A Comparison of Multispecimen J-Integral Methods as Applied to Toughened Polymers

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ABSTRACT

The laboratory measurement of fracture toughness in tough materials has long been recognized as a difficult problem. Both the metals and ceramics industries have turned to the J-Integral method as a means of obtaining this value. While the technique can be applied to toughened polymers to get consistent results, it is still unclear whether a meaningful value for fracture toughness can be obtained for polymers and their blends. The application of ASTM E813-81 leads to an unexpected fracture toughness-thickness relationship. This relationship can be explained by applying the method outlined in E813-87. The effects of ligament size and the physical interpretation of J_{Ic} are also investigated. While it is not clear whether the single parameter, J_{Ic}, can be used in design, a direct comparison of the resistance curves can be used to characterize toughness in toughened polymers. Rubber toughened nylon 66, rubber toughened amorphous nylon, and ABS are used in these studies.

KEYWORDS

ASTM E813; fracture toughness; J-Integral; rubber toughened amorphous nylon; rubber toughened nylon 66; toughened polymers

INTRODUCTION

The J-Integral technique, originally proposed by Rice (1968), has been applied to a variety of polymers including polyethylene (Chan and Williams, 1983), natural rubber (Lee and Donovan, 1985), and a number of toughened blends (Hashemi and Williams, 1986). Although the J technique is more involved than the comparable K test, its advantage is that a plane strain fracture toughness value can be obtained on test specimens that are 3-5 times smaller than those required for K tests (Huang and Williams, 1987). This is important in toughened blends where it is often difficult to make large specimens with the proper morphology for optimum toughness.

Because there is no standard protocol for polymers, much of the earlier work has been modified versions of the multispecimen technique as embodied in ASTM E813. While the results of these studies have been consistent with results found in the metals literature, it is unclear whether the technique can be directly followed to obtain meaningful fracture toughness values. In this investigation, various aspects of the standard, especially those relating to specimen size and geometry will be considered.

EXPERIMENTAL DETAILS

The materials used for this study were rubber toughened nylon 66 (RTN66, "Zytel" ST801), rubber toughened amorphous nylon (RTAN, "Zytel" ST901), and acrylonitrile-butadiene-styrene (ABS, "Cycolac" ABS, grade GSE). Both rubber toughened nylons were injection molded into 100 mm x 250 mm x 12.7 mm and 100 mm x 250 mm x 3.2 mm plaques. The ABS was obtained in both 25 mm and 50 mm thick extruded sheets from Westlake Plastics (Lanni, PA).

Single edged notched bend (SENB) specimens were machined from either the plaques or the sheets. The specimens were deeply notched to half of the depth, D. Unless stated otherwise, D was twice the thickness, B. The span to depth ratio was 4. For the nylons, thinner specimens (down to 6.4 mm) were made by milling equal amounts from the outer surfaces of the plaques. Also, 3.2 mm thick specimens were cut from the 3.2 mm thick plaques. For the ABS, thinner specimens (down to 7.5 mm) were made by sawing the sheet through the thickness. The sawn surface was smoothed by milling. The specimens showed no curvature, so it was assumed that residual stresses were minimal. In all cases, the thickness direction of the plaques or sheets was maintained as the thickness direction of the SENB specimens. The materials were tested dry as molded at 23°C and 50%RH.

The J tests were conducted on servohydraulic equipment with computer data acquisition and analysis. Both the yield stresses and J tests were conducted at a rate of 25 mm/s. At this rate, the yield stresses of RTN66, RTAN, and ABS were 50 MPa, 69 MPa, and 48 MPa, respectively. Crack growths were marked by cooling the specimens in liquid nitrogen followed by fast fracture at 250 mm/s. The crack growth was measured using an optical microscope. Additional details are given in an earlier paper (Huang and Williams, 1987).

ASTM E813

Two versions of the multispecimen J method (ASTM E813-81 and -87) have been followed. The two versions are essentially identical except for data analysis. In this work, the experimental procedures were slightly modified as reported by Huang and Williams (1987).

