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Modeling of axisymmetric slow crack growth of high-density polyethylene with circular notched bar specimen using crack layer theory

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A B S T R A C T

Because of the characteristic of high triaxial stress of a circular notched bar (CNB) specimen under tensile loads, it is a promising candidate for accelerated durability testing of high-density polyethylene (HDPE). To understand the slow crack growth (SCG) behavior of HDPE using a CNB specimen, it is practically important to base the evaluation of the SCG model using a CNB specimen on the concept of fracture mechanics. In this study, the SCG kinetics of HDPE with a CNB specimen is modeled on the basis of the concept of an axisymmetric crack layer (CL) system. CL theory is applied to the modeling of the axisymmetric SCG considering the geometry of the CNB specimen. Green's functions of the stress intensity factor and crack opening displacement of the CNB specimen are calculated in order to simulate the CL kinetics. The obtained Green's functions are also utilized to compute the thermodynamic forces for both the crack growth and the CL growth, and a generalized CL growth algorithm is developed. A parametric study of several key input parameters is conducted for validation of the developed CL model. In addition, actual SCG generated experimentally is simulated using the developed model, and it is found that the actual test results can be successfully simulated using the developed CL model.

1. Introduction

The lifetime prediction of thermoplastic pipes that supply natural gas and portable water has become a critical task in view of the need for replacement of conventional steel pipes with lightweight thermoplastic pipes. Thermoplastic pipes are known to have three different failure modes depending on the applied load level (Chudnovsky et al., 2012) as shown in Fig. 1. Under a high-pressure load, localized ductile fracture with a considerable amount of plastic deformation, i.e., ballooning, is commonly observed, and well-established international test standards, e.g., ISO 9080 and ASTM D2837, are available for characterizing this type of failure. Slow crack growth (SCG), considered as quasi-brittle failure, occurs in the moderate load range; this type of failure is commonly observed in the form of defects or inclusions acting as a crack initiation site. The location of the initiation site may strongly affect the duration of the slow crack growth stage. The time associated with crack initiation may vary widely from 20% to 80% of the total lifetime (Chudnovsky, 2014).Therefore, both crack initiation and SCG resistance can be important factors in the prediction of the lifetime of thermoplastic pipes depending on various material characteristics and loading conditions. At a relatively low load level, the lifetime to failure is dominated mainly by the mechano-chemical degradation of the thermoplastic pipe, which, in turn, is related to the long-term exposure of the pipe to chemical substances. This exposure leads to stress corrosion cracking with multiple microcracks (Choi et al., 2005, Choi et al., 2009b) or environmental stress cracking (Kurelec et al., 2005, Choi et al., 2009c), depending on the contacting chemical substances. Therefore, it is important to understand the relation between the applied load and the change in the lifetime to failure of the pipe with a change in the failure mechanism. Then, simple extrapolation of data obtained from an accelerated test without consideration of fracture mechanisms can be extremely dangerous.

Among the three abovementioned failure modes, quasi-brittle failure has been investigated by several researchers (e.g., (Lu et al., 1991, Showaib and Moet, 1993, Parsons et al., 1999, Parsons et al., 2000, Choi et al., 2009a, Zhang et al., 2014)) because this type of failure occasionally occurs in the field or during testing. Since an actual pipe test with SCG-dominated failure under operation conditions is expensive and time consuming, various lab-scale specimens have been developed and used for accelerated testing. Compact tension (CT) and single-edge-notched tension (SENT) specimens are commonly employed for the assessment of SCG kinetics.

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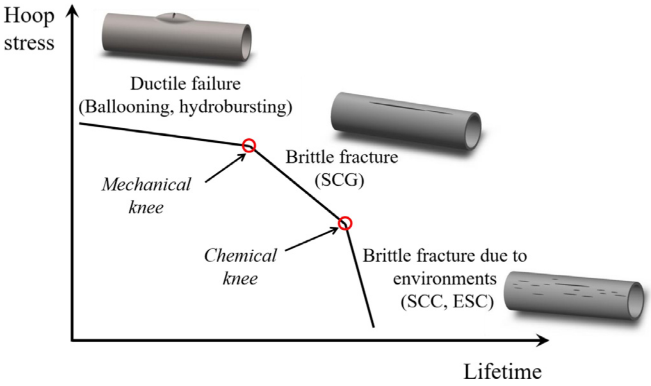

Fig. 1. Schematic diagram of the variation of failure modes of thermoplastic pipes.

