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Applying the crack-layer concept to modeling of slow crack growth in polyethylene

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ABSTRACT

The crack-layer model provides a framework for modeling fracture growth and lifetime prediction. In the past two decades, it has been applied to model brittle fracture in a number of engineering materials. This paper demonstrates in-detail procedure of implementation of crack-layer framework, on the example of slow crack growth in a commercial high-density polyethylene under creep conditions. First, we compute crack-layer driving forces by finite element method and determine experimentally the basic material parameters entering constitutive equations of the model. Then, we develop a numerical simulator of fracture growth.

1. Introduction

We study brittle fracture of high-density polyethylene (HDPE) due to slow crack growth. Slow crack growth in HDPE exhibits complex behavior ranging from continuous propagation, with relatively high acceleration of small cracks, to discontinuous growth with relatively low acceleration of well-developed cracks (Chudnovsky, Zhou, & Zhang, 2012). This makes the conventional methods of brittle lifetime prediction inadequate.

In continuum mechanics, a crack is conventionally considered as an ideal cut in an elastic, elasto-plastic or visco-elasto-plastic medium. The concept of surface (fracture) energy associated with crack faces introduced by Griffith (Griffith, 1921) was the first important step in thermodynamics of brittle failure. Barenblatt (Barenblatt, 1959; Barenblatt, 1962) proposed a simple model of cohesive forces along an extension of crack-cut. Dugdale (Dugdale, 1960) independently developed a similar model for the plastic deformation along an extension of crack-cut. The two models are mathematically identical and commonly referred to as the Dugdale–Barenblatt model, which evolve into Cohesive Zone model.

The essential assumption of the Dugdale–Barenblatt model is that the stress singularity at the crack tip vanishes due to cohesive forces or plastic deformation at the crack front zone. Formally it is expressed as zero stress intensity factor (SIF, K), i.e., $K = 0$. However, the stress singularity is associated with two basic assumptions of linear elastic fracture mechanics: (1) linear elastic stress–strain relations are maintained in the near crack tip region; (2) the crack is perfectly sharp (zero radius of curvature) at the tip. In real engineering materials, however, neither of these two assumptions applies. Indeed, (1) damage in the form of crazing, micro-cracking, shear-banding, cavitation etc. is formed in response to high stresses and the crack–damage interaction lowers stresses in the damage zone region; (2) large deformation of the crack front region results in finite crack tip radius of curvature. Thus, the crack is surrounded by a damage zone (a "process zone") and the crack–damage

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interaction plays a major role in fracture propagation. These concepts have led to the crack-layer (CL) model (Botsis, Chudnovsky, & Moet, 1987a,b; Choi, Balika, Chudnovsky, Pinter, & Lang, 2009; Chudnovsky, Dunaevsky, & Khandogin, 1978; Chudnovsky & Shulkin, 1999; Kadota & Chudnovsky, 1992; Khandogin & Chudnovsky, 1978; Stojimirovic, Kadota, & Chudnovsky, 1992).

This paper presents implementation of CL model on the example of slow crack growth in HDPE under creep loading. The overall structure of the paper takes the form of four sections. After short introduction it gives a brief overview of the CL model in Section 2. The following section begins by laying out the flowchart of CL model simulator, and develops CL computational tools and gathers material properties that enter CL constitutive equations. The next section analyzes the results of simulated slow crack growth process in a compact tension specimen and presents the findings of the research. Finally, brief conclusions are presented in the last section.

2. Crack layer in HDPE

Slow crack growth in HDPE under creep and fatigue conditions has been extensively studied for several decades (Chudnovsky & Shulkin, 1999; Chudnovsky, Zhou, & Zhang, 2012; Chan & Williams, 1983; Choi et al., 2009; Kadota & Chudnovsky, 1992; Lu & Brown, 1990; Lu & Brown, 1991; Showaib & Moet, 1993; Stojimirovic et al., 1992), see (Chudnovsky & Shulkin, 1999) for a comprehensive review. There are several characteristic features of slow crack growth in PE that are important for modeling:

(1) A process zone commonly precedes and surrounds a crack in PE. At low magnification, the process zone appears as a narrow wedge-type strip with a crack in the middle (Fig. 1a).
(2) A process zone consists of drawn fibers and/or membranes. The dimensions (diameter and length) of the fibers and membranes gradually change from coarse to very fine ones toward the process zone front.
(3) Fracture surface morphology also undergoes graduate change from larger diameters of fibers to smaller ones. At certain combinations of loads and temperatures, the fracture surface displays striations that indicate a discontinuous (stepwise) CL growth.
(4) A part of process zone in front of the crack with intact fibers/membranes, called active zone, is shown in Fig. 1a. The fibers/membranes of active zone carry a high load and undergo creep.
(5) Rupture of active zone fibers/membranes results in crack advancement into the active zone.
(6) A part of process zone consisting of remnants of the broken fibers/membranes of active zone and left behind advancing active zone, called wake zone, is shown in Fig. 1a.
(7) CL in PE grows in both continuous and discontinuous manner depending on temperature and the SIF. The CL growth process may also start as a continuous one and then, with an increase of crack length, i.e., an increase in SIF, transfer into a stepwise propagation.

We use polyethylene because its process zone has simple geometry: there is a sharp boundary separating original material from cold drawn fibers (Fig. 1a). The boxed area in Fig. 1a encloses a portion of active zone (tapered shape) and is shown

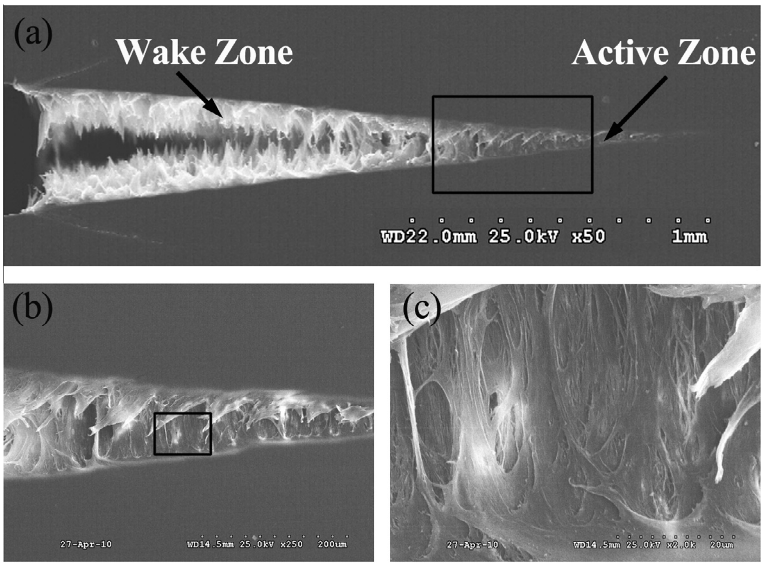

Fig. 1. SEM images of (a) crack layer (50×), (b) active zone with unbroken fibers (250×), and (c) highly oriented fibers within active zone (2000×) in HDPE tested under creep at 23 °C.