	(16.0)	-	-	-	-	-	4.15	102	703
4.20	207	207	207	218	-	94.6	(15.2)	-	-	-	-	32	4.20	100	690
4.25	201	201	201	212	-	93.8	(13.8)	-	-	-	-	31	4.25	98	676
4.30	197	197	197	207	-	92.8	(12.7)	-	-	-	-	30	4.30	95	655
4.35	192	192	192	202	-	91.9	(11.5)	-	-	-	-	29	4.35	93	641
4.40	187	187	187	196	-	90.7	(10.0)	-	-	-	-	-	4.40	90	621
4.45	183	183	183	192	-	90.0	(9.0)	-	-	-	-	28	4.45	89	614
4.50	179	179	179	188	-	89.0	(8.0)	-	-	-	-	27	4.50	87	600
4.55	174	174	174	182	-	87.8	(6.4)	-	-	-	-	-	4.55	85	586
4.60	170	170	170	178	-	86.8	(5.4)	-	-	-	-	26	4.60	83	572
4.65	167	167	167	175	-	86.0	(4.4)	-	-	-	-	-	4.65	81	558
4.70	163	163	163	171	-	85.0	(3.3)	-	-	-	-	25	4.70	79	545
4.80	156	156	156	163	-	82.9	(0.9)	-	-	-	-	-	4.80	76	524
4.90	149	149	149	156	-	80.8	-	-	-	-	-	23	4.90	73	503
5.00	143	143	143	150	-	78.7	-	-	-	-	-	22	5.00	71	490
5.10	137	137	137	143	-	76.4	-	-	-	-	-	21	5.10	67	462
5.20	131	131	131	137	-	74.0	-	-	-	-	-	-	5.20	65	448
5.30	126	126	126	132	-	72.0	-	-	-	-	-	20	5.30	63	434
5.40	121	121	121	127	-	69.8	-	-	-	-	-	19	5.40	60	414
5.50	116	116	116	122	-	67.6	-	-	-	-	-	18	5.50	58	400
5.60	111	111	111	117	-	65.7	-	-	-	-	-	15	5.60	56	386

Source: ASTM E140 – extended

Notes: WC = tungsten carbide, HBS = BHN = HBW; see ASTM E140 for HRE, HRF, HRG, HRK, HR 15 T/30-T/45-T scales for Ni alloys

See ASTM E140 for hardness conversion of ASS and brass

See Fig. 5.12 in this book for DSS

Table A.2c Hardness conversion table (Rockwell C Scale to others)

Equivalent Hardness Values													T.S. (approx)	T.S. (approx)
Rockwell C scale (HRC)	Vickers ZHV10 (HV)	Brinell Φ10 mm, 3000 kgf			Rockwell			Rockwell Special Scale			Shore Sclero-scope	Rockwell C scale (HRC)	ksi	MPa
		STD (HBS)	Hultgren	WC (HBW)	A scale 60 kgf (HRA)	B sclae 100 kg f Φ 1/16 " (HRB)	D scale 100 kgf (HRD)	15-N scale 15 kgf (HR 15-N)	30-N scale 30 kgf (HR 30-N)	45-N scale 45 kgf (HR 45-N)				
68	940	-	-	-	85.6	-	76.9	93.2	84.4	75.4	97	68	-	-
67	900	-	-	-	85.0	-	76.1	92.9	83.6	74.2	95	67	-	-
66	865	-	-	-	84.5	-	75.4	92.5	82.8	73.3	92	66	-	-
65	832	-	-	739	83.9	-	74.5	92.2	81.9	72.0	91	65	-	-
64	800	-	-	722	83.4	-	73.8	91.8	81.1	71.0	88	64	-	-
63	772	-	-	705	82.8	-	73.0	91.4	80.1	69.9	87	63	-	-
62	746	-	-	688	82.6	-	72.2	91.1	79.3	68.8	85	62	-	-
61	720	-	-	670	81.8	-	71.5	90.7	78.4	67.7	83	61	-	-
60	697	-	613	654	81.2	-	70.7	90.2	77.5	66.6	81	60	-	-
59	674	-	599	634	80.7	-	69.9	89.8	76.6	65.5	80	59	326	2248
58	653	-	587	615	80.1	-	69.2	89.3	75.7	64.3	78	58	315	2172
57	633	-	575	595	79.6	-	68.5	88.9	74.8	63.2	76	57	310	2137
56	613	-	561	577	79.0	-	67.7	88.3	73.9	62.0	75	56	295	2034
55	595	-	546	560	78.5	-	66.9	87.9	73.0	60.9	74	55	287	1979
54	577	-	534	543	78.0	-	66.1	87.4	72.0	59.8	72	54	278	1917
53	560	-	519	525	77.4	-	65.4	86.9	71.2	58.6	71	53	269	1855
52	544	500	508	512	76.8	-	64.6	86.4	70.2	57.4	69	52	262	1806
51	528	487	494	496	76.3	-	63.8	85.9	69.4	56.1	68	51	253	1744
50	513	475	481	481	75.9	-	63.1	85.5	68.5	55.0	67	50	245	1689
49	498	464	469	469	75.2	-	62.1	85.0	67.6	53.8	66	49	239	1648
48	484	451	455	455	74.7	-	61.4	84.5	66.7	52.5	64	48	232	1600
47	471	442	443	443	74.1	-	60.8	83.9	65.8	51.4	63	47	225	1551
46	458	432	432	432	73.6	-	60.0	83.5	64.8	50.3	62	46	219	1510
45	446	421	421	421	73.1	-	59.2	83.0	64.0	49.0	60	45	212	1462
44	434	409	409	409	72.5	-	58.5	82.5	63.1	47.8	58	44	206	1420
43	423	400	400	400	72.0	-	57.7	82.0	62.2	46.7	57	43	201	1386
42	412	390	390	390	71.5	-	56.9	81.5	61.3	45.5	56	42	196	1351
41	402	381	381	381	70.9	-	56.2	80.9	60.4	44.3	55	41	191	1317
40	392	371	371	371	70.4	-	55.4	80.4	59.5	43.1	54	40	186	1282
39	382	362	362	362	69.9	-	54.6	79.9	58.6	41.9	52	39	181	1248
38	372	358	358	358	69.4	-	53.8	79.4	57.7	40.8	51	38	176	1214
37	363	344	344	344	68.9	-	53.1	78.8	56.9	39.6	50	37	172	1186
36	354	336	336	336	68.4	(109.0)	52.3	78.3	55.9	38.4	49	36	168	1158
35	345	327	327	327	67.9	(108.5)	51.5	77.7	55.0	37.2	48	35	163	1124
34	336	319	319	319	67.4	(108.0)	50.8	77.2	54.2	36.1	47	34	159	1096
33	327	311	311	311	66.8	(107.5)	50.0	76.6	53.3	34.9	46	33	154	1061
32	318	301	301	301	66.3	(107.0)	49.2	76.1	52.1	33.7	44	32	150	1034
31	310	294	294	294	65.8	(106.0)	48.4	75.6	51.3	32.5	43	31	146	1007
30	302	286	286	286	65.3	(105.5)	47.7	75.0	50.4	31.3	42	30	142	979
29	294	279	279	279	64.7	(104.5)	47.0	74.5	49.5	30.1	41	29	138	952
28	286	271	271	271	64.3	(104.0)	46.1	73.5	48.6	28.9	41	28	134	924
27	279	264	264	264	63.8	(103.0)	45.2	73.3	47.7	27.8	40	27	131	903
26	272	258	258	258	63.3	(102.5)	44.6	72.8	46.8	26.7	38	26	127	876
25	266	253	253	253	62.8	(101.5)	43.8	72.2	45.9	25.5	38	25	124	855
24	260	247	247	247	62.4	(101.0)	43.1	71.6	45.0	24.3	37	24	121	834
23	254	243	243	243	62.0	(100.0)	42.1	71.0	44.0	23.1	36	23	118	814
22	248	237	237	237	61.5	(99.0)	41.6	70.5	43.2	22.0	35	22	115	793
21	243	231	231	231	61.0	(98.5)	40.9	69.9	42.3	20.7	35	21	113	779
20	238	226	226	226	60.5	97.8	40.1	69.4	41. 5	19.6	34	20	110	758
(18)	230	219	219	219	-	96.7	-	-	-	-	33	(18)	106	731
(16)	222	212	212	212	-	95.5	-	-	-	-	32	(16)	102	703
(14)	213	203	203	203	-	93.9	-	-	-	-	31	(14)	98	676
(12)	204	194	194	194	-	92.3	-	-	-	-	29	(12)	94	648
(10)	196	187	187	187	-	90.7	-	-	-	-	28	(10)	90	621
(8)	188	179	179	179	-	89.5	-	-	-	-	27	(8)	87	600
(6)	180	171	171	171	-	87.1	-	-	-	-	26	(6)	84	579
(4)	173	165	165	165	-	85.5	-	-	-	-	25	(4)	80	552
(2)	166	158	158	158	-	83.5	-	-	-	-	24	(2)	77	531
(0)	160	152	152	152	-	81.7	-	-	-	-	24	(0)	75	517

