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Determination of J_c for a polycarbonate (PC)/poly(butylene terephthalate) (PBT) blend based on the analyses of multiple-specimen J–R curves

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Various regression models and data windows have been used to examine the multiple-specimen J integral analysis to provide the best estimate of fracture toughness. The linear regression model (similar to ASTM E813-81) results in the least accuracy in the data fitting and is highly sensitive to the data window. The power law model (similar to ASTM E813-87) gives a better data fitting and is less sensitive to the data window. The polynomial regression models with higher orders ($n = 3$ and 4) give the best data fitting. True crack initiation occurs gradually rather than as an abrupt event, and therefore the critical J strictly based on initiation could be in error. ASTM E813-81 based on the theoretically predicted blunting line tends to give an underestimated J_c. The power law approach of ASTM E813-87 indeed provides a better data fitting but suffers the disadvantage of an overestimated J_c owing to the 0.2 mm offset line. The 0.1 mm offset line approach proposed here results in the most consistent J_c regardless of the regression models and data windows selected.

(Keywords: PC/PBT blend; *J* integral; ASTM E813)

INTRODUCTION

In the last decade, considerable efforts have been extended to the development of a ductile fracture criterion to characterize the fracture behaviour of structural materials employed at temperatures where they exhibit elastic–plastic behaviour. The efforts have focused on the J integral method, which was originally proposed by Rice[1,2] as a means of characterizing the stress–strain singularity at a crack tip in an elastic or elastic–plastic material. Begley and Landes[3,4] applied the J integral concept and developed a method of measurement of the fracture toughness J_c, which represents the energy required to initiate crack growth. Subsequently, numerous methodologies for J integral testing and analysis have evolved. However, the optimum procedures of analysis have yet to be conclusively defined and standardized. Two key ASTM standards, E813-81[5] and E813-87[6], were established for J testing mainly for metallic materials, and have also been extended to the characterization of toughened polymers and blends in the last decade[7–19].

In the crack initiation and stable crack growth regions, the J–R curve is generally recognized to be non-linear. The ASTM E813-81 procedure models the crack growth process as a straight line, and the intersection of the linear regression line with a theoretically predicted blunting line is taken as J_c. On the contrary, the ASTM E813-87 procedure models the crack growth process as a power law regression line rather than a linear regression line, and the intersection of the power law regression with the 0.2 mm offset of the blunting line is taken as J_c. Generally, the J_c values obtained from the E813-87 method are significantly higher than those obtained from the E813-81 method[20–25]. In this study, three sets of J–Δa data windows and two regression models, a linear regression line (E813-81) and a power law regression line (E813-87), have been used to analyse the multiple-specimen J–R curve and then compared with the critical J_c values at the onset of crack initiation.

THE J INTEGRAL

Rice[1,2] developed the path-independent energy line integral, the J integral, which is an energy-based parameter used to characterize the stress–strain field near a crack tip surrounded by small-scale yielding. The J integral is defined by

$$J = \int \bar{W}\,dy - \bar{T}\frac{\partial \bar{U}}{\partial S}\,dx \qquad (1)$$

where $\bar{T}$ is the surface traction, $\bar{W}$ is the strain energy density, $\bar{U}$ is the displacement vector and x and y are the axis coordinates. Rice[1,2] and Begley and Landes[3,4] showed that the J integral can be interpreted as the potential energy change with crack growth, which is expressed by

$$J = -\frac{1}{B}\frac{dU}{da} \qquad (2)$$

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where B is the thickness of the loaded body, a is the crack length and U is the total potential energy, which can be obtained by measuring the area under the load–displacement curve. Sumpter and Turner[26] later expanded the J integral equation as

$$J = J_e + J_p \tag{3}$$

where J_e and J_p are the elastic and plastic components of the total J value, and can be represented as

$$J_e = \frac{\eta_e U_e}{B(W-a)} \tag{4}$$

$$J_p = \frac{\eta_p U_p}{B(W-a)} \tag{5}$$

where U_e and U_p are the elastic and plastic components of the total energy and η_e and η_p are their corresponding elastic and plastic work factors. The term $(W-a)$ is the ligament length, where W is the width of the specimen. For a three-point bend single-edge notched specimen with $a/W = 0.15$, $\eta_p = 2$. When the specimen has a span of $4W$ $(S = 4W)$ and $0.4 < a/W < 0.6$, $\eta_e = 2$. Therefore, equation (3) can be reduced to

$$J = \frac{2U}{Bb} \tag{6}$$

ASTM E813 recommends that equation (6) be used to calculate the J value for a single-edge notched bending (SENB) specimen.

EXPERIMENTAL

The PC/PBT blend (Alotex C701) was obtained from Alotex Polymer Alloy Corporation of Taiwan. Injection-moulded PC/PBT specimens with dimensions of $20 \times 90 \times 8$ mm were prepared using an Arbury injection-moulding machine. All specimens were sharpened with a fresh razor blade. All the notched specimens were annealed at 60°C for 2h to release the residual stress prior to the standard three-point bend test. The current J integral test procedure entails determining the critical J values (J_c) at the onset of crack extension from the J–R curve. The most widely used method of obtaining a J–R curve is the multiple-specimen method, where a number of identical specimens (usually five to 10) are loaded to various levels corresponding to different crack extensions. Each specimen is then unloaded, quenched in liquid nitrogen and broken open by an Izod impacter. The crack extension Δa can then be measured. In this paper, three J–Δa data windows qualifying for J_c testing are described.

J–Δa DATA WINDOW QUALIFYING SCHEMES

The multiple-specimen method offers, in principle, the least ambiguous route to defining the 'best estimate' initiation toughness values, but difficulties arise in producing a meaingful database. Various criteria in terms of data windows and regression models on how to construct the J–R curve have been adopted by different J methods, but very few methods provide enough data to support these criteria. In most cases, it is necessary to reassess the original J–Δa data. In order to measure the fracture toughness (J_c) of the material more meaningfully through the construction of a more accurate crack growth curve, three J–Δa data windows will be examined.

First J–Δa data window (set 1, same as E813-81)

The first J–Δa data window is essentially identical to the valid data window of the standard ASTM E813-81 method. The J–Δa points of the resistance curve are those data points lying between two offset lines, each drawn parallel to the blunting line $J = 2\sigma_y \Delta a$. The minimum offset is 0.6% of the length of the uncracked ligament and the maximum offset is 6% of the length of the uncracked ligament.

Second J–Δa data window (set 2, same as E813-87)

The second J–Δa data window is essentially identical to the valid data window of the standard ASTM E813-87 method. This version defines the J–Δa points for the resistance curve as those data points lying between two offset lines, each drawn parallel to the blunting line $J = 2\sigma_y \Delta a$. The minimum and maximum offsets are 0.15 and 1.5 mm of the crack growth length.

