Lifetime prediction of hdpe pipes grade

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LIFETIME PREDICTION OF HDPE PIPES GRADE

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ABSTRACT

This paper presents the results of notch tests on single edge notch specimen under condition corresponding to the PENT approach, i.e. at temperature 80℃ and nominal stress 2,4 MPa. Tests were performed for one monomodal and two bimodal HDPE materials, both from structural and fracture mechanics point of view. Under conditions corresponding to the PENT test the dependence of a crack opening displacement COD vs. time was measured and the values of the rate of the stable crack growth rate da/dt and time to fracture t_f were estimated. To estimate the residual life of pipes the finite element model with an initial defect was suggested and the values of the stress intensity factor K have been calculated. The computation took into account the change of the crack shape during its growth in the pipe. For assessment of the residual service life of pipes the relation $\mathrm{d}a/\mathrm{d}t = A\,(K)^m$ was applied. The values of the pipe life-time for three studied materials are compared and diagram of the hoop stress versus failure time is presented. The results show that slow crack growth tests can rank qualitatively different pipe grades.

KEYWORDS

HDPE, creep crack, time to rupture curve, PENT test, pipe failure

INTRODUCTION

High-density polyethylene (HDPE) is common thermoplastic material used for pipe structures. There are two basic failure modes of a pipeline system (i) rapid crack propagation (RCP) which could affect a significant length of pipeline, and (ii) the long time brittle failure of the system due to a slow crack growth (SCG) initiated at a flaw in the pipe and resulting in local brittle failure. In this case there is a little macroscopic deformation throughout the material, however, microscopic observations of the fracture surfaces show a state of large deformation (see Fig.1. region B). An important role in determining the lifetime plays the crack initiation stage and the slow crack growth.

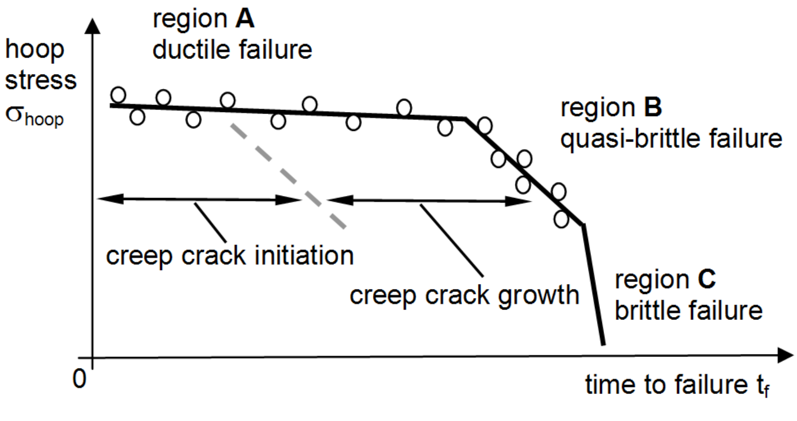

Fig. 1**:** Scheme of the failure behavior of pressurized pipes.

The service life typically required and to be achieved covers a time span of up 50 years. It is clear that pressure pipe applications require polymers with very long lifetimes, but the problem is to develop a test that is able to estimate the lifetime in a relatively short time. The currently used quality check test of slow crack growth (test method EN 33479) generally takes more than 10^3 hours after which the test is terminated. Similarly, in order to qualify a new resin, the conventional hydrostatic pressure test must last 10^4 hours (ISO 9080).
Some accelerated tests, utilising the Fracture Mechanics, have been developed in the last twenty years. The PENT [1-3] test developed by N. Brown and his co-workers produces the same type of brittle fracture that occurs in pipes after long time in service.

From the structure point of view the lifetime is influenced by a large number of structural and morphological parameters [4]. The primary of these is chain structure: (i) molecular weight and its distribution, (ii) number, type and distribution of short and long chain branches and (iii) type and number of unsaturated bindings. Structure together with service or test conditions (temperature, rate, and environment) determines the type of fracture. There are several methods that can be applied to estimate these parameters [5,6]. The primary morphological effect of short chain branches leads to (i) decrease of the lamellar thickness and (ii) increase of number of tie molecules. It is generally believed [7] that the slow process of craze opening involves the disentanglement of the tie molecules, which leads to the fracture of the fibrils. In the following structural as well as PENT tests were used to classify three HDPE pipes grade (one monomodal and two bimodal).

