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The *J*-integral technique applied to toughened nylons under impact loading

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The *J*-integral technique has been used to characterize the toughness of two rubber-toughened nylons under impact loading conditions, at impact speeds from 1–3 $m\,s^{-1}$, using single-edge-notched three-point bend specimens. A falling weight impact tester was used to generate different amounts of crack growth, allowing the resistance curve (*J–R* curve) to be constructed using the multi-specimen technique. The technique is experimentally straightforward and permits the toughness characterization of tough materials with relatively small specimens. For a rubber-toughened nylon 66, the resistance curve is very similar to that obtained at quasi-static loading rates, indicating a low dependence of toughness on rate. However, for a rubber-toughened amorphous nylon, a higher resistance curve was obtained under impact conditions than at low loading rates. This result probably indicates a limitation in the test method, rather than a genuine material response.

1. Introduction

In order to characterize a material using linear elastic fracture mechanics (LEFM), a minimum specimen thickness is required for a valid plane strain test [1]. In the case of polymers it may be impractical to mould a uniform sample of sufficient thickness. For this reason, the *J*-integral method has been adapted from the metals procedures [2] for application to tough polymers at low loading rates [3]. For example, data at loading rates in the range 3.3×10^{-5} to 2.6×10^{-2} $m\,s^{-1}$ [4, 5], using three-point bend specimens, has been obtained on the toughened nylons considered in the present study. Tests at such rates will be referred to as quasi-static loading.

At impact rates (1–3 $m\,s^{-1}$ impacts, also using three-point bend specimens), the yield stresses of the polymers are higher and it is possible to obtain a valid plane strain LEFM fracture toughness using practical specimen sizes in materials such as nylon 66 and polyacetal [6]. However, in materials such as toughened nylon, the thickness required is still large. The loading rate could be increased further to induce brittle fracture, but this would also complicate the test owing to dynamic vibration effects at high rates [6]. The alternative considered in this paper is to use the multi-specimen *J*-integral technique at impact loading rates.

The *J*-integral has not been widely applied to impact tests. Grellmann *et al.* [7] used the technique to characterize the impact performance of thermoplastic composites. Joyce and Hackett [8] used the key curve method to measure the resistance curve of a structural steel under impact conditions. Vu-Khanh [9] has considered different methods for determining impact fracture parameters of ductile polymers. Using the tearing modulus concept, he obtained a toughness of 21 $kJ\,m^{-2}$ for a rubber-toughened 66 nylon in a 3 $m\,s^{-1}$ impact test, compared to 32 $kJ\,m^{-2}$ at quasi-static loading rates.

2. Experimental procedure

Two rubber-toughened nylons were tested: rubber-toughened nylon 66 (RTN66, Zytel® ST801) and rubber-toughened amorphous nylon (RTAN, Zytel® ST901). Specimens of dimensions 100 mm long, 25.4 mm deep, *D*, and 12.7 mm thick, *B*, were cut from 12.7 mm thick injection-moulded plaques. Single-edge-notched three-point bend (SENB) specimens were prepared using a machined pre-notch. A sharp razor knife blade was then drawn firmly across the root of the notch to produce a sharp initial notch approximately equal to half the depth of the specimen ($a/D = 0.5$). All specimens were dry-as-moulded and were tested at 23 °C, using a span, *S*, of 90 mm.

To generate the multi-specimen resistance curve (*J–R* curve), specimens were loaded to different levels of crack growth by impacting them in a falling weight impact tower, with a striker mass of 3.6 kg. The force signal was recorded on a digital oscilloscope and then integrated numerically to obtain the velocity and displacement of the striker during loading, plus the total energy under the loading curve up to maximum deflection. The striker was caught after rebounding from the specimen to prevent a second impact from occurring.

Varying amounts of growth were obtained by using different drop heights, with the same impact weight. This implies some variation in the speed of the striker on impact, with higher rates at the higher impact energies, but it must be remembered that the striker slows to zero during the impact for each energy, so

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that the initial rate is not constant throughout. A different (0.9 kg) striker mass was later used to repeat the tests on RTN66 to verify that the results were not sensitive to the initial impact speed over this modest range. For RTN66 the impact energies varied from 1.6–4.8 J, giving initial impact speeds from 0.9–1.6 $m s^{-1}$ for the 3.6 kg mass and 1.9–3.3 $m s^{-1}$ for the 0.9 kg mass. These rates correspond to loading times to maximum displacement of 4–6 ms for the 3.6 kg mass and 2–3 ms for the 0.9 kg mass. For RTAN, the energy range was 0.8–4.0 J, giving initial impact speeds from 0.6–1.4 $m s^{-1}$, and only the heavier mass was used.