Source: ASTM E140 – extended

Notes: WC = tungsten carbide, HBS = BHN = HBW; see ASTM E140 for HRE, HRF, HRG, HRK, HR 15T/30-T/45-T scales for Ni alloys
See ASTM E140 for hardness conversion of ASS and brass
See Fig. 5.12 in this book for DSS

A.3 Properties of Steels and Alloys

Table A.3 (source: ASM Metal Handbooks)

										at 20 °C
Class	Pure and alloys	Density (g/cm^3)[(1)]	Hardness (HB)[(2)]	T.S. (kg/mm^2)	Elongation (%)	Melting point[(3)] (°C)	Thermal conductivity[(4)] Cal/(cm·sec)	Thermal expansion[(5)] ($\times 10^{-6}$)	Specific heat[(6)] (Cal/gr. °C)	Electric resistivity[(7)] ($\times 10^{-6}$) (Ω/cm^2)
Pure Metal	Zinc	7.1	–	4~12	36	419	0.265	26.3	0.093	6.1
	Aluminum	2.70	25	10	40	657	0.50	25.5	0.219	2.94
	Antimony	6.62	–	10	–	630	0.040	12.0	0.0508	40.5
	Gold	19.32	26	11	30	1063	0.700	13.9	0.0303	2.42
	Silver	10.50	26	22	40	962	0.974	18.8	0.056	1.66
	Chromium	7.14	–	–	–	1800	–	6.8	0.104	2.70
	Cobalt	8.79	124~130	–	–	1480	0.130	82.3	0.103	16.36
	Tin	7.29	–	8	–	232	0.155	21.4	0.0552	11.3
	Tungsten	18.8	100~350	380	–	3500	0.35	3.36	0.034	5.0
	Iron	7.86	83	30	40	1530	0.161	13.10	0.119	9.0
	Copper	8.93	46	22	50	1083	0.918	16.7	0.0936	1.78
	Lead	11.37	–	3	–	327	0.083	27.6	0.0305	20.8
	Nickel	8.90	96	50	40	1452	0.142	12.8	0.109	11.8
	Platinum	21.50	–	25	10	1750	0.166	8.9	0.0324	11.0
	Manganese	7.39	–	–	–	1260	–	18.5	0.122	–
	Magnesium	1.74	–	1.4	30	649	0.376	24.5	0.246	4.35
	Molybdenum	10.00	17	40	–	2450	–	3.6	0.072	4.1
Alloy	Al bronze	7.86	120	50	32	1050	0.165	17	–	12~14
	Invar	8.00	100	60	32	1425	–	1	0.12	85
	Duralumin	2.8	115~128	45~60	6~20	650	–	22.6	–	3.2~5
	Brass (7 : 3)	8.50	50	20	38	910	0.20	18.0	0.092	6
	Brass (4 : 6)	8.40	80	40	35	880	0.20	19.8	0.092	7
	CS- 0.05%C	7.86	70	35	35	1520	0.13	12.0	0.102	14
	CS- 0.2%C	7.85	111	45	25	1510	0.12	12.0	0.103	15
	CS- 0.4%C	7.84	135	60	18	1500	0.12	11.0	0.104	16.5
	CS- 0.8%C	7.82	230	85	12	1450	0.095	11.0	0.105	19
	CS- 0.25%C	7.80	288	87	10	1420	0.095	11.0	0.106	21
	Cast Iron	6.9~7.2	140~220	18~21	–	1240	0.090	11.0	0.115	30
	20% Ni steel	8.92	68	40~46	27	1160	–	9.5	–	–
	40% Ni steel	8.92	90	61	30	1250	0.06	–	0.098	48
	304SS	7.90	135~185	>55	>55	1400	0.038	17.3	0.118	70
	T316SS	7.945	135~185	>55	>50	1400	0.038	16.7	0.118	74
	Ni-Cr alloy	8.41	175~200	>70	>20	1390	0.043	13.2	0.106	108
	Bronze	8.70	65~70	25	16	970	0.90	17.2	–	7~25
	Phosphorus brass	8.50	74~80	40~165	10	980	–	16.8	–	15

Notes

[(1)]Density (g/cm^3) = specific gravity. See Table 2.68 (nickel alloys), Table 2.88 (tantalum alloys), Table 2.126 (density for k value in corrosion rate calculation), Table 2.94 and 2.95 (several thermoplastic materials), Sects. 2.6.2.1 through 2.6.2.6 (several ASTM standard materials), and Table A.4 (Poisson's ratio density of several metals) in this book for more detail

Material Grade	Density(g/cm^3)	Material Grade	Density(g/cm^3)	Material Grade	Density(g/cm^3)	Material Grade	Density (g/cm^3)
Aluminum Alloy 1100	2.71	Hastelloy C-2000	8.50	Monel 400	8.80	17-7PH SS	7.81
Aluminum Alloy 3033	2.73	Hastelloy 'X'	8.22	Monel K500	8.44	S31803 –F51	7.82
Aluminum Alloy 2011	2.83	Hastelloy B-2	9.22	Nilo 42	8.11	S32550	7.80
Aluminum Alloy 2017	2.79	Hastelloy C-4	8.64	301 SS	8.03	S32750 –F53	8.00
Aluminum Alloy 2024	2.78	Hastelloy C-22	8.69	302 SS	7.86	S 32760 – F55	7.70
Aluminum Alloy 5052	2.68	Hastelloy G3	8.31	304 SS	7.94	AL6XN	8.04
Aluminum Alloy 6061	2.70	Incoloy800(H)	7.98	316(L) SS	7.98	Alloy 254SMO	8.00
Aluminum Alloy 6082	2.70	Incoloy 825	8.14	317 SS	7.98	Alloy 654SMO	7.90
Aluminum Alloy 7075	2.81	Inconel 925	8.05	321 SS	7.90	Alloy 20(Cb)	8.08
Alloy Steel 4130	7.85	Inconel 600	8.40	347 SS	8.02	Titanium Alloy	4.40
Alloy Steel 4140	7.85	Inconel 601	8.11	410 SS	7.70	Titanium	4.50
Alloy Steel 4145	7.85	Inconel 617	8.37	420 SS	7.80	90-10 Cu-Ni	8.90
Carbon Steel 1018	7.87	Inconel 625	8.44	430 SS	7.72	70-30 Cu-Ni	8.95
Carbon Steel 1045	7.85	Inconel 718	8.19	15-5PH SS	7.80	Naval Brass	8.41
Hastelloy C276	8.89	Inconel 725	8.30	17-4PH SS	7.74		

[2]Hardness: See Para. 2.6.2.1 through 2.6.2.6 in this book for more detail of several ASTM standard materials
[3]Melting point: See API 579–1/ASME FFS-1, Table 11.14 for more detail
[4]Thermal conductivity: See Table A.6 in this book, ASME Sec. II Part D, Table TCD, and WRC Bulletin 503 for more detail
[5]Thermal Expansion: See Sec. II Part D, Table TE series/ B31.3 Table C-1, 3, 5/ B31.1 Table B-1/ WRC Bulletin 503/ASM Metal Handbook, Vol.1, for more detail
[6]Specific Heat: See Table 1.34 in this book for more detail
[7]Electric Resistivity: See Table 1.33 in this book for more detail

A.4 Poisson Ratio and Rigidity of Steels and Alloys (Source: ASME Sec II-D, Table PRD)

Table A.4 Poisson's ratio and density of metals (1 lb/in^3 = 27.68 g/cm^3)

