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Creep fracture toughness using conventional and cell element approaches

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Abstract

The mechanical response of a polymeric material is loading rate sensitive especially near the glass transition temperature. In this work, the polymeric material is modeled as an elastic-nonlinear viscous solid. A computational scheme based on the finite element method is used to simulate steady-state crack growth in the polymeric material under plane strain mode I, small-scale yielding conditions. The scheme is validated by reproducing the Hui–Riedel singularity field around a steadily growing crack in the elastic-nonlinear viscous solid. It is observed that the Hui–Riedel singularity has a limited range of validity. Thereafter, two fracture approaches are employed to study viscoelastic creep crack growth. One is the conventional critical strain over critical distance ahead of the crack. The other is the cell element approach for crack growth caused by void growth and coalescence, in which the rate-dependent fracture process zone is represented by a nonlinear viscous microporous strip of cell elements. These cell elements are described by a Gurson-like micromechanics model recently proposed for void growth in nonlinear viscous matrix. The computed toughness-velocity curves using strain criterion exhibit mesh dependence while those obtained by cell element approach appear to be robust.

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Keywords: Viscoelastic; Fracture toughness; Crack tip fields; Polymeric material; Rate-dependence; Fracture mechanism

1. Introduction

Loading rate strongly influences the mechanical behavior of polymers, especially for conditions in the proximity of the glass transition temperature. Certain polymers can experience considerable viscoelastic deformation under service conditions (and even at room temperatures), and this can give rise to viscoelastic creep crack growth. Slow viscoelastic creep crack growth in polymeric material is becoming an important area of study because of the increasing use of these polymers in technologies traditionally dominated by metals, including the automotive industry.

The mechanism of slow crack growth in polymeric material typically involves void growth and coalescence in rate-dependent solids [1,2]. A review article on crack growth in viscoelastic solids has been given by Bradley et al. [3]. The mechanics of crack growth in elastic–viscoplastic solids has been studied by Landis et al. [4]. Employing a rate-dependent cohesive law to model the fracture process zone, their analyses of quasi-static steady-state crack growth under small-scale yielding showed that the fracture toughness can either increase or decrease with increasing crack velocity. The effects of viscoelasticity can become even more pronounced under moisture and high temperature assisted failure of IC (integrated circuit) packages during the reflow process [5–7].

Analysis of steady-state crack growth in purely elastic-nonlinear viscous solids was initiated by Hui and Riedel [8], who derived the near-tip stress and strain singularity fields. To supplement the asymptotic analysis, numerical computation on steady-state crack growth under plane strain, small-scale yielding condition was carried out by

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Hui [9]. However, the latter study did not directly compare its numerical results with the Hui–Riedel (HR) singularity fields (e.g. the angular distribution of the near-tip stresses).

Recently, Tang et al. [10] used the cell element approach to examine rate effects on steady-state toughness of the homogeneous polymeric material. In their work, the fracture process zone is modeled as a nonlinear viscous microporous solid described by a Gurson-like micromechanics model (derived following Gurson [11]) while the background material is modeled as an elastic-nonlinear viscous solid. The fracture process zone, comprising cell element, attempts to capture key features of the process of rate-dependent void growth and coalescence. The results shed some light on the crack velocity dependent fracture toughness of polymeric material, as well as how the work of separation in the fracture process zone and energy dissipation in the background material contribute to the macroscopic fracture toughness.

In this paper, we first carry out a validation study of the computational scheme by comparing the full-field numerical solutions with the HR singularity fields [8]. Using the full-field (and self-similar) solutions in conjunction with a conventional strain criterion, we compute the creep fracture toughness. We then employ the cell element approach to simulate steady-state crack growth in nonlinear viscous solids.

2. Problem formulation

In this section, we present the material model and numerical procedure for steady-state crack growth.

