AGING EFFECTS AND FRACTURE MECHANICAL LIFETIME MODELLING OF PRESSURIZED POLY(ETHYLENE) PIPES

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ABSTRACT

Engineering polymers, in particular special grades of poly(ethylene) (PE), are gaining importance in many pipe applications with targeted service lifes of several decades. To ensure proper performance of such pipes over the required lifetime, polymer physics and mechanics concepts are needed which adequately account for effects associated with the presence of defects in real pipes and the effects of time, temperature, environment and local loading conditions. This article is concerned with the applicability of linear elastic fracture mechanics (LEFM) to predict the time-to-failure of pressurized PE pipes in the quasi-brittle failure regime. As to the micromechanisms of failure, particular attention is given to the occurence of general pipe aging and local crack tip aging, and to effects of stabilization on creep crack growth kinetics and pipe failure times.

INTRODUCTION AND SCOPE

Poly(ethylene) (PE) is now used extensively to produce pressure pipes for a wide range of applications including water, wastewater and sewer services and natural gas supply. The service life typically required and to be achieved covers a time span of up to 50 years. As it is obviously not feasible to conduct experiments over this time period to ensure proper pipe performance (especially for new materials entering the pipe market), certain material tests to simulate but accelerate the long-term failure behavior along with extrapolation methodologies have been developed over the last decades [1 - 5]. These are now used to define durability and design limits, and to assist plastics and pipe suppliers, designers, end users and regulatory bodies in the evaluation of the long-term service performance of a particular thermoplastics pipe system.

While a detailed review of various lifetime assessment and prediction models for thermoplastics pipes is beyond the scope of this paper, one of the most promising routes - i.e., the linear elastic fracture mechanics (LEFM) approach - will be briefly described to provide the necessary background for the subsequent discussion. The paper is based on recent experimental results obtained in our laboratory with various types of PE and focuses in particular on effects of material aging and degradation, and on the influence of stabilization on creep crack growth kinetics and pipe failure times.

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BACKGROUND

Failure Behavior of Thermoplastics Pipes under Internal Pressure

The traditional method to compare different types and grades of plastics and to obtain information for pipe design consists of stress rupture experiments with pipes under constant internal pressure. The tests are conducted under specified conditions of internal and external environment (usually water or air), at various pressure levels, and frequently at several temperatures. The time-to-failure, t_f, is recorded and the data are then presented on log hoop stress, σ_{hoop}, versus log time-to-failure coordinates yielding so-called stress rupture or creep rupture curves. Results of such investigations are available for essentially all plastics used in pressure pipes, in some cases covering a time span of more than 10 years [6 - 9].

Based on the extensive amount of data available it is now well established that in general the lifetime of plastics pressure pipes is controlled by three principal failure modes, which may lead to stress rupture curves schematically illustrated in Fig. 1 [1, 4 - 6]. In Region A, associated with high applied stress levels, failure is initiated by extensive plastic deformation at some location along the pipe specimen (i.e., usually in a region of maximum tensile stress and hence at a location of the lowest wall thickness), resulting in bulging or ballooning of the pipe cross section and highly ductile failure. Decreasing the internal pressure and thus the hoop stress in this region delays this yield process as a consequence of the time dependency of the yield stress in polymeric materials, and hence t_f is increased.

In Region B, at lower stress levels, failure occurs with little evidence of plastic flow as a result of the initiation of a (single) crack usually originating at some defect or imperfection (scratch marks, thermally degraded pipe surface layer, second phase impurities, voids, etc.) at or near the inner pipe surface, and subsequent propagation of such a crack through the pipe wall in a brittle or quasi-brittle manner. As will be outlined below, the stress dependence of the time-to-failure in Region B is thought to be controlled by the kinetics of slow crack growth (also termed creep crack growth). While there are hardly any experimental data, at least in principle there may be a Region B' associated with a certain threshold stress level below which no stress-induced failure takes place, thus corresponding to a mechanical endurance limit.

Finally, in Region C, at very low applied stresses and long lifetimes, failure is primarily a result of chemical aging with substantial molecular degradation of the polymer. In this region the double-logarithmic stress rupture curve is nearly independent of the applied stress level revealing a very steep slope.