Metals	Poisson's ratio	Density, g/cm^3	Density, lb/in^{3}	Metals	Poisson's ratio	Density, g/cm^3	Density, lb/in^{3}
Ferrous metals				**Nonferrous metals**			
CS	0.30	7.75	0.280	***Nickel Base-***			
CI	0.29	7.20	0.260	N02200, N02201	0.31	8.89	0.321
LAS: C-Cr-Mo steels Mn, Mn–Mo, Si, and Ni steels	0.30	7.75	0.280	N04400, N04405, N10276	0.31	8.86	0.320
				N05500, N06002, N06985	0.31	8.30	0.300
PHSS: S15500, S17400, S17700	0.31	7.75	0.280	N06022	0.31		0.314
200 series ASS	0.31	7.81	0.282	N06030, N07718	0.31		0.297
300 series ASS	0.31	8.03	0.290	N06045	0.31		0.289
High Si SS: S30600, S30601, S32615, and S38815	0.31	7.61	0.275	N06059	0.31		0.311
				N06200	0.31		0.307
SASS (6% Mo ASS): S32050, S31254, S31266, S31277, S32654	0.31	8.11	0.293	N06230	0.31		0.324
				N06455	0.31		0.312
400 series MSS & FSS	0.31	7.75	0.280	N06600	0.31		0.300
S32202 (DSS)	0.31	7.75	0.280	N06601	0.31		0.291
DSS & SDSS	0.31	7.81	0.282	N06617	0.31		0.302
PHSS: SS66286	0.31	7.92	0.286	N06625	0.31	8.44	0.305
Cast high alloy SS	0.30	7.83	0.283	N06686	0.31	8.72	0.315
Nonferrous metals				N06690, N08024	0.31	8.11	0.293
Aluminum Base-				N06975	0.31	8.17	0.295
Alclad 3003, 3004, 6061, A91060, A91100, A93004, A96061	0.33	2.71	0.098	N07750	0.31	8.25	0.298
				N08020, N08367, J94651, N08904, N08926	0.31	8.05	0.291
A02040, A92014	0.33	2.80	0.101				
A03560, A24430, A95052, A95454, A96063	0.33	2.68	0.097	N08026, N08825, N08925	0.31	8.14	0.294
				N08028	0.31	8.00	0.289
A92024	0.33	2.77	0.100	N08031	0.31	8.11	0.293
A93003	0.33	2.74	0.099	N08330, N08800, N08810, N08811	0.31	8.03	0.290
A95083, A95086, A95154, A95254, A95456, A95652	0.33	2.66	0.096	N10001	0.31	9.16	0.331
				N10003	0.31	8.86	0.320
Chromium Base- R20033	0.31	7.89	0.285	N10242	0.31	9.05	0.327
Cobalt Base- R30556	0.31	8.22	0.297	N10629	0.31	9.19	0.332
R31233	0.31	8.47	0.306	N10665 and N10675	0.31	9.22	0.333
Copper Base-				N12160	0.31	8.08	0.292
C10200, C10400, C10500, C10700, C12000, C12200, C12300, C14200	0.33	8.94	0.323	***Titanium Base-***			
				R50250, R50400, R50550, R52250,	0.32	4.51	0.163
C11000, C97600	0.33	8.89	0.321	R52252, R52254, R52400, R52402,			
C19200, C93700	0.33	8.86	0.320	R52404, R53400			
C19400	0.33	8.91	0.322	R56320, R56323	0.32	4.48	0.162
C23000, C65100	0.33	8.75	0.316	R54250	0.32	4.46	0.161
C28000	0.33	8.39	0.303	***Zirconium Base-***			
C36500, C46400, and C46500	0.33	8.41	0.304	R60702, R60704, R60705	0.35	6.48	0.234
C37700	0.33	8.44	0.305				

Metals	Poisson's ratio	Density, g/cm^3	Density, lb/in^{-3}	Metals	Poisson's ratio	Density, g/cm^3	Density, lb/in^{-3}
C44300, C44400, C44500, C65500, C66100	0.33	8.53	0.308				
C60800	0.33	8.17	0.295				
C61400	0.33	7.89	0.285				
C63000	0.33	7.58	0.274				
C64200	0.33	7.70	0.278				
C68700	0.33	8.33	0.301				
C70400, C70600, C71000, C71500, C72200	0.33	8.94	0.323				
C83600	0.33	8.80	0.318				
C99200	0.33	8.64	0.312				
C95200	0.31	7.64	0.276				
C95400	0.32	7.45	0.269				
C95800	0.32	7.64	0.276				
C95820	0.32	7.45	0.269				

Notes: (1)Poisson's ratio: See ASME Sec. II Part D, Table PRD, WRC 503 for more detail as well
(2)Density: See Table A.3 as well

A.5 Elastic Modulus of Metals

Table A.5 Elastic modulus of various metals (simplified)

Temp (°F) / Mat'l	Elastic modulus, psi × 10^{-6}												
	70	100	200	300	400	500	600	700	800	900	1000	1100	1200
CS, C-Mo, Mn-Mo	29.2	29.0	28.5	28.0	27.4	27.0	26.4	25.3	23.9	22.2	20.1	17.8	15.3
ASS	28.3	28.1	27.6	27.0	26.5	25.8	25.3	24.8	24.1	23.5	22.8	22.1	21.2
1/2 Cr to 2%Cr	29.7	29.5	29.0	28.5	27.9	27.5	26.9	26.3	25.5	24.8	23.9	23.0	21.8
2-1/4 Cr-1 Mo & Cr-1 Mo	30.6	30.4	29.8	29.4	28.8	28.3	27.7	27.1	26.3	25.6	24.6	23.7	22.5
Cr-Mo (5–9% Cr)	30.9	30.7	30.1	29.7	29.0	28.6	28.0	27.3	26.1	24.7	22.7	20.4	18.2
12, 13, 15, & 17% Cr	29.2	29.0	28.5	27.9	27.3	26.7	26.1	25.6	24.7	22.2	21.5	19.1	16.6
Low Ni steels thru 3–1/2%Ni	27.8	27.6	27.1	26.7	26.1	25.7	25.2	24.6	23.0	21.4	19.7	17.5	15.3
Ni-Cu alloy 400	26.0	25.8	25.4	25.0	24.7	24.3	24.1	23.7	23.1	22.6	22.1	21.7	21.2
90–10 Cu-Ni	16.0	17.9	17.6	17.3	16.9	16.6	16.0	15.4					
Aluminum	10.0	9.9	9.6	9.2	8.7								
Ni-Cr-Fe alloy 600	31.0	30.8	30.2	29.9	29.5	29.0	28.7	28.2	27.6	27.0	26.4	25.9	25.3
Ni-Fe-Cr (alloy 800 & 800H)	28.5	28.3	27.8	27.4	27.1	26.6	26.4	25.9	25.4	24.8	24.2	23.8	23.2
Ni-Mo alloy B	31.1	30.9	30.3	29.9	29.5	29.1	28.8	28.3	27.7	27.1	26.4	26.0	25.3
Ni-Mo-Cr alloy C-276	29.8	29.6	29.1	28.6	28.3	27.9	27.6	27.1	26.5	25.9	25.3	24.9	24.3
Nickel 200	30.0	29.8	29.3	28.8	28.5	28.1	27.8	27.3	26.7	26.1	25.5	25.1	24.5
Copper & Al-bronze	17.0	06.9	16.6	16.3	16.0	15.6	15.1	14.5					
Commercial brass	15.0	14.9	14.6	14.1	14.1	13.8	13.4	12.8					
Admiralty brass	16.0	15.9	15.6	15.4	15.0	14.7	14.2	13.7					
Titanium	15.5	15.4	15.0	14.6	14.0	13.3	12.6	11.9	11.2				
70–30 Cu-Ni	22.0	21.9	21.5	21.1	20.7	20.2	19.6	18.8					
Ni-Mo Alloy B-2	31.4	31.2	30.6	30.1	29.8	29.3	29.0	28.6	27.9	27.3	26.7	26.2	25.6
Ni-Fe-Cr-Mo-Cu (alloy 825)	28.0	27.8	27.3	26.9	26.6	26.2	25.9	25.5	24.9	24.4	23.8		
Muntz	15.3	15.0	14.0	12.9	11.8	10.8							
Zirconium		14.4	13.9	13.4	12.4	11.5	10.7	9.9					
Ni-Cr-Mo-Cb (alloy 625 Solution heat treated)	29.7	29.5	29.1	28.6	28.1	27.6	27.2	26.7	26.2	25.6	25.1	24.5	24.0

Source: ASME Sec. II, Part D
References for More Detail
– ASME Sec. II, Part D, Table TM series
– ASTM Special Technical Publication No. 181
– WRC Bulletin 503
– TEMA
– Huntington Alloy Inc. Bulletin #15MI-76T-42

A.6 Thermal Conductivity and Diffusivity of Metals (See ASME Sec. II, Part D, Table TCD for More Detail)

Table A.6 Thermal conductivity and diffusivity of metals (simplified)