Third J–Δa data window (set 3, extended range)

The third J–Δa data window entails an unconventional approach, which also defines the J–Δa points for the resistance curve as those data points lying between two offset lines, each drawn parallel to the blunting line $J = 2\sigma_y \Delta a$. The minimum offset is 0.15 mm of the crack growth length and the maximum offset is 3.0 mm of the crack growth length, which basically extends the data window of the E813-87 method to $\Delta a = 1.5$–3.0 mm.

RESULTS AND DISCUSSION

J–R curve fitting and definition of the 'initiation' J value

The progress of ductile fracture commencing from a sharp crack has been described as being separable into four regimes: (1) the crack-opening stretch or crack tip blunting by plastic flow at the crack tip, (2) crack growth initiation, (3) stable crack growth by material separation at the crack tip and (4) unstable crack propagation. These four events determine the shape of the J–R curve. Crack tip blunting and stable crack propagation predominate during the fracture process described by the J–R curve. Relevant data available in 1980 and 1981 were based almost exclusively on linear J–Δa analyses. Fitting a linear line to a non-linear curve will result in a considerable variability in J_c depending on the selected data window and the distribution of data points. This is particularly true when there are only a limited number of data points, even though the ASTM E813 criterion has been satisfied. These deficiencies suggest that there is a need to represent the non-linear J–R curve more accurately. In this paper, the accuracy of curve fitting is determined by the variance analysis, which calculates the sum of the residual squares divided by the number of degrees of freedom. A lower variance indicates that the equation can model the shape of the J–R curve with greater statistical significance.

In this study, we took significantly more data points than required by the ASTM E813 standards and varied the J–Δa data window. The data window selected can significantly affect the resulting J_c. The J–Δa data windows qualifying for J_c and J–R curve testing were described earlier. The experimentally obtained data points were analysed with a statistical curve-fitting computer program for various regression analyses. It should be noted that some subjectivity must be exercised

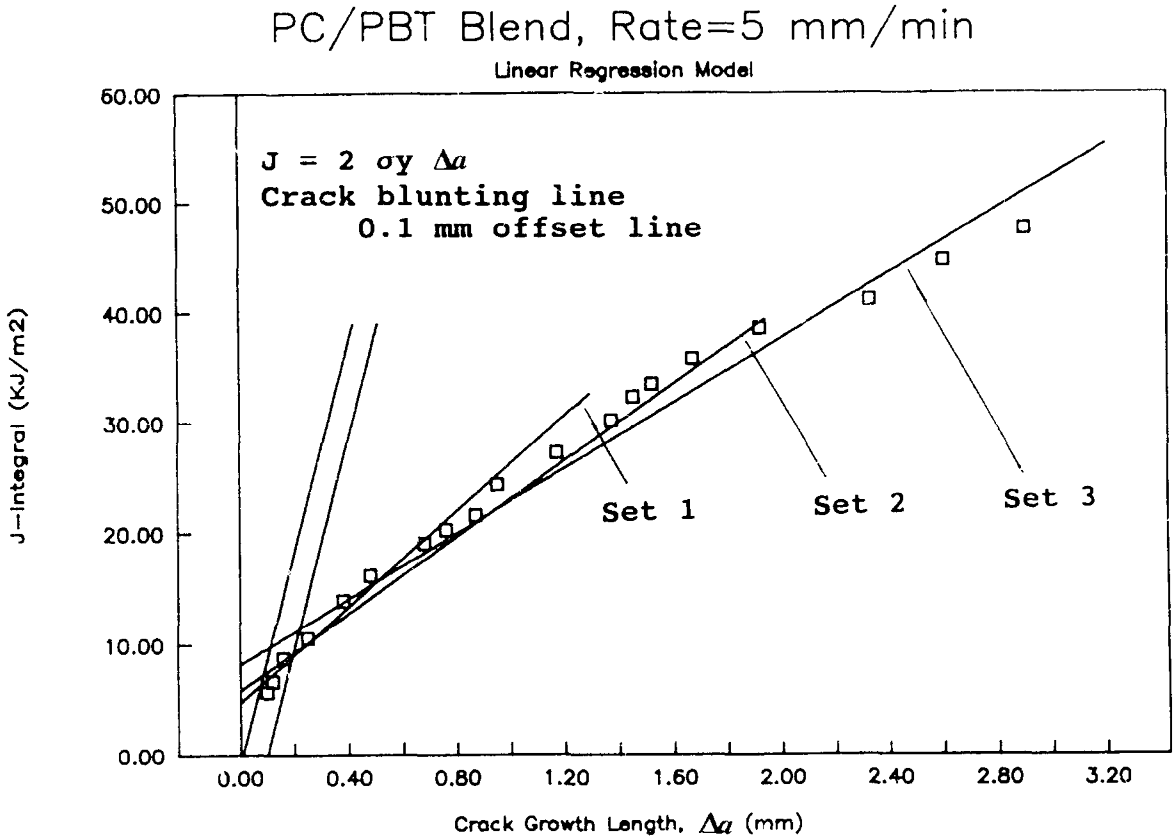

Figure 1 Plots of J versus Δa using the linear regression equation within three data windows for a strain rate of $5\,\text{mm min}^{-1}$

Table 1 Determined variances of linear and power law regression models obtained from three J–Δa data windows and at different strain rates

Strain rate (mm min^{-1})	Variance	
	Linear regression	Power law regression
Determined by set 1 ($\Delta a = 0.1$–$0.8\,\text{mm}$)		
0.5	0.102	0.380
2	0.635	0.420
5	0.669	0.451
10	0.718	0.414
20	0.465	0.409
30	0.726	0.408
50	0.752	0.365
Average	0.581	0.410
Determined by set 2 ($\Delta a = 0.1$–$1.6\,\text{mm}$)		
0.5	1.052	0.490
2	1.988	0.535
5	0.852	0.578
10	2.705	0.499
20	2.977	0.506
30	1.498	0.525
50	1.050	0.496
Average	1.732	0.518
Determined by set 3 ($\Delta a = 0.1$–$3.0\,\text{mm}$)		
0.5	4.830	0.540
2	5.053	0.579
5	5.520	0.629
10	5.980	0.573
20	5.608	0.574
30	5.609	0.585
50	1.814	0.579
Average	4.916	0.580

in choosing the appropriate equation; an appropriate equation must not exhibit an instability within the region of data used to obtain the fit. In other words, J and Δa must continuously increase. To be effective, at least one point for the J–R curve must be obtained near the onset of crack extension; this implies the necessity of a point on the left of the 0.15 mm exclusion line of the J integral analysis.

