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Elastic–plastic fracture toughness of PC/ABS blend based on CTOD and *J*-integral methods

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The elastic–plastic fracture toughness of a PC/ABS blend has been investigated simultaneously by the conventional *J*-integral and the crack tip opening displacement (CTOD) methods for specimen thickness varying from 4 to 15 mm. The critical J (J_c) and the critical CTOD (δ_c) are based on crack initiation. Another new method to determine J_c based on the close relationship between the *J*-integral and CTOD has also been developed. Those three critical J_c values, J_{c-81}, J_{c-NEW}, and J_{c-BS} obtained from the ASTM E813-81, the new J method, and the equation $J_c = m\sigma_y\delta_c\,(1\text{-}\nu^2)$ of the CTOD method, are comparable and are independent of the specimen thickness. The constraint factor m evaluated from the linear elastic fracture mechanics (LEFM) approach using the Dugdale model is about 1.5. A rotation factor r_g of approximately 2 was obtained which is also independent of the specimen thickness. The crack propagation resistance, *J*-curve (dJ/da) or δ-curve ($d\delta/da$), decreases with increasing specimen thickness. A close relationship between CTOD and *J*-integral has been demonstrated in this study. Copyright © 1996 Elsevier Science Ltd.

(Keywords: fracture toughness; *J*-integral; crack tip opening displacement)

INTRODUCTION

The rapid development of the critical application of engineering plastics makes it desirable to have a practical and reproducible measurement of material fracture toughness that can be used in design. Linear elastic fracture mechanics (LEFM) has been successfully applied to those relatively brittle and rigid polymers such as polystyrene (PS) and poly(methyl methacrylate) (PMMA). For ductile polymers, such as polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) polyblend, the problem due to the extensive plasticity at the crack tip precludes the application of LEFM. For LEFM, the thicker specimen required for the plane-strain condition is sometimes impractical experimentally. These shortcomings of the LEFM approach led to efforts to seek other techniques that are suitable for materials with extensive plastic yielding. Two major approaches have been developed: crack tip opening displacement (CTOD)[1] and *J*-integral[2]. The CTOD fracture parameter provides a relatively simple method by extending the fracture mechanics concepts from the plane-strain linear elastic fracture behaviour to the elastic–plastic fracture behaviour. The plane-strain linear elastic fracture toughness (K_c as defined in ASTM E399[3]) can be obtained only at relatively lower temperatures and large specimen size. The J_c (as defined in ASTM E813[4]) toughness is applicable to these polymers with stable and ductile tearing behaviour. Thus, there is a transition region between the K_c and J_c toughness parameters. The CTOD fracture toughness parameter can cover this transition region as well as the regions where K_c and J_c are valid. The British Standard (BS) CTOD method for crack opening displacement (COD) testing (BS 5762[1]) is the standardized method that covers all fracture behaviours between the extremes associated with the K_c and the J_c. It has been demonstrated that the onset of crack growth can be characterized by a critical value of the *J*-integral (J_c)[5] or by a critical crack opening displacement (δ_c)[6]. The subsequent works by Clarke *et al.*[7], Griffith and Yoder[8], and Andrews *et al.*[9,10] supported the earlier observation on crack initiation. Later study by Shin[11] strongly suggested that the crack growth can be characterized in terms of the *J*-resistance or δ-resistance when certain requirements are satisfied. There are many methods that have been used to describe the critical fracture behaviour. ASTM Standards, E813-81[4] and E813-87[12], use the multiple-specimen technique proposed by Landes and Begley[5,13]. These two ASTM Standards were established originally for *J*-testing mainly for metallic materials but have been extended to characterize the toughened polymers and blends during last decades[14–20]. However, the optimum procedures of the test have not yet been conclusively defined and standardized. Subsequently, several different approaches for *J*-integral have been developed. Seidler and Grellmann[21] studied the fracture behaviour and morphologies of PC/ABS blends using a special technique, a stop block method. Mai and Cotterell[22–24] used the essential work method to characterize the fracture

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toughness for many tough polymers. Zhou *et al.*[25] used the single-specimen normalization method to derive the $J-R$ curves and to characterize the toughness of polymeric materials for which the direct measurement of the crack growth length is not required. In our recent studies[26–30], an unconventional approach to the J-integral has been developed based on the crack tip hysteresis properties of polymeric materials. This newly developed hysteresis energy method does not have any drawback of the single-specimen method[25] and is complementary with the existing ASTM E813 standards. The crack tip opening displacement (CTOD) method was also established to characterize the fracture behaviour mainly for metallic materials[31–36]. In this paper, we extend this CTOD method to characterize the fracture behaviour of the PC/ABS blend by varying specimen thickness from 4 to 15 mm. Both CTOD and conventional J-integral methods will be carried out simultaneously for comparative purpose.

CTOD AND J-INTEGRAL FRACTURE PARAMETERS

Crack tip opening displacement (CTOD)

The BS5762 COD test provides the method for analysing the load-clip gauge displacement to obtain the critical CTOD value. The CTOD can be calculated from the following equation,

$$\delta = \delta e + \delta p = \frac{K^2(1-\nu^2)}{2\sigma_y E} + \frac{V_p r_p (W-a)}{r_p W + 0.6a + z} \quad (1)$$

where ν is the Poisson's ratio, V_p is the plastic component of the mouth-opening displacement, W is the ligament length, a is the crack length, z is the knife edge thickness, r_p is the rotation factor, σ_y is the yield stress, K is the stress intensity factor, and E is the Young's modulus. Equation (1) separates the CTOD (δ) into elastic and plastic components δ_e and δ_p. The BS5762 COD test suggests a value of 0.4 for the rotation factor r_p in equation (1). However, a more precise value for the rotation factor can be calculated if the plastic components of load-line displacement and mouth-opening displacement (q_p and V_p, respectively) are known[37],

$$r_p = \left[\frac{1}{(W-a)}\right]\left\{\left(\frac{V_p W}{q_p}\right)\left[1-\left(\frac{q_p}{16W}\right)\right] - (a+z)\right\} \quad (2)$$

This equation is based on an elastic and a plastic component of CTOD and implies the existence of a rotation point below the crack tip. The correlated J-integral value can be estimated from an equation derived by Sumpter and Turner[38] by the following equation,

$$J = \left(\frac{K^2}{E}\right) + \left[\frac{2U_p^v}{B(W-a)}\right]\left\{\frac{W}{[r_p(W-a)+a+z]}\right\} \quad (3)$$

where U_p^v is the area under the load/mouth opening displacement curve. The plastic area U_p^v can be estimated by the following equation,

$$U_p^v \cong P_L V_p \quad (4)$$

where P_L is the limit load.