Temp (°F) / Materials	Thermal conductivity BTU/Hr. ft °F															
	70	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
CS	30.0	29.9	29.2	28.4	27.6	26.6	25.6	24.6	23.5	22.5	21.4	20.2	19.0	17.6	16.2	15.6
C-0.5 Mo steel	24.8	25.0	25.2	25.1	24.8	24.3	23.7	23.0	22.2	21.4	20.4	19.5	18.4	16.7	15.3	15.0
1Cr-0.5Mo & 1.25Cr-0.5Mo	21.3	21.5	21.9	22.0	21.9	21.7	21.3	20.8	20.2	19.7	19.1	18.5	17.7	16.5	15.0	14.8
2.25Cr-1Mo	20.9	21.0	21.3	21.5	21.5	21.4	21.1	20.7	20.2	19.7	19.1	18.5	18.0	17.2	15.6	15.3
5Cr-0.5Mo	16.9	17.3	18.1	18.7	19.1	19.2	19.2	19.0	18.7	18.4	18.0	17.6	17.1	16.6	16.0	15.8
7Cr-0.5Mo	14.1	14.4	15.3	16.00	16.5	16.9	17.1	17.2	17.3	17.2	17.1	16.2	16.6	16.2	15.6	15.5
9Cr-1Mo	12.8	13.1	14.0	14.7	15.2	15.6	15.9	16.0	16.1	16.3	16.1	16.0	15.8	15.6	15.2	15.0
3.5 nickel	22.9	23.2	23.8	24.1	23.9	23.4	22.9	22.3	21.6	20.9	20.1	19.2	18.2	16.9	15.5	15.3
13Cr	15.2	15.3	15.5	15.6	15.8	15.8	15.7	15.9	15.9	15.9	15.8	15.6	15.3	15.1	15.0	15.1
15Cr	14.2	14.2	14.4	14.5	14.6	14.7	14.7	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
17Cr	12.6	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.7	13.8	13.9	14.1	14.3	14.5
304/304L SS	8.6	8.7	9.3	9.8	10.4	10.4	11.3	11.8	22.2	12.7	13.2	13.6	14.0	14.5	14.9	15.3
316/316L SS & 317/317L SS	7.7	7.9	8.4	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.4	12.5	13.3	13.8	14.2	14.6
321 SS & 347 SS	8.1	8.4	8.8	9.4	9.9	10.4	10.9	11.4	11.9	12.3	12.8	13.3	13.7	14.1	14.6	15.0
310 SS	7.3	7.5	8.0	8.6	9.1	9.6	10.1	10.6	11.1	11.6	12.1	12.6	13.1	13.6	14.1	14.5
Nickel 200			38.8	37.2	35.4	34.1	32.5	31.8	32.5	33.1	33.8					
Ni-Cu (alloy 400)	12.6	12.9	13.9	15.0	16.1	17.0	17.9	18.9	19.8	20.9	22.0					
Ni-Cr-Fe (alloy 600)	8.6	8.7	9.1	9.6	10.1	10.6	11.1	11.6	12.1	12.6	13.2	13.8	14.3	14.9	15.5	16.0
Ni-Fe-Cr (alloy 800)	6.7	6.8	7.4	8.0	8.6	9.1	9.6	10.1	10.6	11.1	11.6	12.1	12.7	13.2	13.8	14.5
Ni-Cr-Mo-Cu (alloy 825)			7.1	7.6	8.1	8.6	9.1	9.6	10.0	10.4	10.9	11.4	11.8	12.4	12.9	13.6
Ni-Mo (alloy B)		6.1	6.4	6.7	7.0	7.4	7.7	8.2	8.7	9.3	10.0	10.7				
Ni-Mo-Cr (alloy C-276)		5.9	6.4	7.0	7.5	8.1	8.7	9.2	9.8	10.4	11.0	11.5	12.1		13.2	
Aluminum Alloy (3003)	102.3	102.8	104.2	105.2	106.1											
Aluminum Alloy (6061)	96.1	96.9	99.0	100.6	101.9											
Titanium	12.7	12.5	12.0	11.7	11.5	11.3	11.2	11.1	11.2	11.3	11.4	11.6				
Admiralty brass		70.0	75.0	79.0	84.0	89.0										
Naval brass		71.0	74.0	77.0	80.0	83.0										
Copper		225.0	225.0	224.0	224.0	223.0										
90–10 Cu-Ni		30.0	31.0	34.0	37.0	42.0	47.0	49.0	51.0	53.0						
70–30 Cu-Ni		18.0	19.0	21.0	23.0	25.0	27.0	30.0	33.0	37.0						
Muntz			71.0													
Zirconium			12.0													
Cr-Mo (alloy XM-27)			11.3													
Cr-Ni-Fe-Mo-Cu-Cb (alloy 20Cb)			7.6													
Ni-Cr-Mo-Cb (alloy 625)	68.0	70.0	75.0		87.0		98.0		109.2		121.0		132.0		144.0	

Source: ASME Sec. II, Part D

Notes: 1. See ASME Sec. II, Part D for more detail

2. Thermal conductivity (TC; Btu/Hr ft °F) vs. thermal diffusivity (TD; ft^2/hr)

$$TD = \frac{TC[\text{Btu/hr} \cdot \text{ft}\cdot{}^0\text{F}]}{\text{Density}\ [\text{lb/ft}^3] \times \text{Specific Heat}\ [\text{Btu/lb}\cdot{}^0\text{F}]}$$

A.7 Thermal Expansion Coefficiency of Metals (See ASME Sec. II, Part D, Table TE-1 through TE-5 for More Detail)

Table A.7 Thermal expansion coefficiency of metals

Temp (°F) / Materials	Thermal expansion mean coefficients, inches per inch per °F × 10^{-6} between 70 °F and;															
	−200	−100	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Plain carbon St & C-Mo-St	5.60	5.90	6.50	6.67	6.37	7.07	7.25	7.42	7.59	7.76	7.89					
C-Si St, C-0.5Mo, & 1Cr-0.5Mo	5.60	5.64	5.73	6.09	6.43	6.74	7.06	7.28	7.51	7.71	7.86	8.00				
C-Mn-Si St, 1.25Cr-0.5Mo, & 3Cr-1Mo			5.53	5.89	6.26	6.61	7.17	7.41	7.59	7.77	7.94	8.07	8.24			
Mo-Mo St	5.60	6.08	7.06	7.25	7.43	7.58	7.70	7.83	7.94	8.05	8.14	8.23				
2.5 & 3.5 Ni			6.27	6.54	6.78	6.98	7.16	7.32	7.47	7.61						
2.25Cr-1Mo	5.60	5.90	6.50	6.70	6.90	7.07	7.23	7.38	7.50	7.62	7.72	7.82	7.90	7.97		
5Cr-0.5Mo	5.60	5.90	6.50	6.73	6.87	6.97	7.05	7.15	7.24	7.32	7.41	7.48	7.56	7.64		
7Cr-0.5Mo & 9Cr-1Mo	5.60	5.68	5.85	6.02	6.15	6.29	6.40	6.51	6.62	6.71	6.82	6.90	7.00	7.08		
12Cr & 13Cr	5.10	5.39	5.98	6.15	6.30	6.40	6.48	6.53	6.60	6.67	6.72	6.78	6.83	6.88		
15Cr & 17Cr	5.10	5.19	5.37	5.52	5.65	5.75	5.85	5.95	6.05	6.13	6.22	6.30	6.37	6.44		
17-19Cr (type 439 SS)				5.59	5.70	5.81	5.92	6.03	6.14	6.25	6.36	6.46	5.56	6.65	6.74	6.83
316 & 317 S.S			8.54	8.76	8.97	9.21	9.42	9.60	9.76	9.90	70.02	10.16	10.29	10.40	10.52	10.62
304 S.S			8.55	8.79	9.00	9.19	9.37	9.53	9.69	9.82	9.95	10.07	10.18	10.29	10.39	10.49
321 S.S			9.02	9.16	9.26	9.34	9.42	9.48	9.55	9.61	9.67	9.73	9.79	9.85	9.90	9.95
347 S.S			8.62	8.92	9.22	9.45	9.65	9.83	9.97	10.08	10.22	10.33	10.95	10.56	10.66	10.75
25Cr-12 Ni, 23 Cr-12 Ni, & 25Cr-20 Ni			8.87	9.02	9.10	9.14	9.18	9.21	9.25	9.28	9.32	9.37	9.41	9.47	9.54	9.62
AL-6XN (N08367)				8.50	8.55	8.61	8.72	8.82	8.87	8.95	9.06	9.18	9.29	9.40	9.51	9.68
2205 DSS (S31803)			7.00	7.00	7.25	7.50	7.65	7.80	7.90	8.00						
Aluminum (3003)	11.80	12.04	12.54	12.85	13.15	13.45										
Aluminum (6061)	11.80	12.06	12.60	12.91	13.22	13.52										
Titanium (grades 1, 2, 3, & 7)			4.65	4.70	4.75	4.80	4.85	4.90	4.97	5.05						
Ni-Cu (alloy 400)			7.78	8.08	8.33	8.54	8.69	8.81	8.88	8.91						
Ni-Cr-Fe (alloy 600)			6.90	7.20	7.40	7.57	7.70	7.82	7.94	8.04						
Ni-Fe-Cr (alloy 800 & 800H)			7.95	8.34	8.60	8.78	8.92	9.00	9.11	9.20	9.30	9.40				
Ni-Fe-Cr-Mo-Cu (alloy 825)			7.53	7.71	7.85	7.97	8.09	8.20	8.30	8.40						
NI-Mo (alloy B)			6.08	6.24	6.35	6.40	6.41	6.47	6.57	6.68						
NI-Mo-Cr (alloy C-276)			6.06	6.30	6.50	6.71	6.91	7.08	7.22	7.33						
Nickel (alloy 200)	6.20	6.39	6.77	7.21	7.52	7.74	7.91	8.05	8.16	8.27	8.50	8.60	8.70	8.80	8.90	8.90
3RE60 (S31500)			8.03	8.25	8.45	8.61	8.76	8.90	9.04	9.16						
70–30 Cu-Ni				8.50	8.70	8.90	9.10									
90–10 & 80–20 Cu-Ni					9.50											
Copper	8.60	9.00	9.40	9.60	9.70	9.80	9.90	10.10	10.20	10.30	10.40	10.50				
Brass	9.10	9.30	9.60	9.70	10.00	10.20	10.50	10.70	10.90	11.20	11.40	11.60	11.90	12.10		
Aluminum bronze							9.00									
7Mo (S32900)				5.60	6.00	6.10	6.20	6.35	6.50	6.69	6.88	7.06	7.25	7.44	7.63	7.81
7Mo plus (S32950)						6.39	6.67	6.94	7.22	7.49	7.68	7.88	7.98	8.08	8.12	8.16
Copper-silicon							10.00									
Admiralty								11.20								
Zirconium			3.20		3.50	3.70	3.90		4.10							
Cr-Ni-Fe-Mo-Cu-Co (alloy 20Cb)			8.30	8.30							9.40				9.60	
Ni-Cr-Mo-Cb (alloy 625)	5.20	6.20	6.80	7.10	7.20	7.30	7.35	7.45	7.52	7.60	7.70	7.80	8.00	8.20	8.35	8.50
AL 29-4-2				5.20												
Sea-cure				5.38	5.43	5.62	5.81	5.88	5.95							