Figure 1 shows plots of acceptable J versus Δa using the linear regression equation within three J–Δa data windows (sets 1, 2 and 3) for a strain rate of $5\,\text{mm min}^{-1}$. The accuracy of these three lines was determined by calculation of the statistical variance. *Table 1* summarizes the variances of the data fitting for the linear regression model. The greater range of the data window results in a higher variance for the linear regression model, as shown in *Table 1*. This means that a smaller data window is more appropriate for the linear regression model. ASTM E813-81 correctly chooses the smaller data window in constructing the J–R line in terms of a lower variance.

Figure 1 also shows that the slope of the J–R curve ($\mathrm{d}J/\mathrm{d}a$) decreases with increasing range of the J–Δa data window (the converse is also true). A higher slope of the J–R curve results in a lower J_c, as shown in *Figure 1*. This raises the question of whether a polynomial with a higher order or a power law regression equation (as for E813-87) is able to give a statistically better fit than the linear regression equation.

Figure 2 shows that the three power law regression lines based on the three different data windows are nearly identical. *Table 1* also shows that the variances from these three data windows are fairly close and are significantly lower than those from the linear regression model. This means that the power law regression model can fit the experimental data better than the linear regression model regardless of the data window range.

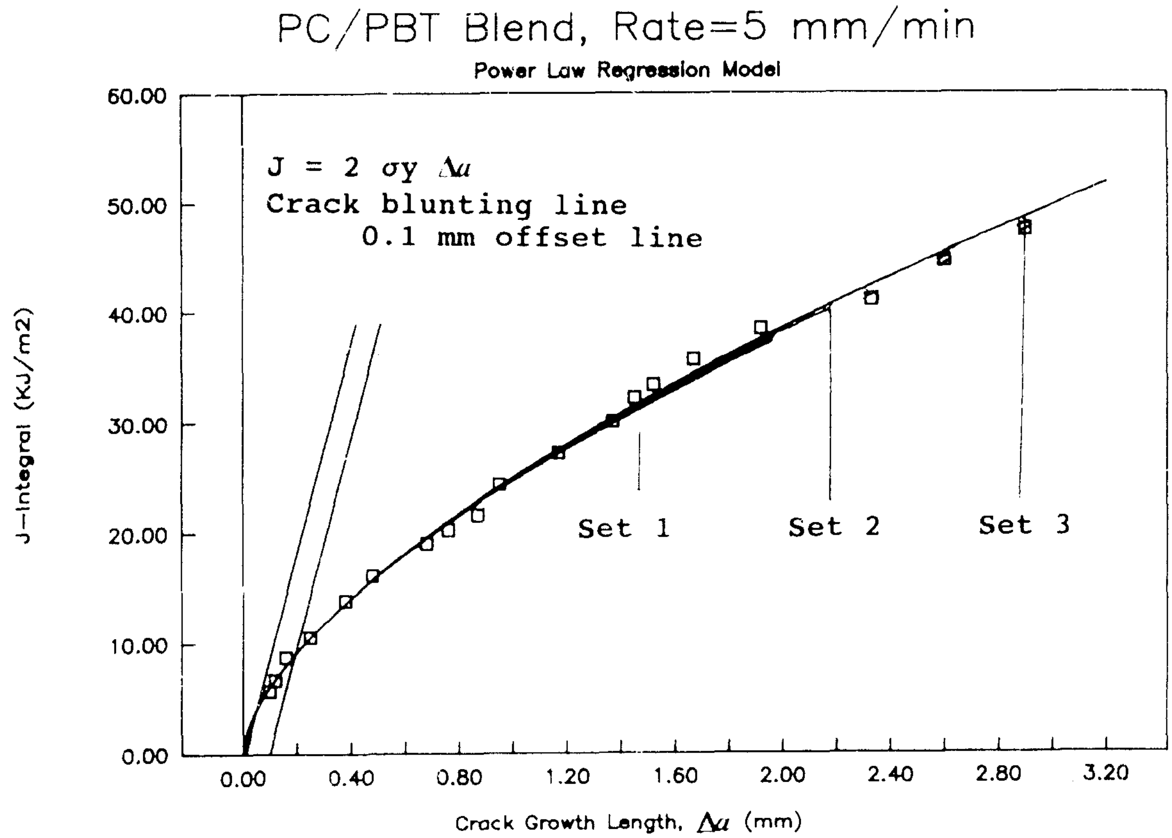

Figure 2 Plots of J versus Δa using the power law regression equation within three data windows for a strain rate of $5\,\mathrm{mm\,min^{-1}}$

Table 2 Critical J_c values and the corresponding critical crack growth length values obtained from the linear regression model

Strain rate ($\mathrm{mm\,min^{-1}}$)	Set 1		Set 2		Set 3	
	Δa_c (mm)	J_c ($\mathrm{kJ\,m^{-2}}$)	Δa_c (mm)	J_c ($\mathrm{kJ\,m^{-2}}$)	Δa_c (mm)	J_c ($\mathrm{kJ\,m^{-2}}$)
0.5	0.072	6.77	0.086	8.45	0.111	10.68
2	0.054	5.71	0.079	8.00	0.098	10.15
5	0.055	6.08	0.066	7.01	0.089	9.51
10	0.059	6.14	0.074	7.91	0.101	10.38
20	0.056	6.27	0.090	9.79	0.106	11.55
30	0.058	6.75	0.076	8.44	0.100	10.74
50	0.059	7.13	0.068	7.91	0.071	8.71
Average	0.059	6.41	0.077	8.22	0.097	10.25

J_c determination

The critical J (J_c) of ASTM E813-81 has the physical meaning of crack initiation, and is obtained from the intersection of the linear regression line with the blunting line ($J = 2\sigma_y\Delta a$). As mentioned above, the slope of the linear regression line tends to increase with decreasing range of the data window. A higher slope of the linear regression line results in a lower J_c, as shown in *Figure 1* and *Table 2*. Within the strain rate range investigated (0.5–$50\,\mathrm{mm\,min^{-1}}$), the effect of the strain rate on J_c is insignificant. The average J_c value from the set 3 data window is $10.25\,\mathrm{kJ\,m^{-2}}$, which is 60% higher than that obtained from set 1 ($6.41\,\mathrm{kJ\,m^{-2}}$ for ASTM E813-81). The corresponding critical crack growth length Δa_c also shows a similar trend to J_c, as would be expected (from 0.059 to 0.097 mm). The above results clearly indicate that an increase in the data window raises the resultant J_c substantially for the linear regression model.