The J-integral

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

$$J = \int (\overline{W} \mathrm{d}y - \overline{T}\frac{\partial \overline{u}}{\partial x} \mathrm{d}s) \quad (5)$$

where $\overline{T}$ is the surface traction, $\overline{W}$ is the strain energy density, $\overline{u}$ is the displacement vector, and x, y are the axis-coordinates. Rice[2], and Begley and Landes[5,13] have shown that the J-integral can be interpreted as the potential energy change with crack growth which is expressed as follows,

$$J = -\frac{\mathrm{d}U}{B\mathrm{d}a} \quad (6)$$

where B is the thickness of the loaded body, and a is the crack length. U is the total potential energy which can be obtained by measuring the area under the load–displacement curve. Sumpter and Turner later expanded the J-integral equation as the following equation[39],

$$J = J_e + J_p \quad (7)$$

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

$$J_e = \frac{\eta_e U_e}{B(W-a)} \quad (8)$$

$$J_p = \frac{\eta_p U_e}{B(W-a)} \quad (9)$$

U_e and U_p are the elastic and plastic components of the total energy. Both η_e and η_p are their corresponding elastic and plastic work factors. b is the ligament length and W is the specimen width. For a three-point bend single-edge notched specimen with $a/W > 0.15$, η_p is equal to 2. When the specimen has a span S of $4W$ ($S = 4W$) and $0.4 < a/W < 0.6$, η_e is equal to 2. Therefore, equation (7) can be reduced to,

$$J = \frac{2U}{B(W-a)} \quad (10)$$

ASTM E813 recommends that equation (10) can be used to calculate the J value for a SENB specimen.

The J_{Ic} validity requirements

For the fracture to be characterized as J_c, a specimen must meet certain size requirements in order to achieve a plane-strain stress state along the crack front. To achieve this stress state, all specimen dimensions must exceed some multiple of J_c/σ_y. According to ASTM E813 method, a valid J_c value may be obtained, whenever,

$$B, (W-a), W > 25\left(\frac{J_c}{\sigma_y}\right) \quad (11)$$

Paris *et al.*[40] developed the tearing modulus concept to describe the stability of a ductile crack in terms of elastic–plastic fracture mechanics. This fracture instability occurs if the elastic shortening of the system exceeds the corresponding plastic lengthening for crack extension. A nondimensional parameter, tearing modulus

(T_m), has been proposed by the following equation[40].

$$T_m = \left(\frac{dJ}{da}\right)\left(\frac{E}{\sigma_y^2}\right) \quad (12)$$

For the $J-\Delta a$ data to be regarded as a material property independent of specimen size, the criterion $\omega > 10$ must be met, where ω is defined as,

$$\omega = \frac{(W-a)}{J_c}\left(\frac{dJ}{da}\right) \quad (13)$$

THE CORRELATION OF VARIOUS FRACTURE PARAMETERS

The J *versus* K

The equation used to estimate K from J are,

$$K^2 = JE \text{ for plane stress} \quad (14)$$

$$K^2 = \frac{JE}{(1-\nu^2)} \text{ for plane strain} \quad (15)$$

These correlations are only strictly valid for linear elastic conditions where J is equivalent to the energy release rate G. In this region, with the proper restrictions on specimen size, it is proper to use the following expression,

$$K_c^2 = \frac{J_c E}{(1-\nu^2)} \text{ for plane strain} \quad (16)$$

The J values used herein are not the results of the conventional J_c testing because the J values are based on the maximum load regardless of prior plasticity or crack extension, and the correlations with K are strictly valid only for linear elasticity.

The CTOD versus K

The equation used to estimate K from CTOD is,

$$K^2 = mE\sigma_y\delta \quad (17)$$

The parameter m is a constraint factor that varies from 1 to 2 based on the thickness constraint.

The relationships between J *and* CTOD

From equations (15) and (17), the CTOD can be correlated with J under small-scale condition yielding the following equation,

$$J = m\sigma_y\delta(1-\nu^2) \quad (18)$$

where m is a dimensionless constant that releases J to CTOD and yield stress; $m = 1$ for plane stress and $m = 2$ for plane strain. The value of m for large-scale yielding should be between 1 and 2. The plastic term in equation (3) is similar to the equation for the plastic CTOD,

$$\delta_p = \frac{[V_p r_p(W-a)]}{[r_p B r_p(W-a)^2]} \quad (19)$$

From equations (3) and (19), one can obtain a simple equation for the ratio of the plastic J to the plastic CTOD,

$$\frac{J_p}{\delta_p} = \frac{2U_p^v W}{[V_p B(W-a)^2]} \quad (20)$$

Equation (20) has been incorporated into a computer program by plotting J_p/δ_p as a function of mouth-opening displacement.

EXPERIMENTAL

Material and test specimens

The PC/ABS blend (Shinblend A783) was obtained from Shing-Kong Synthetic Fiberic Corporation of Taiwan. The tensile yield strength and Young's modulus were measured by using the standard injection moulded specimens (1/8 inch) with an extensometer. The Poisson's ratio of the PC/ABS is assumed to be 0.35. Test specimens are the three point bending bars with dimensions of width (W) 20 mm, length (L) 90 mm, and thickness (B), varying from 4 to 15 mm. The specimens with a single-edged notch of initial crack length, a, of 10 mm ($a/W = 0.5$) were prepared by injection moulding using an Arburg injection moulding machine (*Figure 1*). The initial precrack was then followed by sharpening with a fresh razor blade. All the notched specimens were annealed at 60° for 2–3 h to release possible residual stress prior to the standard bending tests.

Fracture mechanics tests

The CTOD and J methods were simultaneously carried out according to the BS5762 CTOD test and the ASTM E813 methods as shown in *Figure 1*. The CTOD and J tests were performed in displacement control on a 5 kN load cell universal tensile test machine (Instron model 4201). The displacement rate in all tests was 2 mm min^{-1}. The load P, the mouth-opening displacement V, and the load-line displacement q were obtained simultaneously during the test by a computer. A multiple-specimen technique was employed and the specimens were loaded to various displacements to allow different amounts of stable crack growth. The deformed specimens were then frozen in liquid nitrogen and broken open by a TMI impacter. The crack growth length of broken specimen, Δa, was measured by using a travelling optical microscope. The input energy of each test specimen was obtained by measuring the area under the load–displacement curve.