Source: TEMA simplified

A.8 Simplified Materials Cost Ratio Based on the Killed CS (Only for Reference; " – " No Data)

Table A.8.1 Plates

Material	Designation	Cost weight	
		Plate	Clad plate
CS	A36 (non-deoxidation steel)	0.60	–
CS	A516 Gr. 70	**1.00 (base)**	1.00
5% Cr-1/2Mo steel	A837-Gr.5	2.8	–
12% Cr SS	405 SS, 410 SS	3.3–3.9	2.2–2.4
17% Cr SS	430 SS	3.5	2.4
18% Cr-8% Ni SS	304(L) SS, 316(L) SS, 321 SS, 347 SS	5.0–8.0	3.1–5.6
25% Cr-20% Ni SS	310 SS	10	6.8
Aluminum	Al 1100, 3003, 6061, 5456	3.9–4.3	–
Copper	CDA No.110	8.6	6.0
Aluminum bronze(D)	CDA No.614	10	6.4
70–30 copper nickel	CDA No.715	12	6.8
Nickel	Nickel 200, 201	18	9.0
Ni-Cu alloy	Monel 400	17	10
Ni-Cr-Fe alloy	Alloy 800	11	8.0
Ni-Cr-Ni alloy	Inconel 600	20	11
Cu-Cr-Ni alloy	Carpenter 20 Cb3	22	12
Ni-Mo-Cr alloy	Hastelloy B	34	22
Ni-Mo-Cr alloy	Hastelloy C-276	34	22
Titanium	Gr.2/ Gr.12/ Gr.7	30/36/51	22/26/34
Zirconium	Pure	80–100	48
Tantalum	Pure	300–400	72

Table A.8.2 Pipes

Materials	Welded	Seamless	Materials	Welded	Seamless
CS (A106-B)	**1.00 (base)**	1.50	446 SS (26–1)	4.70	10.00
C-0.5Mo	1.04	2.60	904L SS	15.30	19.20
C-1Mo	1.05	2.70	Alloy 28 (Sanicro 28)	16.10	20.20
C-2.5Ni	1.15	2.90	2205 DSS	–	11.80
C-2Ni-1Cu	–	3.30	20Cb-3	15.10	–
C-3.5Ni	1.20	3.10	20Cb-6	18.90	–
Cr-Mo, 1 to 1.25Cr-0.5Mo	–	2.6–2.7	AL6XN	12.00	–
Cr-Mo, 2.25 to 3.0Cr-1Mo	–	3.0–3.2	Alloy 200 (99%Ni)	–	20.90
Cr-Mo, 5 to 7Cr-0.5Mo	–	4.40–5.50	Alloy 400	–	15.50
Cr-Mo, 7Cr-0.5Mo	–	5.50	Alloy B-2	34.90	48.60
Cr-Mo, 9Cr-1Mo	–	6.10	Alloy C-276	29.10	38.10
SA210, fluted, seamless	–	8.40	Alloy C-4	28.70	40.0
SA214, fluted, welded	7.00	–	Alloy G	15.30	24.70
SA214, welded	4.40	–	Alloy X	16.70	27.10
SA334-1, fluted, welded	7.40	–	Alloy 800	11.00	21.80
SA334-1, welded	4.70	–	Alloy 800H	–	18.0
SA334-3, seamless	–	9.00	Alloy 825	–	23.50
304(L) SS	2.8–3.0	6.50–7.00	Alloy 600	19.40	–
309 SS	5.80	14.50	Alloy 625	–	32.70
310 SS	7.40	12.00	Copper (as or deoxidized)	–	4.20
316L SS	4.7–4.8	10.1–11.0	Naval brass	–	3.50
317(L) SS	8.1–6.3	13.0–13.6	70–30 Cu-Ni	4.20	5.50
321 SS	4.20	9.50	90–10 Cu-Ni	3.50	4.60
329 SS	10.50	17.20	Admiralty	–	3.60
330 SS	7.90	12.90	AL-brass	–	3.70
347 SS	5.50	13.70	AL-bronze	–	4.10
405 SS	6.00	15.00	Aluminum	–	1.60
410(S) SS	6.9–7.1	17.2–17.5	Titanium Gr. 2	11.00	22.00
430 SS	5.40	10.60	Titanium Gr. 7	21.00	42.00
439 SS	5.00	11.20	Titanium Gr. 12	14.00	28.00
444 SS	7.80	8.80	Zirconium 702 & 705	35.0 & 39.0	43.7 & 48.7