Table 3 summarizes the critical J_c values and their corresponding critical crack growth lengths obtained from the power law regression equation for strain rates varying from 0.5 to $50\,\mathrm{mm\,min^{-1}}$. J_c is located at the intercept of the power law regression line and the 0.2 mm offset line, as shown in *Figure 2*. The J_c determined from the set 2 data window is actually identical to that obtained from the ASTM E813-87 test procedure. For the power law regression equation, *Table 3* shows that the determined J_c values are fairly independent of the selected J–Δa data window and testing rate. The J_c values obtained from the E813-87 method (*Table 3*, set 2) are about 100% higher than those obtained from the E813-81 method (*Table 2*, Set 1). *Figure 3* shows the effect of the data window on J_c for the E813-81 and

Table 3 Critical J_c[a] values and the corresponding critical crack growth length values obtained from the power law regression model

Strain rate ($mm\,min^{-1}$)	Set 1		Set 2		Set 3	
	Δa_c (mm)	J_c ($kJ\,m^{-2}$)	Δa_c (mm)	J_c ($kJ\,m^{-2}$)	Δa_c (mm)	J_c ($kJ\,m^{-2}$)
0.5	0.350	12.72	0.343	12.61	0.347	12.60
2	0.363	13.72	0.349	12.51	0.345	12.45
5	0.347	13.27	0.338	12.08	0.328	11.78
10	0.377	14.37	0.363	13.59	0.372	13.58
20	0.373	14.13	0.369	13.85	0.357	13.23
30	0.353	14.34	0.349	13.65	0.343	12.89
50	0.329	12.45	0.339	13.26	0.339	13.87
Average	0.356	13.57	0.350	13.08	0.347	12.91

[a] Using the 0.2 mm offset line of the E813-87 method

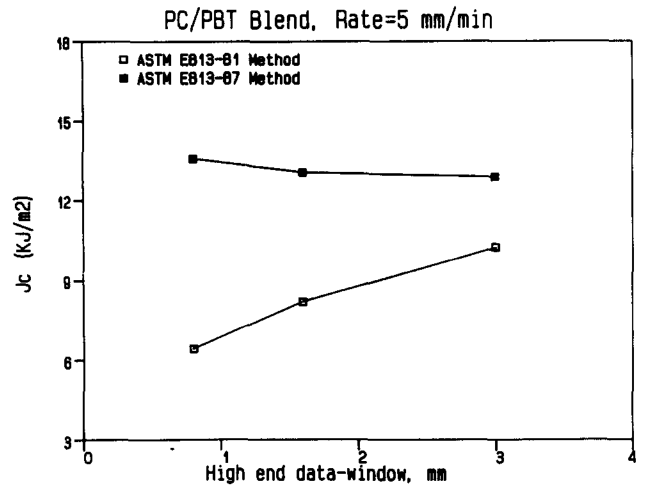

Figure 3 Effect of the data window on J_c for the E813-81 and E813-87 methods

E813-87 methods. The values of J_c obtained from the E813-87 method are higher than those obtained from the E813-81 method. The corresponding critical crack growth lengths from the E813-87 method (*Table 3*) are several times greater than those from the E813-81 method (*Table 2*) mainly owing to the 0.2 mm offset line specified in E813-87.

Only very limited comparative J_c data between these two ASTM standards (E813-81 and E813-87) for polymeric materials have been previously reported. In a study comparing J_c values from E813-81 and E813-87 for toughened nylon 6,6, Huang[27] tended to favour the E813-87 method solely because of the more consistent results, but neglected the fact that significantly higher J_c values are obtained from E813-87 relative to E813-81. We have found that the J_c values obtained from the E813-87 method for elastomer-modified polycarbonate[20] and high-impact polystyrene[22] are also significantly higher than those obtained from the E813-81 method. However, if the 0.2 mm offset line specified in E813-87 is now reset at 0.1 mm and the rest of the procedure is unchanged as shown in *Figure 2*, the J_c obtained are now somewhere between those from the E813-81 and E813-87 methods. Further discussion of this subject will be presented later.

Table 4 Other regression equations

Regression model	Equation[a]
Polynomial regression model, $n = 2$	$Y = A + Bx + Cx^2$
Polynomial regression model, $n = 3$	$Y = A + Bx + Cx^2 + Dx^3$
Polynomial regression model, $n = 4$	$Y = A + Bx + Cx^2 + Dx^3 + Ex^4$
Logarithmic regression model	$Y = A\ln(x) + B$
Exponential regression model	$Y = A\,e^{Bx}$

[a] A, B, C, D and E are coefficients, $Y = J$, $x = \Delta a$

J–R CURVES ANALYSED BY OTHER REGRESSION EQUATIONS

Other regression equations were also tested to see how well they could model a multiple-specimen J–R curve for the PC/PBT blend. *Table 4* lists the different regression equations investigated. The accuracy of fitting was determined by a least-squares procedure for the regression of crack growth length Δa on J from 18 J–Δa data points over the range of crack growth lengths $\Delta a = 0.1$–3.0 mm.

Figures 4–6 show J–R curves fitted using polynomial regression equations with orders of 2, 3 and 4, respectively. The variances of the regression results are summarized in *Table 5*. The results indicate that a polynomial regression model can fit the J–Δa data points significantly better than a linear regression model. *Figure 4* shows that a polynomial regression model with an order of 2 can fit the J–Δa points reasonably well within these three data windows. As would be expected, the higher-order polynomial regression equations fit the data points slightly better within these three J–Δa data windows, as indicated by the lower variances (*Table 5*).

Figures 7 and *8* shows the plots of J *versus* Δa for logarithmic and exponential regression equations, respectively, within three J–Δa data windows. The significantly higher variances obtained from the logarithmic regression model (*Table 5*) indicate that the logarithmic regression model poorly fits the data points. The exponential regression model results in an even worse data fit, as shown in *Figure 8*. Therefore, both logarithmic and exponential regression equations cannot model the J–R curve very well and should not be selected to evaluate the multiple-specimen test.

Figure 9 compares the effects of the data window range on the variance of the J–Δa curve fit for polynomial regression equations with orders of 2, 3 and 4, the linear regression equation and the power law regression