While the general failure curve depicted in Fig. 1 is thought to describe in principle the behavior of many if not all plastics pressure pipes, the quantitative location of the failure curve in such a diagram depends of course strongly on the specific material investigated and on the test conditions. In addition to the nature and the molecular mass distribution of the polymer, the degree of crystallinity and the crystalline morphology (in semicrystalline plastics like PE) and various kinds of additives (e.g., various stabilizers against thermal, thermo-oxidative and UV-light degradation) play an important role. As to the test conditions, the primary factors affecting the failure times are the test temperature, the nature of the surrounding environment (e.g., air, water etc.), the occurrence of deliberately, unintentionally or unavoidably introduced imperfections (e.g., inclusions and impurities, voids, degraded pipe wall surface layers, scratch marks, notches, etc.), and to some degree the pipe specimen dimensions. Hence, it may well be, that for a particular material investigated under specific test conditions, the various failure regimes indicated in Fig. 1 may be more or less pronounced or may even dissapear.

Fracture Mechanics Approach and Lifetime Modelling of Thermoplastics Pressure Pipes

Based upon the observation, that failure in Region B of the stress rupture curve, which is of utmost practical importance, is governed by a two stage process consisting of a crack growth initiation stage and a period of stable, slow crack growth, linear elastic fracture mechanics has been recently applied by several authors [3 – 5, 10 - 15] to study and characterize the SCG resistance also in thermoplastics for pipes. In creep crack growth experiments a constant load is applied to a prenotched or precracked specimen (see Fig. 2a) and the crack length, a, is monitored as a function of the loading time, t. A typical crack length versus time curve is depicted in Fig. 2b, indicating a time period t_{in} for the initiation of creep crack growth and, as indicated by the changing slope of the curve, a subsequent creep crack growth phase with an accelerating crack speed, da/dt. At the critical crack length, a_c, crack growth becomes unstable and the specimen ultimately breaks.

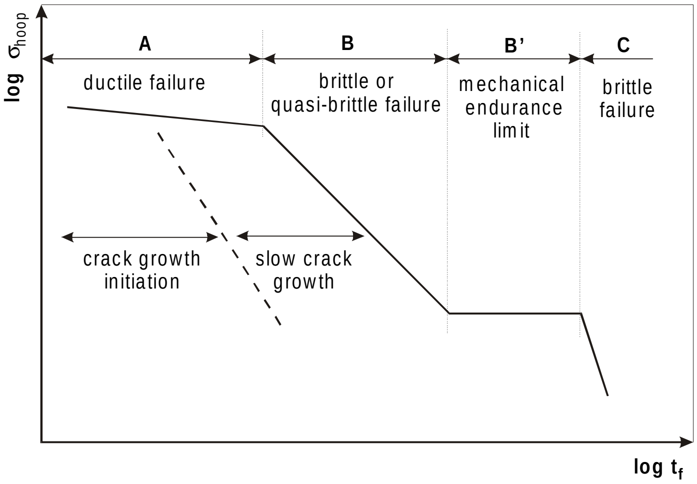

Figure 1: Schematic stress rupture curve of an internally pressurized thermoplastic pipe illustrating the various regions of pipe failure