A.9 Thickness Gauge Conversion and Pipe Schedule Tables

Table A.9.1 Thickness gauge conversion table

	Wire gauge							Sheet & plate gauge		
	S. W. G.	BWG	BWG	B & S	B & S	J. de P.	W. G.	B. G.	U. S. S.	U. S. S.
Gauge no.	mm	mm	inch	mm	*inch*	mm	mm	mm	mm	inch
0000000	12.699								12.700	0.5000
000000	11.785			14.73	0.5799				11.906	0.4688
00000	10.972	12.70	0.500	13.12	0.5165				11.113	0.4375
0000	10.159	11.532	0.454	11.68	0.4600				10.319	0.4062
000	9.448	10.495	0.425	10.40	0.4096			12.700	9.525	0.3750
00	8.839	9.652	0.380	9.266	0.3648	(PD) 100		11.303	8.732	0.3438
0	8.229	8.636	0.340	8.255	0.3249	(P) 500		10.069	7.938	0.3125
1	7.620	7.620	0.300	7.348	0.2893	600	0.60	8.971	7.144	0.2813
2	7.010	7.213	0.284	6.543	0.2576	700	0.68	7.993	6.747	0.2656
3	6.401	6.579	0.250	5.827	0.2294	800	0.76	7.122	6.350	0.2500
4	5.873	6.045	0.238	5.189	0.2043	900	0.80	6.350	5.953	0.2344
5	5.385	5.588	0.220	4.620	0.1819	1.000	0.88	5.652	5.556	0.2188
6	4.877	5.156	0.203	4.115	0.1620	1.100	1.00	5.032	5.159	0.2031
7	4.470	4.572	0.180	3.665	0.1443	1.200	1.12	4.481	4.763	0.1875
8	4.064	4.191	0.165	3.264	0.1285	1.300	1.20	3.988	4.366	0.1719
9	3.658	4.759	0.148	2.906	0.1144	1.400	1.30	3.551	3.969	0.1563
10	3.251	3.404	0.134	2.588	0.1019	1.500	1.40	3.175	3.572	0.1406
11	2.946	3.048	0.120	2.304	0.0907	1.600	1.56	2.827	2.175	0.1250
12	2.632	2.769	0.109	2.052	0.0808	1.800	1.66	2.517	2.778	0.1094
13	2.337	2.413	0.095	1.826	0.0720	2.000	1.84	2.240	2.381	0.0938
14	2.032	2.108	0.083	1.628	0.0641	2.200	2.04	1.994	1.984	0.0781
15	1.829	1.829	0.072	1.450	0.0571	2.400	2.20	1.775	1.786	0.0703
16	1.626	1.651	0.065	1.290	0.0508	2.700	2.40	1.588	1.588	0.0625
17	1.422	1.473	0.058	1.151	0.0453	3.000	2.60	1.412	1.429	0.0563
18	1.219	1.245	0.049	1.024	0.0403	3.400	2.92	1.257	1.270	0.0500
19	1.016	1.067	0.042	0.9116	0.0359	3.900	3.40	1.118	1.111	0.0438
20	0.9144	0.8886	0.035	0.8128	0.0320	4.400	3.84	0.9956	0.9525	0.0375
21	0.8128	0.8128	0.032	0.7239	0.0285	4.900	4.20	0.8865	0.8731	0.0344
22	0.7112	0.7109	0.028	0.6426	0.0243	5.400	4.65	0.7938	0.7938	0.0313
23	0.6096	0.6347	0.025	0.5740	0.0226	5.900	5.45	0.7077	0.7114	0.0281
24	0.5588	0.5585	0.022	0.5105	0.0201	6.400	5.96	0.6289	0.635	0.0250
25	0.5080	0.5078	0.020	0.4547	0.0179	7.000	7.00	0.5598	0.5556	0.0219
26	0.4572	0.4570	0.018	0.4039	0.0159	7.600	7.60	0.4981	0.4763	0.0188
27	0.4166	0.4062	0.016	0.3607	0.0142	8.200	8.80	0.4432	0.4366	0.0172
28	0.3759	0.3555	0.014	0.3200	0.0126	8.800	9.40	0.3969	0.3969	0.0156
29	0.3454	0.3300	0.013	0.2875	0.0113	9.400	10.00	0.3531	0.3572	0.0141
30	0.3150	0.3046	0.012	0.2540	0.0100	10.000		0.3124	0.3175	0.0125
31	0.2946	0.2539	0.010	0.2268	0.0089			0.2794	0.2778	0.0109
32	0.2743	0.2286	0.009	0.2019	0.0080			0.2489	0.2580	0.0102
33	0.2540	0.2031	0.008	0.1798	0.0071			0.2210	0.2381	0.0094
34	0.2337	0.1777	0.007	0.1600	0.0063			0.1956	0.2183	0.0086
35	0.2134	0.1269	0.005	0.1425	0.0056			0.1753	0.1984	0.0078
36	0.1930	0.1016	0.004	0.1270	0.0050			0.1579	0.1786	0.0070
37	0.1727			0.1112	0.0045			0.1372	0.1687	0.0066
38	0.1524			0.1006	0.0040			0.1219	0.1588	0.0063
39	0.1321			0.0897	0.0035					
40	0.1219			0.0799	0.0031					

S.W.G. British Imperial Standard Wire Gauge, *BWG* Birmingham Wire Gauge, *B & S* Brown and Sharpe Wire Gauge (American Standard Wire Gauge), *J. de P.* Paris Wire Gauge, *W.G.* Westphalia Wire Gauge, *B.G.* Standard Birmingham Sheet and Hoop, *U.S.S.* US Standard for Sheet and Plate Iron and Steel

Table A.9.2 Pipe schedule – wall thickness

Nominal (NPS)	O.D. inches	Wall thickness, inch per Pipe schedules (suffix "s" is for stainless steel)															
		5 s	5	10s	10	20	30	40s& Std	40	60	80s & E.H	80	100	120	140	160	Dbi. E.H.
1/8	0.405		0.035	0.049	0.049			0.068	0.068		0.095	0.095					
1/4	0.540		0.049	0.065	0.065			0.088	0.088		0.119	0.119					
3/8	0.675		0.049	0.065	0.065			0.091	0.091		0.126	0.129					
1/2	0.840	0.065	0.065	0.083	0.083			0.109	0.109		0.149	0.149				0.187	0.294
3/4	1.050	0.065	0.065	0.083	0.083			0.113	0.113		0.154	0.154				0.218	0.308
1	1.315	0.065	0.065	0.109	0.109			0.133	0.133		0.179	0.179				0.250	0.358
1–1/4	1.660	0.065	0.065	0.109	0.109			0.140	0.140		0.191	0.191				0.250	0.382
1–1/2	1.900	0.065	0.065	0.109	0.109			0.145	0.145		0.200	0.200				0.281	0.400
2	2.375	0.065	0.065	0.109	0.109			0.154	0.154		0.281	0.281				0.343	0.436
2–1/2	2.875	0.083	0.083	0.120	0.120			0.203	0.203		0.276	0.276				0.375	0.552
3	3.500	0.083	0.083	0.120	0.120			0.216	0.216		0.300	0.300				0.437	0.600
3–1/2	4.000	0.083	0.083	0.120	0.120			0.226	0.226		0.318	0.318					0.636
4	4.500	0.083	0.083	0.120	0.120			0.237	0.237	0.281	0.337	0.337		0.437		0.531	0.674
4–1/2	5.000							0.247			0.355						0.710
5	5.563	0.109	0.109	0.134	0.134			0.258	0.258		0.375	0.375		0.500		0.625	0.750
6	6.625	0.109	0.109	0.134	0.134			0.280	0.280		0.432	0.432		0.562		0.718	0.864
7	7.625							0.301			0.500						0.875
8	8.625	0.109	0.109	0.148	0.148	0.250	0.277	0.322	0.322	0.406	0.500	0.500	0.593	0.718	0.812	0.906	0.875
9	9.625							0.342			0.500						
10	10.750	0.134	0.134	0.165	0.165	0.250	0.307	0.365	0.365	0.500	0.500	0.593	0.718	0.843	1.000	1.125	
11	11.750							0.375			0.500						
12	12.750	0.156	0.165	0.180	0.180	0.250	0.330	0.375	0.406	0.562	0.500	0.687	0.843	1.000	1.125	1.312	
14	14.000	0.156		0.188	0.250	0.312	0.375	0.375	0.437	0.593	0.500	0.750	0.937	1.931	1.250	1.406	
16	16.000	0.165		0.188	0.250	0.312	0.375	0.375	0.500	0.656	0.500	0.843	1.031	1.218	1.437	1.593	
18	18.000	0.165		0.188	0.250	0.312	0.437	0.375	0.562	0.750	0.500	0.937	1.156	1.375	1.562	1.781	
20	20.000	0.188		0.218	0.250	0.375	0.500	0.375	0.593	0.812	0.500	1.031	1.280	1.500	1.750	1.968	
24	24.000	0.218		0.250	0.250	0.375	0.562	0.375	0.687	0.968	0.500	1.218	1.531	1.812	2.062	2.343	
26	26.000				0.312	0.500		0.375			0.500						
28	28.000				0.312	0.500	0.625	0.375									
30	30.000	0.250		0.312	0.312	0.500	0.625	0.375			0.500						
32	32.000				0.312	0.500	0.625		0.375	0.688		0.500					
34	34.000				0.312	0.500	0.625	0.375	0.688								
36	36.000				0.312		0.625	0.375	0.750		0.500						

Source: ASME B36.10

A.10 Molar Heat Capacities for Various Gases

Table A.10 Heat capacity ratio (*k*) for various gases

Temp.,°C	Gas	*k*	Temp.,°C	Gas	*k*	Temp.,°C	Gas	*k*
−181	H_2	1.597	200	Dry Air	1.398	20	NO	1.400
−76		1.453	400		1.393	20	N_2O	1.310
20		1.410	1000		1.365	−181	N_2	1.470
100		1.404	2000		1.088	15		1.404
400		1.387	0	CO_2	1.310	20	Cl_2	1.340
1000		1.358	20		1.300	−115	CH_4	1.410
2000		1.318	100		1.281	−74		1.350
20	He	1.660	400		1.235	20		1.320
20	H_2O	1.330	1000		1.195	15	NH_3	1.310
100		1.324	20	CO	1.400	19	Ne	1.640
200		1.310	−181	O_2	1.450	19	Xe	1.660
−180	Ar	1.760	−76		1.415	19	Kr	1.680
20		1.670	20		1.400	15	SO_2	1.290
0	Dry Air	1.403	100		1.399	360	Hg	1.670
20		1.400	200		1.397	15	C_2H_6	1.220
100		1.401	400		1.394	16	C_3H_8	1.130