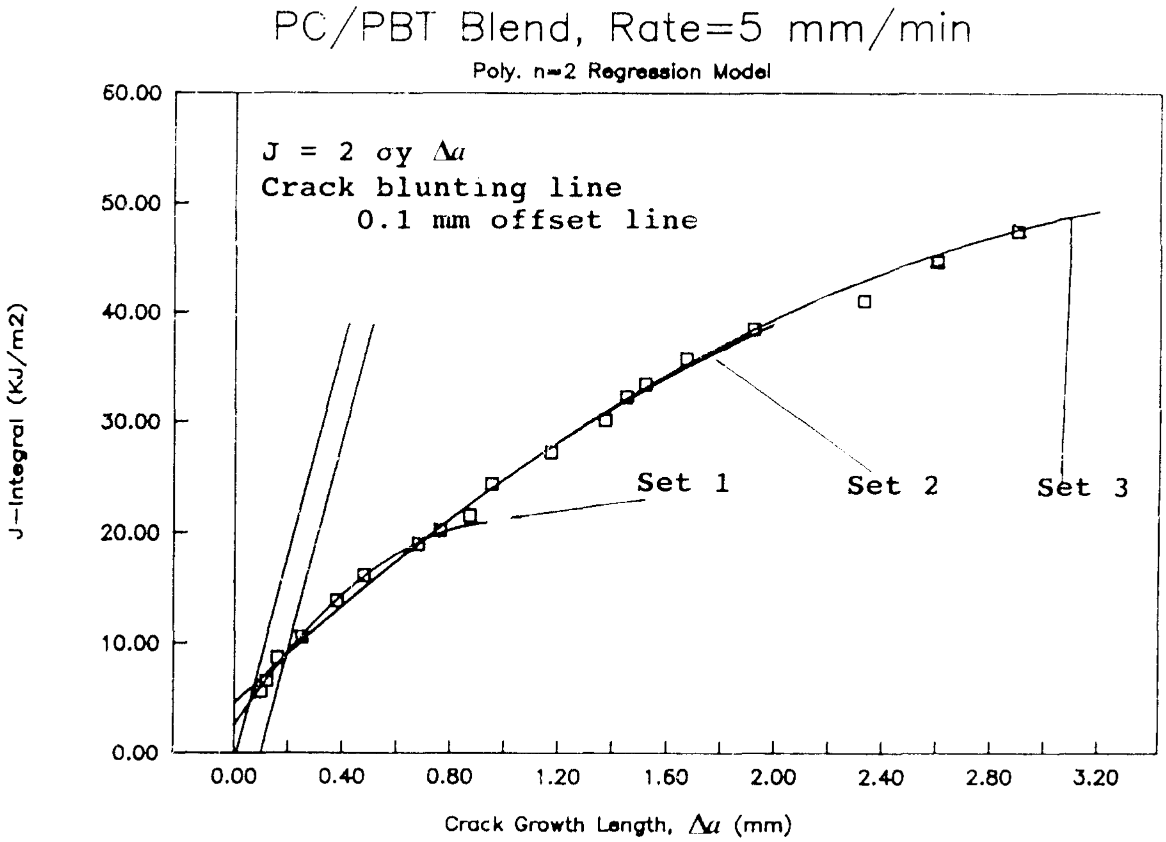

Figure 4 Plots of J versus Δa using a polynomial ($n = 2$) regression equation within three data windows for a strain rate of $5\,\mathrm{mm\,min^{-1}}$

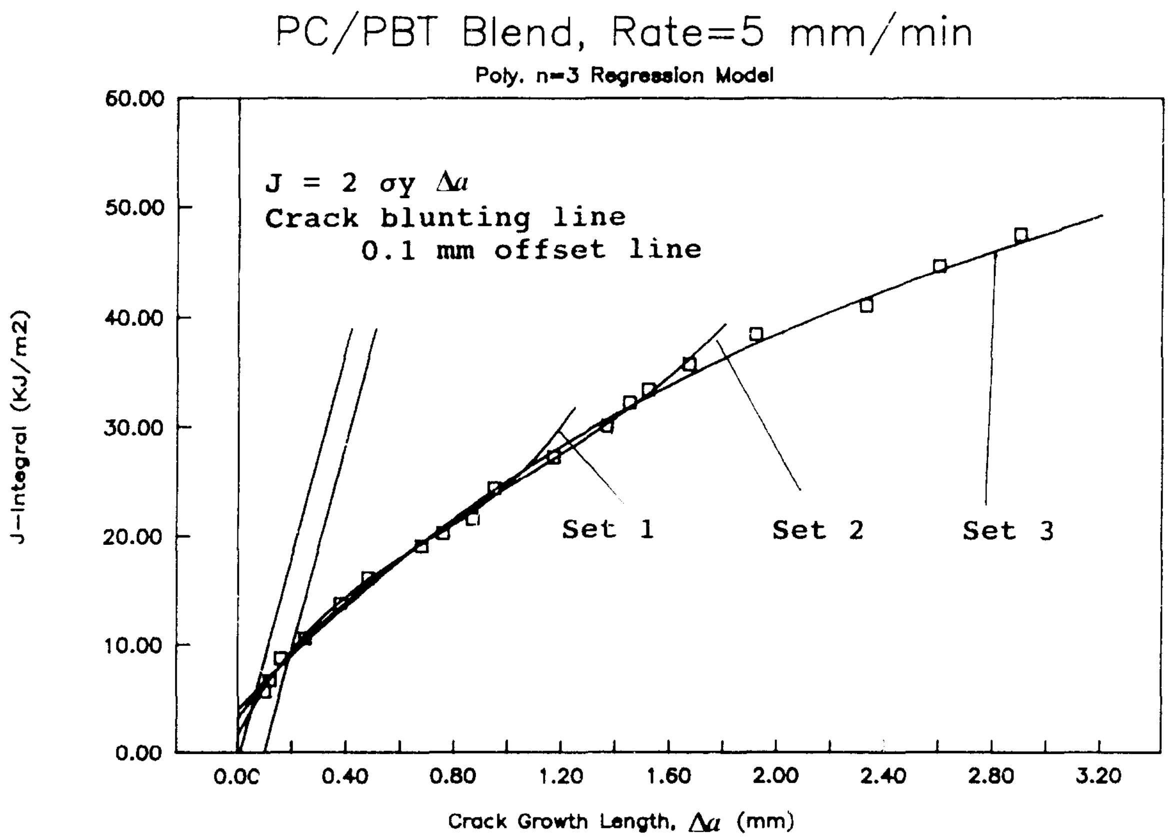

Figure 5 Plots of J versus Δa using a polynomial ($n = 3$) regression equation within three data windows for a strain rate of $5\,\mathrm{mm\,min^{-1}}$

