Lifetime prediction of PE100 and PE100-RC pipes based on slow crack growth resistance

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LIFETIME PREDICTION OF PE100 AND PE100-RC PIPES BASED ON SLOW CRACK GROWTH RESISTANCE

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KEYWORDS

Polyethylene, lifetime, cracks, slow crack growth, material testing

ABSTRACT

Due to the high slow crack growth resistance of modern polyethylene pipe grades a reliable lifetime assessment of pipes with focus on stage II failure has become challenging. The current paper presents a scientific approach for a fracture mechanics lifetime prediction based on Cyclic Cracked Round Bar (CRB) Tests. Based on this standardized tests (ISO 18489) a more sophisticated concept enables the determination of SCG rates which is necessary for development of material laws based on fracture mechanics. In combination with practically proven boundary conditions and modern numerical models this concept is able to predict the stage II failure of a PE100 and a PE100 RC pipe grade in relatively short time.

INTRODUCTION

Polymer pipes used for gas and water supply as well as for sewage systems provide an inconspicuous but tremendous contribution to secure the high living standard of our modern society. Meanwhile polymer pipes have been used successfully for more than 60 years and they further demonstrate increasing growth and importance compared to traditional materials [1–5]. Today, for high-quality pipes made of modern thermoplastic materials, minimum lifetimes of 100 years are generally expected.

The lifetime of polymer pipes highly depends on the resistance of the material against crack initiation and slow crack growth (SCG). In the context of polyethylene (PE) pipes the material classification, which implies an estimation of long-term hydrostatic strength or pressure to achieve the designed lifetimes, is based in internal pipe pressure tests at different temperatures as standardized in ISO 9080 [6] or ASTM D2837 [7]. As a result of continuous research in the chemical structure of PE, over the years different generations of pipe grades have been developed which allow increased pressure rates, harsher installation conditions or higher application temperatures. However, as a result of increasing SCG resistance also new challenges for material testing have been raised. To address the issue of modern and time effective material characterization with a reliable interpretation of SCG resistance, recent developments resulted in two new test methods, the Strain Hardening (SH) Test [8–10] and the Cyclic Cracked Round Bar (CRB) Test [11–17]. Both methods, which have already been standardized in ISO 18488 [10] and ISO 18489 [17], allow a material ranking based on SCG properties of modern PE pipe grades within only a couple of days. While the SH Test focus on the characteristics of the stress-strain curve above the natural draw ratio at a temperature of T=80 °C, the Cyclic CRB Test produces real failure by crack initiation and SCG. A further important characteristics of the Cyclic CRB Test is, that the materials are typically tested at ambient temperatures of T=23 °C and without any additional stress cracking liquids which is significantly closer to real pipe application conditions then the other mentioned tests.

Beside a qualitative comparison of the SCG performance of different materials, a quantitative lifetime assessment of pipes has always been of special scientific and practical interest. Internal pipe pressure testing would be the best option for a reliable lifetime prediction. However, within feasible testing times only old generations of PE pipe grades or polyethylene with high density (PE HD) usually used for other applications (e.g. blow moulding) will lead to reasonable failure data [18,19]. For modern PE pipe grades alternative solutions for lifetime prediction are required. In this context methods of the linear elastic fracture mechanics (LEFM) have demonstrated promising results. The current paper presents a new test methodology which combines the advantages of the Cyclic CRB Test with modern concepts for fracture mechanics lifetime calculation.

BACKGROUND

The long-term failure behavior of pressurized PE pipes has been well investigated based on internal pipe pressure tests as well as on field failure [1–3,20–22]. Depending on the applied load, three characteristically failure regions can be observed: At high internal pressures resulting in high hoop stresses σ_{hoop} the failure of stage I is dominated by ductile deformation with the generation of large plastic zones already after relatively short times t_f. This region is mainly controlled by the yield stress of the material and failure usually occurs at the smallest wall thickness or at defects. With decreasing σ_{hoop} the failure mechanism passes a transfer knee and switches into a quasi-brittle failure characteristics of stage II which is the most important and lifetime dominating failure mechanism for long-term pipe applications. There the failure is caused by crack initiation and SCG with only small scale plastic deformations at the crack tip. The total failure time of the pipe consists of crack initiation and SCG [3,21]. Finally, the nearly load independent third failure region of stage III becomes relevant after relatively long times and is a result of thermo-oxidative aging and polymer degradation. The resistance against this failure is basically controlled by stabilizer systems [2,22].