Source: www.engineeringtoolbox.com
k = ratio of specific heat for the test fluid = Cv (constant volume)/Cp (constant pressure) = 1.4 for air

A.11 Dew Point (°C) Determination

Table A.11 *Dry bulb temperature, °C

Relative Humidity (%)																					
*		**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
0		-34.9	-27.8	-23.4	-20.2	-17.6	15.4	-13.6	-11.9	-10.5	-9.1	-7.9	-6.8	-5.8	-4.8	-3.9	-3.0	-2.2	-1.4	-0.7	0.0
1		-34.2	-27.0	-22.6	-19.3	-16.7	-14.5	-12.7	-11.0	-9.5	-8.2	-7.0	-5.9	-4.8	-3.8	-2.9	-2.0	-1.2	-0.4	0.3	1.0
2		-33.5	-26.3	-21.8	-18.5	-15.9	-13.7	-11.8	-10.1	-8.6	-7.3	-6.1	-4.9	-3.9	-2.9	-1.9	-1.1	-0.2	0.5	1.3	2.0
3		-32.8	-25.5	-21.0	-17.7	-15.0	-12.8	-10.9	-9.2	-7.7	-6.4	-5.1	-4.0	-2.9	-1.9	-1.0	-0.1	0.7	1.5	2.3	3.0
4		-32.1	-24.7	-20.2	-16.8	-14.2	-11.9	-10.0	-8.3	-6.8	-5.4	-4.2	-3.0	-2.0	-1.0	0.0	0.9	1.7	2.5	3.3	4.0
5		-31.3	-23.9	-19.4	-16.0	-13.3	-11.1	-9.1	-7.4	-5.9	-4.5	-3.3	-2.1	-1.0	0.0	1.0	1.9	2.7	3.5	4.3	5.0
6		-30.6	-23.2	-18.6	-15.2	-12.5	-10.2	-8.2	-6.5	-5.0	-3.6	-2.3	-1.1	-0.1	1.0	1.9	2.8	3.7	4.5	5.3	6.0
7		-29.9	-22.4	-17.8	-14.3	-11.6	-9.3	-7.4	-5.6	-4.1	-2.7	-1.4	--0.2	0.9	1.9	2.9	3.8	4.7	5.5	6.3	7.0
8		-29.2	-21.6	-17.0	-13.5	-10.0	-8.5	-6.5	4.7	-3.2	-1.8	-0.5	0.7	1.8	2.9	3.9	4.8	5.6	6.5	7.3	8.0
9		-28.5	20.9	-16.1	-12.7	-9.9	-7.6	-5.6	-3.8	-2.3	-0.8	0.5	1.7	2.8	3.8	4.8	5.7	6.6	7.5	8.2	9.0
10		-27.7	-20.1	-15.3	-11.8	-9.1	-6.7	-4.7	-2.9	-1.3	0.1	1.4	2.6	3.7	4.8	5.8	6.7	7.6	8.4	9.2	10.0
11		-27.0	-19.3	-14.5	-11.0	-8.2	-5.8	-3.8	-2.0	-1.4	1.0	2.3	3.6	4.7	5.8	6.8	7.7	8.6	9.4	10.2	11.0
12		-26.3	-18.6	-13.7	-10.2	-7.4	-5.0	-2.9	-1.1	0.5	1.9	3.3	4.5	5.6	6.7	7.7	8.7	9.6	10.4	11.2	12.0
13		-25.6	-17.8	-12.9	-9.4	-6.5	-4.1	-2.1	-0.2	1.4	2.8	4.2	5.4	6.6	7.7	8.7	9.6	10.5	11.4	12.2	13.0
14		-24.9	-17.0	-12.1	-8.5	-5.7	-3.3	-1.2	0.6	2.3	3.8	5.1	6.4	7.5	8.6	9.6	10.6	11.5	12.4	13.2	14.0
15		-24.2	-16.3	-11.3	-7.7	-4.8	-2.4	-0.3	1.5	3.2	4.7	6.1	7.3	8.5	9.6	10.6	11.6	12.5	13.4	14.2	15.0
16		-23.5	-15.5	-10.5	-6.9	-4.0	-1.5	0.6	2.4	4.1	5.6	7.0	8.3	9.4	10.5	11.6	12.6	13.5	14.4	15.2	16.0
17		-22.8	-14.7	-9.7	-6.1	-3.1	-0.7	1.5	3.3	5.0	6.5	7.9	9.2	10.4	11.5	12.5	13.5	14.5	15.3	16.2	17.0
18		-22.1	-14.0	-8.9	-5.2	-2.3	-0.2	2.3	4.2	5.9	7.4	8.8	10.1	11.3	12.5	13.5	14.5	15.4	16.3	17.2	18.0
19		-21.4	-13.2	-8.1	-4.4	-1.4	1.1	3.2	5.1	6.8	8.4	9.8	11.1	12.3	13.4	14.5	15.5	16.4	17.3	18.2	19.0
20		-20.6	-12.4	-7.3	-3.6	-0.6	1.9	4.1	6.0	7.7	9.3	10.7	12.0	13.2	14.4	15.4	16.4	17.4	18.3	19.2	20.0
21		-19.9	-11.7	-6.5	-2.8	0.3	2.8	5.0	6.9	8.6	10.2	11.6	12.9	14.2	15.3	16.4	17.4	18.4	19.3	20.2	21.0
22		-19.2	-10.9	-5.8	-1.9	1.1	3.7	5.9	7.8	9.5	11.1	12.6	13.9	15.1	16.3	17.4	18.4	19.4	20.3	21.2	22.0
23		-18.5	-10.2	-5.0	-1.1	2.0	4.5	6.7	8.7	10.4	12.0	13.5	14.8	16.1	17.2	18.3	19.4	20.3	21.3	22.2	23.0
24		-17.8	-9.4	-4.2	-0.3	2.8	5.4	7.6	9.6	11.3	12.9	14.4	15.8	17.0	18.2	19.3	20.3	21.3	22.3	23.1	24.0
25		-17.1	-8.6	-3.4	0.5	3.6	6.2	8.5	10.5	12.3	13.9	15.3	16.7	18.0	19.1	20.3	21.3	22.3	23.2	24.1	25.0
26		-16.4	-7.9	-2.6	1.3	4.5	7.1	9.4	11.4	13.2	14.8	16.3	17.6	18.9	20.1	21.2	22.3	23.3	24.2	25.1	26.0
27		-15.7	-7.1	-1.8	2.2	5.3	8.0	10.2	12.3	14.1	15.7	17.2	18.6	19.9	21.1	22.2	23.2	24.3	25.2	26.1	27.0
28		-15.0	-6.4	-1.0	3.0	6.2	8.8	11.1	13.1	15.0	16.6	18.1	19.5	20.8	22.0	23.1	24.2	25.2	26.2	27.1	28.0
29		-14.3	-5.6	-0.2	3.8	7.0	9.7	12.0	14.0	15.9	17.5	19.0	20.4	21.7	23.0	24.1	25.2	26.2	27.2	28.1	29.0
30		-13.6	-4.9	0.6	4.6	7.8	10.5	12.9	14.9	16.8	18.4	20.0	21.4	22.7	23.9	25.1	26.2	27.2	28.2	29.1	30.0
31		-12.9	-4.1	1.4	5.4	8.7	11.4	13.7	15.8	17.7	19.3	20.9	22.3	23.6	24.9	26.0	27.1	28.2	29.2	30.1	31.0
32		-12.2	-3.4	2.2	6.3	9.5	12.3	14.6	16.7	18.6	20.3	21.8	23.2	24.6	25.8	27.0	28.1	29.2	30.1	31.1	32.0
33		-11.5	-2.6	3.0	7.1	10.4	13.1	15.5	17.6	19.5	21.2	22.7	24.2	25.5	26.8	28.0	29.1	30.1	31.1	32.1	33.0
34		-10.9	-1.9	3.7	7.9	11.2	14.0	16.4	18.5	20.4	22.1	23.7	25.1	26.5	27.7	28.9	30.0	31.1	32.1	33.1	34.0
35		-10.2	-1.1	4.5	8.7	12.0	14.8	17.2	19.4	21.3	23.0	24.6	26.1	27.4	28.7	29.9	31.0	32.1	33.1	34.1	35.0
36		-9.5	-0.4	5.3	9.5	12.9	15.7	18.1	20.3	22.2	23.9	25.5	27.0	28.4	29.6	30.9	32.0	33.1	43.1	35.1	36.0
37		-8.8	0.4	6.1	10.3	13.7	16.5	19.0	21.1	23.1	24.8	26.4	27.9	29.3	30.6	31.8	33.0	34.0	35.1	36.1	37.0
38		-8.1	1.1	6.9	11.1	14.5	17.4	19.9	22.0	24.0	25.7	27.4	28.9	30.2	31.6	32.8	33.9	35.0	36.1	37.1	38.0
39		-7.4	1.9	7.7	11.9	15.4	18.2	20.7	22.9	24.9	26.7	28.3	29.8	31.2	32.5	33.7	34.9	36.0	37.0	38.0	39.0
40		-6.7	2.6	8.4	12.8	16.2	19.1	21.6	23.8	25.8	27.6	2.92	30.7	32.1	33.5	43.7	35.9	37.0	38.0	39.0	40.0
41		-6.0	3.4	9.2	13.6	17.0	20.0	22.5	24.7	26.7	28.5	30.1	31.7	33.1	34.4	35.7	36.8	38.0	39.0	40.0	41.0
42		-5.3	4.1	10.0	14.4	17.9	20.8	23.3	25.6	27.6	29.4	31.1	32.6	34.0	35.4	36.6	37.8	38.9	40.0	41.0	42.0
43		-4.6	4.9	10.8	15.2	18.7	21.7	24.2	26.5	28.5	30.3	32.0	33.5	35.0	36.3	37.6	38.8	39.9	41.0	42.0	43.0
44		-4.0	5.6	11.6	16.0	19.5	22.5	25.1	27.3	29.4	31.2	32.9	34.5	35.9	37.3	38.5	49.7	40.9	42.0	43.0	44.0
45		-3.3	6.3	12.4	16.8	20.4	23.4	25.9	28.2	30.3	32.1	33.8	35.4	36.9	38.2	39.5	40.7	41.9	43.0	44.0	45.0
46		-2.6	7.1	13.1	17.6	21.2	24.2	26.8	29.1	31.2	33.0	34,7	36,0	37,8	39.2	40.5	41.7	42.8	43.9	45.0	46.0
47		-1.9	7.8	13.9	18.4	22.0	25.1	27.7	30.0	32.1	33.9	35.7	37.3	38.7	40.1	41.4	42.7	43.8	44.9	46.0	47.0
48		-1.2	8.6	14.7	19.2	22.9	25.9	28.5	30.9	33.0	34.8	36.6	38.2	29.7	41.1	42.4	43.6	44.8	45.9	47.0	48.0
49		-0.5	9.3	15.5	20.0	23.7	26.8	29.4	31.7	33.8	35.8	37.5	39.1	40.6	42.0	43.3	44.6	45.8	46.9	48.0	49.0
50		0.1	10.0	16.2	20.8	24.5	27.6	30.3	32.6	34.7	36.7	38.4	40.0	41.6	43.0	44.3	45.6	46.8	47.9	49.0	50.0