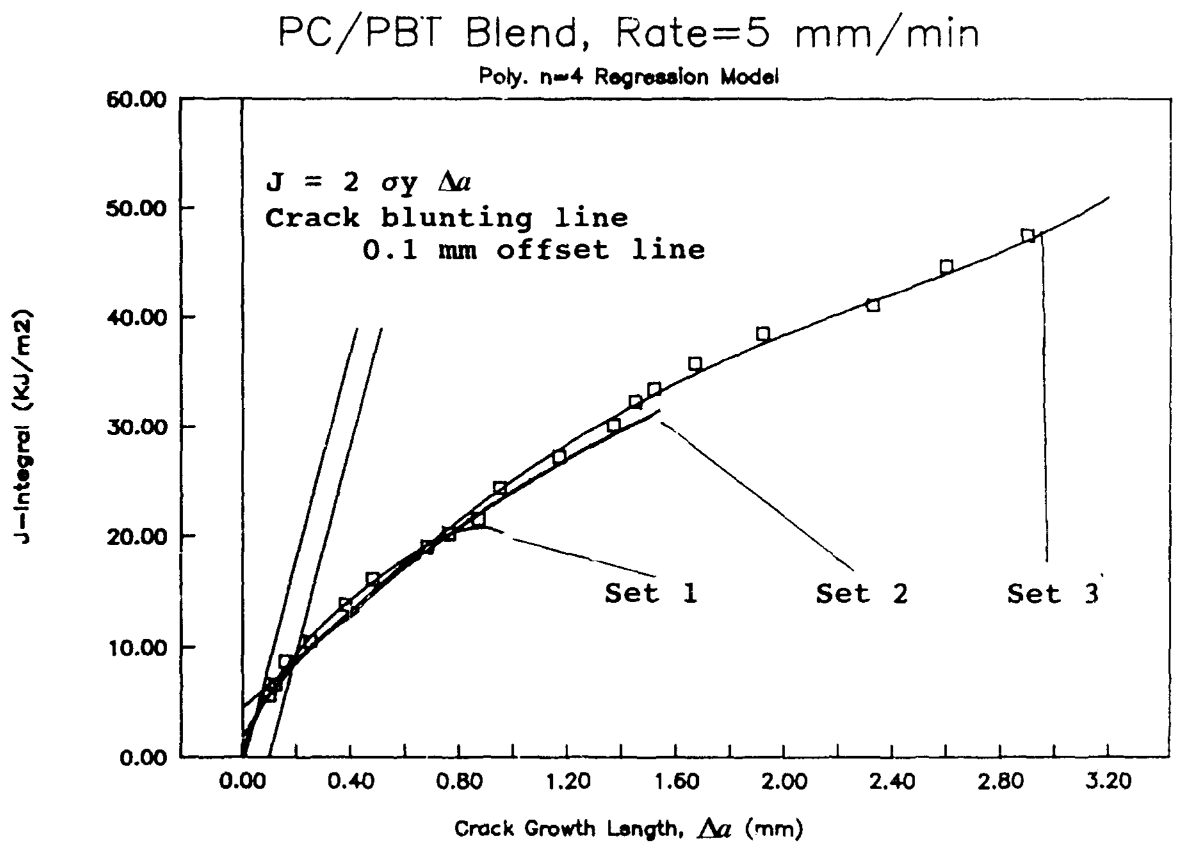

Figure 6 Plots of J versus Δa using a polynomial ($n = 4$) regression equation within three data windows for a strain rate of $5\,\mathrm{mm\,min^{-1}}$

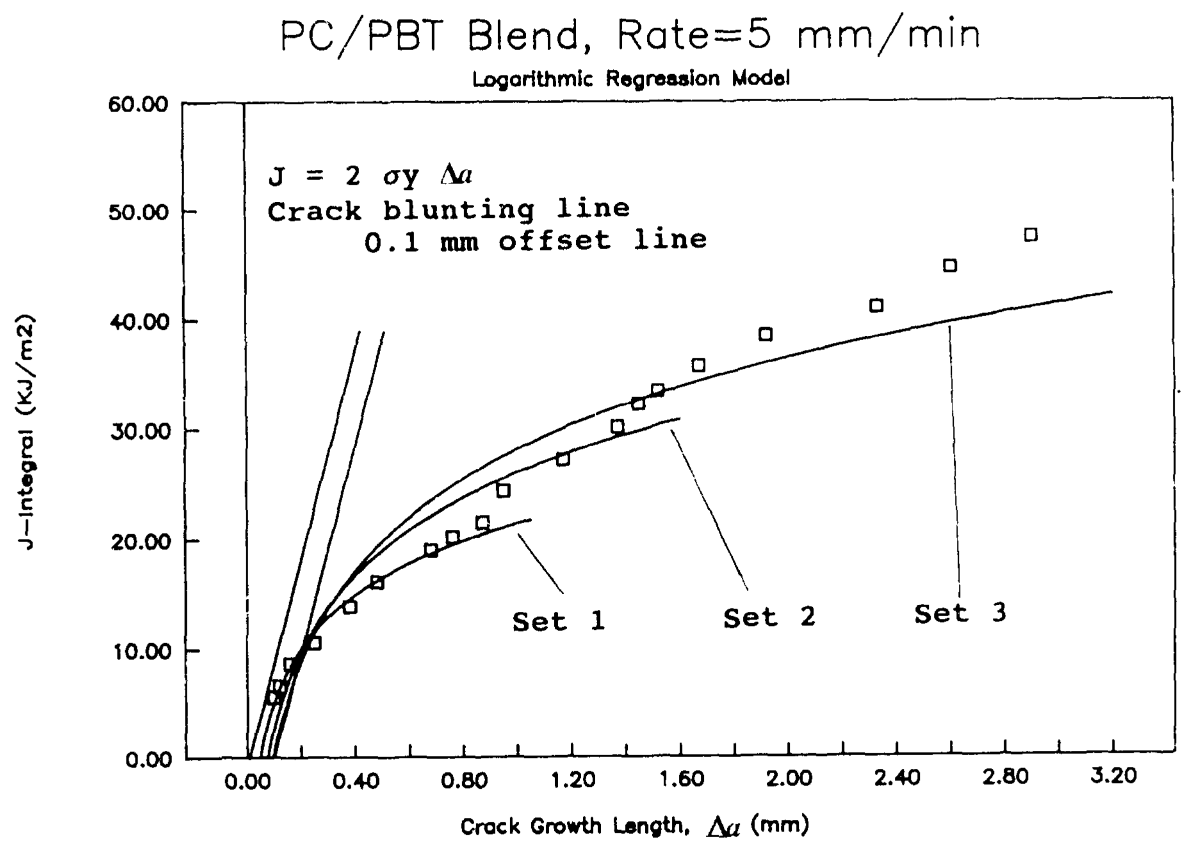

Figure 7 Plots of J versus Δa using the logarithmic regression equation within three data windows for a strain rate of $5\,\mathrm{mm\,min^{-1}}$