In many cases the used HDPE materials contain small flaws. Their existence can substantially reduce the time for crack initiation and the service life of pipes corresponds approximately to the time for crack propagation from initial crack to final failure. In these cases the residual life can be used for assessment of HDPE pipe grades resistance against failure due to SCG.

The aim of this study was to propose a simplified approach that can contribute to description of the Region B in Fig.1. The suggested approximate approach based on PENT test methodology has been used to estimation of service life of HDPE pipes used in praxis.

STRUCTURAL METHODS

Two methods were used for characterisation of the materials in the study: SIS/DSC analysis and rapid SIS/DSC*. The SIS (Stepwise Isothermal Segregation) method consists of a sequenced heating-cooling-heating treatment of the material to distinguish the macromolecular species with regard to their respective crystallitabilities. The DSC (Differential Scanning Calorimetry) record after SIS procedure gives several peaks according to the number of isothermal steps [8]. The location and the area of these peaks get information about the average number of short chain branches (SCB) in each individual fraction and about the representation of this fraction in polymer.

The modified SIS version (rapid SIS/DSC*) differs on both experimental and data analysis levels. The rapid SIS/DSC* procedure runs completely in the DSC equipment and takes 90 minutes in comparison to the SIS/DSC procedure that takes 9 days [5,6]. This procedure permits description of the kinetics of crystallization. A DSC facility is used for the thermal characterisation of the materials. The so-called "*drift*" molecular parameter - τ [5] is defined by equation 1.

$$\tau = \frac{\Delta H_c^{119} / k^{119}}{\Delta H_c^{114} / k^{114}} , \qquad (1)$$

where ΔHc^{119} and ΔHc^{114} is the enthalpy of crystallisation at 119°C and 114°C respectively, and $k^{114,\,119}$ are crystallization kinetic parameters, see Tab.1. From this expression it is thus possible to evaluate the bimodality level of the distribution (crystallization enthalpies), taking into account the influence of comonomer branches [5].

APPLICATION OF PENT TEST

For evaluation of long time brittle failure behaviour of considered materials was applied PENT test [1]. The geometry of the specimens corresponds to SEN (single edge notch) tensile specimen, see Fig.2, and can be taken either from compression-moulded plaques or directly from pipes. The notch is made by pressing a fresh razor blade into the specimen at a constant speed of 330 µm/min. The notch depth is chosen to minimise the failure time, but not to produce an excessive creep on the remaining ligament. The width, thickness and side grooves are chosen to ensure that the fracture is almost entirely plane strain. The kinetics of the failure process is observed under a constant nominal stress of 2.4 MPa and temperature of 80℃.The crack opening displacement, COD, was measured on the specimen surface with an optical microscope with resolution about 2 µm (Fig.2).

