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An evaluation of the short rod technique to measure the fracture toughness of polymers

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The investigation of the fundamental variables which influence the fracture toughness of structural plastics is greatly hampered by a large amount of scatter and uncertainty associated with the fracture toughness measurement. A major part of the problem is due to a lack of adherence to ASTM Standard E399, mainly with regard to the requirement for a fatigue crack. A razor-blade arrested crack, which is often blunted, is common practice in the plastics field. It is also common to ignore size (plane strain) and precise machining requirements. The short rod (SR) method was evaluated as a potentially more precise and simpler fracture toughness measurement. This toughness measurement is made on a slowly moving and presumably sharp crack, and the geometry of the sample enforces plane strain conditions. Toughness measurements on compact tension (CT) specimens via ASTM E399 were performed on one-inch (25 mm) samples of poly(methyl methacrylate) (PMMA), polystyrene (PS), polycarbonate (PC) and polysulphone (PSO). Also, a constant compliance method using a contoured double cantilever beam (CDCB) was used to evaluate the toughness of PS, PC, and PSO, but in general we did not achieve stable crack growth. The used samples were then fabricated into SR specimens and their toughness measured. The CT and CDCB methods agreed with each other for PSO and PC, but for PS the CDCB method gave high values. It is argued that the SR method should be compared to the other methods without using a plasticity correction. Then the SR method agrees well with the CT method for PSO and PS and is 15% higher for PC. The PMMA SR results were invalid. Differences between the methods are explained in terms of crack blunting, rate effects, non-homogeneity, residual stresses and the global nature of the crack front. The SR method has promise for polymer evaluation but more experience and evaluation is needed. The method is unique in the ability to study the effects of thermal history and of the environment on fracture toughness.

Nomenclature

a	Distance from load line in the crack plane to the crack tip.
a_0	Distance from load line in the crack plane to the chevron tip. Equal to 10.11 ± 0.287 mm.
A	Calibration constant: $A = 22$ at $r = 0.555$, $A = 50.9r^2 - 56.25r + 37.58$ for $r > 0.555$, $A = 77.87r^2 - 86.05r + 45.77$ for $r < 0.555$. These relationships for A, supplied to us by Terra Tek, were found to be valid for $r = 0.4$ to 0.75.
B	SR specimen diameter, equal to 19.1 ± 0.23 mm in this study or to specimen thickness for CT and CDCB specimens.
C	Correction for SR specimen sizes which do not exactly meet specifications of compliance calibration.
C_a, C_b, C_w, C_Θ	C corrections for a, B, W and Θ, respectively.
F	SR load at $r = 0.555$.
K	Stress intensity factor (MPa m$^{1/2}$).
K_c	Critical value of K at point of instability.
K_{Ic}	K_c in opening mode.
K_{IA}	Arrest toughness.
K_{sr} ($=K_{Isr}$)	Short-rod determined toughness. When used in conjunction with K_{srp}, refers to toughness value without the p correction.
K_{srp} ($=K_{Isrp}$)	K_{sr} with p correction. A prime (as used in K'_{srp}) is used to differentiate between toughness at r_c and at the downloadings.
m	Constant-compliance constant for CDCB specimen derived from specimen geometry and beam theory.
m'	Correction to m obtained from experimental compliance calibration. Corrects for side grooves.
p	Ratio of difference in strain for two SR downloading curves at load = 0 to that at load = F. Must be less than 0.2. See Fig. 3.
p'	p correction due to plasticity alone.
r	SR initial compliance divided by

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	compliance at point of interest = (load/strain)/(load/strain)$_{\text{initial}}$.
r_c	Critical r at $r = 0.555$.
W	SR specimen length, equal to 28.575 ± 0.584 mm in this study.
Θ	Chevron angle in degrees. Equal to 55.2 in this study.

1. Introduction

It is well recognized that under service loading, materials usually fail by fracturing due to progressive growth of inherent flaws. It is necessary to know the fracture toughness of a material to predict how large a flaw it can tolerate. Fracture mechanics attempts to quantify the resistance to the onset of rapid cracking in terms of K_{Ic}, the fracture toughness in the opening or cleavage mode, Mode I. Briefly, the stress intensity factor K is a measure of the intensity of the stress field in the vicinity of the crack field and K_c is the critical value of K at the point of unstable crack propagation.

In the metals field a well-established procedure, known as ASTM Standard E399, has been developed after a great amount of research and experience. This standard specifies testing procedures for a number of specimen types including the compact tension specimen and requires that a host of criteria be met, three of which, in our opinion, are especially important for polymers. First, the precrack must be a fatigue crack. This assures a sharp and reproducible crack in metals, but it is less certain that a fatigue crack in polymers produces a sharp and reproducible crack. Second, the crack length and specimen thickness must be greater than two and one half times the square of the measured K_{Ic} divided by the square of the yield stress of the material. Experience in metals has shown that this criterion assures plane strain conditions, i.e. a minimum K_{Ic} for a given class of metals. Third, the specimen must be machined to precise specified dimensions. In the metals field the E399 criteria are routinely followed, but in the polymer field these criteria are frequently ignored.

Toughness measurements in the plastics field are usually characterized by a great amount of scatter. A $\pm 10\%$ deviation is considered very good, similar to that observed with metals. A $\pm 40\%$ deviation is, however, more common [1]. It is quite possible that not adhering to E399 criteria is a major cause of this scatter. In polymer laboratories the instrumentation necessary to produce a fatigue crack is usually not available. Moreover, it is tedious to induce a fatigue crack in a polymer because of the danger of unstable crack propagation (popping) and the necessity to minimize the temperature rise. An arrested crack, initiated either by a razor blade blow or a pull on a tensile tester, is the more common choice. Such a crack, however, is difficult to reproduce and may be blunted, resulting in a higher measured K_{Ic} [2]. The thickness criterion may also be violated, for example, because the cure exotherms may limit sample thickness.

