Small Compact Tension Specimens for Polymer Toughness Screening

INTRODUCTION

As engineering polymers are considered for use in structural applications, toughness characterization is becoming an essential screening tool.[1] Although the need for a small-scale test has been recognized,[2] the usual compact tension,[3] single-edge-notched, or bend test,[4] requires 7–60 cm^3 of material per specimen. This is a serious handicap in laboratory-scale work with new polymers. A miniature version of the standard ASTM test for metals[5] has been shown to give valid results for brittle ceramics.[6] The purpose of the present note is to demonstrate that, with some care, a value equivalent to the plane-strain fracture toughness K_{Ic} may be determined with less than 2 cm^3 of a tough polymer.

SAMPLE SIZE CONSIDERATIONS

In testing tough materials, the usual concern is to make the sample thick enough to guarantee plane strain conditions across most of the crack front. In the present work, thicknesses b were chosen to satisfy the requirement in ASTM Standard E399, namely $b \geq 2.5\,(K_c/\sigma_{ys})^2$, where K_c is the measured critical stress intensity factor and σ_{ys} is the polymer yield strength.[5] For polycarbonate, the toughest of the glassy polymers considered here, this requires $b \geq 0.8$ cm.

In miniaturizing a specimen, there is more to be gained, however, by decreasing the width (and height) than by decreasing the thickness alone. The size limit on the width is determined by the requirement that the crack length a be large compared to the dimensions of the crack tip plastic zone. In the ASTM method, this requirement is specified as $a > 2.5\,(K_c/\sigma_{ys})^2$. For the small specimens tested in the present work, a was typically 0.6 cm (see Fig. 1). Larger specimens—either rectangles twice as wide, or 5.7 cm round specimens[3]—were also tested for comparison.

EXPERIMENTAL

With the exception of the cast acrylic sheet, the polymers tested were obtained as pellets from commercial sources and compression-molded 50–100°C above their respective glass transition temperatures at 400 psi (2.8 MPa), and then cooled under pressure in the mold. The plates were machined to size, and sharp naturally arrested cracks were introduced by driving a liquid-nitrogen chilled razor blade into a saw cut. A fresh blade was used for each specimen. Whenever possible, large and small specimens were cut from the same plate. Precracked samples were examined between crossed polarizers to eliminate those with gel particles or other extraneous stress concentrations near the crack tip.

Fracture was performed at a crosshead rate of 0.127 cm/min. Critical stress intensity factors were calculated from

$$K_c = P_c Y/(bW^{1/2}) \tag{1}$$

where P_c is the maximum load seen on the chart record and Y is a geometrical factor[7] valid over the range $0.2 \leq a/W \leq 1$. For the compact tension specimen (CTS)

$$Y = \frac{(2 + X)(0.886 + 4.64X - 13.32X^2 + 14.72X^3 - 5.6X^4)}{(1 - X)^{3/2}}$$

$$X = a/W$$

In most cases, the load maximum was followed by slow stable crack growth. When this occurred, several data points could be obtained with a single specimen. To do this, the crosshead was stopped, 1 min. was allowed for the crack to stabilize, and a line was scribed on each side of the specimen to mark the new crack length. Then the specimen was partially unloaded and the crosshead was started down again. Crack growth resumed at a load equal to the arrest value. After the tests, the specimen halves were separated and arrest lines on the fracture surfaces, identified with the help of the scribe marks, were used to determine crack lengths. Since a crack front is rarely perpendicular to the specimen sides, and average crack length was determined by measuring at three points along each arrest line.[2] Fracture surfaces were flat, with no evidence of shear lips.

Journal of Applied Polymer Science, Vol. 32, 5653–5655 (1986)
 CCC 0021-8995/86/065653-03$04.00

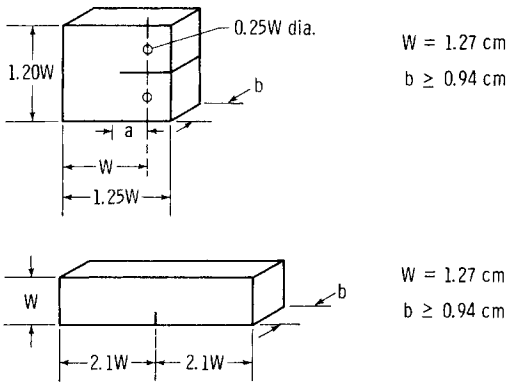

Fig. 1. Dimensions of small fracture toughness specimens.

RESULTS AND DISCUSSION

Results for both large and small specimens are shown in Table I. Each value is an average of 4–20 measurements; standard deviations from the mean are used to represent the experimental scatter.

The good agreement with other data in the literature suggests that the specimen thicknesses, the methods of precracking, and the data reduction procedures employed may be adequate not only for relative screening purposes, but also for interlaboratory comparisons. In examining toughness data for a given polymer, it should be borne in mind that it is customary to regard the lowest values obtained in a series of measurements as most characteristic of the material. Unusually high values are blamed on blunt cracks and discarded.

From Table I it is also apparent that the small specimen and the larger specimen produce practically equivalent results. Consequently, the small specimen is now used routinely in this laboratory for new materials.