RESULTS AND DISCUSSION

Critical CTOD δ_c obtained from the BS5762 COD method

A typical plot of load vs clip-gauge displacement with

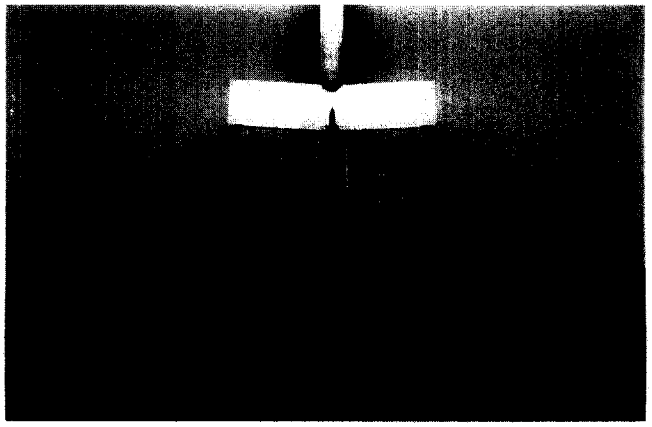

Figure 1 Three point bending setup

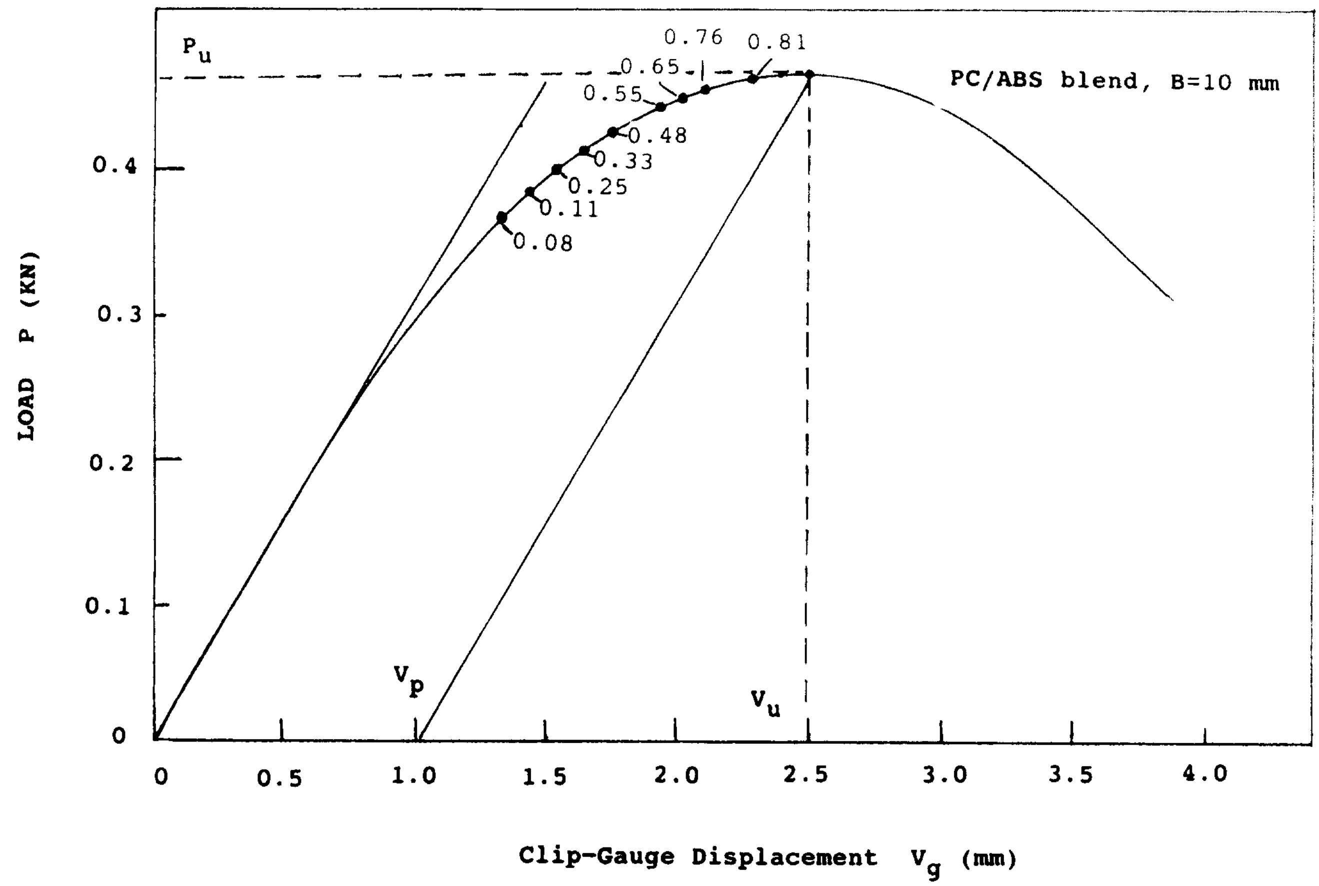

Figure 2 Plot of load vs clip-gauge displacement with corresponding Δa for $B = 10$ mm specimen

corresponding crack growth length Δa is shown in *Figure 2*. The plastic components of clip-gauge displacements V_p are then determined from the corresponding Δa shown in *Figure 2*. The V_p values are used to calculate the COD values by equation (1) and the results are summarized in *Table 1*. *Figure 3* shows the plot of crack opening displacement δ vs crack growth length according to the BS5762 COD method. The interception of the linear regression line of the δ-resistance curve with the Y-axis ($\Delta a = 0$) is defined as the critical fracture toughness δ_c. *Table 2* shows that the critical δ_c values are essentially independent of the specimen thickness. The values of the resistance δ-curve, $d\delta/da$, are also nearly independent of the specimen thickness which are also listed in *Table 2*.

ASTM E813-81 method

The J value for each specimen is calculated by using

Table 1 Summarized COD and J data for a typical PC/ABS blend with $B = 10$ mm

V_g (mm)	V_p (mm)	P (kN)	q (mm)	U (J)	a (mm)	COD (mm)	J (kJ m^{-2})
1.30	0.150	0.375	1.44	0.230	0.08	0.095	4.60
1.40	0.190	0.392	1.56	0.258	0.11	0.109	5.16
1.50	0.231	0.410	1.67	0.406	0.25	0.127	8.12
1.60	0.289	0.424	1.78	0.466	0.33	0.145	9.32
1.70	0.346	0.436	1.90	0.551	0.48	0.183	11.02
1.90	0.475	0.456	2.12	0.605	0.55	0.208	12.10
2.00	0.560	0.466	2.23	0.655	0.65	0.231	13.11
2.10	0.645	0.472	2.36	0.697	0.76	0.280	16.94
2.30	0.830	0.478	2.57	0.757	0.81	0.328	18.14

V_g (mm): Clip-gauge displacement
V_p (mm): Plastic component of clip-gauge displacement
P(kN): Load
q (mm): Load-line displacement
U (J): Input energy
a (mm): Crack growth length
COD(mm): Crack opening displacement
J (kJ m^{-2}): J value calculated from the equation $J = 2U/Bb$