Indentation energy correction Because the J values are calculated from the total energy measured from the area under the load-load point displacement curve, an indentation energy correction was made. This accounts for local deformation at the loading and support points. A fully supported unnotched specimen of the same thickness and depth as the J test specimen is indented with the load point. This test is conducted at the same rate as the J test. Again, a load-load point displacement curve was recorded. The contact stiffness, S, was found to be linear up to the maximum load, P_{max}, in the individual J tests. The energy due to indentation is then

$$U_{in} = \frac{3}{4}\frac{P_{max}}{S} \qquad (1)$$

where U_{in} = Total indentation energy

For an SENB specimen, the total J, $J_T = 2\ (U_T)/Bb$, where U_T is the total energy, B is the specimen thickness, and b is the ligament. The indentation J, J_{in}, can similarly be calculated from U_{in}. The real J value for each test specimen is equal to $J_T - J_{in}$. Depending on the size of the specimen, this correction ranged from 3-5 kJ/m^2.

Selection of Data There is some confusion in the guidelines for data selection in both versions of ASTM E813. The procedures recommend the use of data exclusion lines which are constructed parallel to the blunting line at offset values of 0.15 mm and 1.5 mm. Only data points which are found between those two offset lines are considered valid. However, earlier numerical work (Shih et al, 1978) suggested limiting the crack growth to 6% of the ligament, b, to ensure J-controlled crack growth. In order to satisfy both the 6% b criterion and the fixed offset lines, the specimen must be at least 25 mm thick. This minimum thickness is not stated explicitly in the standard. The only guideline to size is that the specimen thickness must be greater than $25(J_Q/\sigma_y)$ to obtain plane strain conditions (σ_y is the yield stress). In this work, crack growth up to 6% b has been allowed. Valid data points are those located between data exclusion lines which are parallel to the blunting lines and are offset by 0.6% and 6% b.

Definition of J_Q Provided the J_Q value satisfies a number of criteria, it can be considered a plane strain value, J_{Ic}. In ASTM E813-81, the provisional fracture toughness, J_Q, is found at the intersection of the two straight lines which approximate the initial portion of the resistance (J-R) curve. Physically, this was described as the point at which crack tip blunting stopped and crack growth started. Thus, J_Q represented an initiation energy. In E813-87, this definition was changed. J_Q is the J value at the intersection of the power law curve and a line parallel to the blunting line that is offset by 0.2 mm. Physically, J_Q no longer represents the initiation energy, but the energy that is required to produce 0.2 mm of crack extension.

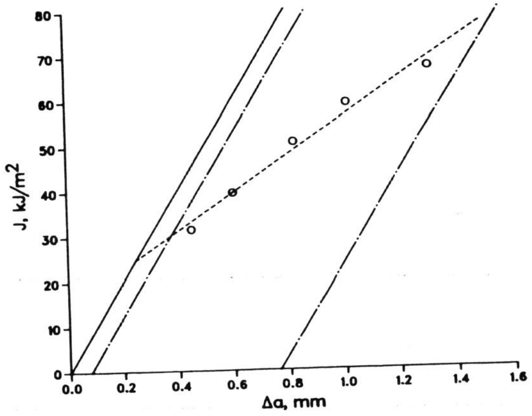

Fig. 1. J results (ASTM E813-81) for RTN66.
B = 12.7 mm, J_Q = 24.2 kJ/m^2.

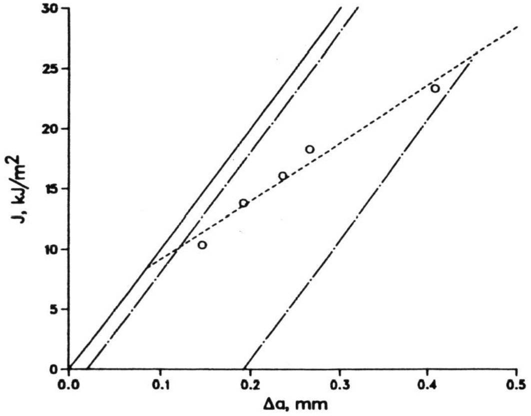

Fig. 2. J results (ASTM E813-81) for RTN66.
B = 3.2 mm, J_Q = 8.2 kJ/m^2.

RESULTS AND DISCUSSION

ASTM E813-81 Results

In earlier work (Huang and Williams, 1987), the J results for both RTN66 and RTAN were consistent in form with results obtained for metals. Examples of J results for RTN66 for two different thicknesses are shown in Figs. 1 and 2. In these tests, the crack growth was limited to 6% of the ligament. In both cases, a straight line was fitted to the crack growth part of the curve. The data shows little scatter. For these two cases, the J_Q values were 24.2 kJ/m^2 and 8.2 kJ/m^2 for the 12.7 mm and 3.2 mm thick specimens, respectively.