After impact, the specimens were cooled in liquid nitrogen and then fractured at high rate to produce a brittle break. The amount of crack growth generated during the impact could then be measured from the fracture surface. This was done using a travelling optical microscope. Seven measurements of the crack growth were made across the thickness of the specimen and averaged, with half as much weight attached to the surface measurements as to the five internal measurements in the averaging process. This is similar to the averaging process recommended in the J-integral protocols [2, 3]. A conservative, and also experimentally easier, estimate of toughness was also obtained by using the maximum crack growth anywhere across the thickness of the specimen.

To determine the contact stiffness of each material, which was needed to correct the analysis for energy dissipation around the impact points, impacts were made on fully supported unnotched samples to determine the slope of the loading curve, which was approximately linear up to the maximum impact energy considered here.

3. Analysis

The J-integral can be expressed as [10]

$$J = J_e + J_p = (\eta_e U_e + \eta_p U_p)/B(D-a) \quad (1)$$

where a is the initial crack length and J_e and J_p are the elastic and plastic contributions to J, η_e and η_p are the elastic and plastic work factors and U_e, U_p are the elastic and plastic components of the total energy, U_t. The η_p factor always equals 2, but the elastic factor, η_e, is dependent on the S/D ratio and the notch depth (a/D). However, for $a/D > 0.4$ and $S/D = 4$, $\eta_e = 2$, making it unnecessary to partition the total energy into elastic and plastic components in order to calculate J. In the present work, due to material restrictions, $S/D = 3.5$. At this span to depth ratio $\eta_e = 2.2$. Therefore, the maximum error in not partitioning the energies is 10% when the load–deflection curve is completely elastic and reduces as the amount of plastic deformation increases [4]. Owing to the non-linearity of the loading curves, this was felt to be an acceptable error and J was calculated using the simpler formula

$$J = 2U_t/B(D-a) \quad (2)$$

The total energy, U_t, was obtained from the area under the load–deflection curve at maximum deflection, but was then corrected by subtracting an estimate of the energy dissipated due to indentation around the impact point and the two support points, U_{in}. This correction was obtained from the contact stiffness using the expression [4]

$$U_{in} = 0.75P^2/K \quad (3)$$

where K is the measured contact stiffness and P is the load reached during the test.

A power law curve of the form

$$J = C_1 \Delta a^{C_2} \quad (4)$$

where Δa is the crack growth, was then fitted to the data using only the data lying in the range of crack growth greater than 0.05 mm and less than 10% of the initial ligament. This is in accordance with the proposed protocol for J-integral testing of polymers [3].

The total input energy can also be calculated from the change in potential energy of the striker as it falls from the initial drop height. This should be corrected for the deflection of the specimen itself, from the moment of impact up to the maximum deflection. It was found that this correction was no more than 5% of the total drop height for the heavier mass, and still smaller for the lighter mass which is dropped from a greater height to give the same impact energy. It is, therefore, unnecessary to measure the impact force, except for the contact stiffness correction. This would make the technique simpler to use. Although the force signal shows dynamic oscillations about the overall trend, as in Fig. 1, the energy-based analysis makes the quality of the signal less important.

