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Test Method

Cyclic crack growth tests with CRB specimens for the evaluation of the long-term performance of PE pipe grades

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Abstract

It is well known that resistance against slow crack growth is important for the lifetime of pressurized polyethylene (PE) pipes. Thus, several methods have been proposed in recent years to evaluate the long-term performance of PE using fracture mechanics. It is generally believed that this leads to results more quickly compared to internal pressure tests. In the presented research work, a method was implemented using fatigue loading of cracked round bar (CRB) specimens to characterize crack growth resistance. The method was applied to five commercially available PE pipe materials and the results were compared with the full notch creep test (FNCT). The same ranking was found with both methods, but it was obvious that fatigue crack growth (FCG) experiments were faster by up to two orders of magnitude, especially when characterizing modern (bimodal) PE types.

Keywords: Polyethylene; Slow crack growth; Fatigue; Ranking

1. Introduction

Pressurized polyethylene (PE) pipes have been used successfully for more than 40 years, primarily in fuel gas and water supply systems. Consequently, substantial experience concerning the failure behavior and the fitness for purpose of PE piping systems is available. Among other things, it is well known that crack initiation followed by creep crack growth (CCG) is the most important long-term failure mechanism, which is reflected by numerous publications dealing with this topic [1–7].

Internal pressure tests on pipe specimens are the traditional way to determine the long-term properties of PE pipes. Unfortunately, this method is expensive and very time-consuming, especially when information on the CCG behavior is needed [3]. Due to this, strong efforts have been put into the development of fracture mechanics tests, which are able to simulate CCG behavior of pipes in a laboratory test and to obtain information on the long-term behavior of PE pipes within a reasonable time frame. CCG tests evaluated according to linear elastic fracture mechanics (LEFM), the full notch creep test (FNCT), the Pennsylvania notch test (PENT), the notched pipe test (NPT) and the cone test, among others, were introduced and are widely used throughout the industry, as well as the scientific community [2,5,7–14].

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Parallel to the development of these methods, the influence of the molecular structure on crack growth was investigated and the distribution of the molecular mass and, in particular, the distribution of the short-chain branches were identified as the most important parameters [15–18]. Specific improvements in the polymerization process of PE followed and the development of third-generation resins in particular has led to outstanding CCG resistance. This was achieved by a bimodal distribution of the molecular mass and the specific placement of the short-chain branches on the high molecular mass fraction. Even with the above-mentioned fracture mechanics methods, testing of these materials exceeds practicable time frames. Consequently, quicker test methods are needed to evaluate the long-term behavior of modern PE pipe materials.

One such method to propagate cracks, even in high-performance PEs, by purely mechanical means is to apply cyclic loads and to characterize the fatigue crack growth (FCG) behavior. Despite the differences in loading conditions, investigations on PE showed that the micro-mechanisms of crack growth have at least qualitative similarity, and rankings based on FCG generally correlate well with those obtained for CCG [1,7,14,19–24]. Furthermore, it is possible to predict CCG from FCG experiments by extrapolation [21,22,25], and currently major efforts are directed towards calculating the lifetime of PE piping systems based on FCG test results [26,27].

As much as 15 years ago, the first reports about static and cyclic crack growth tests on round circumferentially notched bars were published in Japan [24,28]; later, some work was done also in Europe under static [29,30] as well as cyclic loads [7,14,19,31]. In these studies, the failure behavior and failure mechanisms were studied under different testing parameters. A big advantage of this specimen type is that it is geometrically very simple so that it can be manufactured easily from compression-molded plaques as well as from pipes. Moreover, a well-defined plane strain condition prevails along the whole notch, and the stress in the remaining ligament is in the same range as in pipes under internal pressure.

The main objective of this work was to establish a quick screening and ranking tool for PE pipe materials that correlates with existing tests and offers the potential to be used in an industrial environment. Therefore, preliminary tests on two PE pipe materials were performed where also crack growth initiation and fracture surfaces were closely investigated. Afterwards, a test procedure was established and three additional PE pipe materials were characterized. The ranking was compared with results from the FNCT, which is widely used, especially in Europe.

2. Experimental

All investigations in this study were performed on commercially available PE-HD pipe materials with a minimum required strength of 8 MPa (MRS 8 or PE 80) and 10 MPa (MRS 10 or PE 100), respectively. This material classification is established from internal pressure tests on pipes, and means that pipes made from these materials, loaded with a hoop stress of 8 and 10 MPa, respectively, have a durability of 50 years at 23 °C. Some characteristic material properties are summarized in Table 1. Compression-molded plates with a thickness of 10 and 15 mm were manufactured from these materials. Subsequently, FNCT specimens ($10 \times 10 \times 100$ mm) (Fig. 1) as well as cracked round bar (CRB) specimens ($D = 14$ mm, $L = 100$ mm) (Fig. 2) were machined from the plates.

The FNCT can be described as a constant load tensile test, measuring the failure time of notched specimens at elevated temperatures in a surface

Table 1
Characteristic material properties of the investigated materials (from data sheets)

Material-code	Color	ρ (g/cm^3)	M_n (kg/mol)	M_w (kg/mol)	SCB (1/1000 C)	Comonomer	E (N/mm^2)	σ_y (N/mm^2)
PE80-A	Black	0.955	16	290	4	Hexene	1000	22
PE80-B	Black	0.948	15	190	5.5	Hexene	700	18
PE80-C	Yellow	0.94	15	190	5.5	Hexene	700	18
PE100-D	Black	0.96	8	365	3.8	Butene	1100	25
PE100-F	Black	0.959	7.5	230	—	Butene	1400	26

ρ: density; M_n and M_w: number and weight average molecular mass; SCB: number of short side-chain branches; E: Young's modulus; σ_y: yield stress.