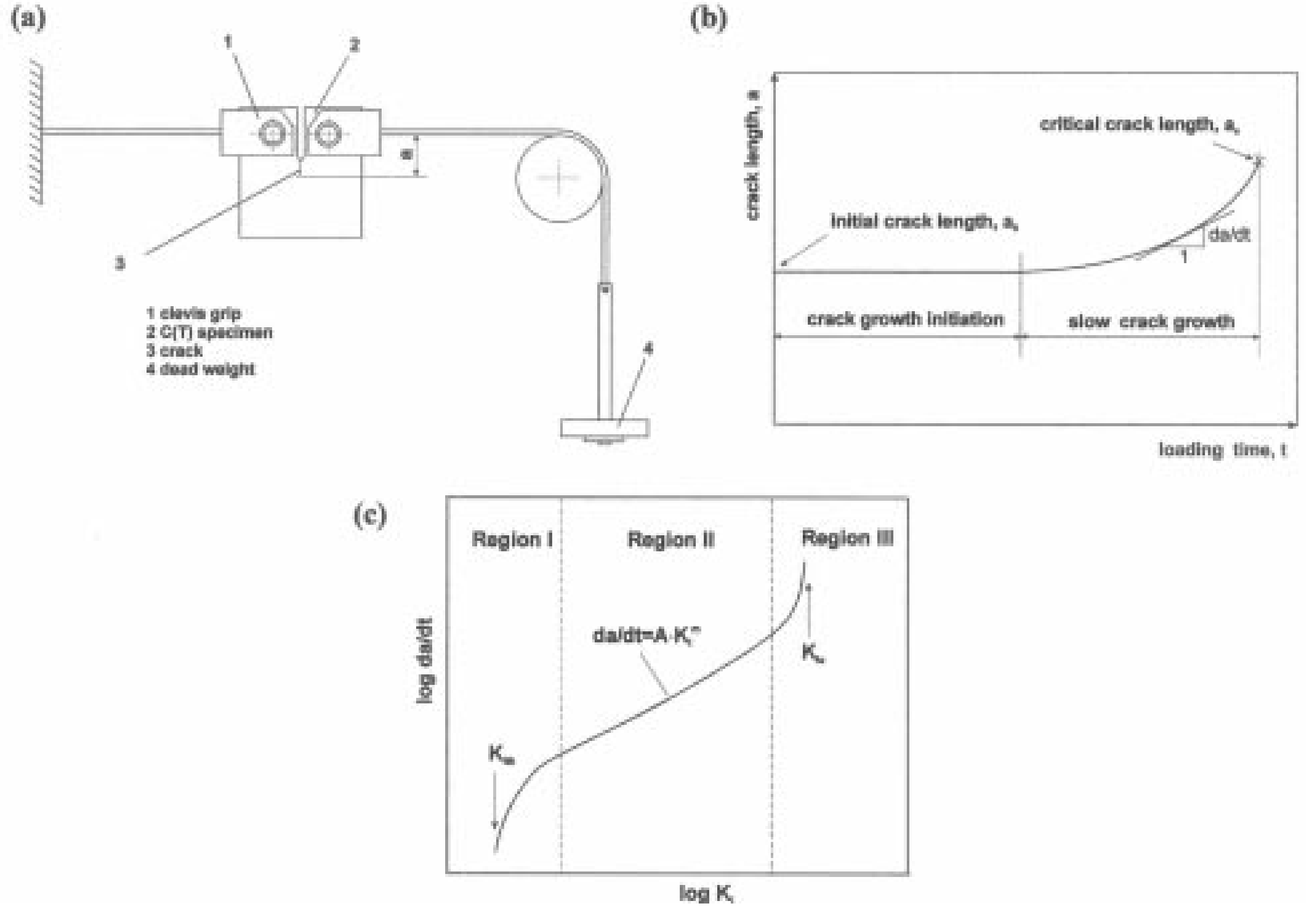

Figure 2: Creep crack growth testing and data reduction; (a) test and loading device for a compact-type (C(T)) specimen containing a notch; (b) typical curve of crack length versus loading time; (c) creep crack growth rates as a function of the applied stress intensity factor, K_I

According to LEFM principles, growth rates of such cracks under static loads are governed by the applied stress intensity factor, K_I (index I stands for opening mode or pure tensile loading conditions), which describes the local crack tip stress and strain field. Using these concepts, creep crack growth rates may then be plotted as function of K_I, and frequently an extended linear section is revealed on a double logarithmic scale by many plastics, indicating a power law relationship of the form

$$\frac{da}{dt} = A \cdot K_I^m \tag{1}$$

where A and m are constants which depend on the material as well as on test variables such as temperature and environment. However, this relationship generally holds true only over an intermediate range of crack growth rates. When investigating a wide range of da/dt, deviations from the power law may be observed as illustrated schematically in Fig. 2c. That is, crack growth rates in Region I, decrease rapidly to vanishingly small values as da/dt approaches the threshold value, K_{Ith}, and they increase markedly in Region III as K_I approaches the material's fracture toughness, $K_{Ic,}$ and crack propagation becomes unstable.

As to the creep crack growth initiation phase, a power law of the form

$$t_{in} = B \cdot K_I^{-n} \tag{2}$$

has been suggested [3, 4, 10], where B and n are again constants depending on the material and on test conditions (i.e., temperature, environment, prenotching or precracking conditions).

