Polymer Testing 33 (2014) 161–171

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test method comparison

Evaluation of the applicability of the cracked round bar test as standardized PE-pipe ranking tool

A. Frank [a,*], G. Pinter [b]

[a] Polymer Competence Center Leoben GmbH, Roseggerstr. 12, 8700 Leoben, Austria
[b] Department of Polymer Engineering and Science, University of Leoben, Austria

A R T I C L E I N F O

Article history:
Received 30 September 2013
Accepted 27 November 2013

Keywords:
Polyethylene
Pipe
Slow crack growth
Fatigue

A B S T R A C T

Several tests methods are available for the characterization of the slow crack growth (SCG) resistance of polyethylene (PE) for pipe applications. Unfortunately, due to the increase of the SCG resistance of modern PE pipe grades, these test methods are exceeding practical time frames so that new test methods for accelerated and reliable material ranking are required. The Cyclic CRB Test was proposed as a promising test method for a quick material ranking of PE pipe grades by their SCG resistance, even at ambient temperatures. In this, paper different studies about the Cyclic CRB Test are summarized. On the one hand, the results show the potential for a quick and reliable material ranking at ambient temperatures within only a couple of days, even for modern PE 100-RC grades. On the other hand, results of two Round Robin Tests will be discussed. The presented results demonstrate high reproducibility and reliability of the Cyclic CRB Test in terms of material ranking by SCG resistance.

1. Introduction

For the reliable supply of our modern infrastructure with natural gas or water, buried pipes play an inconspicuous but important role to maintain high living standards. In the field of pressurized pipes, polymer pipes made of polyethylene (PE) have been successfully used for more than fifty years [1–6]. Initially, PE pipes were applied in the low pressure regime up to 4 (gas) and 6 bar (water), respectively, today they are typically operated at pressure levels of up to 10 (gas) and 16 bar (water) and even higher.

Pressurized PE pipes are designed to fulfill operating times of at least 50 years. As a result of improvements of the raw materials, particularly in the bimodal molecular mass distribution and in the controlled implementation of short chain branches, an increase in minimum service life has been achieved so that, especially for the last generation PE pipe grades, possible lifetimes of 100 years and even more are discussed [5].

The material classification of PE pipe grades is based on the long-term failure behavior using internal pipe pressure tests at different temperatures and extrapolation methods as described in EN ISO 9080 [7] or ASTM D2837 [8]. Based on such tests, the minimum required strength (MRS) to ensure pipe lifetimes of at least 50 years is determined and leads to a classification of the materials as PE 63 (MRS = 6.3 MPa), PE 80 (MRS = 8 MPa) or PE 100 (MRS = 10 MPa). For PE 100, which also accords with PAS 1075 [9], an additional classification PE 100-RC (RC = Resistant to Crack) has been defined.

The responsible long-term failure mechanisms of pressurized PE pipes have been studied comprehensively and are known as crack initiation and quasi-brittle slow crack growth (SCG) [2,3,10–12]. Internal pipe pressure tests on PE pipe grades typically last several months or even years. In practice, testing of pipes that do not fail

* Corresponding author. Tel.: +43 3842 42962 26.
E-mail address: andreas.frank@pccl.at (A. Frank).

0142-9418/$ – see front matter
http://dx.doi.org/10.1016/j.polymertesting.2013.11.013

after 10^4 hours (approx. 13.5 months) is usually stopped. The material improvements of the raw material suppliers have shifted the failure time of internal pipe pressure tests to unpractical time scales, resulting in time consuming and expensive test procedures. Especially for modern grades of the classification PE 100 and PE 100-RC, no quantitative information about the relevant quasi-brittle failure region can now be determined with internal pipe pressure tests.

To meet the demand for an accelerated material characterization and to rank different materials by their resistance against crack initiation and SCG, several laboratory tests such as the Notched Pipe Test (NPT) [13–15], the Pennsylvania Edge-Notch Test (PENT) [16–19], the Notched Ring Test (NRT) [20] and the Full Notch Creep Test (FNCT) [21–23] have been developed. All of these test methods are usually conducted at elevated temperatures of $T = 80$ °C or even under the influence of stress cracking liquids (FNCT). Although all the mentioned test methods provide a significant acceleration of testing times, characterization of modern PE pipe grades is still related to long testing times of several months up to years. As regards further time reduction in the characterization of SCG properties, recent studies have shown promising results for two new test methods, the Strain Hardening Modulus [24–27] and the Cyclic Cracked Round Bar (CRB) Test [28–47] which has recently been standardized by the Austrian Standards Institute in ONR 25194 [48].