2.1. Elastic power-law creep

The polymeric material is taken to be an elastic-nonlinear viscous solid with Young's modulus E and Poisson's ratio ν. The viscous behavior obeys the power-law creep

$$\dot{\varepsilon}^{\mathrm{c}}_{ij} = \frac{3}{2}\dot{\epsilon}_0\left(\frac{\sigma_{\mathrm{e}}}{\sigma_0}\right)^n \frac{s_{ij}}{\sigma_{\mathrm{e}}} \tag{1}$$

where $\dot{\epsilon}_0$ is the reference inelastic strain rate under the reference stress σ_0, n the strain rate or creep exponent, σ_{e} the effective stress such that

$$\sigma_{\mathrm{e}} = \sqrt{\frac{3}{2}s_{ij}s_{ij}}$$

and $s_{ij} = \sigma_{ij} - \sigma_{\mathrm{m}}\delta_{ij}$ is the deviatoric stress with $\sigma_{\mathrm{m}} = \sigma_{kk}/3$ signifying the mean stress. The elastic strain rate is given by

$$\dot{\varepsilon}^{\mathrm{e}}_{ij} = \frac{1+\nu}{E}\dot{\sigma}_{ij} - \frac{\nu}{E}\dot{\sigma}_{kk}\delta_{ij}. \tag{2}$$

Note that the inelastic strain is incompressible.

2.2. Small-scale yielding

Fig. 1a shows the computational model for steady-state crack growth with constant crack velocity $\dot{a}$ under plane strain, small-scale yielding conditions. Along the remote boundary of the domain, the stress field

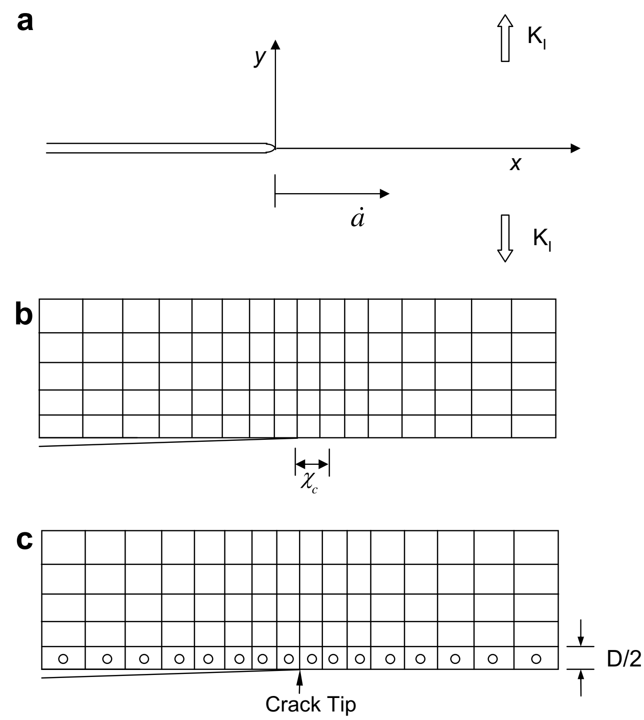

Fig. 1. (a) Steady-state crack growth in nonlinear viscous solids under small-scale yielding conditions with constant stress intensity factor K_{I} and crack velocity $\dot{a}$. (b) Schematic of FEM model using conventional strain crack growth criterion imposed at χ_{c}. (c) Schematic of FEM model using a layer of cell elements (of width $D/2$ – representing half of the fracture process zone), which are placed both ahead of the crack and along the crack flank.

$$\sigma_{ij} = \frac{K_{\mathrm{I}}}{\sqrt{2\pi r}}\hat{\sigma}_{ij}(\theta) \tag{3}$$

is applied with the constant stress intensity factor, K_{I}. Here (r, θ) are the polar coordinates relative to the moving crack tip and $\hat{\sigma}_{ij}$ is the universal function of stresses.

Under small-scale yielding conditions, the mode I stress intensity factor K_{I} is related to the J-integral by

$$J = \frac{1-\nu^2}{E}K_{\mathrm{I}}^2 \tag{4}$$

which is also the crack driving force. The condition for steady-state crack growth can be stated as

$$\Gamma_{\mathrm{ss}} = J \tag{5}$$

where Γ_{ss} signifies the steady-state fracture toughness.

The finite element mesh is fixed with respect to the moving crack tip. For the mode I loading, only the upper half plane needs to be analyzed taking advantage of the overall symmetry. This is modeled by a large rectangular domain (Fig. 1b).

An iterative finite element solution procedure is adopted to solve the steady-state problem, which is similar to that used by Dean and Hutchinson [12] and Landis