According to the above considerations, and applying LEFM principles the total life time, t_f, of a pipe containing a flaw- or crack-like defect consists of the time for crack growth initiation, t_{in}, and the time for slow crack growth, t_{scg}, from an initial crack size, a_o, to the critical crack size, a_c, when failure takes place. Using Eqn. 2 for the crack growth initiation time, and integrating Eqn. 1 for the stable crack growth time, the total pipe lifetime is given as

$$t_f = t_{in} + t_{scg} = B \cdot K_I^{-n} + \int_{a_o}^{s} \frac{da}{A \cdot \left[K_I\left(\sigma_{hoop}, a\right)\right]^m} \tag{3}$$

where the stress intensity factor, K_I, depends on the hoop stress and the critical crack size or crack depth is assumed to be the pipe wall thickness, s. The integral in Eqn. 3 describing the crack growth phase may (either) be resolved analytically assuming some approximations or by numerical procedures.

EXPERIMENTAL INVESTIGATIONS AND RESULTS

The potential of the LEFM approach to predict brittle or quasi-brittle failure of pressurized pipes has been recognized for some time and documented by several authors [3-5, 10-15]. However, as has been pointed out before [4], an LEFM approach based on comparatively short-term testing will only accurately describe real pipe behavior, if any potential polymer aging and degradation effects are restrained to an area in the immediate vicinity of the crack tip (i.e. local crack tip aging). Under these circumstances the crack tip similitude concept, which is a basic requirement for the validity of LEFM, may still be valid and the kinetics of crack growth may inherently also control the available local aging time. On the other hand, if gross aging of a pipe material takes place under real service conditions, the LEFM approach may either be invalid or may require modifications. Hence, in the following more recent investigations performed in our laboratory as to the role of aging in creep crack growth and hydrostatic stress rupture tests will be described and discussed.

Creep crack growth initiation data and creep crack growth data representing the equilibrium crack growth behavior in the stable crack growth range are shown in Fig. 3 for a pipe grade PE-HD, designated in this paper as PE-HD 1. The data were recorded at 80 °C in water using compact type (C(T)) specimens from extruded sheets (nominal specimen thickness of 10 mm). For the same material stress rupture experiments with pipes under internal pressure were also performed at 80 °C. A comparison between predicted time-to-failures based on the above described fracture mechanics approach and experimental time-to-failures of experiments with pressurized pipes (nominal wall thickness of 3.7 mm) is illustrated in Fig. 4. While the shaded scatter band on the right corresponds to the predicted total lifetime consisting of crack growth initiation and slow crack growth, the scatter band on the left ignores the initiation phase, thus representing a lower-bound prediction of failure times (i.e., conservative lifetime estimate). The width of the two scatter bands for the calculated lifetimes reflects the variations in the assumed initial flaw size, a_o, from 100 to 400 µm, a size range which was verified by fracture surface investigations [10].

While the above results provide evidence for a rather favorable comparison between lifetimes based on fracture machanics experiments and calculations, and stress rupture tests on pipes, effects of material aging on lifetime modelling of plastics pressure pipes via a fracture mechanics methodology must be carefully evaluated. In this regard it was found for this particular test series with PE-HD 1 that the change-over from ductile-to-brittle failure in the stress rupture behavior of pressurized pipes corresponds with a drop-off in the materials oxidation induction time (OIT), indicative of a significant amount of stabilizer consumption.