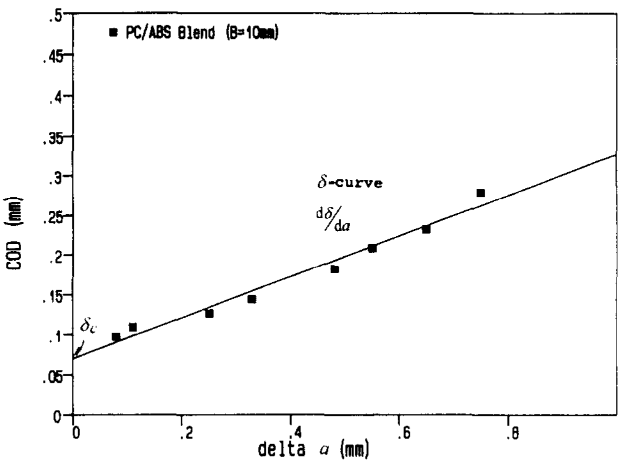

Figure 3 Plot of the COD (δ) vs crack growth length (Δa) for $B = 10$ mm specimen

Table 2 Critical fracture toughness obtained from different methods

Critical δ_c and J_{C-BS} obtained from COD method						
Thickness B (mm)	4	6	8	10	12.5	15
δ_c ($\Delta a = 0$)	0.066	0.068	0.058	0.071	0.055	0.071
$d\delta/da$	0.325	0.264	0.311	0.257	0.249	0.270
m value	1.53	1.65	1.49	1.44	1.59	1.46
J_{c-BS} ($\Delta a = 0$)	4.05	4.50	3.74	4.10	3.51	4.11
Critical J_{c-81} obtained from ASTM E813-81 method						
Thickness B (mm)	4	6	8	10	12.5	15
J_{c-81}	4.99	4.53	3.92	4.17	3.72	3.88
dJ/da	14.93	14.40	13.80	14.05	13.89	13.26
$25(J_c/\sigma_y)$	2.65	2.33	2.01	2.14	1.91	1.99
T_m value	12.94	12.48	11.96	12.18	12.04	11.49
ω parameter	29.92	31.79	35.20	33.69	37.33	34.17
Critical J_{c-NEW} obtained from new J method						
Thickness B (mm)	4	6	8	10	12.5	15
q_{crit} ($\Delta a = 0$)	1.28	1.29	1.32	1.39	1.31	1.36
J_{c-NEW} ($\Delta a = 0$)	4.21	4.54	3.86	4.48	4.09	4.15

δ_c ($\Delta a = 0$): standard COD method
$d\delta/da$: slope of δ-resistance curve
dJ/da: slope of J-resistance curve
$T_m = dJ/da\ (E/\sigma_y^2)$
$\omega = (W - a)/J_c dJ/da$

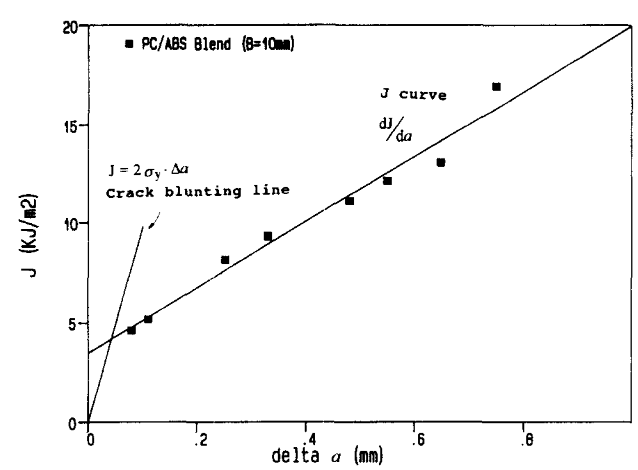

Figure 4 Typical plot of J-integral by ASTM E813-81 method

equation (10), and the detailed data for the specimens with $B = 10$ mm are summarized in *Table 1*. *Figure 4* shows the plot of the acceptable J vs Δa by linear regression R-curve according to the ASTM E813-81 method for $B = 10$ mm. The linear regression R-curve intercepts with the blunting line ($J = 2\delta_y \Delta a$) to locate the J_{c-81} value. The J_{c-81} determined from varying the specimen thickness are summarized in *Table 2*, where the thinner specimens ($B = 4$, 6 mm) have a slightly higher J_c values than the thicker specimens ($B = 12.5$, 15 mm). The dJ/da values obtained according to the linear regression R-curves of ASTM E813-81 are summarized in *Table 2*. The slope of the J resistance curve (dJ/da) increases slightly with decreasing specimen thickness.

The size criterion of specimens

ASTM E813 specifies that for a valid J_c measurement the size criterion requirements of equation (11) must be met. The size criterion parameters $[B, (W - a), W > 25(J_c/\sigma_y)]$ according to the ASTM E813 methods for a valid J_c are all satisfied as shown in *Table 2*. The size criteria for J-testing allow for the use of significantly smaller specimen dimensions than those required for LEFM. The tearing modulus [as equation (12)], T_m is used to describe the stability of the crack growth. *Table 2* also shows that the tearing modulus T_m value of specimen geometries are nearly independent of the specimen thickness. In order for the J–Δa data to be regarded as an intrinsic material property independent of specimen size, the criterion parameter, $\omega > 10$ [as equation (13)] must be met. In this paper, the criterion $\omega > 10$ is met (*Table 2*).

New J *method*

In this paper, both the clip-gauge displacement (V) and the load–time displacement (q) can be simultaneously determined by a computer and the typical results ($B = 10$ mm) are listed in *Table 1*. *Figure 5* shows a linear relationship of V vs q. *Figure 6* also shows the linear relationship of δ vs q where the critical initial displacement q_{crit} is determined at the onset of the critical δ_c value obtained from *Figure 3*. As soon as the q_{crit} is determined, the critical J_{c-NEW} can be obtained from the plot of J vs q at the onset of the q_{crit} value as shown in *Figure 7*. All of these determined q_{crit} and J_{c-NEW} values are summarized in *Table 2*. The q_{crit} and J_{c-NEW} values obtained from this new J method are fairly independent of the specimen thickness.