One further aspect of the use of these compact specimens deserves mention. The ASTM method E399 would restrict crack lengths to $(a/W) = 0.5 \pm 0.05$, but this requirement is frequently not obeyed, for several reasons: (1) It is difficult, especially when working with unfamiliar materials, to obtain precracks of controlled length. (2) It is useful to verify that razor precracks and "natural" cracks formed by slow propagation give comparable K_c values. This verification is most easily done by making multiple measurements in one specimen at increments in crack growth, i.e., at increasing values of a/W. (3) Multiple measurements on each specimen can be used to get a statistical average when the available quantity of material is limited, as it usually is when an experimental resin is being evaluated.

Figure 2 displays part of an extensive collection of data on one polymer taken to determine that the K_c obtained for different crack lengths is constant. Evidently it is, although the experimental scatter is larger for the longer cracks. This is what one would expect given that the geometrical factor Y in eq. (1) is a much more sensitive function of a/W in this range, and there can be considerable uncertainty in crack length when the crack front is curved or when it is not

TABLE I
Critical Stress Intensity Factors for Various Polymers K_c (MPa $m^{1/2}$).

Material	Bend specimen	Small CTS	Large CTS	Literature	Refs.
Polycarbonate	3.39 (±13%)	3.63 (±9%)	3.55 (±8%)	3.52–3.62	8, 9
Polysufone		2.41 (±10%)	2.45 (±3%)	2.4–3.4	10, 11, 12
Polyetherimide		3.39 (±9%)	3.52 (±14%)	3.1–3.6	12, 13
Phenoxy		2.53 (±15%)	2.30 (±14%)		
Cast acrylic[a]		0.97 (±14%)	0.95 (±20%)		

[a]6.1 mm thick sheet.

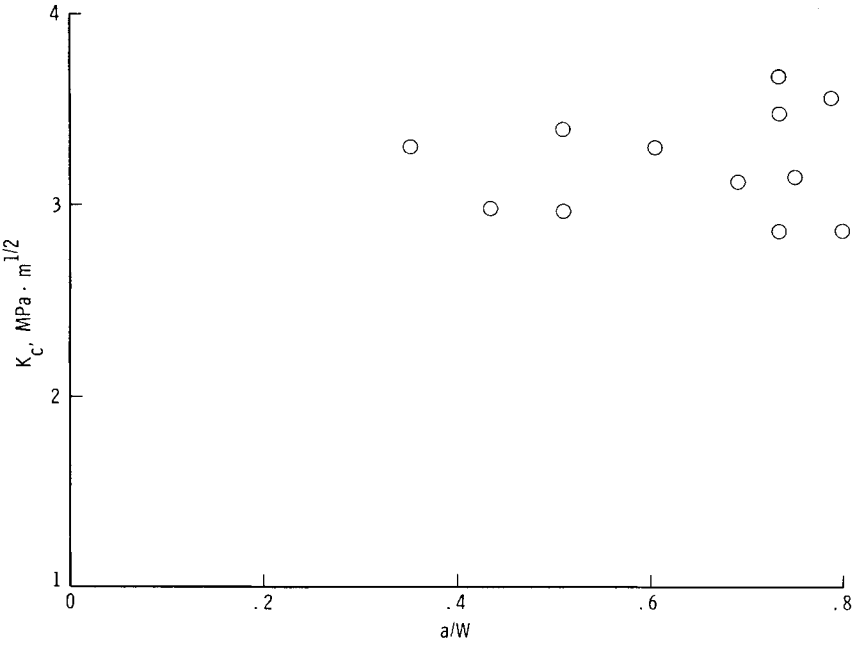

Fig. 2. Critical stress intensity vs. normalized crack length for polyetherimide samples.

perpendicular to the specimen sides. The use of uneven cracks is one reason there tends to be more scatter in K_c data on polymers in general than in metals testing.[12,5]

In conclusion, it has been shown that valid fracture toughness characterization is possible over the range $0.3 \leq a/W \leq 0.8$ on 1.3-cm-wide specimens of even the toughest glassy thermoplastics. The specimens are easy to handle and test, very little material is needed, and the results appear to be very reliable.

References

1. For example, W. D. Bascom, J. L. Bitner, and R. L. Cottington, *Am. Chem. Soc., Org. Coat Plast. Prepr.*, **38**, 477 (1978).
2. C. Y.-C. Lee and W. B. Jones, Jr., *Polym. Eng. Sci.*, **22**(18), 1190 (1982).
3. R. Y. Ting and R. L. Cottington, *J. Appl. Polym. Sci.*, **25**, 1815 (1980).
4. S. Hashemi and J. G. Williams, *J. Mater. Sci.* **19**, 3746 (1984).
5. ASTM E399-83.
6. G. Dewith and N. Hattu, *J. Mater. Sci.*, **16**, 1702 (1981).
7. J. E. Srawley, *Int. J. Fracture*, **12**, 475 (1976).
8. W. W. Gerberich and G. C. Martin, *J. Polym. Sci. (Phys.)*, **14**, 897 (1976).
9. S. P. Petrie, A. T. Dibenedetto, and J. Miltz, *Polym. Eng. Sci.*, **20**(6), 385 (1980).
10. R. D. R. Gales and N. J. Mills, *Eng. Fracture Mech.*, **6**, 93 (1974).
11. N. J. Mills, *Rheol. Acta*, **13**, 185 (1974).
12. D. L. Hunston, *Compos. Technol. Rev.*, **6**(4), 176 (1984).
13. N. J. Johnston, private communication.

J. A. HINKLEY

NASA Langley Research Center
Mail Stop 226
Hampton, Virginia 23665

Received August 23, 1985
Accepted December 12, 1985