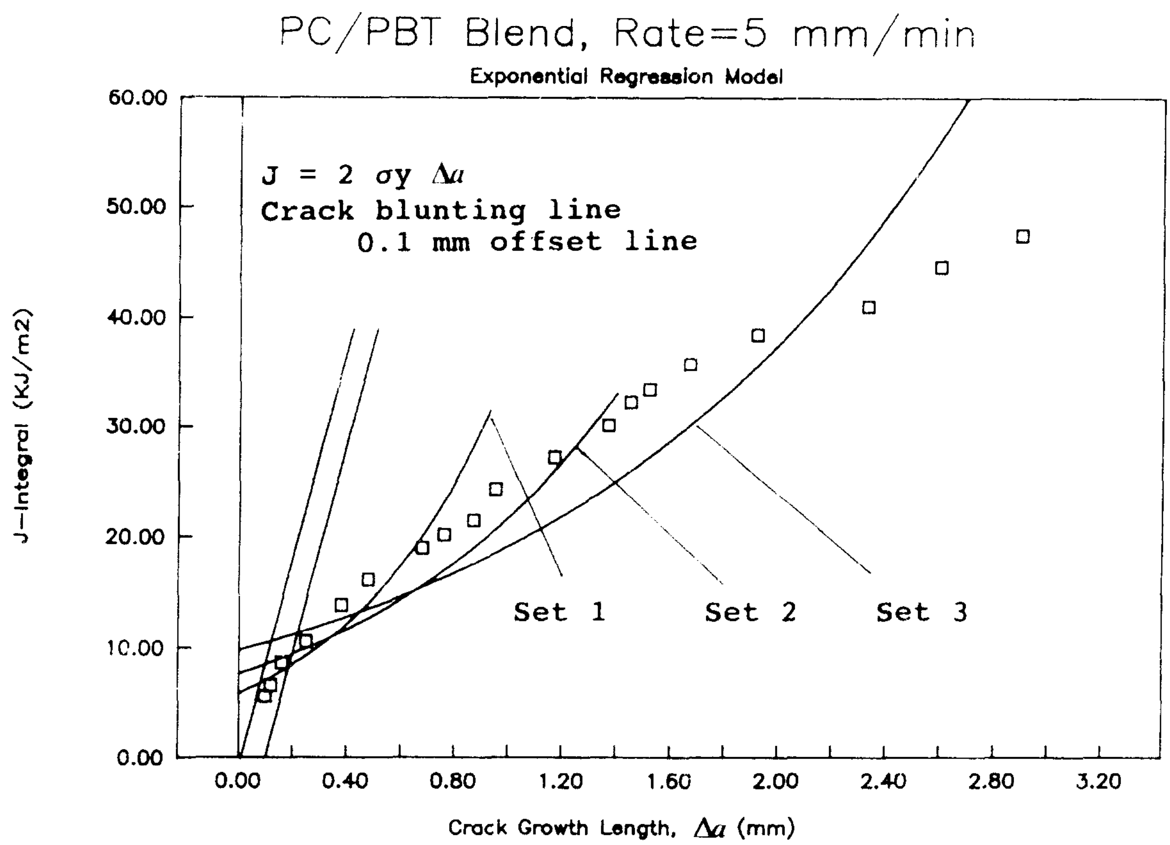

Figure 8 Plots of J versus Δa using the exponential regression equation within three data windows for a strain rate of $5\,\mathrm{mm\,min^{-1}}$

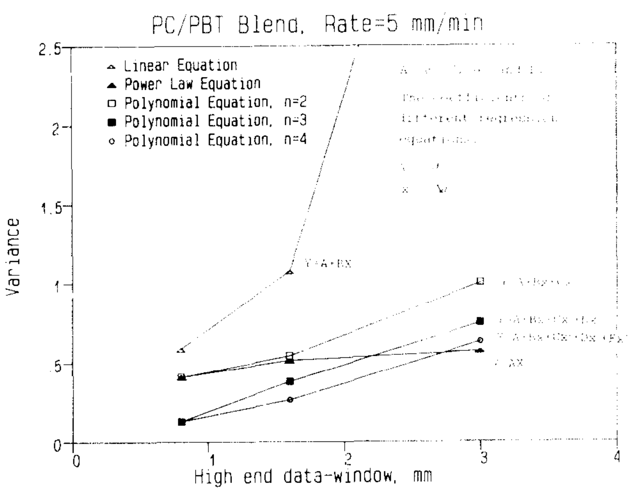

Figure 9 Effects of the data window range on the variance of the J–Δa curve fit

equation. The corresponding plots from the logarithmic and exponential regression equations are not included in *Figure 9* because of their significantly higher variances. Among those five regression equations employed, it is clear that the variances determined from the linear regression equation are significantly higher than those determined from the other regression equations, especially at higher data windows.

BEST ESTIMATES OF THE FRACTURE TOUGHNESS

In this work we observed that the crack extension from the J–R curve was non-linear, as would be expected. In the transition period from crack blunting to stable crack growth, only a gradual slope change (*Figure 2*) rather than the abrupt change assumed by the E813-81 analysis was observed. Thus, a combination of a linear regression line based on those data points collected in the stable crack extension region and the theoretically predicted blunting line cannot represent accurately the true J–R curve behaviour in the crack initiation region. If J_c is defined for true crack initiation, the J_c determined by E813-81 can be higher or lower than the true J_c depending on the disparity between the theoretically predicted blunting line ($J = 2\sigma_y\Delta a$) and the true blunting curve and selected data window. When we consider the crack tip processes occurring in this transition region (from blunting to growth), we discover that voids may form and grow at certain favourable sites (such as chain ends or impurity particles) along the stretched blunting front. This may result in localized crack extension, while most of the blunting front remains to be blunted. Such an uneven crack extension is probably responsible for the observed gradual slope change in the transition region (*Figure 2*). Therefore, a true initiation point is difficult or totally impossible to define. As a matter of fact, crack initiation is actually a continuous process rather than an abrupt event. To avoid such confusion, the E813-87 method chooses the 0.2 mm offset line to determine J_c, which is an engineering definition rather than a physical event of crack initiation. Alternatively, E813-87 may be considered as being applicable to macroscopic crack initiation, involving an additional 0.2 mm of crack growth after initiation based on the theoretically predicted value. The 0.2 mm offset line specified in

Table 5 Determined variances of the other regression models obtained from three J–Δa data windows and at different strain rates

	Variance			
Strain rate ($mm\,min^{-1}$)	Polynomial regression, $n = 2$	Polynomial regression, $n = 3$	Polynomial regression, $n = 4$	Logarithmic regression
Determined by set 1 (Δa = 0.1–0.8 mm)				
0.5	0.406	0.041	0.038	5.060
2	0.800	0.055	0.055	4.418
5	0.748	0.075	0.069	5.213
10	0.215	0.269	0.266	5.337
20	0.327	0.293	0.285	5.337
30	0.337	0.221	0.200	5.099
50	0.016	0.004	0.000	3.942
Average	0.407	0.136	0.130	4.915
Determined by set 2 (Δa = 0.1–1.6 mm)				
0.5	0.435	0.297	0.265	8.099
2	0.611	0.460	0.408	8.595
5	0.453	0.237	0.153	9.687
10	0.415	0.346	0.342	8.338
20	0.399	0.269	0.268	8.564
30	0.749	0.403	0.337	9.268
50	0.725	0.704	0.601	8.227
Average	0.541	0.388	0.262	8.683
Determined by set 3 (Δa = 0.1–3.0 mm)				
0.5	0.550	0.525	0.263	10.49
2	1.417	0.632	0.629	11.20
5	0.796	0.732	0.703	12.69
10	0.939	0.579	0.401	12.18
20	1.608	1.275	0.985	12.26
30	0.826	0.757	0.721	12.62
50	0.827	0.758	0.742	12.29
Average	0.994	0.751	0.635	11.96