It has been comprehensively confirmed over the past decades that LEFM provides reliable methods to describe and study structural failures of materials [23–30]. Originally developed for metals, the methods of LEFM may also be utilized for plastics materials as long as the two following basic requirements are met: 1st the global loading situation of specimen or component is within the range of linear viscoelasticity, and 2nd the formation of plastic deformations at the crack tip is only small [31]. Quasi-brittle SCG is a result of small initial defects or inhomogenities inside a stress loaded structure which lead to initial cracks. The stress distribution in the vicinity of such a crack tip is described by the stress intensity factor K_I (equation 1) which is a function of the global loading σ, the crack length a and a geometric factor Y that is well known for several specimens and component shapes [32]. It may also be derived by means of finite element method (FEM) simulation. The index "I" specifies the loading mode I, which refers to pure tensile crack opening and represents the most relevant loading mode for practical applications [33].

The crack growth rate $\mathrm{d}a/\mathrm{d}t$ is expected to be a function of K_I which typically represents a S-shaped relationship in log-log scale. At very low loads σ the stress intensity factor is below a threshold $K_\mathrm{I,th}$ which is too small for the initiation of the physical mechanisms which are responsible for SCG. With increasing loads, SCG gets initiated and the crack growth rate yields into a linear region. This region of stable crack growth can be described by equation 2 which was originally proposed by Paris and Erdogan [34,35]. Therein the crack growth rate follows a power law in which $\mathrm{d}a/\mathrm{d}t$ is a function of K_I as well as of the constants A and m, which are parameters depending on the material, the temperature and the loading conditions. If the crack growth rate for one geometrical structure is known (e.g. test specimen), it can be transferred to any other component (e. g. pipe) as long as all geometrical and loading parameters are known and the above mentioned requirements for the application of LEFM are met. With continuing increase of σ also K_I increases until a significant deviation from stable crack growth indicates rapid and ultimate failure of the structure. The resistance of a material against stress loaded rupture has been originally described by Griffith [30] and is characterized by the fracture toughness K_IC of a material.

$$K_\mathrm{I} = \sigma \cdot \sqrt{a} \cdot Y \tag{1}$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = A \cdot K_\mathrm{I}^{\,m} \tag{2}$$

Typical crack kinetic curves and failure times of pressurized pipes for two materials are shown schematically in Fig. 1 [36]. In this context, Material B is the one with higher resistance against SCG. Hence, compared to Material A it fails in stage II after longer times. Analogously, at similar K_I the crack growth rate for Material B is lower indicating a slower crack growth rate than for Material A.

Considering a specific loading configuration, the lifetime of a structure with respect to stage II failure can be assessed by equation 3 where the total failure time t_f is the sum of the time for crack initiation t_ini, the time for SCG t_SCG and the time for final ductile failure t_duc. The time for crack initiation usually contributes a significant part to the total failure. According to equation 4 a power law has been suggested in which t_ini is a function of K_I as well as of material constants B and n [3,35]. Although many studies focused on the investigation of crack initiation in thermoplastics materials, the complex physical and micromechanical processes of craze formation are still not fully understood today so that no reliable models for crack initiation are available yet [3,37–40]. For engineering fracture mechanical lifetime assessment the contribution of t_{ini} is usually neglected what always leads to conservative predictions of failure times.