The m *factor*

A typical photograph of the loaded PC/ABS SENB

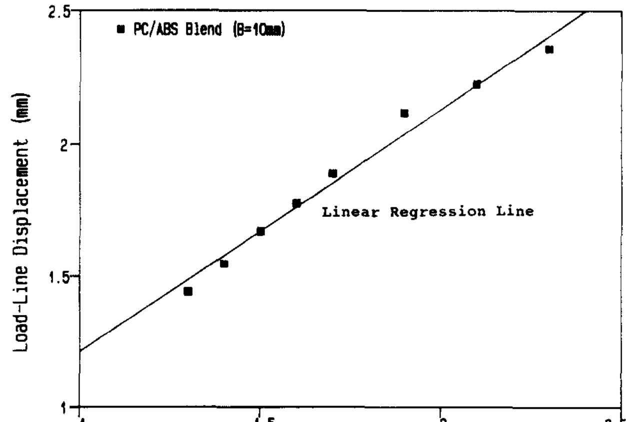

Figure 5 Plot of the load-line displacement (q) vs clip-gauge displacement (V) for $B = 10$ mm specimen

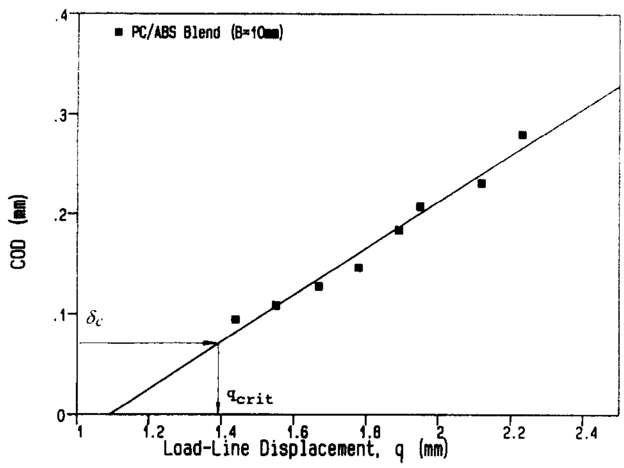

Figure 6 Plot of COD (δ) vs load-line displacement (q) for $B = 10$ mm specimen

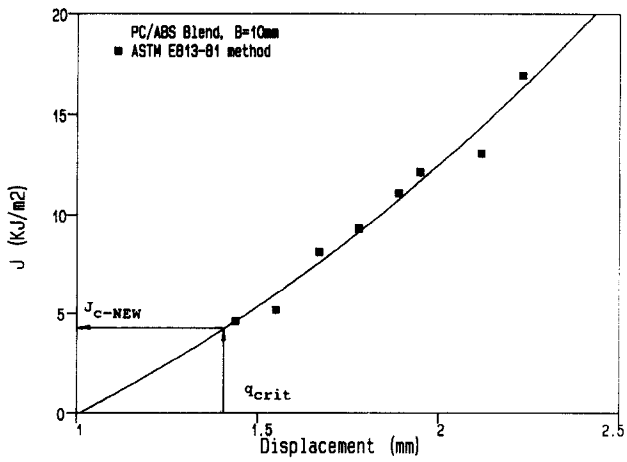

Figure 7 Plot of J vs the load-line displacement (q) for $B = 10$ mm

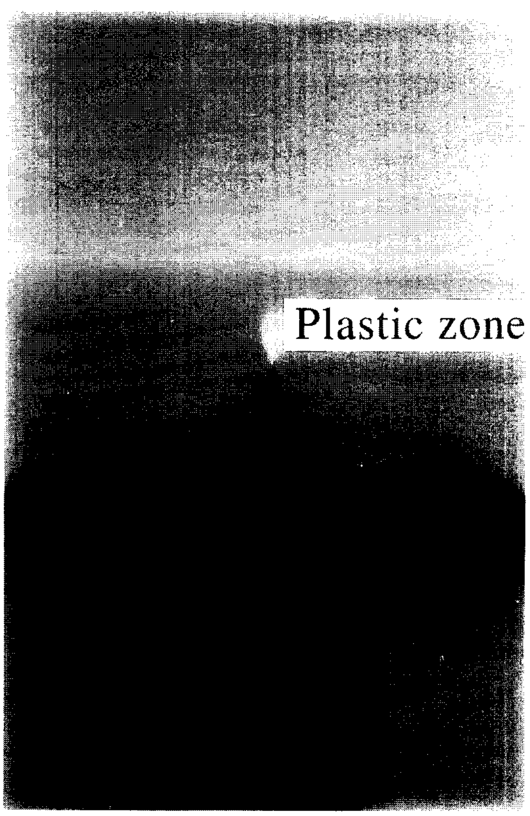

Figure 8 Photograph of the deformed SENB specimen

specimen is shown in *Figure 8* where a sharply defined plastic zone ahead of the crack tip can be clearly observed. The plastic zone increases with the increase of the crack growth length. The length of the primary plastic zone (r_{PZ}) was measured from an optical micrograph of the central section of the specimen and the data are summarized in *Table 3*. It was postulated earlier that an LEFM parameter[41–43] can be used to characterize the fracture behaviour of toughened materials by assuming the crack initiation occurring shortly after the onset of nonlinearity. The stress intensity factor, K is calculated by the following equation,

$$K = Y\sigma_y a^{1/2} \tag{21}$$

where Y is a geometry factor, and $a = a_0 + \Delta a$. The Dugdale model predicts the plastic zone, r_p, ahead of a crack tip as,

$$r_p = 0.393\left(\frac{K}{m\sigma_y}\right)^2 \tag{22}$$

where m is the plastic constraint factor. The K values are then calculated from equation (22) by using the length of the measured primary plastic zone. Three constraint factors, $m = 1$, $m = 2^{1/2}$, and $m = 3^{1/2}$ are assumed to calculate the corresponding K values. The calculated K values are summarized in *Table 3*. Furthermore, the K values can be converted into the J value by using the $J = K^2(1 - \nu^2)/E$ equation. Three sets of the calculated J values from the corresponding K values are also summarized in *Table 3*. *Figure 9* shows the plots of the J vs the crosshead displacement for ASTM E813-81 method and from the LEFM approach with various constraint factors for $B = 10$ mm. The constraint m factor is then estimated from the J–q curve of the ASTM E813-81 method and the determined m values are summarized in *Table 2*. The constraint m factor is essentially independent of the specimen thickness varying from $B = 4$ to 15 mm. However, the m values obtained are lower than 2 (plane-strain condition) and are higher than 1 (plane-stress condition). This is due to the large-scale yielding of polymeric materials and the m value should be between 1 and 2.