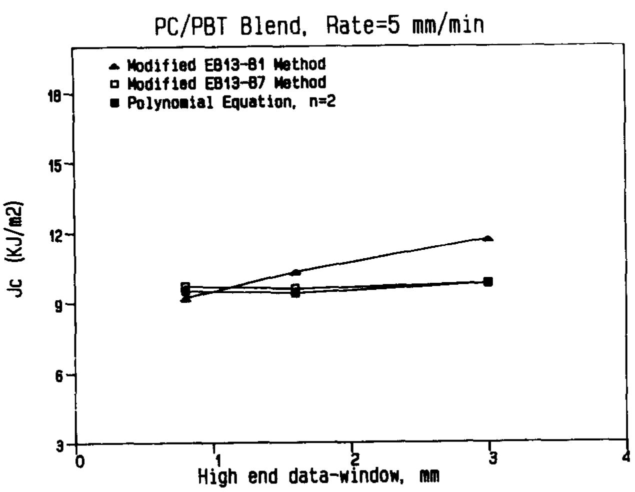

Figure 10 Effect of the data window on J_c for modified ASTM E813-81, modified ASTM E813-87 and the polynomial equation with order 2

E813-87 is only an arbitrarily selected distance and the resultant J_c value may be appropriate for metals, but it is significantly higher than the corresponding value from E813-81 for most polymeric materials. In our previous published papers[20–25], we proposed a 0.1 mm offset line for E813-87, and the obtained J_c was found to be close to or only slightly higher than that obtained from E813-81.

Table 6 summarizes various J_c values obtained at the intersections between the 0.1 mm offset line and the curves from three different data windows and three different regression models (linear, power law and polynomial). It is interesting to note that the J_c values obtained are fairly similar when using the 0.1 mm offset line. The average J_c values from the set 1 data window and the three regression equations are 9.23, 9.71 and 9.49 $kJ\,m^{-2}$, while the corresponding critical crack growth lengths Δa_c are 0.189, 0.207 and 0.199 mm. The results from the other data windows (sets 2 and 3) show similar trends. *Figure 10* shows that the J_c values obtained by using the 0.1 mm offset line and these three regression equations are fairly independent of the data window. The critical J_c values obtained by using this 0.1 mm offset line are 10–40% higher than those obtained from the E813-81 method (set 1 in *Table 2*) and 25–45% lower than those obtained from the E813-87 method (set 2 in *Table 3*). Since a true crack initiation point is difficult or impossible to define, the J_c measurement based on the proposed 0.1 mm offset line may represent a more appropriate compromise in defining the critical J. The most important point we want to emphasize here is that more consistent results can be obtained by using this 0.1 mm offset line approach

Table 6 Critical J_c values and the corresponding crack growth length values obtained from the 0.1 mm offset line

Strain rate ($mm\,min^{-1}$)	Set 1 Δa (mm)	Set 1 J_c ($kJ\,m^{-2}$)	Set 2 Δa (mm)	Set 2 J_c ($kJ\,m^{-2}$)	Set 3 Δa (mm)	Set 3 J_c ($kJ\,m^{-2}$)
Linear regression equation						
0.5	0.198	9.40	0.202	10.40	0.225	12.17
2	0.183	8.64	0.207	10.12	0.225	11.01
5	0.190	9.02	0.197	9.39	0.212	11.26
10	0.189	9.19	0.203	10.32	0.219	11.49
20	0.189	9.42	0.214	11.62	0.224	13.09
30	0.191	9.51	0.200	10.53	0.221	12.60
50	0.188	9.46	0.181	9.82	0.200	10.59
Average	0.189	9.23	0.200	10.31	0.218	11.74
Power law regression equation						
0.5	0.212	9.82	0.203	9.76	0.205	9.78
2	0.203	9.23	0.199	8.94	0.199	9.56
5	0.195	9.17	0.193	8.89	0.193	8.89
10	0.226	10.10	0.221	10.12	0.237	10.75
20	0.212	9.65	0.215	9.89	0.216	10.46
30	0.208	10.46	0.205	10.02	0.206	9.99
50	0.192	9.55	0.191	9.37	0.195	9.56
Average	0.207	9.71	0.204	9.57	0.207	9.85
Polynomial regression equation with order 2						
0.5	0.211	9.67	0.198	9.87	0.202	9.75
2	0.199	9.29	0.195	9.05	0.203	9.78
5	0.199	9.15	0.197	8.96	0.196	9.21
10	0.204	9.73	0.199	9.42	0.205	10.02
20	0.195	9.20	0.198	9.38	0.196	10.10
30	0.195	9.89	0.202	10.11	0.199	10.20
50	0.195	9.52	0.188	9.29	0.197	9.73
Average	0.199	9.49	0.197	9.45	0.202	9.82

regardless of the regression model and data window chosen. That is why we consider this 0.1 mm offset line approach as the best estimate of the fracture toughness.

CONCLUSIONS

In this work we intentionally took more data points and wider data window ranges than required by the ASTM standards to evaluate the data-fitting accuracy (in terms of variance) of different regression models and data windows and to compare the resultant J_c values with those obtained from the established ASTM standards. The linear regression model (similar to ASTM E813-81) results in the least accuracy in the data fitting, and this model is also highly sensitive to the range of the data window. The power law regression model (similar to ASTM E813-87) gives fairly good data fitting, and its data-fitting accuracy is nearly independent of the selected data window. The polynomial regression models, especially at higher orders ($n = 3$ or 4), results in the best data fitting. True crack initiation occurs gradually rather than abruptly. The ASTM E813-81 method using the theoretically predicted blunting line and the linear J–R curve based on a smaller data window range (set 1) indeed gives better data fitting than the higher data window ranges, but the obtained J_c may be underestimated. The power law approach of ASTM E813-87 provides better data fitting but has the disadvantage of overestimating the J_c value because of the 0.2 mm offset line. The proposed 0.1 mm offset line approach gives more consistent J_c values regardless of the regression model or data window. The determined J_c values using this 0.1 mm offset line lie between those from E813-81 and E813-87. Since true crack initiation can only be ambiguously defined, the critical J based on the 0.1 mm offset line provides an appropriate compromise to define the fracture toughness. These conclusions are drawn only from the results for the PC/PBT blend in this study. More studies on other polymeric materials are needed to prove the validity of the above conclusions.

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