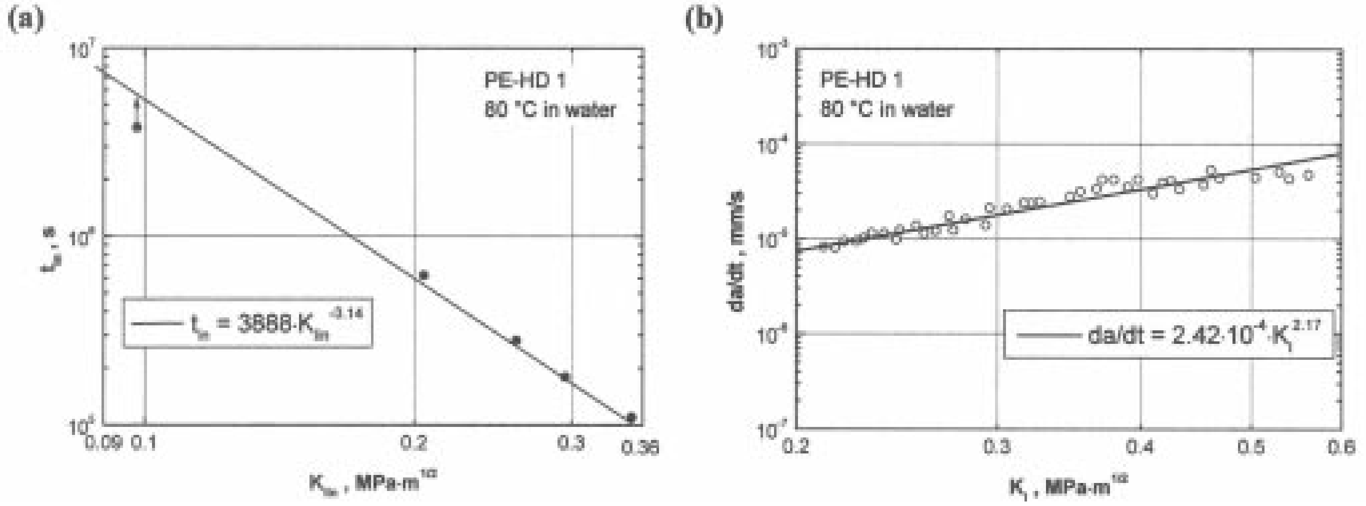

Figure 3: (a) Creep crack growth initiation time, t_{in}, as a function of initial stress intensity factor, K_{Iin}; (b) creep crack growth rate, da/dt, as a function of stress intensity factor, K_I (material: PE-HD 1; test temperature: 80 °C)

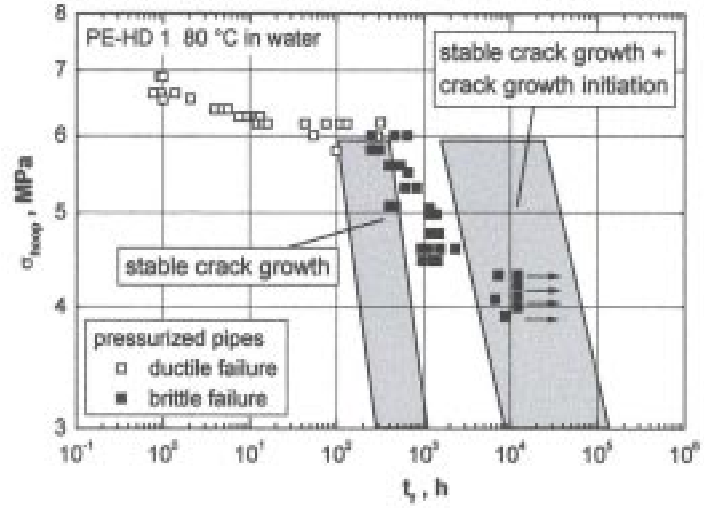

Figure 4: Comparison of measured (square data points) and calculated (shaded areas) lifetimes for PE-HD 1 pipes at 80 °C (calculation accounts for and neglects crack initiation times, respectively)

To further elaborate the influence of aging and stabilization, a systematic study on the effects of various stabilizers in a given type of PE-HD (designated in this paper as PE-HD 2) on creep crack growth behavior and on the failure of pressurized pipes was performed [15, 16]. PE-HD 2 was a blow-moulding grade PE with a high degree of crystallinity which was specifically selected for this study to enhance the tendency for crack growth initiation and crack propagation. Regarding stabilizer effects it is well known that stabilizer type and concentration in a given PE base polymer may have a pronounced effect on pipe lifetimes (up to a factor of

40 in the brittle failure regime) [9, 17, 18]. As stabilizers act to delay the autooxidation and degradation of the polymer, they may also be effective near the tip of a growing crack and thus should influence local aging and hence creep crack growth rates.