Critical J_c *values obtained from different methods*

The m values for different thickness specimens determined as described in the above section were used to calculate the corresponding critical J_{c-BS} values according to equation (18) and the results are summarized in *Table 2*. *Figure 10* shows a linear relationship with slope = 1 of the J obtained from the ASTM E813-81 method (equation 10) and the J calculated from the COD method (equation 18). That means the J values from the ASTM and COD methods at different stages of deformation are essentially identical based on this study. Such observation emphasizes the close relationship between these two methods. There are three critical J_c values, J_{c-81}, J_{c-NEW}, and J_{c-BS}, can be derived from the ASTM E813-81 method, the new J method, and J calculated from equation (18) of the COD method, respectively. These three critical J_c values are shown in *Table 2*. These critical J_c values obtained from the above three methods are very close to each other and

Table 3 Summarized J data for a typical PC/ABS blend with $B = 10\,\mathrm{mm}$

q (mm)	r_{PZ} (mm)	K value $m = 1$ (MPa m)	$m = 2$ (MPa m)	$m = 3$ (MPa m)	J $m = 1$ ($\mathrm{kJ\,m^{-2}}$)	$m = 2$ ($\mathrm{kJ\,m^{-2}}$)	$m = 3$ ($\mathrm{kJ\,m^{-2}}$)
0.9	0.14	0.91	1.29	1.58	0.36	0.72	1.08
1.0	0.15	0.96	1.35	1.65	0.39	0.78	1.17
1.1	0.42	1.58	2.24	2.74	1.07	2.15	3.22
1.3	0.80	2.19	3.10	3.80	2.06	4.12	6.18
1.4	0.91	2.33	3.29	4.04	2.33	4.66	6.99
1.5	0.99	2.44	3.45	4.23	2.55	5.10	7.66
1.6	1.41	2.91	4.11	5.03	3.62	7.24	10.86
1.7	1.88	3.36	4.75	5.82	4.85	9.70	14.55
1.8	2.07	3.52	4.98	6.10	5.32	10.64	15.96
1.9	2.32	3.74	5.28	6.47	5.98	11.96	17.94
2.0	2.35	3.76	5.31	6.50	6.05	12.10	18.15
2.1	2.40	3.80	5.37	6.57	6.18	12.36	18.54
2.3	2.53	3.90	5.51	6.75	6.51	13.03	19.54
2.4	2.53	3.90	5.51	6.75	6.51	13.03	19.54
2.5	2.60	3.95	5.59	6.84	6.69	13.39	20.08
2.6	2.67	4.01	5.66	6.93	6.87	13.75	20.62
2.7	2.75	4.06	5.74	7.04	7.08	14.16	21.24
2.9	3.13	4.33	6.13	7.51	8.06	16.12	24.18
3.0	3.17	4.36	6.17	7.56	8.16	16.32	24.48

q: Load-line displacement
$K = (r_p/0.363)^{1/2} m\sigma_y$
$J = K^2(1-\nu^2)/E$
r_{PZ}: Length of the plastic zone

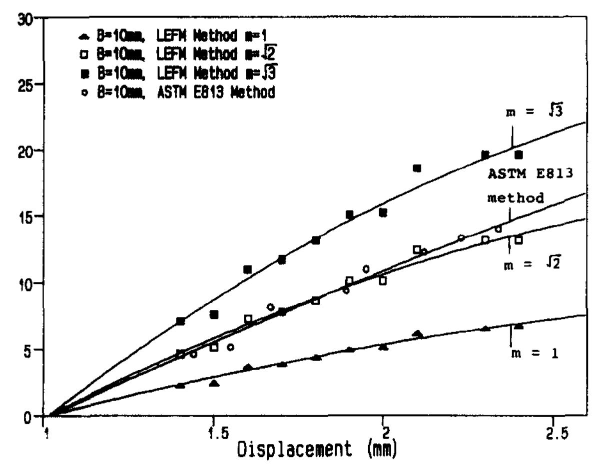

Figure 9 Plots of J vs displacement from the ASTM E813 and LEFM methods with various constraint factors for $B = 10\,\mathrm{mm}$

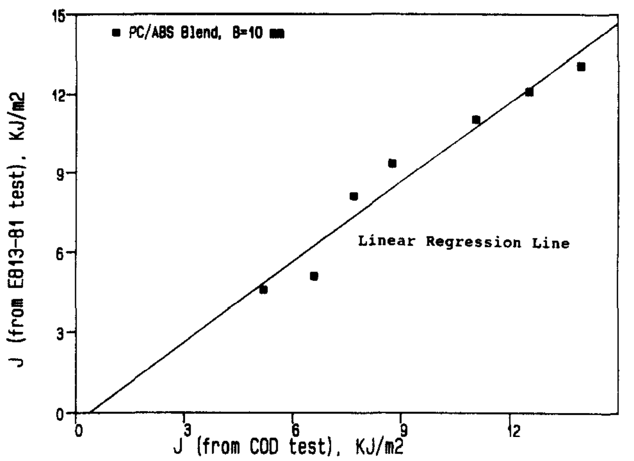

Figure 10 Plot of J obtained from the ASTM E813-81 method vs J obtained from the COD method

are essentially independent of the specimen thickness as illustrated in *Figure 11*.

J obtained from different methods

Three different J values at various V_p, J_{SUM}, J_{ASTM}, and J_{BS}, can be calculated using the Sumpter equation (equation (3)), the ASTM E813 equation (equation (10)), and the COD calculation equation (equation (18)), respectively. *Figure 12* shows three curves of calculated J_{ASTM}, J_{BS}, and J_{SUM} vs crack growth length. The calculated J_{ASTM} values are nearly identical to the calculated J_{BS} values (as shown in *Figure 10*) but are higher than the calculated J_{SUM} values when Δa is greater than 0.2 mm. The resistance curves of both of the ASTM E813 method $\mathrm{d}J_{ASTM}/\mathrm{d}a$ and the COD method $\mathrm{d}J_{BS}/\mathrm{d}a$ are comparable but are higher than $\mathrm{d}J_{SUM}/\mathrm{d}a$ of the Sumpter derived J equation. The elastic and plastic components of the J value, J_e and J_p, can be calculated from equation (3) at ambient plastic component of clip-gauge displacement V_p. *Figure 13* shows the plots of the J_e and J_p vs the crack growth length, respectively. The increment rate of the elastic component $\mathrm{d}J_e/\mathrm{d}a$ is nearly constant while the plastic component $\mathrm{d}J_p/\mathrm{d}a$ increases gradually with Δa.

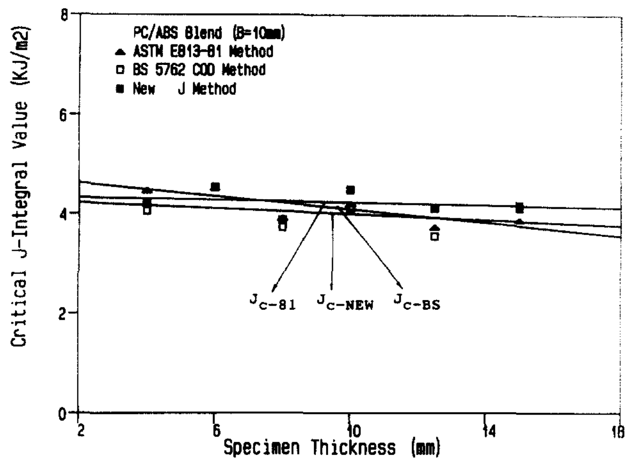

Figure 11 Plots of the critical J_c vs the specimen thickness according to three different methods