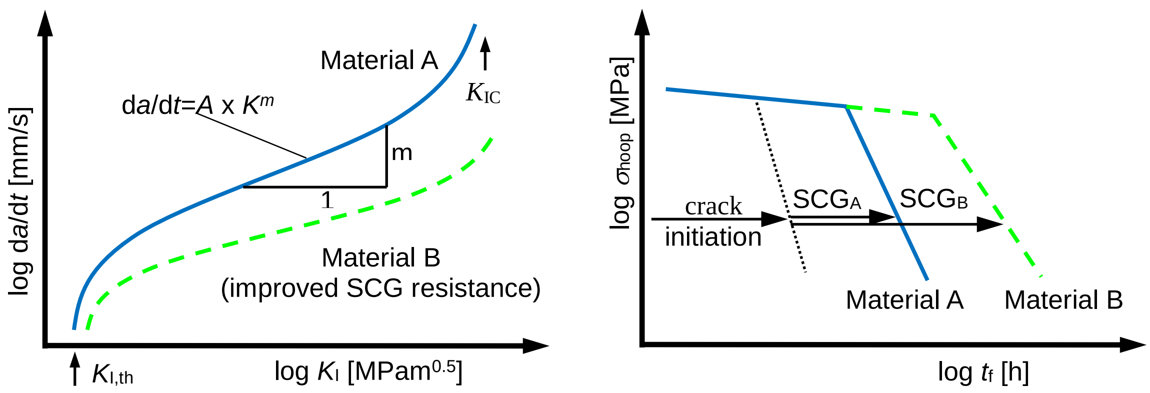

Fig. 1: Schematically illustration of two PE with different SCG characteristics: Left: Slow crack growth rate. Right: Pipe lifetimes [36].

$$t_f = t_{ini} + t_{SCG} + t_{duc} \tag{3}$$

$$t_{ini} = B \cdot K_I^{-n} \tag{4}$$

The calculation of the time that a crack needs to grow from an initial defect size until final failure is based on a transformation of equation 2. In this context, t_{SCG} is an integral function of K_I, A and m starting from an initial crack length a_{ini} until a final failure crack length a_f.

$$t_{SCG} = \frac{1}{A} \cdot \int_{a_{ini}}^{a_f} \frac{1}{K_I^m} \cdot da \tag{5}$$

The time t_{duc} is related to K_{IC} and final failure with large scale ductile deformation. As this failure mechanisms appears at the very end of the lifetime of the structure and within relatively short times, the contribution of this part can be neglected for practical lifetime assessment.

EXPERIMENTAL

For the presented study two material “Material A” (PE100) and “Material B” (PE100-RC) were selected. Both materials are commercially available black high density PE pipe grades frequently used for the manufaction of pressure pipes for gas and water distribution. According to ISO 9080 [6] both materials show a minimum required strength of *MRS*=10 MPa. Material B meets additional requirements of PAS 1075 [41] or ÖVGW/GRIS QS-W405/1 [42] representing extraordinary resistance to cracks (RC).

The determination of the required SCG kinetic laws under static conditions is based on measurements of fatigue crack growth rates at different loading ratios *R* (=minimum load/maximum load) followed by an extrapolation to *R*=1.0 [12,19,36,43–46]. The extrapolation concept is schematically shown in Fig. 3 where SCG rates at *R*=0.1, 0.4 and 0.7 are extrapolated to a synthetic SCG kinetics at *R*=1.0, representing static loading [12,43,44].

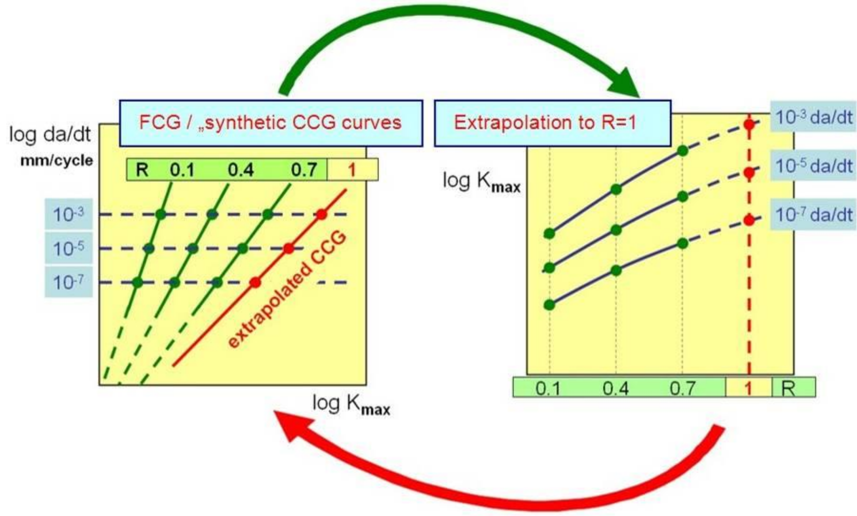

Fig. 2: Crack kinetics extrapolation concept to determine a synthetic static SCG kinetics at *R*=1.0 based on several SCG kinetics at *R*<1.0 [12,43,44].