A short rod or chevron-notched specimen test is being considered by ASTM Committee E24 as a standard toughness test. We foresee possible advantages for this test, especially as applied to polymers. These advantages are:

1. A sharp crack can usually be initiated without fatigue due to the high stresses at the point of the chevron.
2. The measurement is made on a slowly moving crack which is presumably sharp.
3. Much smaller sample sizes can be used while maintaining the plane strain condition.
4. A relatively simple method has been developed to correct for a small plastic zone and residual stresses [3, 4].
5. Polymer toughness can be evaluated on a nascent crack before contamination or more easily under a controlled atmosphere.

For the purposes of our own research, it would be of value to increase the preciseness of the measurement and thereby differentiate small differences in toughness due to polymer structure variations or thermal history effects. In engineering applications reduced scatter would allow the use of smaller safety (knockdown) factors by the design engineer, providing that accuracy was also achieved by the short rod test.

To resolve some of these matters, four glassy polymers were tested using the E399 compact tension method with a fatigue crack, a crack-length-independent specimen method (only three polymers) and the short rod method, and the comparative results are presented.

2. Experimental procedure

2.1. Materials

The polymers, polystyrene (PS), poly(methyl methacrylate) (PMMA), polycarbonate (PC) and polysulphone (PSO) were commercial one-inch (25 mm) plate stock. The samples of each polymer were machined from a single plate.

2.2. Short rod (SR) specimens

A Terra Tek Systems "Frackjack apparatus" Terra Tek Systems (University Research Park, Salt Lake City, USA) Model 4702, with its accompanying signal conditioner, a 250 pound "Strainsert" Model flo25u load cell, and a Model 4901 specimen saw were used. The "Frackjack" was rigidly mounted to a Model TM-SM Instron which was used only to pull the "Frackjack", while the outputs of the load cell and the strain gauge were sent to the signal conditioner. The outputs of the signal conditioner were recorded on a Bascom–Turner Model 3110 digital recorder. A computer was used for permanent storage of data and to assist in data analysis.

All the SR specimens were machined from specimens made up for and usually run by one of the other two methods of this study. The final machining of the chevron was performed with the saw using a water-dispersed cutting oil. The finished specimen was cleaned in an ultrasonic cleaner, rinsed well with water and dried with a paper towel. The Instron pulled the Frackjack at a rate of 0.05 cm min^{-1}, and the grips of the Frackjack pulled the specimen at a rate of 0.01 cm min^{-1}.