The scope of this paper is to discuss the reproducibility and reliability of the Cyclic CRB Test. The first focus will be put on the ability of this test in terms of material ranking of different PE pipe grades based SCG resistance. In this context, correlations with FNCT and PENT will also be shown. The second part of this paper is dedicated to the reproducibility of the Cyclic CRB Test across different testing laboratories. For this purpose, the results of two consecutively conducted Round Robin tests will be presented and discussed.

2. Background

For long-term applications of pressurized pipes, it is very well accepted that crack initiation and SCG are the critical failure mechanisms. Slow crack growth always starts at an initial defect which is usually located at or near the inner pipe wall surface [10]. This initial defect creates a stress singularity which is responsible for the formation of crazes in which micro-deformations are nucleating local micro-voids. Within the craze, a combination of local shearing in the amorphous phase and transformation of the crystalline phase leads to highly drawn fibrils which enlarge the craze. During this time, which is the crack growth initiation time, the size of the initial defect remains essentially constant. Subsequently, SCG initiates. At the same time, the stress at the tip of the craze zone increases and continues the craze formation. This procedure of permanent craze formation and breakdown of fibrils is characteristic for SCG in polyethylene and many other polymers, and has already been investigated in numerous studies [49–53]. Due to the complex micro-mechanical mechanisms of craze formation, chain disentanglement and craze breakdown, this process is referred to as quasi-brittle SCG. Besides the described effects, chain rupture may be assumed to have an additional contribution to the failure of fibrils [54,55], and also local crack tip aging affects the mechanisms of SCG [56–58].

In general, the mechanisms of SCG can be described by methods based on Linear Elastic Fracture Mechanics (LEFM). Originally developed for metals, two major requirements must be met for the applicability of LEFM on polymeric materials [58–68]: 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 limited to a small area [62].

The driving parameter for SCG is the stress intensity factor K_I (Equation 1, index “I” describes crack opening mode) which describes the stress field in the vicinity of a crack tip and is a function of the global loading σ, the crack length a_c and a geometric factor Y that is well known for several specimens and component shapes [69], or may also be derived from Finite Element Methods (FEM) simulation [35–37].

$$K_I = \sigma \cdot \sqrt{a_c} \cdot Y \qquad (1)$$

The Cyclic CRB Test is based on this K_I-concept. The CRB specimens are of cylindrical shape with diameter $D = 10$ to 15 mm and length $L = 80$ to 100 mm (Fig. 1). At the middle of the bar, a circumferential notch a_c is inserted with a razor-blade to a depth of 10% of the diameter to provide an initial defect. This geometry ensures an extraordinary constraint (plain strain conditions) along the crack tip so that the formation of SCG retarding plastic zones is minimized. This leads to a quick initiation of SCG. If a crack is growing, the increase of a_c also results in a rise of K_I, which is directly connected to an increase of the crack growth rate.

The major time acceleration of the Cyclic CRB Test is a result of the cyclic (fatigue) load (Fig. 1). For this purpose, the load is applied sinusoidally with $R = 0.1$, which is the ratio of minimum/maximum load F (or $K_{I,min}/K_{I,max}$ or $\sigma_{min}/\sigma_{max}$), and a frequency of up to $f = 10$ Hz. In this context, the test load is also defined by ΔK_I which is the difference between the maximum and the minimum applied stress intensity factor in one cycle.

Different studies have confirmed that, within the boundaries of LEFM for SCG, the same failure mechanisms are frequently responsible in cyclic tests as well as in static tests. Furthermore, these studies show that results of

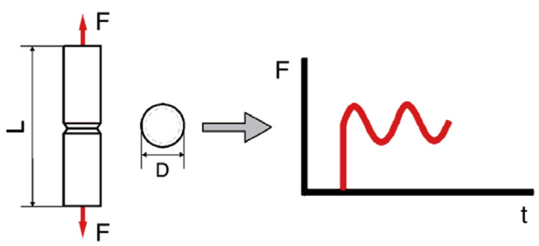

Fig. 1. Schematically illustration of the CRB specimen and the loading mode in Cyclic CRB Test [31].