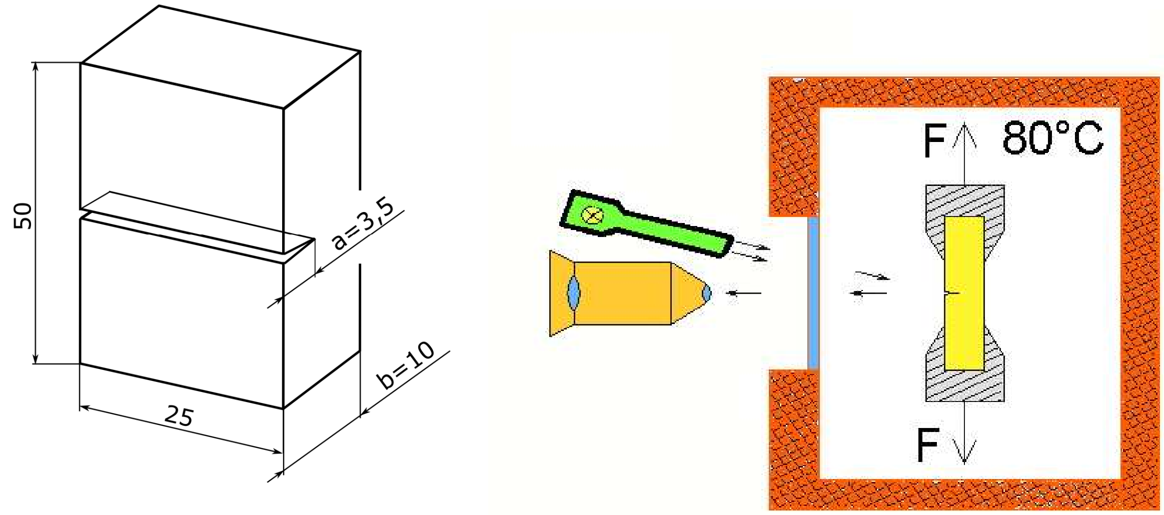

Fig. 2**:** The scheme of specimen prepared from moulded plaque (on the left). Schematic arrangement of the PENT test used in laboratory (on the right).

The test is performed at constant temperature and constant load and the dependence of the crack (mouth) opening displacement on the specimen surface, COD, vs. time t is measured. Two basic parameters are extracted from the data (i) the slope of the linear part on curve COD vs. time representing the rate of stable crack growth and (ii) the time to failure (t_f).

Table 1**:** Structural characterisation of three HDPE grade obtained by SIS/DSC analysis and rapid SIS/DSC*

Sample	SCB CH3/1000C	ΔHc^{119} * [J/g]	ΔHc^{114} * [J/g]	κ^{114*} [s^{-1}]	κ^{119*} [s^{-1}]	τ *
M	3.68	82.26	24.71	7.1E-2	2.7E-4	876
B1	2.58	104.11	18.52	9.2E-2	1.81E-3	286
B2	3.39	92.50	26.43	7.2E-2	2.35E-5	11 168

RESULTS OF TESTING

As the experiment objects three HDPE pipes grade were tested. One material was monomodal (M) and two bimodal (B1, B2). The structural characteristics obtained by SIS/DSC and rapid SIS/DSC* analysis, respectively are summarised in Tab.1
Knowledge of the way of comonomer incorporation between macromolecules is desirable if we want to distinguish between monomodal and bimodal materials because it tells a lot about both the application qualities and its synthesis technology. But we are not able to judge the fracture behaviour from the structural parameters obtained from SIS/DSC and rapid SIS/DSC*, respectively. We need to use other method [4].

From the dependence of the COD versus time, (Fig.4), the following values were estimated:

- rate of the stable crack growth d*a*/d*t*
- time to failure t_f.

The structural analysis (SIS/DSC and rapid SIS/DSC*) made it possible to distinguish the materials with higher resistance against SCG but only in the range of structural similar materials (monomodal or bimodal). The dependence of t_f and the rate of stable crack growth are shown in Fig.4.