To take advantage of accelerated material testing the Cyclic CRB Test according ISO 18489 has been used for material characterization. For a precise determination of the SCG kinetics in CRB specimens, a triple extensometer system has been placed around the initial pre-crack in order to measure the crack opening displacement and the material compliance, respectively. A compliance calibration concept, which is a frequently used technique in fracture mechanics material testing, has been used to ascertain the SCG rates during each test [43,44,47]. All tests were conducted at ambient temperature of *T*=23 °C with a test frequency of *f*=10 Hz and without any additional stress cracking liquids.

DISCUSSION

The SCG resistance of both materials of this study was characterized with the Cyclic CRB Test according to ISO 18489 [17]. The determined failure curves presented in Fig. 3 show that there is a clear difference in the ranking between the two pipe grades, confirming a significantly higher SCG resistance for the PE100-RC. The required testing times were 110 h for Material A and 160 h for Material B. Figure 4 also includes the failure range of typical PE100 and PE100-RC pipe grades which have been published previously [48,49]. This comparison demonstrates that the materials of the current study are average representatives for PE100 and PE100-RC grades, respectively.

The crack growth rates measured at *T*=23 °C with Cyclic CRB Tests at different *R*-ratios are shown in Fig. 4. For the PE100 grade the SCG kinetic curves were determined at *R*=0.1, 0.2, 0.3 and 0.5, for PE100-RC at *R*=0.1, 0.2, 0.3 and 0.4. In log-log-scale all curves demonstrate a linear correlation of the crack growth rate d*a*/d*t* and the maximum stress intensity factor $K_{I,max}$. According to the concept shown in Fig. 2 the measured crack kinetic curves were extrapolated to *R*=1.0 in order to develop the crack kinetic laws for static loading conditions. The desired fracture mechanical material parameters were determined to A=7.5777x10^{-7} and m=6.7276 for Material A and A=9.2452x10^{-8} and m=6.2793 for Material B.

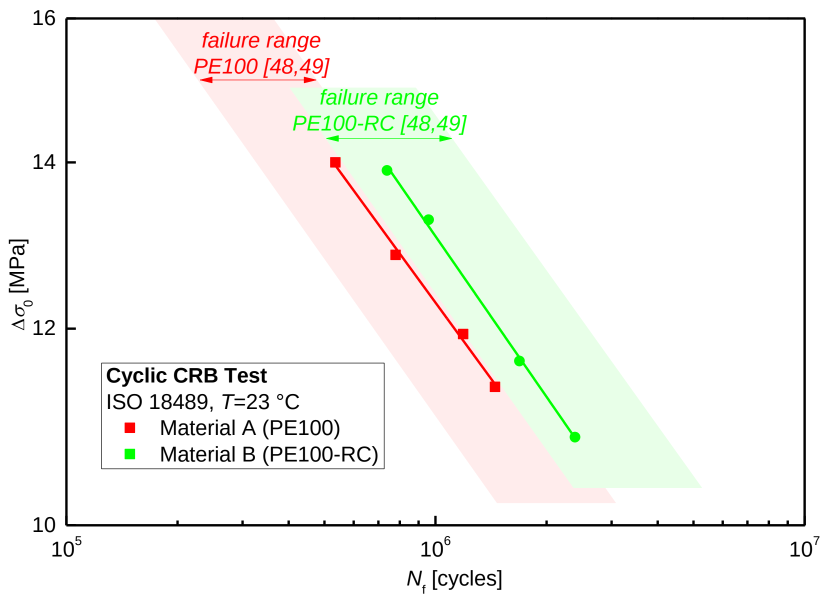

Fig. 3: Slow crack growth resistance of Material A and Material B compared to typical failure ranges of different PE100 and PE100-RC pipe grades characterized with the Cyclic CRB Test according ISO 18489 [17,48,49].