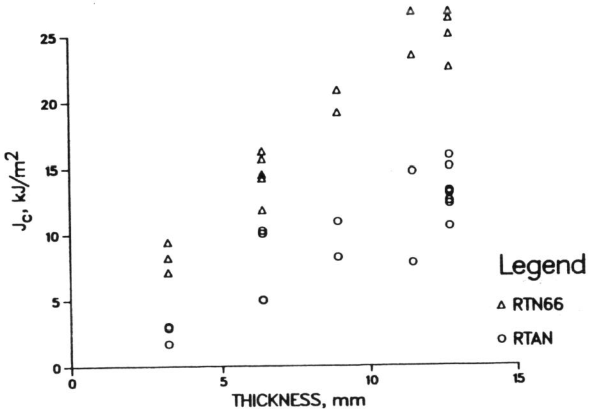

Fig. 3. J_Q vs thickness for RTN66 and RTAN.

Additional J_Q vs thickness data for RTN66 and RTAN are presented in Fig. 3. Although there is scatter in the J_Q values, there is a definite trend towards decreasing toughness with decreasing thickness for both materials. Average values are given in Table 1. B_{min} is calculated from the ASTM minimum thickness recommendation (25 J_Q/σ_Y).

Table 1. J_Q results for RTN66 and RTAN (E813-81)

Material	Thickness, mm	J_Q, kJ/m^2	B_{min}, mm
RTN66	12.7	25.1	12.6
RTN66	11.4	25.0	12.5
RTN66	8.9	20.0	10.0
RTN66	6.4	14.5	7.3
RTN66	3.2	8.2	4.1
RTAN	12.7	12.6	4.6
RTAN	11.4	11.2	4.1
RTAN	8.9	9.6	3.5
RTAN	6.4	7.5	2.7
RTAN	3.2	2.5	0.9

For the RTN66, B_{min} suggests that valid plane strain values may be obtained on specimens that are 12 mm thick or larger. Some work has been conducted on grooved specimens (Huang, 1987) which supports this recommendation. However, because the thin specimens should have been under mixed mode conditions, their J_Q values were expected to be greater than 25 kJ/m^2. For RTAN, the results are even more confusing. Based on the large specimen data, the ASTM recommendation suggests that specimens as thin as 4.6 mm can yield plane strain fracture toughness values. Thus, for this set of tests, the J_Q values for test specimens larger than 6.4 mm thickness should have been constant. Again, as seen in Fig. 3, the J_Q values decrease with decreasing thickness.

ASTM E813-87 Results

One explanation of this unexpected trend is the use of two straight lines to approximate the initial part of the J-R curve. As mentioned earlier, E813-87 suggests that fitting the crack growth data to a power law of the form $J = A(\Delta a)^c$. Because the specimens were geometrically similar and the failure modes appeared to be the same, all the data from the different sized J tests were plotted on the same curve. The results are shown in Fig. 4 for RTN66 and RTAN. To test the generality of the power law relationshipe, a third toughened blend, ABS, was tested with specimens that were 7.6 mm, 15.2 mm, and 25.4 mm thick. The results are also given in Fig. 4.

Power law relationships have been fitted to this aggregate data. The power law fit appears to be appropriate. The power law parameters and the J_Q values are given in Table 2. The RTN66 and RTAN results have been corroborated by additional J tests using 100 mm x 25.4 mm x 12.7 mm SENB specimens in which the allowable crack growth range was expanded to cover the same range obtained from the different sized specimens. In this set of experiments, the minimum allowable crack growth was 0.03 mm (0.2% b). As seen in Table 2, the J-R curves for these extended crack growth tests are similar to the aggregate results.