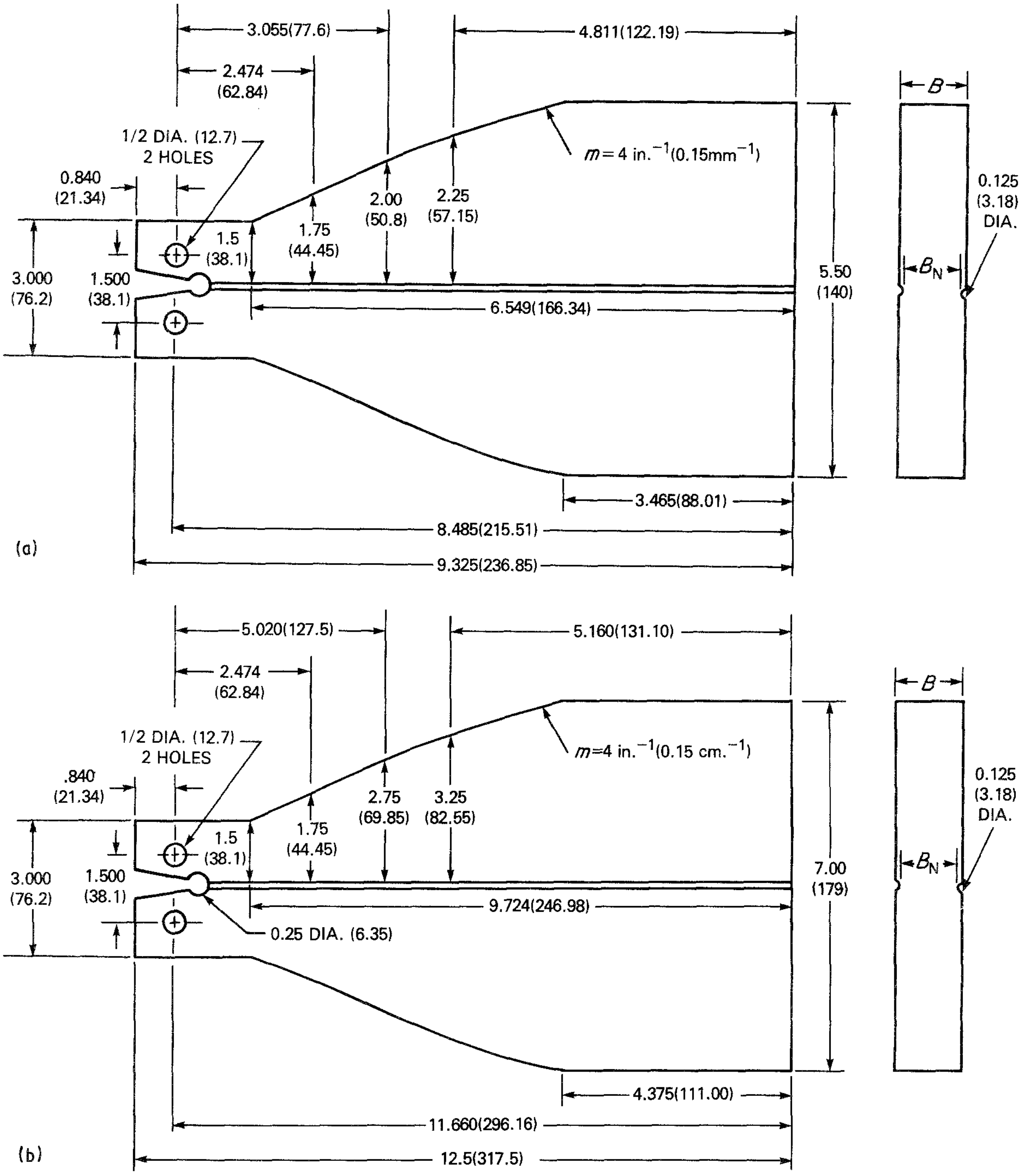

Figure 1 Contoured double cantilever beam specimen: dimensions in in. (mm) for (a) PS and PC, (b) PSO. $B_N/B = 0.75$.

2.3. Contoured double cantilever beam (CDCB) specimens

The CDCB method has previously been described [5]. Figs 1a and b and Table I give the dimensions of each of the three polymers tested with this method. A crack was initiated in these side-grooved specimens by tapping with a razor blade at the chevron starter and the cracks arrested in the start of the tapered regions. The specimens were pulled by an Instron at a rate of 0.13 cm min^{-1}, and the data were recorded on a Model 3120 Bascom–Turner recorder.

2.4. Compact tension (CT) specimens

One-inch (25 mm) samples were used, and the ASTM E399 standard was followed. However, the loading rates were significantly slower than specified by E399 because the rate criterion specific for metals would not be applicable to polymers which are significantly less tough. Also, only one satisfactory run was obtained for PS instead of the specified three. The yield stress of the materials was measured following ASTM D638. The specimens were fatigued at a low rate, as

TABLE I Dimensions of CDCB specimens*

Polymer	Average thickness, B (mm)	Variation in thickness (mm)
Polystyrene	25.65	+0.05 −0.43
Polysulphone	26.04	+0.05 −0.13
Polycarbonate	27.18	+0.10 −0.18

*m = 102 mm^{-1}; m′ = 138.4 mm^{-1}; notch width B_N = 20.37 + 0.076 to +0.356 mm.

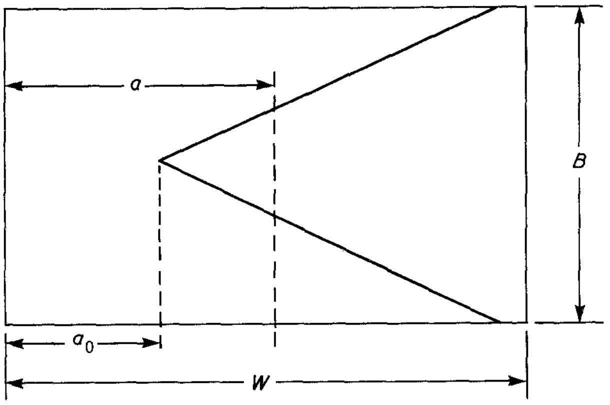

Figure 2 Short rod specimen: $a_0 = 10.11$ mm, $B = 19.1$ mm, $W = 28.6$ mm in this study; a = crack length.

TABLE II Conditions for fatigue cracking in CT test*

Polymer	Initial frequency (Hz)	Frequency after crack initiation (Hz)
PMMA	1	0.5
PS	1	0.5
PSO	5	2
PC	5	3

*Time to fatigue crack varied from 1 to 24 h.

described in Table II, so as not to significantly heat the crack tip.

2.5. Thermal analysis

A Perkin Elmer Model DSC-7 was used to check the homogeneity of PC.

2.6. Short rod procedure

The short rod or chevron-notch method of fracture toughness measurement is fully described elsewhere [6]. The dimensions of the specimen used are shown in Fig. 2. Briefly, a geometry providing a known compliance is used, and a crack is self-initiated and slowly driven through the chevron, leading to a load deformation curve as in Fig. 3. In a linear elastic situation the maximum load, F, is directly proportional to fracture toughness. The proportionality constant A has been determined both theoretically [7] and experimentally [8, 9]. Also the crack length at the maximum load is a constant. Of importance is r, a ratio of the initial compliance to that at some other point near Point F in Fig. 3. The compliance, crack length and A as a function of the ratio of the download slope to the original slope, r, have been previously determined [4], and therefore there is no need to measure the deformation absolutely but only relatively. In a non-linear situation, Point F no longer occurs at the maximum load but always occurs at $r = 0.555$, referred to as r_c. Non-linearity was corrected by downloading before and after Point F and determining p, the ratio of the difference in the deformation at zero load to that at load $= F$, as shown in Fig. 3. As such, the K_{sr} obtained is presumably the same as K_{Ic} from the following relationship:

$$K_{sr} = AFC(1 + p)B^{-1.5}$$

The relationship for the C correction is

$$C = C_b C_w C_a C_\Theta$$

where (referring to Fig. 2)

$$C_b = 1 - 1.25(B - 19.1)/19.1$$

$$C_w = 1 - 0.5(W - 28.575)/28.575$$

$$C_a = 1 + (10.11 - a_0)/10.11$$

$$C_\Theta = 1 - 0.01(55.2 - \Theta)$$

We were unable to measure Θ in a reproducible fashion and therefore assumed that it was always machined correctly and $C_\Theta = 1$.