4. Results and discussion

The results obtained using the 3.6 and 0.9 kg strikers for RTN66 are shown in Fig. 2, based on the averaged crack growth. In Fig. 3 these fitted curves are compared to data based on the maximum crack growth

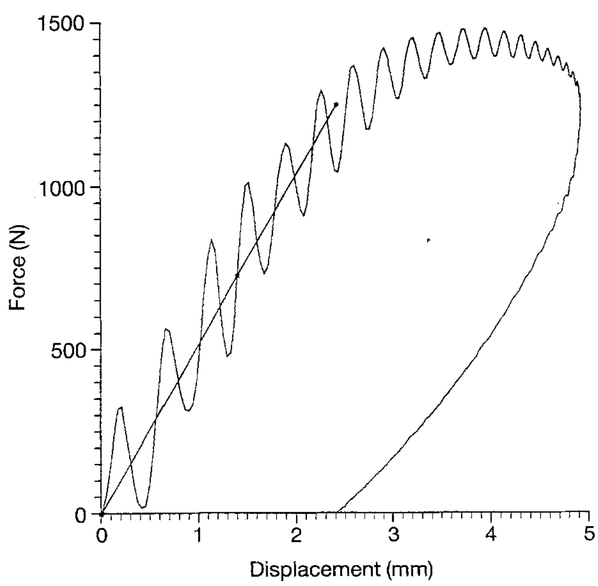

Figure 1 Typical loading curve (RTN66, 3.6 kg striker, 4.8 J impact energy).

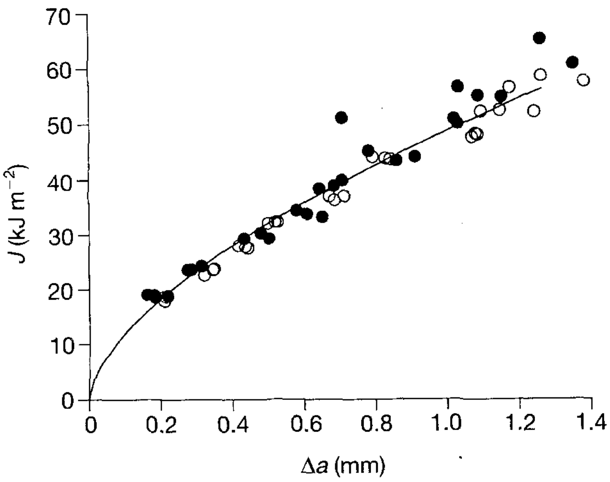

Figure 2 Impact *J–R* curve for RTN66, based on average crack growth. Mass: (●) 3.6 kg, (○) 0.9 kg.

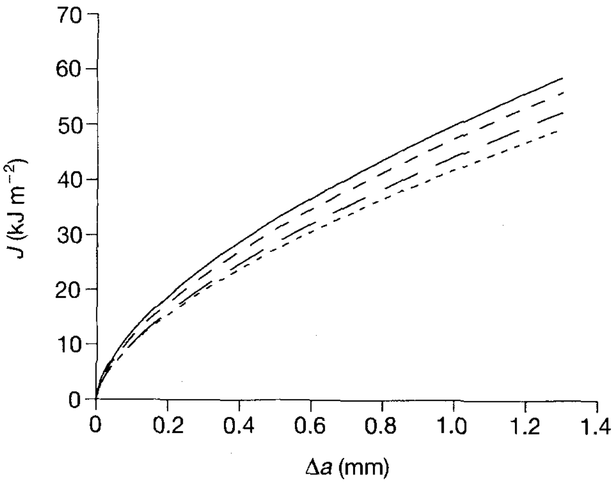

Figure 3 Impact *J–R* curves for RTN66: comparison of the two loading rates based on maximum or average crack growth. (– – –) 0.9 kg mass, average growth; (- - -) 0.9 kg mass, maximum growth; (——) 3.6 kg mass, average growth; (——) 3.6 kg mass, maximum growth.

anywhere across the crack front at each impact energy. It is seen that in both cases, using the maximum crack growth leads to a lower resistance curve, and hence a lower estimate of toughness. The lighter mass, higher rate, data lie a little below the curve generated using the heavy mass in both cases.

In Fig. 4 data obtained by Huang [4] at $2.6 \times 10^{-2}\ \mathrm{m\,s^{-1}}$ loading rate and by Hashemi and Williams [5] at $3.3 \times 10^{-5}\ \mathrm{m\,s^{-1}}$ loading rate are compared to the present data based on the maximum crack growth. Both Huang, and Hashemi and Williams used the maximum growth for their analysis and for all practical purposes their curves are the same. The data of Huang include a contact stiffness correction, as used here, those of Hashemi and Williams do not. This correction reduces the energy at each crack growth by 2–3 $\mathrm{kJ\,m^{-2}}$. The fitted power-law coefficients for the different sets of data are shown in Table I.