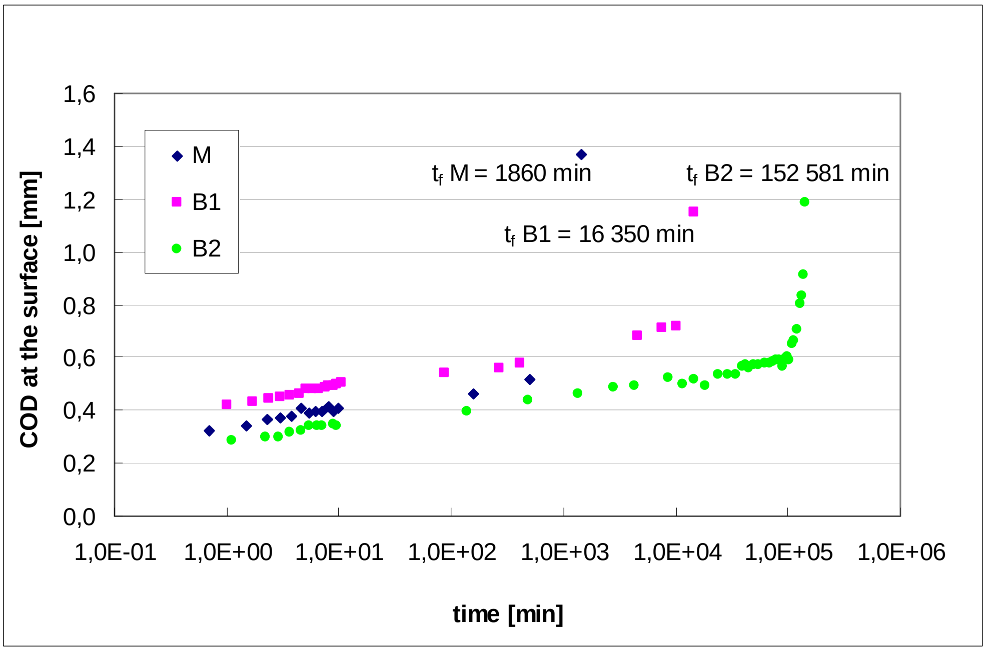

Fig. 3**:** COD vs. time dependence for the studied materials

According to the PENT test methodology, see [9] for details, under given conditions the slow crack growth rate is approximately equal to the rate of crack opening displacement at the specimen surface, i.e.

$$\frac{d(COD)}{dt} \cong \frac{da}{dt} \qquad (2)$$

The Figure 4 show data extracted from Fig.3, i.e. time to failure (t_f) and the rate of SCG (d*a*/d*t*). The results presented in Fig.4 enable to distinguish HDPE pipe grades with respect to the resistance against SCG, can be used for estimation of a residual life of pipes and can substitute the conventional hydrostatic pressure test.

Stress intensity factor, K, is a good correlating parameter where a SEN specimen geometry and single method of loading are considered [9]. The value of stress intensity factor is given by equation (3)

$$K = \sigma\sqrt{(\pi a)}Y(a/b) \tag{3}$$

where $Y(a/b)$ depends on the geometry and crack length. For our specimen (see Fig.2) we can use the value of $Y(a/b)$ [10] in the form defined by equation 4:

$$Y = \left[1.12 - 0.231(a/b) + 10.55(a/b)^2 - 21.72(a/b)^3 + 30.39(a/b)^4\right] \tag{4}$$

where b is the thickness of the specimen (b = 10 mm) and a is the notch depth (a = 3.5 mm). Using the values of a, b and the constant stress σ = 2.4 MPa, we obtain the value of stress intensity factor K = 0.467 MPa m$^{1/2}$ in the present case.