Even without a specimen mounted on the Frackjack, a load was measured as the Frackjack was opened. This load was measured as a function of relative strain and subtracted from a specimen run. Typical runs for each of the polymers are shown in Figs 4 to 7 where the non-specimen base line has been subtracted. Upon downloading and uploading to determine p, hysteresis occurred and therefore the construction of the downloading curve was not straightforward. We used the method recommended by Barker [10] to construct the download curve from the high value of the load on the downloading before the strain begins to decrease, and the point where the load is one-half this value (midpoint load) on the uploading curve. Except for PMMA the straight line so constructed always passed through a portion of the uploading curve in the vicinity of the midpoint load. The combination of the digital recorder and the computer allowed the data to be recorded (load, strain, time), saved, the non-specimen base line subtracted, and the data analysed to determine p and the toughness at r_c and at each of at least two downloadings, both with and without the p correction.

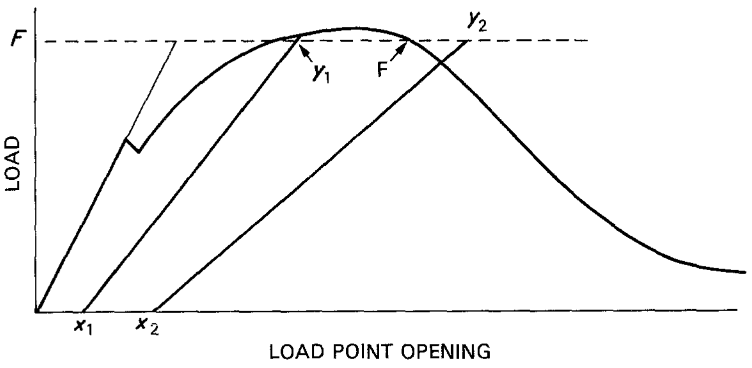

Figure 3 Idealized load–strain curve for short rod specimen. The first (second) download is from the intersection of line x_1y_1 (x_2y_2) and the SR curve to x_1 (x_2). Load F is determined by the intersection of a line, of slope equal to 0.555 of the initial slope, drawn from the intersection of the two downloading lines and the SR curve. $p = (x_2 - x_1)/(y_2 - y_1)$.

TABLE III Toughness by CT method

Sample	K_{Ic}(MPa m$^{1/2}$)	Loading rate (MPa m$^{1/2}$ min^{-1})
Poly(methyl methacrylate)		
1	1.08	1.1
2	1.00	1.1
3	1.07	1.1
Average	= 1.05 (S.D. = 0.04)	
4	1.23	10.1
Polystyrene		
1	1.53	0.55
Polysulphone		
1	2.50	0.33
2	2.63	0.33
3	2.59	0.33
4	2.50	0.33
Average	= 2.51 (S.D. = 0.07)	
5	2.73	3.3
Polycarbonate		
1	3.48	0.33
2	3.44	0.33
3	3.45	0.33
Average	= 3.45 (S.D. = 0.02)	
4	3.60	3.3

3. Results and discussion

The toughness results for the CT, CDCB and SR test specimens are shown in Tables III to VIII. Four materials – PS, PMMA, PC and PSO – were used. The CT toughness values obtained with the procedures specified by the ASTM E399 standard were used as reference for the toughness determined by the SR and CDCB methods.

Tests on CT specimens were by no means easy to perform; however, data scatter was least for these tests. The most difficult task in preparing polymeric fracture toughness test specimens is the introduction of a suitably sharp and straight precrack prior to testing. The fatigue conditions used to precrack CT specimens are shown in Table II. For the CT specimens, more than 20% of the specimens were lost prior to toughness evaluation. Additionally, some of the CT specimens were lost in testing as a consequence of the test conditions not meeting the ASTM E399 criteria. Consequently, all of the CT test programme could not be completed due to a lack of material. For PS, only a single run was valid. Nevertheless, the value of K_{Ic} for this test was assumed to be within the same small standard deviation as that found in multiple-specimen CT tests on other polymers. Once the technique of fatigue precracking was developed, CT tests proved to be less of a problem.

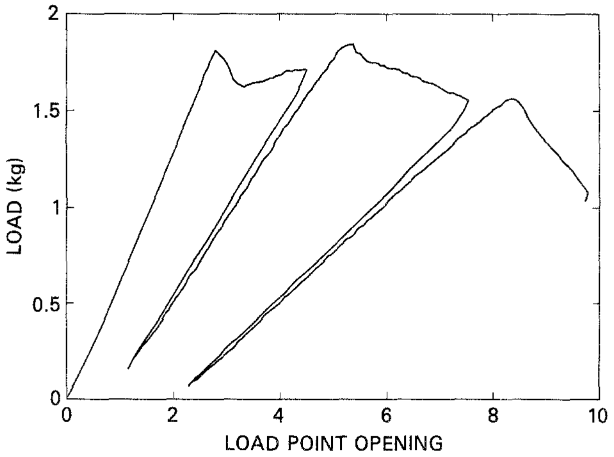

Figure 4 Typical short rod run for poly(methyl methacrylate). Base line subtracted. Strain is a relative value.

