Original Contributions

On the viscoelastic fracture criteria for polymers: experiments and analysis

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Abstract: Creep deformation and fracture tests on two polymeric materials were performed at various temperatures and strain rates. The data obtained were analyzed and used to test four viscoelastic fracture criteria, based on different theoretical approaches. No definitive conclusion could be reached as to the identification of an appropriate invariant fracture parameter.

Key words: Viscoelasticity; polymers; fracture; fracture-criteria

Introduction

The fracture behavior of materials that are not linear-elastic has received much attention, but the main developments in this field regard the characterization of fracture in materials that exhibit more or less confined plasticity. In polymeric materials, due to their viscoelastic nature, energy dissipation may often be diffuse in the whole stressed body, rather than somehow localized, as in the case of plasticity, which, on the other hand, may also take place.

The problem of fracture in viscoelastic bodies has been addressed, over the past 20 years, within the framework of fracture mechanics, by several authors using different approaches [1-9]; several criteria have been advanced, either local to the failure zone or global, whereby the energy conservation principle is applied to the overall system.

Of the theories that have been developed to deal with fracture in viscoelastic bodies, however, none seems to have been confirmed by experimental results on a large number of materials.

In this work, we have mainly considered a theory developed by Schapery [1, 2] that generates some simple equations for predicting, inter alia, time-to-fracture initiation in media that are, on the whole, linearly viscoelastic. The investigation was carried out on two crosslinked polymeric materials at temperatures around their glass transition temperature, at which the deformation shows substantial viscoelasticity, while plastic effects are absent in the fracture process. Fracture tests were performed at various temperatures and strain rates and, for each test, the instant of fracture initiation was picked up and the stress intensity factor at fracture initiation was determined according to linear fracture mechanics. Since application of Schapery’s criterion calls for knowledge of the viscoelastic deformational behavior of the material, this too, was experimentally determined.

Recall of Schapery’s criterion for viscoelastic fracture

Based on a crack model (sketched in Fig. 1), analogous to that used by Barenblatt [10] and Dugdale [11] to represent a small-scale wedge-shaped yielded zone ahead of the crack tip in time-independent materials, Schapery assumes failure to occur in a small region just behind the crack tip, and develops a theory to predict initiation and growth of fracture in time-dependent, viscoelastic materials for the pure opening mode (Mode I) [1, 2]. For a detailed analysis of all the assumptions required for developing the theory, the reader is referred to the original papers.

For the purposes of this work, however, some important limitations of the theory, which directly follow from the original assumptions, need to be pointed out. Firstly, the theory assumes that the
material outside the failure zone shows linear viscoelastic behavior during the fracture process; this assumption may not always be verified in practice, in view of the high stresses and strains reached during fracture in many polymeric materials. Secondly, the failure zone size (\(\alpha\) in Fig. 1) should be small compared to the relevant dimensions of the body (ligament and crack length). No restriction is placed on the constitutive properties of the damaged material in the failure zone, whose mechanical behavior may be highly non-linear and rate-dependent.

The assumption of a very localized failure zone is quite often realistic in polymeric materials. In glassy thermoplastics, a wedge-shaped zone ahead of the crack tip is the most frequent form of process zone observed, but also in crystalline and rubber-modified thermoplastics, and even in rubbers, the process zone observed often fits the proposed model quite well.

With some other minor assumptions, Schapery (Eqs. (62) and (64) in [2]) evaluates the work done on the failure zone by the surrounding, linearly viscoelastic continuum up to fracture initiation as:

\[ 2\Gamma = \int_0^{t_i} D(t_i - t) \frac{\partial K_I^2(t)}{\partial t} dt, \tag{1} \]

where \(D(t)\) is the tensile creep compliance of the material and \(K_I(t)\) is the (applied) stress intensity factor. Strictly speaking, Eq. (1) holds for plane stress conditions at the crack tip; the plane strain variant is obtained by multiplying the compliance by \((1 - v^2)\), \(v\) being the Poisson ratio.

\(\Gamma\) is identified with the so-called fracture energy. It is expected, on a theoretical basis, not to depend appreciably on the history of the external loading; however, it may depend on temperature and other environmental factors as well as on the size of the damage zone, \(\alpha\) [2].

Equation (1) can be re-written as follows (Eq. (64) in [2]):

\[ 2\Gamma = K_{II}^2 D^*(t_i), \tag{2} \]

where

\[ D^*(t) = [K_{II}^2(t)]^{-1} \int_0^{t_i} D(t_i - t) \frac{\partial K_I^2(t)}{\partial t} dt \]

and \(K_{II} = K_I(t_i)\). Equation (2) is virtually identical to the condition for fracture initiation in a linearly elastic body, except that a so-called secant compliance \(D^*(t)\) appears in place of \(1/E\), \(E\) being the elastic modulus of the material. If \(K_I\) is a non-decreasing function of time (as in a monotonic, constant strain-rate test), the theory predicts that for any time \(t\), prior to initiation:

\[ D^*(t) \leq D(t) \tag{3} \]

in which \(D(t)\) is the creep compliance of the material at an instant \(t\). Thus, if one uses the "pseudo-elastic" approximation to calculate the strain energy release rate \(G_{II}\) (at fracture initiation) according to the relationship

\[ G_{II} = K_{II}^2 D(t_i), \tag{4} \]

one would generally obtain an overestimated value of the fracture energy.

Obviously, in the limit of linear elastic behavior, \(D = \text{const.}\) and Eqs. (1) and (4) are reduced to the strain energy release rate criterion stated by linear elastic fracture mechanics.

**Experimental**

Two polymeric materials were considered for the present investigation: i) a fluorinated rubber containing 30 phr of carbon black, especially formulated for operating in aggressive environments, supplied by Montefluos SpA (Italy); ii) a transparent, highly flexible epoxy resin, used for insulation in electrical applications, supplied by EniChem Synthesis SpA (Italy).

The glass transition temperatures of the two polymers were determined by DSC obtained at a heating rate of 10°C/min: the fluorinated rubber showed a fairly sharp transition at about \(-10°C\), while the epoxy resin displaced a broad transition around \(-8°C\).