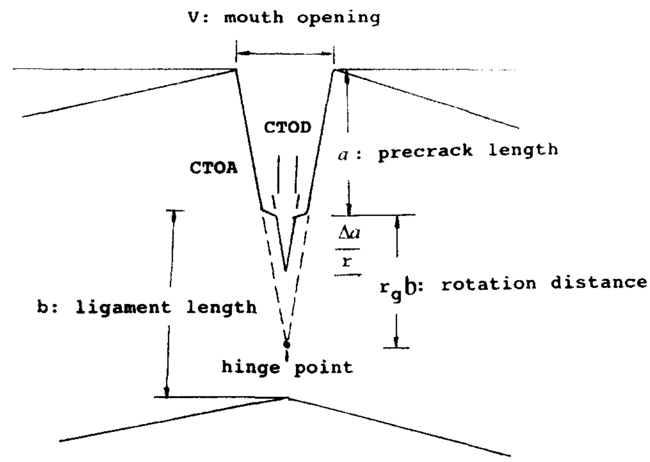

Figure 14 Schematic sketch illustrating the hinge point construction during crack growth

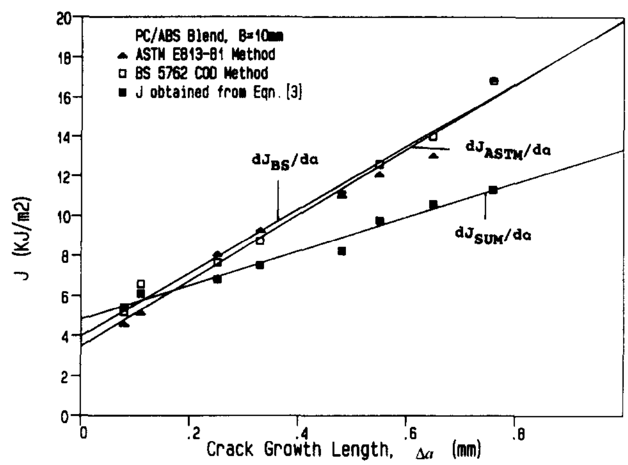

Figure 12 Plots of the calculated J vs the crack growth length (Δa) according to equations (3), (10) and (15)

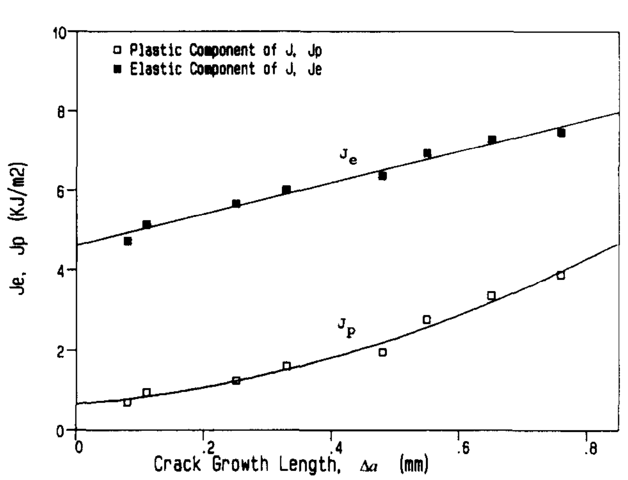

Figure 13 Plots of J_e and J_p vs crack growth length Δa

Further discussion: effect on crack initiation

The effect of specimen thickness on crack growth resistance can be interpreted in terms of crack tip constraint and deformation remote from the crack tip. *Figure 14* schematically illustrates the plastic hinge construction. After onset of initiation, the increase of the clip-gauge displacement $\mathrm{d}V$ and the crack opening displacement $\mathrm{d}\delta$ above their respective initiation values V_c and δ_c are related by the following equation,

$$\mathrm{d}\delta = \frac{(r_g b \mathrm{d}V)}{(r_g b + a)} \tag{23}$$

The $r_g b$ is the rotation distance and is defined as the hinge point position during crack growth, r_g is the rotation factor, b is the ligament length. Similarly, the crack opening displacement at the crack tip of the growing crack [crack-tip opening displacement (CTOD)] and the crack tip opening angle (CTOA) are related by the distance r by the following equation,

$$\mathrm{CTOA} = 2\tan^{-1}\left(\frac{\mathrm{CTOD}}{2r}\right) \tag{24}$$

As there is only elastic deforming behind the crack tip, $r_g b$ is directly proportional to r. CTOA is related to $\mathrm{d}\delta/\mathrm{d}a$ by the following equation,

$$\mathrm{CTOA} = 2\tan^{-1}\left(\frac{\mathrm{d}\delta}{2\mathrm{d}a}\right) \tag{25}$$

Table 4 summarizes the values of the rotation distance ($r_g b$) calculated from equation (23) by using the measured crack-opening and the clip-gauge displacements. It can be seen from *Table 4* that the rotation distance $r_g b$ and the rotation factor r_g decrease slightly with the increase of thickness up to $B = 15$ mm. Since both δ_c and δ are functions of the rotation factor (or constraint) of the crack tip, a greater thickness will result in lower δ_c and δ. Decreasing CTOD (δ_c) while holding r constant will lead to a decrease in CTOA (equation (24)) and the crack opening resistance $\mathrm{d}\delta/\mathrm{d}a$ (equation (25)). This will result in a smaller change in the area under the load vs clip-gauge displacement curve with crack growth and hence a decrease in $\mathrm{d}J/\mathrm{d}a$. *Figure 15* shows that $\mathrm{d}J/\mathrm{d}a$ decreases with increasing specimen thickness. A

Table 4 Critical r_g from the BS:5762 COD test method

Thickness B (mm)	4	6	8	10	12.5	15
$\mathrm{d}\delta/\mathrm{d}V$	0.216	0.195	0.172	0.207	0.183	0.171
$r_g b$ (mm)	0.275	0.243	0.209	0.254	0.224	0.206
r_g	2.75	2.43	2.09	2.54	2.24	2.06

$r_g b$: Rotation distance
r_g: Rotation factor
b: Ligament length ($b = W - a$)

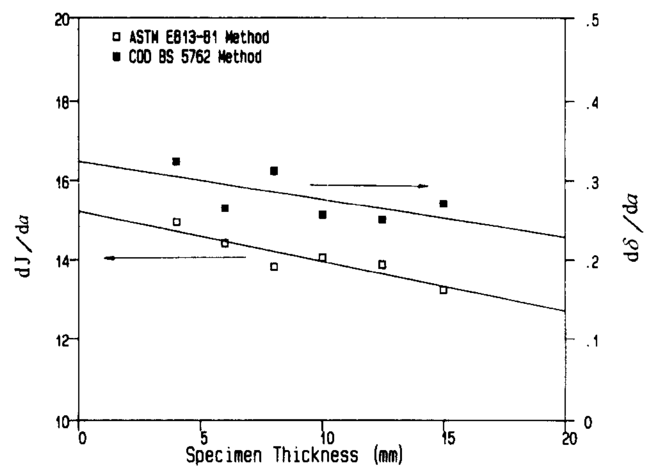

Figure 15 Plots of the resistance curves, dJ/da and $d\delta/da$, vs the specimen thickness

decreasing CTOD (δ) would be anticipated as J_c is also decreased. However, when the specimen thickness is increased above the size requirements, the CTOD will be expected to remain constant and J_c will achieve a minimum plateau value. Furthermore, if the specimen is essentially under plane-strain conditions, the size and shape of the plastic zone is not expected to alter with the increase of the specimen thickness, and r is expected to remain constant. Therefore, the critical J_c values are expected to remain constant. Three different critical fracture toughness J_c values (J_{c-81}, J_{c-BS} and J_{c-NEW}) are shown in *Table 2* and the results are fairly independent of the specimen thickness varying from 4 to 15 mm.