Only a few CDCB specimens were used in this programme because they are much larger than any of the other types used: each CDCB specimen contained about five times the volume of material used for a CT specimen. No studies of PMMA were performed using CDCB specimens because we began with too small a sample stock. In addition to its crack-length independence, this large specimen was chosen because of the ease with which a natural crack could be driven in from a machined chevron placed on the crack plane near the loading holes. The specimen as used here has the added advantage that the initial "pop-in" from the machined notch gives the value of arrest toughness, K_{IA}, which has been shown in metals to give an estimate of the usually difficult-to-measure dynamic toughness [11, 12]. This is important because polymers tend to have velocity–K_{Ic} profiles that have several ranges of instability, so that obtaining both initiation and arrest toughness on the same specimen may be indicative of its performance in service. Additionally, these data measure the effect of rate on the ability of a given polymeric microstructure to absorb energy due to crack propagation.

The CDCB test differs from the CT test in that the crack is generally self-arresting and can often be

TABLE IV Toughness by CDCB method

Polymer	Specimen	Arrest toughness, K_{IA}(MPa m$^{1/2}$)	Initiation toughness, K_{Ic}(MPa m$^{1/2}$)	difference from CT toughness (%)
Polystyrene	1	2.59	2.59 to 2.66	69.1 to 76.3
	2	0.78	2.51	64.0
Polysulphone	1	1.08	2.27	−9.7
		2.26	2.40	−4.4
		2.26	2.40	−4.4
		2.31	2.45	−2.2
		2.41	2.42	−3.5
		2.37	2.68	7.0
Polycarbonate	1	1.13	3.45	0.0
	2	1.16	3.62	4.8
	3	1.05	3.53	2.2

TABLE V Toughness of poly(methyl methacrylate) by the short rod method*

Sample	K_{Isrp} (MPa m$^{1/2}$)	p	K'_{Isrp} (MPa m$^{1/2}$)
1	1.08	0.28	1.01
2	1.13	0.24	1.05
3	1.02	0.27	0.98
4	1.01	0.31	0.97
5	1.05	0.34	1.09
6	1.00	0.20	1.02

Average K_{Isrp} plus K'_{Isrp} = 1.03 (S.D. = 0.050; difference from CT = −1.7%).

Average K_{Isrp} = 1.05 (S.D. = 0.051; difference from CT = −0.7%).

*K_{Isrp} = toughness at r_c with p correction applied; K'_{Isrp} = toughness at first download with p correction applied.

TABLE VII Toughness of polysulphone by the short rod method*

Sample	K_{Isrp} (MPa m$^{1/2}$)	p	K_{Isr} (MPa m$^{1/2}$)
1	2.76	0.05	2.63
2	2.64	0.00	2.64
3	2.66	0.09	2.45
4	2.60	0.12	2.31
5	2.72	0.03	2.65
Average	2.67		2.54
S.D.	0.07		0.07
Difference from E399	4.7%		−0.7%
Total average including both downloadings	2.64		2.50

*K_{Isrp} = toughness at r_c with p correction applied.

driven over a substantial length where toughness measurements are valid and independent of crack length. For many tough polymers crack growth proceeds slowly and stably as displacement is applied. Indeed, one of the expectations for the CDCB test was that the crack could be driven at a rate dictated by the testing machine in much the same way that it advances in the SR test. However, none of the materials with the possible exception of PS (i.e. PS Sample 1) behaved in this manner. Nevertheless, although limited, the CDCB data provided a check on the CT results, especially with respect to the effect of the initial starter crack and face grooves on measured toughness. An added bonus of the CDCB specimen was that in some cases more than one toughness determination was obtained on a single specimen, which provided a basis for evaluation of material/test variations in the measured quantities.

For PC the CDCB toughness agreed well with the values obtained with CT test specimens. However, the CDCB toughness of PS was more than 60% higher than that for SR or CT specimens. This difference could be attributed to an increased plastic zone size resulting from a naturally arrested crack; visual examination of the crack front strongly suggests this possibility. Other possibilities include the effect of the face notch and residual stress differences between specimens.

For PSO, multiple values of toughness could be obtained on a single CDCB specimen because of relatively stable crack growth. In general, the first few of these values were valid in that the crack front was reasonably straight and remained on the crack plane delineated by the face notches. The toughness value obtained for the first arrested crack was approximately 14% lower than the average obtained with the fatigue precracked CT specimen, and this crack was visibly sharper than that for the subsequent valid toughness values which agreed well with CT results. These results suggest that an arrested crack may sometimes be sharper than a fatigue-produced crack if crack front sharpness is responsible for the 14% lower toughness of the CDCB method. Data on PS, PC and on PSO demonstrate that differences in the starting notch, and possibly other effects, some of which will be discussed later, may correlate with the substantial differences in toughness obtained with different test methods.

An obvious requirement for an SR measurement is that the crack does not pop too far upon initiation at the chevron. For PSO, three samples were lost in this manner and for PS one. Moreover, working with other materials not in this study we have sometimes

TABLE VI Toughness of polystyrene by the short rod method*

Sample	K_{Isrp} (MPa m$^{1/2}$)	p	K_{Isr} (MPa m$^{1/2}$)
1	2.07	0.31	1.57
2	2.08	0.23	1.69
3	1.87	0.36	1.38
4	1.84	0.19	1.55
5	2.02	0.20	1.69
6	1.96	0.23	1.58
7	2.00	0.27	1.57
8	1.94	0.25	1.55
9	2.05	0.29	1.58
10	1.93	0.25	1.54
Average	1.98		1.58
S.D.	0.08		0.09
Difference from E399	29.6%		3.72%
Total average including both downloadings	1.98		1.57

*K_{Isrp} = toughness at r_c with p correction applied.