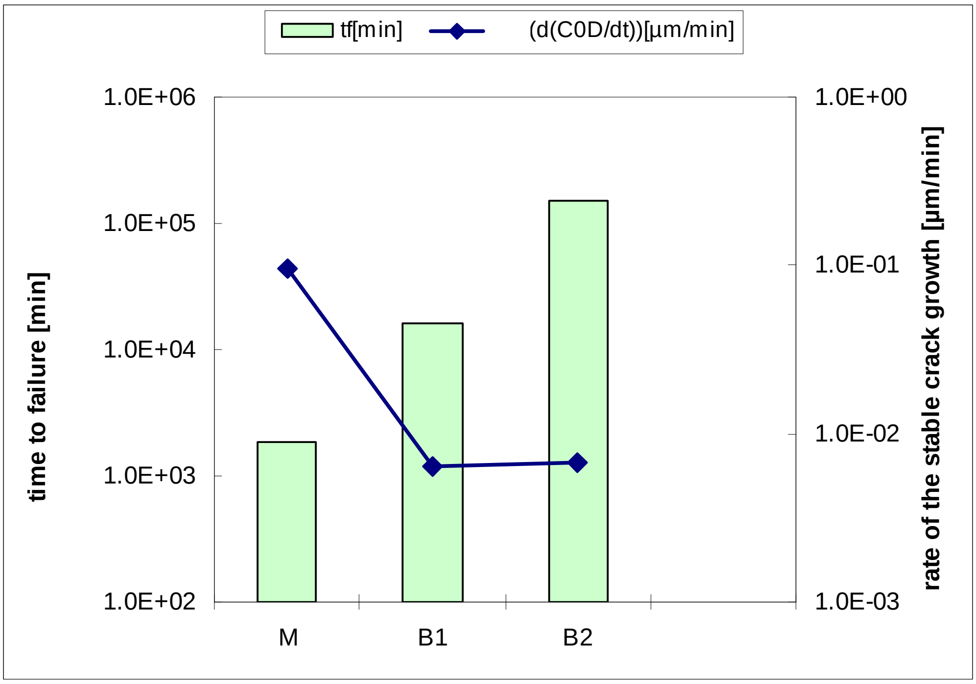

Fig. 4**:** The dependence of t_f and the rate of stable crack growth for the used materials.

Under the present test conditions, where the rate of SCG and consequently the corresponding increase of the crack length are very small, it can be assumed that stress intensity factor K in the range where rate is estimated is approximately constant.

The region of stable crack growth (SCG, see Fig.1) can be described by an exponential relationship [11]:

$$\frac{da}{dt} = A(K)^m \tag{5}$$

where A and m are material parameters. The measured values of da/dt and the calculated stress intensity factor K were used for formulation of the dependence da/dt versus K (see eq.5). In fact our experimental results are related to constant value of the stress intensity factor, because we have carried out the PENT test under conditions corresponding to one stress level and one notch depth only. In paper [11] the similar HDPE pipe grade was tested. Based on similarity of used materials we have approximated the exponent *m* in Eq. (5) by the value *m = 2* (corresponding to [11]) even for prediction of the curve *da/dt* versus *K* in our case. The results are summarised in Tab. 2.

Table 2: Estimation of material parameter *A* for materials characterized by exponent *m* = 2 corresponding to the studied class of HDPE.

Material	da/dt [µm/min]	A
M	0,0946	0,4348
B1	0,00635	0,02912
B2	0,00681	0,03123

PIPE LIFTIME ESTIMATION

To predict residual lifetime of a pressured pipe with an initial defect, is necessary to estimate stress intensity factors during the creep crack propagation and apply Eq. (5). Therefore, finite element model of the structure was suggested. Geometry of the pipe is schematically shown in Fig.5.

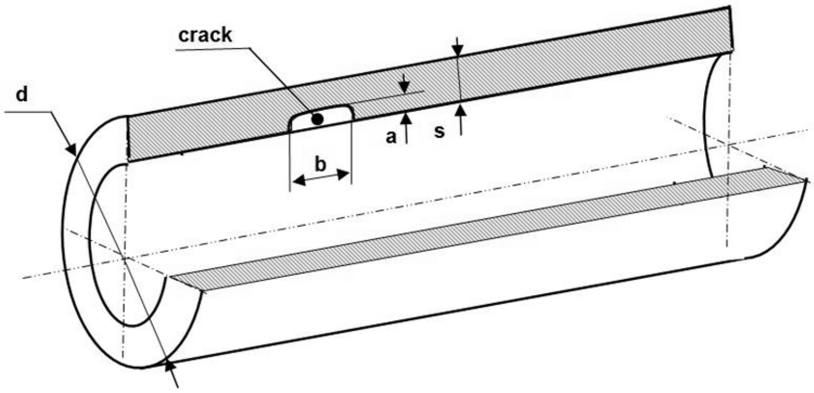

Fig. 5: Scheme of pressured pipe geometry

The typical size of the initial defect a_0 was estimated on the base of experimental observations as 0.1 mm. The configuration of the propagating crack was estimated using a special algorithm, which optimized shape of the crack for constant value of the stress intensity factor along the crack front. A typical model used for calculation was symmetrical and included around 150 000 finite elements strongly non-homogenously distributed in the structure because of mesh refinement around the crack front.