It seems that the resistance curve for RTN66 is very similar at quasi-static loading rates to that obtained at the far higher average rates used here. However, there is a trend in Table I of the constant increasing and the

TABLE I Power-law fitted coefficients; $J = C_1 \Delta a^{C_2}$ (J in $\mathrm{kJ\,m^{-2}}$, Δa in mm)

Material	Loading rate ($\mathrm{m\,s^{-1}}$)	Crack growth	C_1	C_2
RTN66	1.9–3.3	Average	47.63	0.616
RTN66	0.9–1.6	Average	50.10	0.604
RTN66	Both data	Average	48.78	0.608
RTN66	1.9–3.3	Maximum	42.04	0.616
RTN66	0.9–1.6	Maximum	44.39	0.634
RTN66	2.6×10^{-2}	Maximum	48.20	0.700 [4]
RTN66	3.3×10^{-5}	Maximum	47.58	0.673 [5]
RTAN	0.9–1.6	Average	46.45	0.601
RTAN	0.9–1.6	Maximum	42.46	0.634
RTAN	2.6×10^{-2}	Maximum	35.70	0.680 [4]
RTAN	3.3×10^{-5}	Maximum	33.75	0.669 [5]

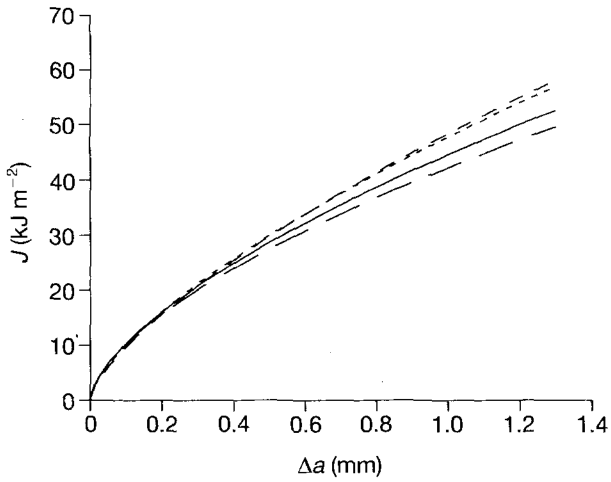

Figure 4 *J–R* curves for RTN66: impact compared to quasi-static data, based on maximum crack growth. (——) 0.9 kg mass, maximum growth; (——) 3.6 kg mass, maximum growth; (– – –) Huang [4]; (- - -) Hashemi and Williams [5].

power-law exponent dropping (i.e. a flatter curve) with increasing rate when the data based on maximum crack growth are compared (Fig. 4). The flattening of the resistance curve may indicate that the material is becoming more brittle at higher loading rates, but the difference is small.

The data and fitted curve obtained using the 3.6 kg striker for RTAN are shown in Fig. 5, based on the average crack growth. In Fig. 6 the fitted curve is compared to the previously reported $2.6 \times 10^{-2}\ \mathrm{m\,s^{-1}}$ data of Huang, the $3.3 \times 10^{-5}\ \mathrm{m\,s^{-1}}$ data of Hashemi and Williams, and the results obtained by using the maximum crack growth. In this case the impact curves lie significantly above the quasi-static data, even when presented in terms of maximum crack growth, which seems to suggest an improvement in crack-growth resistance at higher strain rates. This result is most unexpected, and probably indicates a limitation in the validity of generating a resistance curve using this approach, rather than showing a genuine material response. Further investigation is needed.

It should be noted that the drawn-razor initial notches used in this study, for both materials, had some downward curvature at the ends, leading to slightly longer initial crack lengths near the surfaces in

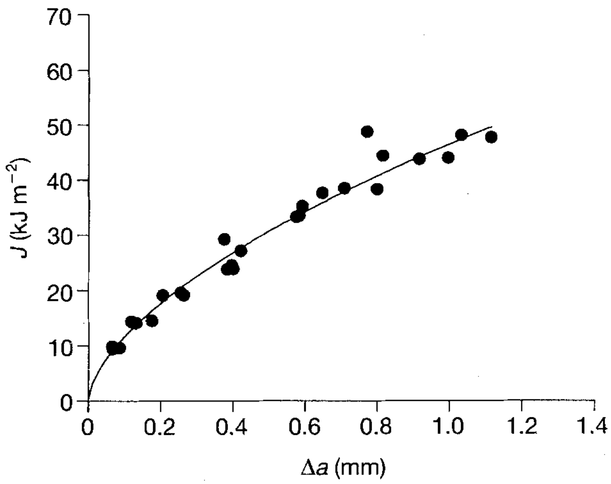

Figure 5 Impact J–R curve for RTAN, 3.6 kg mass, based on average crack growth.