TABLE VIII Toughness of polycarbonate by the short rod method*

	K_{Isrp}(MPa m$^{1/2}$)	K_{Isr}(MPa m$^{1/2}$)
K_{Isr} at r_c		
Average	4.29	3.96
S.D.	0.28	0.21
Difference from E399	24.3%	14.7%
K_{Isr} at first download		
Average	4.38	4.04
S.D.	0.34	0.31
K_{Isr} at second download		
Average	4.35	4.02
S.D.	0.29	0.21

*Number of specimens = 22; p = 0.01 to 0.2.

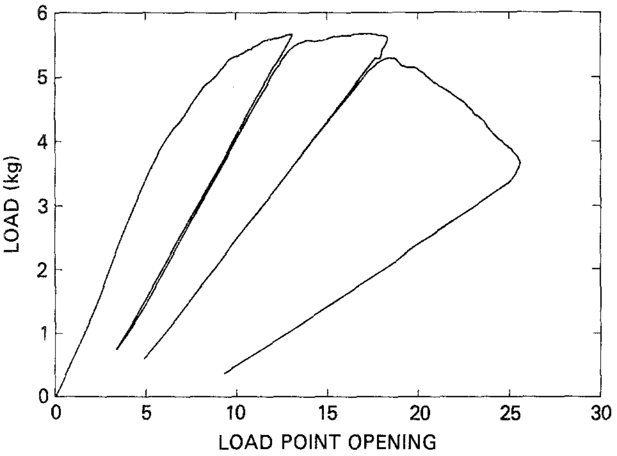

Figure 5 Typical short rod run for polystyrene. Base line subtracted. Strain is a relative value.

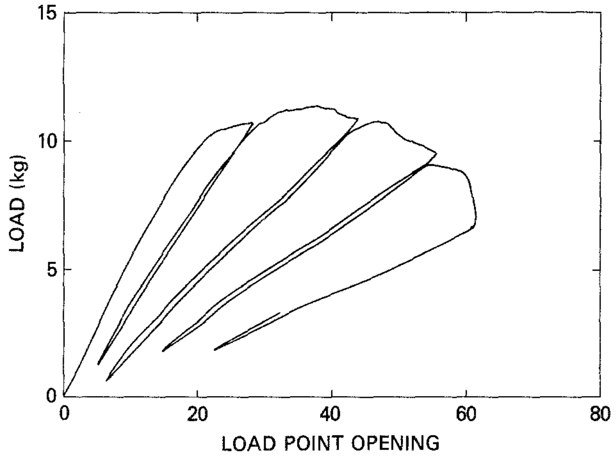

Figure 7 Typical short rod run for polycarbonate. Base line subtracted. Strain is a relative value.

found an even greater amount of extended popping, and with some materials a cleavage perpendicular to the chevron.

The determination of SR toughness was done in the most accurate way possible. At least two downloadings were used to determine the p correction factor. Data analysis gave p and included the toughness at the critical ratio and the toughness at each of the downloadings, both with and without the p correction. Downloadings that did not fall into the range of r = 0.4 to 0.75 were disregarded. One check on the methodology is the degree of consistency, within experimental error, of the measured SR toughness irrespective of r (in the valid range). Except for PMMA all measurements were quite consistent. It should be noted that PMMA and PS gave p values greater than or equal to 0.2, which is beyond the valid range. It was expected for the essentially brittle polymers tested here that none of the materials tested would require significant plasticity corrections. We can quantify our expectation through the use of an expression derived by Barker [13] for metals which gives p due to plasticity (p') as a function of the measured SR toughness and the yield stress. Table IX lists the yield stresses of the polymers used in this programme determined in accordance with ASTM D638. The strain rates used were no more than an order of magnitude greater than those used in the toughness tests) the rates are comparable. Nevertheless, computed on the basis of a time-to-initiate an effect (i.e. yielding in simple tension or crack extension in the toughness tests) the rates are compable. Nevertheless, assuming a rate effect on yield stress of about a factor of two (i.e. a lowered yield stress in the toughness tests) the value of p' would be 0.002 for PMMA and 0.02 for PS and PC based upon Barker's relationship. Actual rate effects on yield stress are known from the literature [14] for PC to be of the order of 4% which would result in an even lower value of p'.

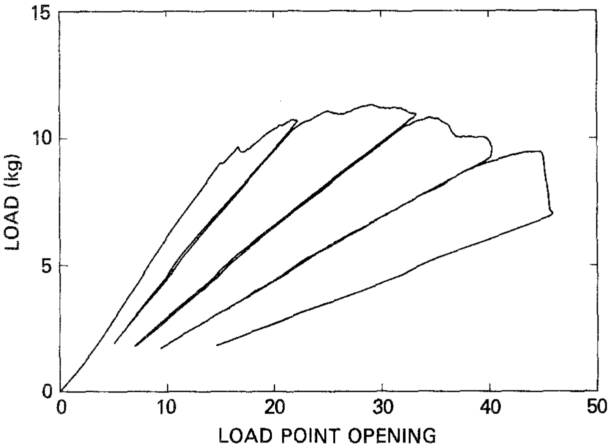

Figure 6 Typical short rod run for polysulphone. Base line subtracted. Strain is a relative value.