The values of the stress intensity factor obtained by 3D calculation for all considered SDR ratios for the pipe loaded by homogenous internal pressure *p* can be expressed by the simple relation:

$$K_I = \frac{p\,d}{s}\sqrt{\pi a}\,Y\left(\frac{a}{s}\right)$$

where (6)

$$Y = 0.3417 + 0.0588\left(\frac{a}{s}\right) - 0.0319\left(\frac{a}{s}\right)^2 + 0.1409\left(\frac{a}{s}\right)^3,$$

a is a crack length, *d* is pipe outer diameter, *s* is pipe wall thickness and *p* is internal pressure. The advantage of eq. (6) compared to other relations given by literature [10] is that it contains the change of the crack shape during crack propagation in the pipe.

Residual lifetime then can be calculated using integration of Eq. (5) from initial defect to final defect (6 mm in our case). In Fig. 6 residual lifetimes for internally pressured pipe for different materials (see Tab.2) and obtained from the 3D model are shown as a function of the crack length. The initial defect size a_o was assumed equal to 0.1 mm. Geometry of the pipe was d=100 mm, s=6.3 (SDR 17.6).

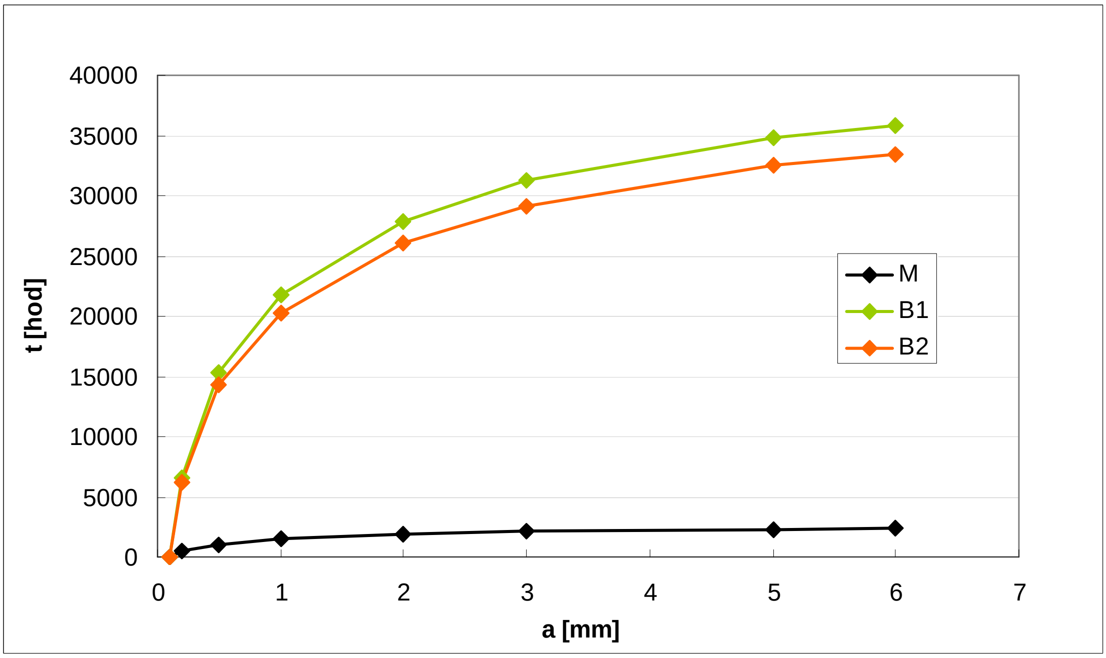

Fig. 6: Residual lifetimes for internally pressured pipe for different material properties (applied hoop stress is 6 MPa)

The estimated residual lifetime considers only the contribution of creep crack growth and the time for crack initiation is not taken into account. This is the reason, why the numerical results underestimate in the diagram hoop stress versus failure time obtained from internally pressured tests on full pipes [12]. Final diagram hoop stress versus failure time estimated numerically is shown in Fig.7.