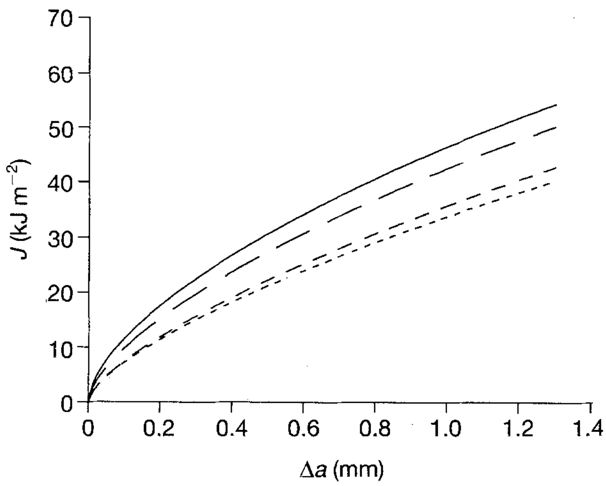

Figure 6 J–R curves for RTAN: impact compared to quasi-static data, based on maximum or average crack growth. (——) 3.6 kg mass, average growth; (– – –) 3.6 kg mass, maximum growth; (– – –) Huang [4]; (- - -) Hashemi and Williams [5].

both materials. However, this curvature never increased the initial crack length at the surface by more than 10% of the length at the centre and never extended into the specimen more than 10% of the thickness. This may have caused a small reduction in the average crack growth, but should not have affected data based on the maximum growth. An underestimate of crack growth would overestimate toughness, but the magnitude of the effect would certainly not be sufficient to explain the differences seen in Fig. 6.

5. Conclusions

The J-integral method is experimentally easy to apply to impact tests on tough polymers. One striker mass can be used and different impact energies generated by varying the drop height. Using this approach, resistance curves for two toughened nylons have been generated. The resistance curve of a rubber-toughened nylon 66 obtained using this technique is very similar to that measured at lower rates, while for an amorphous rubber-toughened nylon, the high-rate resistance curve appears to lie above the low-rate data. This unexpected result needs further investigation.

References

1. J. G. WILLIAMS, "Fracture Mechanics of Polymers" (Ellis Horwood, Chichester, 1984).
2. ASTM E813-87, "Standard Test Method for J_{IC}, A Measure of Fracture Toughness", Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, PA, 1987) p. 968.
3. "A Testing Protocol for Conducting J-R Curve Tests on Plastics", edited by G. E. Hale, ESIS Technical Committee for Polymers and Composites (European Structural Integrity Society, 1991).
4. D. D. HUANG, in "Elastic-Plastic Fracture Test Methods: The User's Experience" Vol. 2, ASTM STP 1114, edited by J. A. Joyce (American Society for Testing and Materials, Philadelphia, PA, 1991) p. 290.
5. S. HASHEMI and J. G. WILLIAMS, *J. Mater. Sci.* **26** (1991) 621.
6. G. C. ADAMS, R. G. BENDER, B. A. CROUCH and J. G. WILLIAMS, *Polym. Engng Sci.* **30** (1990) 241.
7. W. GRELLMANN, S. SEIDLER and J. BOHSE, *Kunstsoffe* **81** (1991) 157.
8. J. A. JOYCE and E. M. HACKETT, in "Fracture Mechanics: Seventeenth Volume", ASTM STP 905, edited by J. A. Joyce (American Society for Testing and Materials, Philadelphia, PA, 1986) p. 741.
9. T. VU-KHANH, *Polymer* **29** (1988) 979.
10. J. D. SUMPTER and C. E. TURNER, *Int. J. Fract.* **9** (1973) 320.

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