Creep crack growth data for PE-HD 2 compounded with two different phenolic antioxidants (designated as formulation S1 and S2, respectively) are shown in Fig. 5 again for a test temperature of 80 °C in water. For these tests, however, C(T) specimens from compression moulded plaques were used (nominal specimen thickness 12 mm). Whereas hardly any differences between the formulations S1 and S2 could be detected in crack growth initiation times, in the low creep crack speed region formulation S1 results in considerably higher crack growth rates than formulation S2. As the characterization methods used so far (i.e., average molecular mass and molecular mass distribution, degree of crystallinity, lamella thickness) could not detect any differences between the two stabilizer formulations, global aging can be excluded in these fracture mechanical crack growth tests lasting only for a few days to a few weeks. Hence, the differences observed for the two formulations at low creep crack growth rates are believed to be a result of local aging around the crack tip related to the combined influence of time, the elevated temperature, the presence of oxygen and water, and the high mechanical stresses in the immediate crack tip region (see Fig. 6). As the time scale for local aging is reduced at high crack speeds, the creep crack growth curves of the two formulations in Fig. 5a converge at high K_I values.

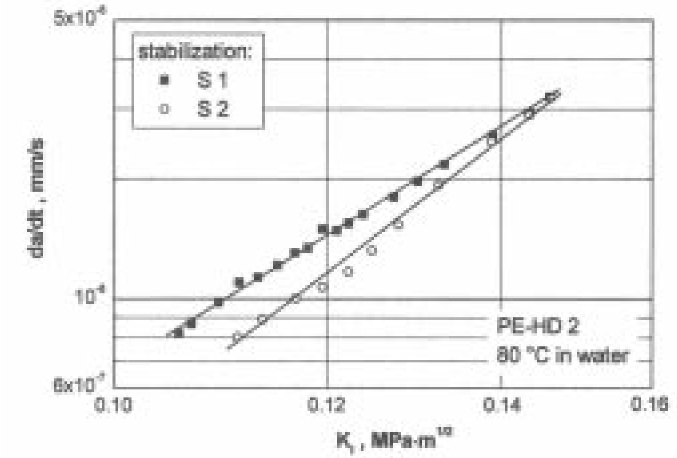

Figure 5: Creep crack growth rates, da/dt, as a function of stress intensity factor, K_I, for the formulations S1 and S2 of PE-HD 2 at 80 °C

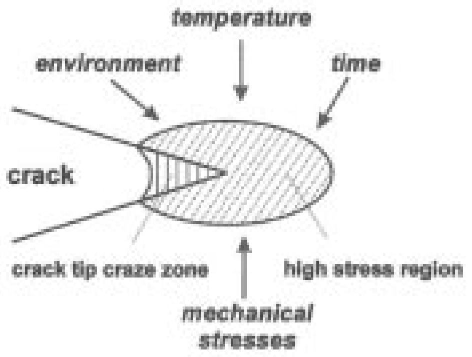

Figure 6: Schematic illustration of the crack tip region in PE-HD along with the parameters controlling local crack tip aging

Corresponding stress rupture curves of pipes (nominal outer pipe diameter of 20 mm, nominal pipe wall thickness of 2 mm) extruded from the same PE formulations S1 and S2 and tested at 80 °C are shown in Fig. 7. In good agreement with the creep crack growth experiments, in the quasi-brittle pipe failure regime formulation S2 exhibits longer lifetimes. Moreover, the increasing difference in lifetimes between the two stabilizer formulations with decreasing hoop stress levels apparently reflects the stronger separation of the creep crack growth curves of these two materials at lower stress intensity values in Fig. 5. In other words, the influence of stabilizers in both types of experiments becomes more pronounced as low creep crack growth rates are involved providing sufficient time for potential local crack tip aging processes.

With regard to Fig. 7 one further aspect deserves mentioning. That is the indication of a mechanical endurance limit following the quasi-brittle failure regime at even lower hoop stress levels below about 2.8 MPa and t_f values above 800 h, referred to region B‘ in Fig. 1. To our knowledge such an endurance limit was explicitly verified experimentally for the first time in this test series. As some of the experiments of this test series are still ongoing, future results will provide further insight on the significance of such a regime and the transition to region C with substantial global aging and molecular degradation of the polymer.

Finally, analogous to Fig. 4 for PE-HD 1, a comparison of calculated and experimental pipe lifetimes for the PE stabilizer formulation S1 is shown in Fig. 8. The shaded area in this diagram for the calculated lifetime range is again based on the assumption of initial defect sizes, a_0, ranging from 100 to 400 µm (which was verified by fracture surface observations of pipe failures [15]). However, in this example stable creep crack growth only was considered in the predicted lifetimes and crack growth initiation was neglected. The agreement is not quite as good as for PE-HD 1 above. The deviations may possibly be related to differences in the material morphology and aging states, as compression moulded specimens were used for the fracture mechanics experiments and extruded pipes for the internal pressure tests. Nevertheless, the ranking of materials containing different stabilizers was found to be equivalent in creep crack growth tests with compression moulded C(T) specimens and stress rupture tests of pipes [15, 16, 19, 20].