CONCLUSIONS

The residual service life of HDPE pipes is analysed. To this aim corresponding HDPE materials were examined. Structural as well as PENT tests were used to classify three HDPE pipes grade (one monomodal and two bimodal).Two methods were used for characterization of the materials structure in the study: SIS/DSC analysis and rapid SIS/DSC*. The fracture properties of the material were estimated using the PENT test. For assessment of the residual service life of pipes the relation d*a*/d*t* = *A* $(K)^m$ was applied. Under conditions corresponding to the PENT test the dependence of a crack opening displacement COD vs. time was measured and the values of the rate of the stable crack growth rate *da/dt* and time to fracture t_f were estimated. For the class of studied HDPE materials the value of parameter *m* was taken from the literature and the parameter *A* was estimated from PENT measurements. To estimate the residual life the finite element model of a pipe with initial defect was suggested and the values of the stress intensity factor *K* have been calculated. The computation took into account the change of the crack shape during its growth in the pipe.

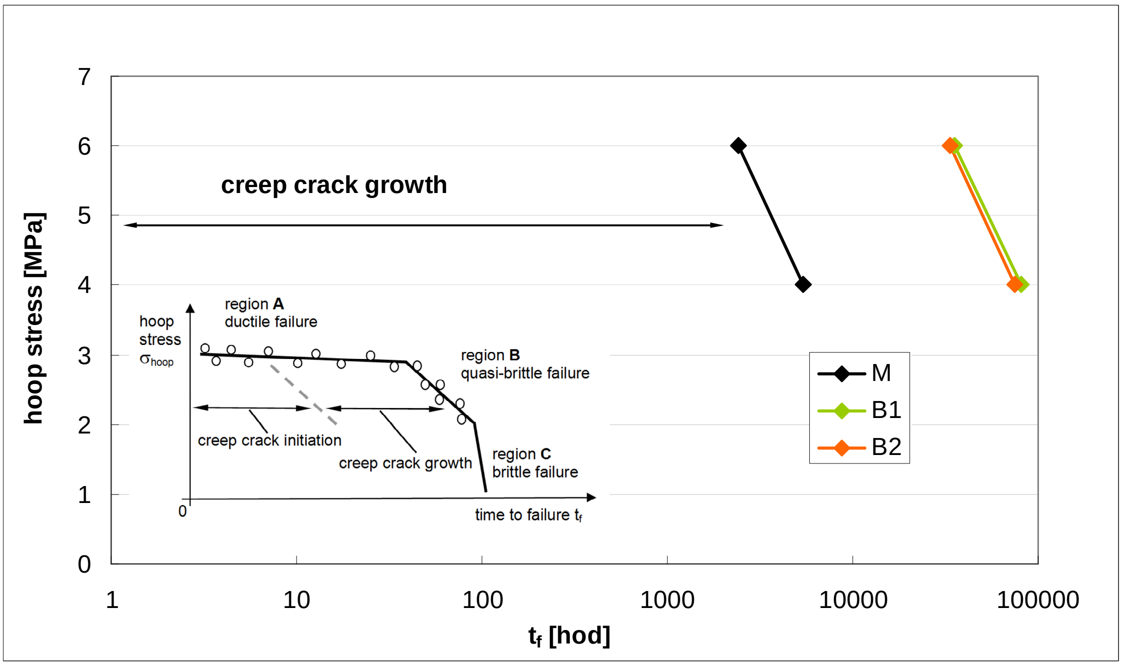

Fig. 7: Diagram hoop stress versus failure time estimated numerically for different material properties corresponding to Tab.2.

As results the values of the pipe life time for three studied materials and corresponding to the PENT test conditions are compared and diagram of the hoop stress versus failure time is presented. It can be seen, that there is a large difference in slow crack growth resistance between monomodal and bimodal pipe grades. The results show that slow crack growth tests can rank qualitatively different pipe grades. The approach can be used especially in the case of materials with small initial flaws, where the time to crack initiation can be neglected.

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