Furthermore, the well-known ASTM standard for evaluating the resistance to brittle failure, i.e., ASTM F1473 (PENT test), was developed using a modified SENT specimen. However, because of the development of new pipe resins, test samples occasionally do not fail for periods longer than a year when subjected to the conventional PENT test; therefore, the development of a new accelerated test method has become necessary. So, specimens with asymmetrical geometry, such as full notched creep tensile (FNCT) and circular notched bar (CNB) specimens, have been considered as alternative candidates for use in quick ranking of the resistance of pipe-grade polyethylene (PE) materials to brittle failure (Plummer et al., 2001, Pinter et al., 2007, Zhao et al., 2013, Redhead et al., 2013, Frank and Pinter, 2014, Plummer et al., 2003, Ben Hadj Hamouda et al., 2009, Nezbedova et al., 2013). Especially CNB specimen can ensure shorter test periods given that it generates very high triaxial stress in front of the notch tip owing to constraint effects (Ha et al., 2004). In the case of CT and SENT specimens, an elevated temperature is required for ensuring a reasonable testing time when SCG-dominated failure is involved. However, in the CNB specimen, brittle failure can occur even in a significant load range, because the high triaxial stress can be maintained over most of the lifetime. That is, with the use of the CNB specimen, SCG-dominated failure can be induced at the service temperature of pipes, even in shorter testing times. In case of the utilization of the CNB specimen, the characterization of SCG may not be easy owing to some technical issues related with the asymmetric crack growth (Zhao et al., 2011, Kim et al., 2013, Zhang et al., 2001, Cao et al., 2015). So, CNB specimen may be much better geometry to characterize crack initiation behaviors rather than SCG because the crack initiation of HDPE does not include possibly severe asymmetric SCG due to various test errors such as asymmetric notch, misalignment of the specimen, material inhomogeneity and so on . However, the geometry of CNB specimen can still be beneficial for an accelerated SCG test if well-defined axisymmetric SCG can be achieved (Pinter et al., 2007, Frank and Pinter, 2014, Frank et al., 2009).

Due to complex features of SCG in PE, phenomenological modeling of SCG based on various approaches such as experimental observations, numerical analysis and conventional fracture mechanics has been popularly proposed (Lu et al., 1991, Ben Hadj Hamouda et al., 2009, Nezbedova et al., 2013, Lu and Brown, 1995, Hutar et al., 2011, Frank et al., 2012). However, the SCG behavior of PE is quite different from metals, so it is also quite important to construct SCG model and predict the lifetime of PE using theoretical fracture mechanics approaches based on unique features of SCG of PE. The full-scale SCG kinetics of thermoplastics can be mathematically modeled using crack layer (CL) theory. According to this theory, the CL is defined as a system comprising a main crack and a surrounding damage zone, i.e., process zone (PZ) (Chudnovsky, 1984, Chudnovsky and Shulkin, 1999). The growth of the main crack and the PZ can be simulated by considering the physical interactions between the main crack and the surrounding damaging phenomena such as crazing, microcracking, and/or local drawing. For example, discontinuous/continuous SCG, which is commonly observed in high-density polyethylene (HDPE), can be precisely simulated using the CL model (Choi et al., 2009a, Zhang et al., 2014). However, thus far, the CL-theory-based simulation has been employed mainly under the 2D plain strain condition, in which the CL configurations can be assumed as independent of the thickness direction, as is the case with the SENT and CT specimens.

In the present study, the SCG kinetics of HDPE with a CNB specimen is modeled according to the concept of an axisymmetric CL system. The transition of SCG behaviors between discontinuous and continuous manners depending on loading and environmental conditions is quite interesting, but, in this study, unique discontinuous SCG behaviors are considered to be modeled. The main objectives of this study are as follows: (1) development of a CL model for an axisymmetric solid for expanding the applicability of CL theory and (2) simulation of the full-scale SCG kinetics for HDPE with the geometry of the CNB specimen, which has a simple PZ configuration. For development of the CL model for the CNB specimen with a modified configuration, the corresponding Green's functions of the stress intensity factor (SIF) and crack opening displacement (COD) are required to be determined beforehand. Therefore, CL theory is first extended to an axisymmetric solid, and the Green's functions for the CNB specimen are established through finite element analysis (FEA). After the development of the CL model, the thermodynamic forces (TFs) for both the crack growth and the CL growth are computed on the basis of the simulated SCG kinetics for HDPE with the geometry of the CNB specimen, and a generalized CL growth algorithm is developed. A parametric study of several key input parameters is conducted for validation of the developed CL model. In addition, actual SCG generated experimentally is simulated using the developed CL model, and it is found that the results of the actual test can be successfully simulated using the developed model.

2. Application of CL theory to axisymmetric solid

2.1. Modification of CL theory to CNB specimen using quasi-equilibrium irreversible thermodynamics

Fig. 2 shows the general CL configuration in an axisymmetric solid, with a circumferential main crack from CNB specimen. As mentioned earlier, the generalized CL is a system comprising a main crack and a surrounding PZ (Chudnovsky, 2014). The PZ can be divided further into two regions: an active zone (AZ) and a wake zone (WZ). The rate of discontinuous density ($\dot{\rho}$) generated by crazing or microcracking is positive in the AZ and zero in the WZ owing to the traction-free nature of the crack face. The configurational lengths of the CL, the main crack length (l_{CR}), the CL length (L), and the CL width (w)are indicated in Fig. 2. The boundary between the AZ and WZ is called the trailing edge (Γ_t). The leading edge (Γ_l) is the front edge of the AZ, which is to be migrated from the solid curve to the dotted one. The migration vector along Γ_l is represented by $\delta\xi_i^{PZ}$. The subscript i refers to the local coordinates in Fig. 2. Under the assumption that the migration vectors on the crack front edge (Γ_{CR}) are directed along x_1 and invariant along Γ_{CR}, the migration vector on Γ_{CR}, denoted as $\delta\xi_i^{CR}$, is the same as δl_{CR}. Since the PZ evolution processes, including crack propagation, can be thought of as being irreversible, the following CL theory is derived on the basis of irreversible thermodynamics. Let us introduce the generalized damage parameter P of the CL (Chudnovsky, 1984). Then, the rate of the global dissipation function ($\dot{\Psi}$) in the irreversible damage evolution process under