CONCLUSIONS

The fracture behaviour of PC/ABS polyblend has been investigated simultaneously by both COD and J-integral methods with various specimen thicknesses. The critical δ_c values from the COD method and J_c from the J-integral method are essentially independent of the specimen thickness varying from 4 to 15 mm. Three critical J_c values, J_{c-81}, J_{c-NEW} and J_{c-BS}, obtained from the ASTM E813-81 method, the new J method, and equation (18) of the COD method, are very close and are also independent of the specimen thickness, three different J values (J_{SUM}, J_{ASTM} and J_{BS}) can be calculated from equations (3), (10) and (18), respectively. The calculated J_{ASTM} is close to the calculated J_{BS} but is higher than the calculated J_{SUM} at higher crack growth length. A plastic zone can be identified and measured from the central section of the specimen and the size of the plastic zone r_{PZ} increases with the increase of the crack growth. The constraint m factor from the ASTM E813 method was determined to be greater than unity but less than 2 due to the large-scale yielding of polymeric materials. Finally, the rotation factors r_g were found to be independent of the specimen thickness and are close to 2. The crack propagation resistance, J-curve (dJ/da) or δ-curve ($d\delta/da$), decreases with the increase of the specimen thickness. A close relationship between COD and J-integral has been demonstrated in this study.

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REFERENCES

1 British Standard Method for Crack Opening Displacement (COD) Testing, BS 5762: 1979
2 Rice, J. R. *J. Appl. Mech.* 1968, **35,** 379
3 ASTM Standard E399-78 in 'Annual Book of ASTM Standards', part **10,** 1987, p. 540
4 ASTM Standards E813-81 in 'Annual Book of ASTM Standards', part **10,** 1981, p. 810
5 Begley, J. A. and Landes, J. D. ASTM STP 514, 1972, 1
6 Green, G. and Knott, J. F. *J. Mech. Phys. Solids* 1975, **23,** 167
7 Clarke, G. A., Andrews, W. R., Paris, P. C. and Schmidt, D. W. ASTM STP 590 1976, 27.
8 Griffith, C. A. and Yoder, G. R. *Trans. ASME, J. Eng. Mater. Technol.* 1979, **98,** 152
9 Shin, C. F., Delorenzi, H. G. and Andrews, W. R. ASTM STP 668, 1979, 65
10 Andrews, W. R. and Shin, C. F., ASTM STP 668, 1979, 426
11 Shin, C. F. *J. Mech. Phys. Solids* 1981, **29,** 305
12 ASTM Standard E813-87 in 'Annual Book of ASTM Standards', part **10,** 1987, p. 968
13 Landes, J. D. and Begley, J. A. ASTM STP 560, 1974, 170
14 Chan, M. K. V. and Williams, J. G. *Int. J. Fract.* 1983, **19,** 145
15 Hashemi, S. and Williams, J. G. *Polymer* 1986, **27,** 85
16 Huang, D. D. and Williams, J. G. *J. Mater. Sci.* 1987, **22,** 2503
17 Narisawa, I. *Polym. Eng. Sci.* 1987, **27,** 41
18 Parker, D. S., Sue, H. J., Huang, J. and Yee, A. F. *Polymer* 1990, **31,** 2267
19 Narisawa, I. and Takemori, M. T. *Polym. Eng. Sci.* 1989, **29,** 671
20 Huang, D. D. and Williams, J. G. *Polym. Eng. Sci.* 1990, **30,** 1341
21 Seidler, S. and Greilmann, W. *J. Mater. Sci.* 1993, **28,** 4078
22 Mai, Y. W. and Cotterell, B. *J. Mater. Sci.* 1980, **15,** 2296
23 Mai, Y. W. and Cotterell, B. *Eng. Fract. Mech.* 1985, **21,** 123
24 Wu, J., Mai, Y. W. and Cotterell, B. *J. Mater. Sci.* 1993, **28,** 3373
25 Zhou, Z., Landes, J. D. and Huang, D. D. *Polym. Eng. Sci.* 1994, **34,** 128
26 Lee, C. B. and Chang, F. C. *Polym. Eng. Sci.* 1992, **32,** 792
27 Lu, M. L. and Chang, F. C. *Polymer* 1995, **36,** 2541
28 Lee, C. B., Lu, M. L. and Chang, F. C. *J. Appl. Polym. Sci.* 1993, **47,** 1867
29 Lu, M. L. and Chang, F. C. *J. Polym. Res.* 1995, **2,** 13
30 Lu, M. L., Lee, C. B. and Chang, F. C. *Polym. Eng. Sci.* 1995, **35,** 1433
31 Wellman, G. W. and Rolfe, S. T. ASTM STP 856, 1985, 230
32 Anderson, T. L., McHenry, H. I. and Dawes, M. G. ASTM STP 856, 1985, 210
33 Gibson, G. P. and Gruce, S. G. ASTM STP 856, 1985, 166
34 Bakker, A. ASTM STP 856, 1985, 394
35 Dawes, M. G. ASTM STP 668, 1979, 306
36 Fernandez-Saez, J., Chao, J., Duran, J. and Amo, J. M. *J. Mater. Sci.* 1993, **28,** 5340
37 Lin, H. I., Anderson, T. L., Dewit, R. and Dawes, M. G. *Int. J. Fract.* 1982, **20,** 3
38 Sumpter, J. D. and Turner, C. E. ASTM STP 601, 1976, 3
39 Sumpter, J. D. and Turner, C. E. *Int. J. Fract.* 1973, **9,** 320
40 Paris, P. C., Tada, H., Zahoor, A. and Ernst, H. ASTM STP 668, 1979, 5
41 Williams, J. G. 'Fracture Mechanics of Polymers', Ellis Horwood, Chichester, 1987
42 Strebel, J. J. and Moet A. *J. Mater. Sci.* 1992, **27,** 2981
43 Moskala, E. J. *J. Mater. Sci.* 1992, **27,** 4883