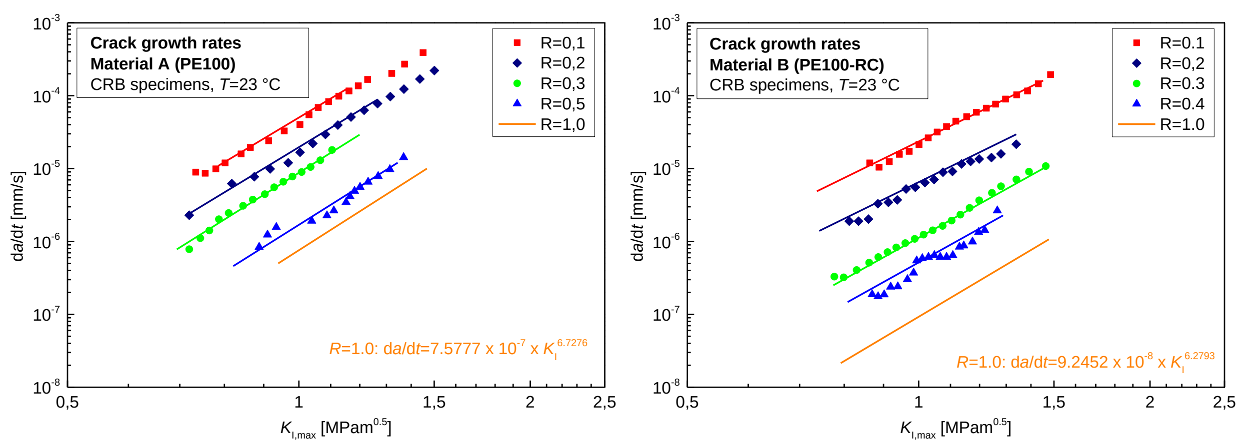

Fig. 4: Crack growth rates da/dt as a function of the maximum stress intensity factor $K_{I,max}$ in CRB specimens at different R-ratios and extrapolated SCG kinetics at static loading conditions of R=1.0 for Material A and Material B at a temperature of T=23 °C.

For a reliable calculation of the pipe lifetime according to equation 5 some boundary conditions regarding initial defect size and crack front shape must be considered. Several studies confirmed that the origin of fracture in internal pipe pressure tests are unavoidable inherent defects located at or near the inner pipe wall surface creating stress singularities such as impurities, polymer agglomerates, material inhomogenities or cavities. The typical size of such defects is in the range of 10-400 µm [3,50–52]. To be conform to a conservative lifetime prediction, within the presented work an initial defect size of a_{ini}=400 µm was defined.

Regarding the crack front geometry, which considerably influences K_I and the lifetime calculation, respectively, it has been demonstrated that cracks growing inside a pipe wall usually start at the initial defect with a semi-circular crack front changing into a semi-elliptical crack front during propagation [21,23,26,44,52]. To take this change in the crack front geometry into account a suitable calculation of K_I shown in equation 6 has been developed by Finite Element Methods [53].

$$K_I = \frac{p \cdot D}{t} \cdot \sqrt{\pi \cdot a} \cdot \left[0.3417 + 0.0588 \cdot \left(\frac{a}{t}\right) - 0.0319 \cdot \left(\frac{a}{t}\right)^2 + 0.1409 \cdot \left(\frac{a}{t}\right)^3 \right] \quad (6)$$

The predicted failure times of pipes with the dimensions of D160 SDR 11 at a temperature of T=23 °C based on previously discussed assumptions and the developed material laws are shown in Fig. 5. In a typical log-log-scale the calculated stage II failure results in a linear correlation of the hoop stress σ_{hoop} and the internal pipe pressure p_i, respectively. The considered loading situation of the calculated pipe is conform to those in ISO 9080 (internal pipe pressure test).