This set of calculations demonstrates that the p correction is not a result of plasticity and most likely (following Barker) is due to changes in the crack tip damage profile, e.g. plasticity, crazing and voids, resulting from the effects of residual stress. However, this conclusion is tentative, and the measured p correction may be due to some other irreversible process. We will, however, refer to non-plasticity p corrections as residual stress corrections for simplicity. Toughness test methods other than SR test all use test specimens in a configuration designed to ensure the limited plasticity demanded for plane strain conditions. However, such tests measure toughness without regard to residual stresses, although it is expected that these added stresses must be a factor in measured toughness. The SR test attempts to account for the influence of residual stress on toughness and, consequently, may be able to measure a toughness independent of these stresses. One could no doubt download in a CDCB test and apply a similar type of correction. Although it remains to be proven in a more thoroughgoing manner, it is postulated that the SR toughness data without the p correction are the ones to be used in comparison to other toughness tests, and that the

TABLE IX Yield stress of polymers

Polymer	Modulus (MPa)	Strain rate (min^{-1})	Yield stress (MPa)
PMMA	2942	0.034	579.4
PS	3018	0.033	448.5
PSO	2412	0.042	647.0
PC	2260	0.044	491.9

values obtained with the correction are for samples free of residual stress effects. It is expected that the effect of residual stresses will be similar for CT and CDCB specimens due to the similarity of loading and geometry. Such is not necessarily expected for SR tests, where the sample of material measured and the load stress varies in position relative to the centre line during the test. In summary, it is suggested that SR measurements without the p correction be compared to those from CT and CDCB methods. Agreement is expected only if the SR p correction is small or if the effect of residual stresses is the same in all test types.

Except for PMMA, to be discussed later, an examination of SR test data on the tested polymers shows that a better correlation with CT toughness can be obtained if the p correction is not used, which is what would be expected from our previous discussion. Note that the p correction is small and does not affect the PSO data significantly. Moreover, very large p corrections were obtained for PS, a relatively brittle material where little if any correction is expected (except due to residual stresses, as discussed above). If we do not use the p correction, we find good agreement between CT and SR tests for PS and PSO but a 15% higher value for SR compared with CT toughness of PC.

Beyond the problems in the SR PMMA tests previously mentioned, the downloading curves were atypical. Figs 4 to 7 are typical SR curves for each of the polymers used in this study. Typically, the uploading curve either falls on or near the preceding downloading curve, at least for the first half of the uploading. For PMMA, however, the uploading curve fell well below the downloading curve, which is indicative of an invalid measurement. It is not clear whether the atypical behaviour is related to material response or to SR methodology. One conjecture is that for PMMA, SR tests can show crack growth during downloading and/or show higher rates than defined by the rate of grip motion, thus resulting in lower measured loads than would be the case were no unexpected crack motion to occur. Surprisingly, the PMMA SR toughness, with the p correction, for the first downloading and for r_c does agree with the CT results. However, on the basis of earlier and valid SR tests on another batch of PMMA (and on all the other polymer systems) as well as the arguments presented above, it is believed that the current SR tests on PMMA give toughness values which are specific to the PMMA SR test and not comparable to other toughness test types. The PMMA SR results should therefore be disregarded, as should any SR test with an atypical curve profile.

In metallic materials effects such as residual stresses are of less importance than for polymers, because metallic materials are generally tougher and most of the effects are second-order. Moreover, the effects of residual stresses can usually be eliminated by an appropriate thermo-mechanical treatment. But in polymers such a treatment can of itself strongly affect the toughness. This is of special concern for PC where toughness is the result of shock-cooling during manufacture. One theory [15] attributes the relatively high toughness of PC to residual stresses. Two other factors are relevant to the PC results: material non-homogeneity and the dynamic aspect of the SR test.

The 15% higher toughness in the SR test for PC, compared to the CT and CDCB tests, could be due to material non-homogeneity. Here we do not mean specimen to specimen differences because, on the contrary, the small standard deviations clearly show that the plate of each polymer was homogeneous in the planar dimension. We suspect, however, that PC was non-homogeneous in the thickness dimension. In the SR test only the inner third of the specimen cross-section participates in the toughness determination, compared to 75% in the face-grooved CDCB test and 100% in the CT test. Some of the PC SR crack fronts were slanted, and this fracture morphology did not occur for the other materials. Moreover, the crack fronts of the PC CT specimens were unusually straight instead of being fingernail-shaped as is normal. This may be due to decreased toughness of the outer edges of PC.

In an attempt to determine the extent of PC material non-homogeneity, a series of test slices were evaluated with the differential scanning calorimeter (DSC). Thin slices were cut across the thickness of a PC specimen, using a Jeweller's saw, starting from the outside and ending near the centre. Typical scans of the outer and interior sections are shown in Figs 8a and b. The first heating scans showed crystallization below the glass transition temperature, T_g, an endothermic peak above T_g, and crystallinity above T_g. All of these effects, which did not appear in subsequent cooling and heating scans, are evidence of a lower toughness [16]. The effects were larger near the exterior of the sample. Thus, if the exterior portions are of lower toughness, test methods that integrate toughness over the entire cross-section (e.g. CT) would be expected to give lower toughness. We suggest the possibility that this lower toughness of the exterior portions of PC led to the 15% increased toughness for the SR method, which measures only the inner third of the specimen, but is too small to show up as a difference between the side-grooved CDCB and non-side-grooved CT methods. The involvement of such material non-homogeneity is one that is best addressed by multiple specimen tests that evaluate different cross-sections.