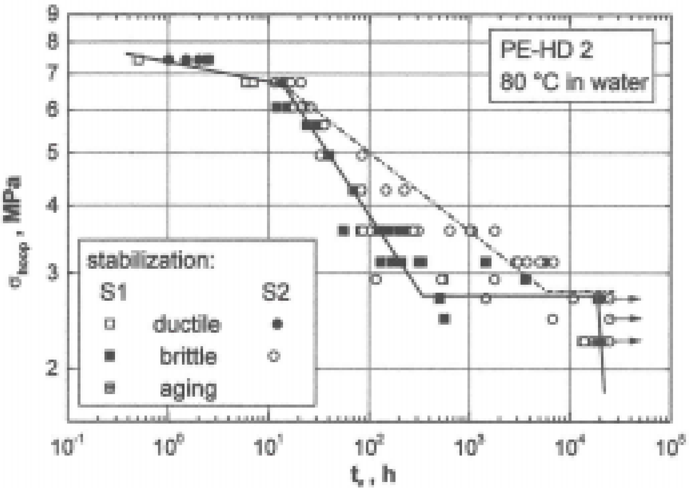

Figure 7: Stress rupture behavior of the formulations S1 and S2 of PE-HD 2 at 80 °C

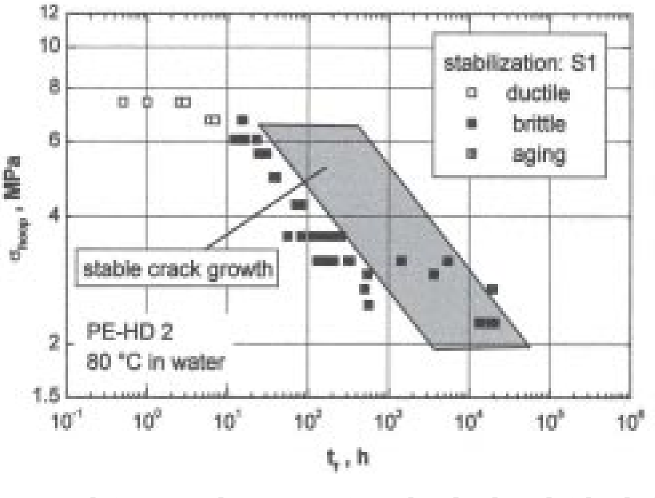

Figure 8: Comparison of measured (square data points) and calculated (shaded area) lifetimes for PE-HD 2 pipes (formulation S1) at 80 °C (calculation neglects crack initiation times)

CONCLUSIONS

Based on experimental findings on creep crack growth initiation and the kinetics of crack growth, the failure behavior of pressurized pipes in the quasi-brittle failure regime was modelled applying a LEFM methodology. In general promising results were obtained when comparing lifetimes of pressurized pipe experiments with those of LEFM model calculations. While good quantitative aggreement between measured and predicted lifetimes was found for a commercial pipe grade material (designated PE-HD 1), for the case of another PE type (designated PE-HD 2) containing different stabilizers, the calculated lifetimes exceeded the experimental ones. However, at least in terms of material ranking a good correlation could be established in the latter case.

Thus it could be shown, that different stabilizer systems in PE-HD influence crack growth rates in creep crack growth tests in the same way as lifetimes of pressurized pipes in the regime of brittle pipe failure are affected. This result may be of great practical and scientific significance. First, for the purpose of material and/or stabilizer screening as well as for the study of structure property relationships, creep crack growth tests may well substitute tests of pressurized pipes with the advantage of getting more detailed information on the failure kinetics at a simultaneously much reduced testing time. Second, the experimental results indicate that local crack tip aging may take place in the stress field near crack tips, a phenomenon which could be studied in further detail by LEFM methods.

Nevertheless, overall these results also indicate that still further research is needed before ultimately applying LEFM principles to define durability limits and to evaluate the long-term service performance of pressurized pipe systems in regulatory procedures.

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