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Published in *International Journal of Fracture* **112** (2001), pp. L9–L12.
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Rate Effects on Mode-I Delamination Toughness of a Graphite/Epoxy Laminated Composite

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Mechanical properties of composite materials made of high modulus fibers and relatively low modulus polymeric matrix, such as graphite/epoxy laminated composites, are sensitive to loading rate and temperature. Generally, at fixed loading rate, when temperature increases, the fracture toughness of polymers also increases; however, it will decrease with the increase of loading rate at constant testing temperature [1–4]. Rate effects on fracture toughness are of critical to understand the fracture transition from ductile to brittle of some polymers. However, there have been fewer studies of rate effects on delamination toughness of laminates compared to that of pure polymers. In the present work, the double-cantilever beam (DCB) test geometry is utilized for studying the effects of loading rate and testing temperature on mode-I delamination toughness of a graphite/epoxy laminate made of commercial thermal-setting prepreg, Hexcel T2G190/F263. The thermal activation model of fracture is suggested for data reduction.

Twenty-four ply unidirectional samples are fabricated from the thermal-setting prepreg, Hexcel T2G190/F263, originally supplied by Hercules. Samples are cured in accordance with the manufacturer's recommended curing cycle and cut using a diamond-tipped rotary saw. Artificial delaminations are created by placing a 12.7-μm thick Teflon film between the 12th and 13th plies. The interlaminar crack growth direction is corresponding to the fiber direction.

DCB mode-I delamination tests are conducted under displacement control on a standard servo hydraulic MTS machine. Specimens (125 mm × 25 mm × 4 mm) are loaded at a constant crosshead speed of 2, 20, 200, and 2000 mm/min, respectively, with the load being applied continuously via two hinges that are bonded onto the delaminated end of each arm of the specimen, respectively. Tests with temperature higher than room temperature (45°C, 75°C, 100°C, 120°C and 140°C) are performed in a thermal-chamber with automatic temperature control, and the chamber temperature is kept constant during each test.

In the present work the loading rate is relatively small, so the dynamic effects on fracture toughness are negligible [5]. On the basis of the recorded load-displacement curve of each DCB specimen, the average mode-I delamination toughness, G_{IC}, is determined experimentally by the area method [6]. Scatters in Figure 1 show the relationship of fracture energy release rate with testing temperature at several loading rates. At each loading rate, the fracture energy release rate increases with the increase of testing temperature, while at each fixed testing temperature, the fracture energy release rate decreases with the increase of loading rate, similar to the fracture results of some pure polymers [1–4].

The total fracture toughness, G_{IC}, is divided into two components, namely the component dependent on temperature and rate, G_{ICa}, and the component independent on rate and temperature, G_{ICo}. The total mode-I delamination toughness, G_{IC}, is expressed as

$$G_{IC}(\dot{\varepsilon},T) = G_{ICo} + G_{ICa}(\dot{\varepsilon},T). \tag{1}$$

It is assumed that G_{ICa} is controlled by thermal activation. According to the Arrhenius Law, the thermally activated strain rate can be described as

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp(-\Delta G/kT) \tag{2}$$

where $\dot{\varepsilon}_0$ is a structure factor, ΔG is the activation energy, k is the Boltzmann's constant ($k = 8.6112 \times 10^{-5}$eV/K), and T is the testing temperature.

There exists a relation between the strain rate at the crack tip and the crack tip opening displacement (CTOD) rate.

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{d(\delta_y - \delta_{y0})}{\delta_{y0}dt} = \frac{\dot{\delta}_y}{\delta_{y0}} \tag{3}$$

where δ_y is the CTOD, $\dot{\delta}_y$ is the CTOD rate determined according to Smiley and Pipes [5], and δ_{y0} is a scale parameter related to characteristics of the cohesive zone at crack tip.

Substitution of (3) into (2) yields

$$\dot{\delta}_y = \dot{\delta}_{y0} \exp(-\Delta G/kT) \tag{4}$$

where $\dot{\delta}_{y0} = \dot{\varepsilon}_0 \delta_{y0}$ is an unknown constant to be determined.