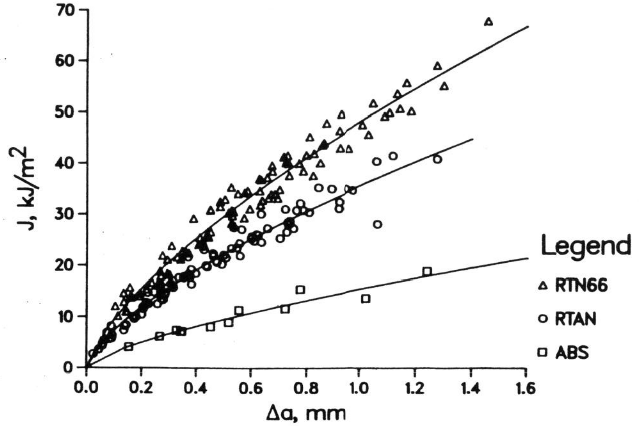

Fig. 4. Aggregate J results for RTN66, RTAN, and ABS.

It is interesting to note that the J_Q values of the nylons are higher than those obtained by E813-81. This is because of the new definition of J_Q as the energy required to grow the crack 0.2 mm. While this value may be appropriate for design of large (< 25 mm thick) metal structures, it is unclear whether it is appropriate for plastic components which are usually substantially smaller. In addition, it is an open question whether it leads to a value which is suitable for characterization. One alternative for characterization purposes is to compare the J-R curves. For the materials tested here, the ranking would be RTN66 > RTAN > ABS. As seen in Table 2, the exponents, C, are similar for the three materials, approximately .69. However, the preexponentials, A, vary with that of RTN66 being the largest (48.2) and ABS the smallest (15.5). Thus, for any value of Δa, the J to obtain that growth would be greater for RTN66 than ABS.

Table 2. J_Q and Power Law Parameters

Material	Specimen Size, mm	A	C	J_Q, kJ/m^2
RTN66	3.2 < B < 12.7	48.2	.70	29.2
RTN66*	B = 12.7	49.3	.63	32.7
RTN66	B = 6.4	42.8	.62	26.5
RTN66	B = 6.4; D = 25.4	46.4	.63	29.7
RTAN	3.2 < B < 12.7	35.7	.68	16.3
RTAN*	B = 12.7	37.0	.71	16.4
RTAN	B = 6.4	32.7	.63	15.8
RTAN	B = 6.4; D = 25.4	33.3	.72	14.0
ABS	7.6 < B < 25.4	15.5	.70	6.1

All were SENB with D = 2B, except where specified.

* Minimum crack growth down to 0.2% of the ligament allowed.

The power law relationships provides an explanation of the unexpected trend of decreasing J_Q with decreasing thickness that was found using the E813-81 technique. E813-81 represents the J-R curve with two straight lines, the blunting line and a linear approximation to part of the power law curve. Since

$$J = A\ (\Delta a)^C \tag{2}$$

$$\frac{dJ}{da} = AC(\Delta a)^{C-1} \tag{3}$$

For C < 1, dJ/da increases as Δa decreases. Because Δa is limited by 6% of the ligament, Δa decreases as specimen size decreases. Thus, small specimens will have steeper crack growth lines, leading to low J_Q values.

Specimen Depth Effects One route to satisfying both the maximum 6% b crack growth requirement and the fixed crack growth window for specimens less than 25.4 mm in thickness is to increase the D/B ratio. In E813-87, D/B ratios of up to 4 are allowed. Thus it is possible to obtain crack growths which are both less than 1.5 mm and less than 6% b. Table 2 gives the results for RTN66 and RTAN specimens which were 6.4 mm thick with two different depths, 12.7 mm and 25.4 mm. The effect of depth is not consistent for these two materials. For RTN66, larger specimen depth gave "better" results, i.e., they are similar to the aggregate results. For RTAN, the smaller specimen depth gave "better" results. More work is required to identify an acceptable range of depths.

CONCLUSIONS

The J-R curves defined by ASTM E813-87 describe crack growth behavior in toughened polymers better than E813-81. The power law representation of the J-R curve explains some artifacts in the toughness-thickness relationship that are obtained using the earlier method. For these materials, the original model of crack tip blunting followed by crack growth does not appear valid since crack growths can be measured at very small Δa values. This model has, however, been found to be valid for other polymers (Theuer et al, 1988). Although the power law representation of the J-R curve is appropriate, other aspects of E813-87 must be investigated further before the procedure can be considered suitable for polymers. Procedural details regarding the maximum allowable crack growth, specimen depth effects, the plane strain size criterion, and the definition of J_Q must be sorted out. However, the current J approach does appear to offer a route to characterization of toughened blends by direct comparison of the J-R curves.

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