Of possible concern in the values obtained by the three test methods is the effect of loading rate. In metallic materials rate effects are often less severe than in polymers; the total variation is less than 10% for a tenfold variation in rate of the applied stress intensity. In polymers the magnitude of the effect depends on the polymer. For the current test series, all the initial loading rates on the different specimen types were comparable. Values of the rate of applied stress intensity ($\mathrm{MPa\,m^{\frac{1}{2}}\,min^{-1}}$) were 0.55 to 1.1 for the CDCB, 0.33 to 1.1 for the CT and 0.44 for the SR specimens. However, the SR test is made on a slowly moving crack, whereas the CT and CDCB tests measure an initiation toughness as an "onset of rapid fracture". In a CDCB experiment, if we were to obtain stable crack growth, we would measure not only an initiation toughness, but also a toughness of the moving crack. In a CDCB experiment, if stable crack growth were

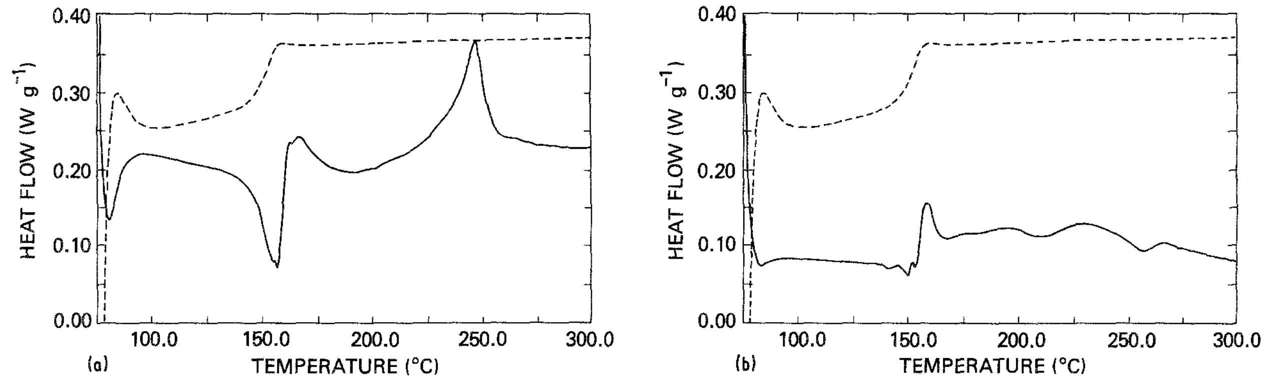

Figure 8 Typical DSC scans for (a) the outer edge of a polycarbonate specimen and (b) the middle of a polycarbonate specimen. The DSC scans involved three ramps at a rate of 20° C min^{-1}: Ramp 1 = 75 to 300° C, Ramp 2 = 300 to 75° C, Ramp 3 = Ramp 1. (---) Ramp 3 showing a normal T_g; (——) Ramp 1 minus Ramp 3.

obtained, the comparison between the initiation toughness and SR toughness (as determined on a moving crack) would be less ambiguous if the toughness were independent of crack speed, or if toughness were determined at the same crack speed in both tests.

In the SR method we do not measure "initiation toughness". It can be argued [3], however, that a slowly moving crack mimics an initiation crack since even at initiation, the crack tip is strained as much as 5% in E399. If this is correct, the SR method and initiation method results should be comparable at comparable loading rates. However, it also may be argued that a moving crack measures a toughness which is more global than an initiation crack, i.e. the influence of the crack tip on the stress field within the sample is not localized close to the crack tip but depends on the geometry ahead of the tip and the stress intensity gradient, and hence may lead to a larger toughness value. This is of special concern for conditions of crazing, which applies to all the specimens of this study, or some other type of large irreversibility, which may give large p values. This may explain the increased SR PC toughness but the non-homogeneity of the sample is a more likely explanation. The determination of a so-called "rising R curve" [17, 18] for the polymers of this study would tell us if the toughness of a moving crack differs from that of a stationary one.

4. Conclusions

1. For the polymers used in this study, the three methods of determining toughness (CT, CDCB and SR) did not always agree. Some possibilities for the differences include material non-homogeneity in the thickness direction, crack tip sharpness, the differences in crack growth rates between the SR test relative to other test types, and differences in the effect of residual stresses on measured values.

2. The CT test, despite the difficulty in preparing the fatigue precrack, gave the highest specimen-to-specimen reproducibility. The high CT reproducibility and the extent of agreement that was found among the methods suggests that the materials were homogeneous at least in the planar dimensions.

3. Test results with the CDCB method were substantially more variable than those using CT or SR specimens. In view of the relatively reproducible CT test results and the areas of agreement between CT and SR results, this variability is likely to be due to differences in precrack sharpness (arrested as opposed to fatigue-extended or slowly moving cracks). The large difference in initiation and arrest toughness shown for some of the polymers with the CDCB test indicates substantial rate effects on dynamic toughness, a material property in the same sense as initiation toughness. More understanding of dynamic toughness is needed to define the effects observed in initiation from sharp cracks relative to slow growing cracks. Neither specimen configuration, CT or SR, is well suited to a determination of rate effects.

4. The p correction in the SR test presumably corrects for plasticity and the effects of residual stress. In brittle polymers where plasticity is negligible, as with the polymers used in this test series, the p correction may serve to correct for the effects of residual stress or irreversible damage different from plasticity, such as crazing. This is an advantage of the SR test since other test methods do not correct for residual stresses. For brittle polymers, comparison between the SR test and the CT and CDCB tests are best made without the p correction.

5. The SR test method gave toughness results close to those defined by the standard ASTM E399 CT specimen for PSO and PS. However, PMMA results were taken to be invalid and PC results were 15% higher than for the other methods. The SR results are encouraging but limited, and more work is needed. The specimen-specific effects of non-homogeneity and residual stresses (irreversibility) and the possible global nature of a moving crack are the more likely explanations for differences in SR and CT toughness.

6. The SR methodology for materials for which a slowly moving crack can be driven is an inexpensive, easy to produce, easy to test method and should be explored further to evaluate the toughness of polymers. The SR method can be especially useful in evaluating the effect of various variables, such as temperature or environment, upon toughness. It should not, however, be used as the sole method for toughness evaluation of a given polymer until further experience is gained and the effects of other variables are better known.

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