Similarly to Liu and Song [4], it is assumed that

$$\dot{\delta}_{y0} = V_0 \, (G_{ICa}/G_0)^m \tag{5}$$

where V_0 is a structure factor, G_0 is a unit energy and m is an unknown constant.

Substituting (4) and (5) into (1) obtains the following general equation

$$G_{IC} \, (\dot{\varepsilon},T) = G_{ICo} + G_0 \, (\dot{\delta}_y / V_0)^{1/m} \exp(\Delta G / m\mathrm{k}T) \tag{6}$$

where unknown constants G_{ICo}, V_0, m, and ΔG are determined by fitting the experimental results.

Experimental results for mode-I delamination toughness, G_{IC}, of the unidirectional graphite/epoxy laminate and their description by (6) are shown in Figure 1. The unknown parameters G_{ICo}, V_0, m, and ΔG in (6) are determined by the regression analysis of the experimental G_{IC}-T curves at 4 fixed loading rates (2, 20, 200, 2000 mm/min). The parameters are approximated as G_{ICo} = 0.105 kJ/m^2, V_0 = 7.861 × 10^{-3} m/s, m = –4.471, and ΔG = 0.7206 eV. The analysis shows that the thermal activation model of fracture provides reasonable description of experimentally observed behavior, except for the highest testing temperature. The latter effect may be due to the proximity to the glass transition temperature.

Acknowledgment

The support of this work by the U.S. Army Research Office is gratefully acknowledged. The authors are very grateful to Professor K. Friedrich at University of Kaiserslautern, Germany, for helpful comments.

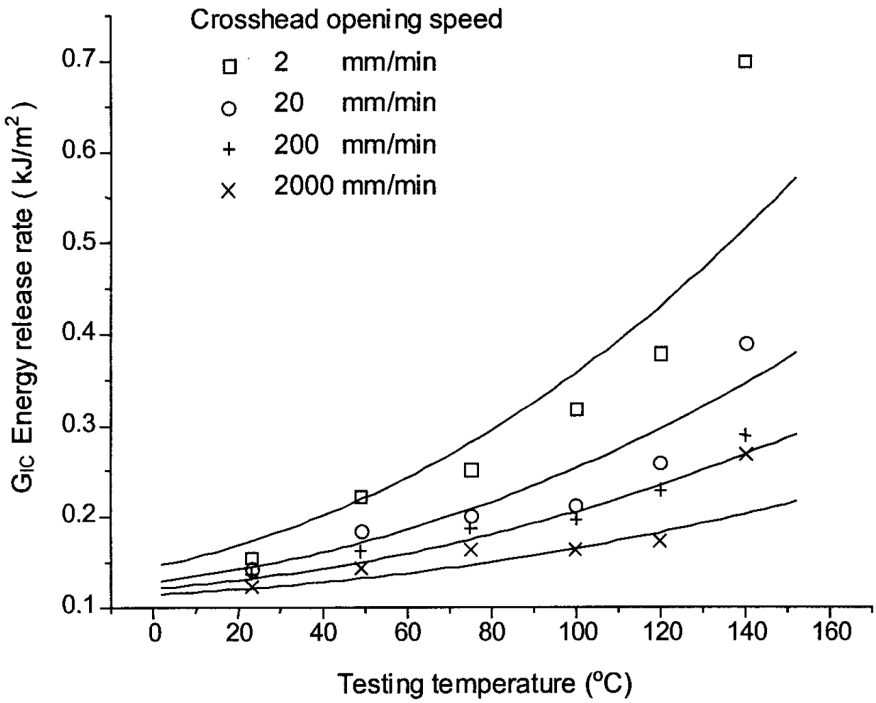

Figure 1. Variation of G_{IC} with loading rate and temperature. Scatters = experimental results; solid lines = calculated by Equation (6).

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