Source: Perry H/B

A.12 Unit Conversion Table

Table A.12 (1/2) e.g., 1A = (C) B, 1A = (1/D) B

A. Unit	B. Conversion to	C. Multiply by	D. Reciprocal
Linear measure			
Mil (0.001 inch)	Micrometer	25.4	0.03937
Mil (0.001 inch)	Millimeter	0.0254	39.37
Inch	Millimeter	25.4	0.03937
Foot	Meter	0.3048	3.281
Yard	Meter	0.9144	1.0936
Mile	Kilometer	1.6093	0.6214
Nautical mile	Kilometer	1.8532	0.5396
Square measure			
Inch ^{2}	Square millimeter	645.2	0.00155
Inch ^{2}	Square centimeter	6.452	0.155
Foot ^{2}	Square meter	0.0929	10.764
Yard ^{2}	Square meter	0.8361	1.196
Acre	Hectare	0.4047	2.471
Acre	Square meter	4047	0.0002471
Acre	Square foot	43,560	0.00002296
Mile ^{2}	Acre	640	0.001562
Mile ^{2}	Square kilometer	2590	0.3863
Volume			
Inch ^{3}	Cubic centimeter	16.387	0.06102
Foot ^{3}	Cubic meter	0.02832	35.31
Foot ^{3}	Gallon (US)	7.48	0.1337
Foot ^{3}	Liter	28.32	0.03531
Yard ^{3}	Cubic meter	0.7646	1.3079
Ounce (US liq)	Cubic centimeter	29.57	0.0338
Quart (US liq)	Liter	0.9464	1.0566
Gallon (US)	Gallon (imperial)	0.8327	1.2009
Gallon (US)	Liter	3.785	0.2642
Barrel (US petroleum)	Gallon (US)	42.	0.238
Barrel (US petroleum)	Liter	158.98	0.00629
Mass			
Arain	Milligram	64.8	0.01543
Ounce (avoirdupois)	Gram	28.35	0.03527
Pound (avoirdupois)	Kilogram	0.4536	2.205
Short ton	Metric ton	0.9072	1.1023
Long ton	Metric ton	1.0161	0.9842
Pressure or stress			
Atmosphere	mm Hg (at 0 °C)	760.0	0.001316
Atmosphere	Pound-force per inch^2	14.696	0.06805
Atmosphere	Bar	1.013	0.9872
Atmosphere	Megapascal (Mpa)	0.1013	9.872
Torr (mm Hg)	Pascal	133.32	0.007501
Inch of water	Pascal	248.8	0.004019
Foot of water	Pound-force per inch^2	0.4335	2.307
Dyne per centimeter^2	Pascal	0.1000	10.00
Pound-force per inch^2 (psi)	Kilopascal (kPa)	6.895	0.1450
Kip per inch^2 (ksi)	Megapascal (Mpa)	6.895	0.1450
Pound-force per inch^2	Bar	0.06895	14.50
Kip per inch^2	Kilogram per millimeter^2	0.7031	1.4223

Table A.12 (2/2) e.g., 1A = (C) B, 1A = (1/D) B

A. Unit	B. Conversion to	C. Multiply by	D. Reciprocal
Work, heat, and energy			
British thermal unit (Btu)	Joule	1055.	0.0009479
Foot pound-force	Joule	1.356	0.7375
Calorie	Joule	4.187	0.2389
Btu	Foot pound-force	778.	0.001285
Kilocalorie	Btu	3.968	0.252
Btu	Kilogram meter	107.56	0.009297
Btu per hour	Watt	0.2929	3.414
Watthour	Joule	3600.	0.0002778
Horse power	Kilowatt	0.7457	1.341
Thermal properties			
(Btu per foot^2, hour, °F) per inch	(kilocalorie per meter^2, hour, °C) per meter	0.1240	8.064
(Btu per foot^2, hour, °F) per inch	Watt per meter, K	0.144	6.944
Btu per foot^2, hour, °F	Kilocalorie per meter^2, hour, °C	4.882	0.2048
Btu per foot^2, hour, °F	Watt per meter^2, K	5.674	0.1762
Btu per foot^2	Kilocalorie per meter^2	2.712	0.3687
Btu per foot^2	Joule per meter^2	11,360.	0.00008803
Miscellaneous			
Pound per foot^3	Kilogram per meter^3	16.02	0.06242
Pound per gallon (US)	Gram per liter	119.8	0.00835
Grains per 1000 foot^3	Milligram per meter^3	22.88	0.0437
Ounces per foot^2	Gram per meter^2	305.2	0.003277
Pound mole (gas)	Cubic foot (STP)	359.	0.00279
Gram mole (gas)	Liter (STP)	22.4	0.0446
Day	Minute	1440.	0.000694
Week	Hour	168.	0.00595
Year	Hour	8766.	0.0001141

A.13 Mathematical Symbols and the Greek Alphabet

A.13.1 Mathematical Signals and Symbols

$=$ Equals
$\cong$ Equals approximately
$\neq$ Is not equal to
$\equiv$ Is identical to; is defined as
$>$ Is greater than (>> is much greater than)
$<$ Is less than (<< is much less than)
$\geq$ Is greater than or equal to
$\leq$ Is less than or equal to
$\pm$ Plus or minus (for example, $\sqrt{4} = \pm 2$)
$\propto$ Is proportional to (for example, Hooke's law: $\mathbf{F} \propto \mathbf{x}$, or $\mathbf{F} = -\mathbf{kx}$)
$\sum$ The sum of
$\bar{x}$ The average value of **x**

A.13.2 The Greek Alphabet

Alpha	Α	α	Nu	Ν	ν
Beta	Β	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	Ο	ο
Delta	Δ	δ	Pi	Π	π
Epsilon	Ε	ε	Rho	Ρ	ρ
Zeta	Ζ	ζ	Sigma	Σ	σ
Eta	Η	η	Tau	Τ	τ
Theta	Θ	θ	Upsilon	Υ	υ
Iota	Ι	ι	Phi	Φ	φ, φ
Kappa	Κ	κ	Chi	Χ	χ
Lambda	Λ	λ	Psi	Ψ	ψ
Mu	Μ	μ	Omega	Ω	ω

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