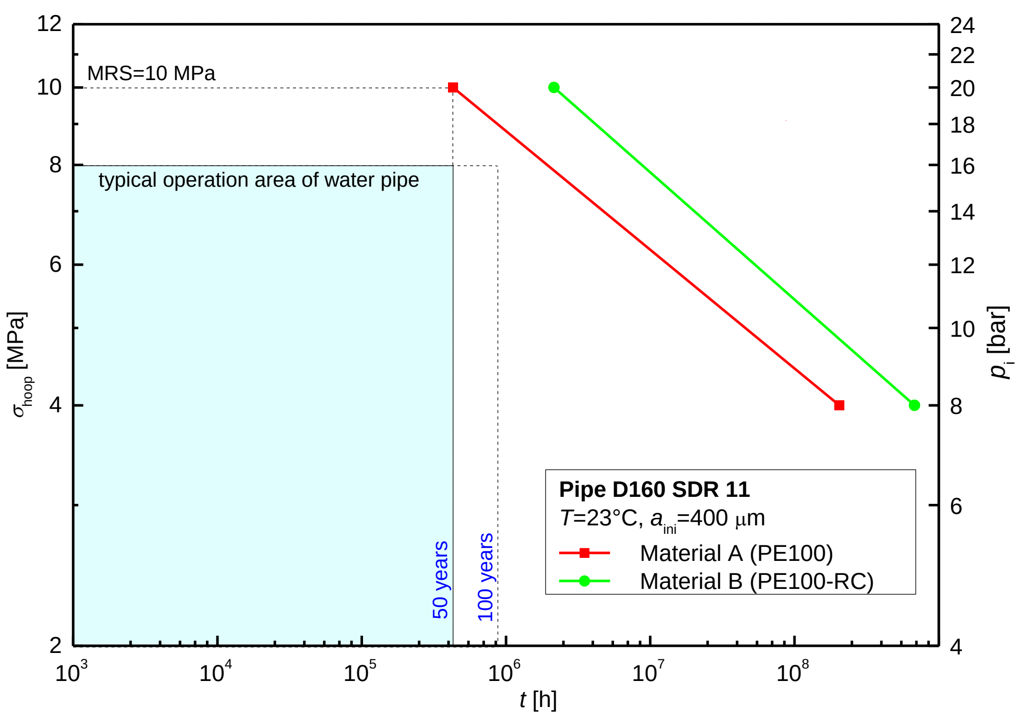

Fig. 5: Predicted failure times t of a pipe with the dimensions of D160 SDR 11 made of Material A and Material B as a function of the hoop stress σ_{hoop} and the internal pipe pressure p_i, respectively.

With respect to the MRS classification the predicted pipe lifetime of the PE100 pipe (Material A) at σ_{hoop}=10 MPa is exactly in agreement with the minimum requirement of 50 years. It must be considered that the presented fracture mechanics lifetime prediction is based on SCG times only. The time for crack initiation is not considered in this assessment but will give an additional safety for the real pipe. In Fig. 5 also a typical operation area of a water pipe considering a safety factor of 1.25 is depicted, resulting in a maximum operation pressure of 16 bar and σ_{hoop}=8 MPa, respectively. At this pressure level the failure curve of the Material A pipe is in clear distance from the minimum required lifetime of 50 years and is even exceeding lifetimes of 100 years.

The failure curve of Material B shows a parallel characteristics to the Material A but with a significantly higher SCG resistance. At σ_{hoop}=10 MPa the lifetime of the PE100-RC pipe is predicted with 250 years which is five times longer than for the Material A pipe. This considerably improvement in the SCG resistance across the whole loading range emphasizes the additional safety against stage II failure of modern PE100-RC pipe grades especially in the context of modern no-dig pipe installation techniques.

Following the predicted failure curves down to lower loads will result in theoretical lifetimes of several thousand years. Though, in this context it must be emphasized that a prediction of such long lifetimes is not serious anymore. At lower loadings a lifetime limitation according to the resistance against thermo-oxidative degradation (stage III) is much more realistic and must be accessed by different approaches.

CONCLUSIONS

The presented study demonstrates the potential of the Cyclic CRB Test not only for a standardized quick material ranking by SCG resistance, but also for fracture mechanics based lifetime prediction of modern PE pipe grades. The investigated PE100 and PE100-RC pipe grades show clear differences in their SCG resistance in material ranking as well as in the characteristics of their crack kinetic curves, confirming significantly higher SCG resistance for the PE100-RC.

Based on material laws for SCG at static loading, at least for the investigated materials lifetimes of 50 years at the reference stress of 10 MPa has been confirmed. Under the consideration of safety factors resulting in practical relevant hoop stresses of 8 MPa, even pipe lifetimes clearly exceeding 100 years can be expected. Comparing the two studied materials, for pipes made of Material B five times longer lifetimes can be expected than for pipes made of Material A. For all presented lifetime predictions it must be considered that they are referring to an internal pressurized pipe of the dimensions D160 SDR 11 and an initial defect size of a_{ini}=400 µm at the inner pipe wall surface. A clear benefit of the presented fracture mechanics approach is, that numerous different additional pipe situations can be defined and used for an application oriented lifetime predictions, such as outside cracks, soil loads, bending forces or even point loads.

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