

# Fracture Toughness of High-Impact Polystyrene Based on Three $J$ -Integral Methods

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## SYNOPSIS

Three  $J$ -integral methods and their modified versions have been used to characterize the fracture toughness of high-impact polystyrene (HIPS) with different thicknesses. The  $J_c$  values obtained were highest from the E813-87 method, followed by the E813-81 method, then by the hysteresis method. The hysteresis method based on the steep rising of hysteresis energy under constant displacement-controlled loading in  $J_c$  determination has many advantages over the ASTM E813-81 or the E813-87 method. The requirement of crack growth length measurements is no longer necessary and the controversial issue on the crack blunting line can also be avoided. The E813-87 method resulted in significantly higher  $J_c$  values for polymers, but the modified version of E813-87, by moving the offset line from the original 0.2 to 0.1 mm, resulted in comparable  $J_c$  values. Since crazes as the main failure mechanism for HIPS, well-defined crack blunting does not expect to occur and the  $J_c$  obtained by the original E813-81 based on the theoretically predicted blunting line is indeed slightly higher. The modified version of E813-81 by neglecting the blunting line in  $J_c$  determination is believed to be more reasonable for HIPS. The nature of polymers will determine whether the crack tip will be blunted, partially blunted, or not blunted. ASTM E813-81 is appropriate for those polymers with a well-defined blunted crack tip (such as elastomer-modified polycarbonate), whereas the modified version of ASTM E813-81 seems better for those polymers with craze as the main failure mechanism (such as HIPS). Experimental results indicated that this hysteresis method is able to inherently adjust the crack blunting effect and therefore can be applied to any type of ductile polymer. © 1993 John Wiley & Sons, Inc.

## INTRODUCTION

The  $J$ -integral proposed by Rice<sup>1</sup> as an analytical tool for elastic-plastic crack tip field analysis has been applied successfully by Begley and Landes<sup>2,3</sup> for metals. Since then, two important ASTM Standards, E813-81 (Ref. 4) and E813-87 (Ref. 5), using multiple single-edge notched bend specimens have been established. In the ASTM E813-81, the crack blunting line,  $J = 2\sigma_y \cdot \Delta a$ , is used to intersect the  $J$ - $R$  line obtained by linear regression of the crack growth data to give a measure of  $J_c$  for crack initiation.  $J_c$  represents an initiation value that the blunted crack resharpenes for propagation. In the ASTM 813-87, the  $J$ - $R$  curve is fitted to a power

law,  $J = C_1 \cdot \Delta a^{C_2}$ , and the critical value is at the intersection of the power law and the line  $J = 2 \cdot \sigma_y \cdot \Delta a - 0.4\sigma_y$ . Therefore, the critical  $J$  value from the ASTM E813-87 represents an engineering definition rather than a physical event.

In last few years, these two ASTM Standards, originally designated for metals, have been extended to measure the fracture toughness of various ductile and toughened polymers and blends. Williams and co-workers applied the ASTM E813-81 version<sup>3</sup> to characterize the fracture toughness of several different grades of polyethylene (PE),<sup>6,7</sup> polypropylene (PP) copolymers<sup>8</sup> and nylon 6/6.<sup>9</sup> So and Broutman<sup>10</sup> investigated the compact specimen fracture toughness of high-impact polystyrene (HIPS) and acrylonitrile-butadiene-styrene (ABS) by using a  $J$ -integral technique (E813-81 version). Moskala and Tant<sup>11</sup> determined the fracture toughness of a copolyester/elastomer blend using the  $J$ -

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integral method (E813-81 version). Rimnac et al.<sup>12</sup> studied the fracture toughness of the ultrahigh molecular weight polyethylene (UHMWPE) by using the ASTM E813-87 method. Narisawa<sup>13</sup> studied the fracture processes of PE, PP, and PP-PE block copolymers by  $J$ -integral and experienced difficulty in obtaining the value of  $J_c$  for PE and PP from the blunting lines. Narisawa and Takemori<sup>14</sup> extended the study to several impact-modified polymers and raised the questions about the validity of the crack blunting line equation since the crack tip blunting was not being observed and the  $J_c$  obtained at the intersection points was higher than the real value corresponding to the actual subcritical crack growth directly observed on the polished side surfaces and suggested that the true  $J_c$  can be obtained by extrapolating the straight-line relationship for  $JR - \Delta a$  to zero crack growth. Huang and Williams<sup>15</sup> suspected the crack face may close due to plasticity-induced crack closure, completely obscuring any blunting of the crack tip. Huang<sup>16</sup> studied the *in situ* SEM crack growth on rubber-toughened nylon 6/6 and observed the crack tip blunting, but the growth process was not identical to that proposed for metals. Zhang and co-workers<sup>17</sup> were able to observe the crack blunting when they investigated the fracture behavior of ABS by two  $J$ -integral methods: the crack growth and the stress whitening. Yee<sup>18</sup> and co-workers employed the slightly modified version of E813-81 to investigate the core-shell rubber-modified polycarbonates and the  $J_{1c}$  of about 5.5 kJ/m<sup>2</sup> was obtained. Mai et al.<sup>19,20</sup> used the specific essential fracture work ( $We$ ) concept for toughness characterization of ductile polymers in plane stress conditions. Chudnovsky and co-workers<sup>21-25</sup> developed the crack-layer theory describing the crack propagation resistance in terms of material transformation preceding the crack tip (active zone) and applied it to several polymeric materials. Tung<sup>26</sup> reported that the development of crazes for the toughened semiductile linear amorphous polymers prevents the occurrence of general yielding and therefore the crack blunting. Barry and Delatycki<sup>27</sup> reported the effect of molecular structure on the fracture resistance of high-density polyethylene based on the  $J$ -integral.

In our recent study of the fracture toughness of the elastomer-modified polycarbonates,<sup>28,29</sup> we proposed a new  $J$ -integral method based on hysteresis and the  $J_c$ 's obtained were close to the results from the E813-81 method and/or the stress-whitening method, but were significantly lower than those from the E813-87 method. Recently, we also studied the fracture toughness of ABS<sup>30</sup> and the PC/ABS

blend<sup>31</sup> by comparing the  $J_c$ 's from three  $J$ -integral methods and very similar conclusions were obtained. Experimentally, this newly proposed  $J$ -integral method is relatively simple since the tedious measurement on crack growth length is not necessary. For this hysteresis approach to be generally applicable to all ductile and toughened polymeric materials, comparative tests on other toughened polymers must be carried out. In this paper, we compare the  $J_c$  values of HIPS obtained from the hysteresis method, ASTM E813-81, and E813-87 and their modified versions.

## EXPERIMENTAL

Commercial-grade high-impact polystyrene, Maxiflex 301, was obtained from BC Chemical Corp. of Taiwan. Injection-molded HIPS specimens with three dimensions, 20 × 90 × 10 mm, 20 × 90 × 12.5 mm, and 20 × 90 × 15 mm were prepared by an Arbory injection-molding machine. A starter crack of one-half of depth was made by using a saw cut followed by sharpening with a fresh razor blade. All the notched specimens were annealed at 60°C for 2 h to release residual stress prior to the standard three-point bending tests. The  $J$ -integral method was carried out according to the multiple-specimen technique outlined in ASTM E813-81 and ASTM E813-87 at ambient condition and at a crosshead speed of 2 mm/min and a span to width ratio of 4. Experiments were carried out by loading at a predetermined displacement, then unloading at the same rate by using an Instron Model 4201. Complete data on loading and unloading were recorded for hysteresis energy analysis. The crack growth length was measured at the center of the fracture surface using a traveling microscope by freezing the specimen in liquid nitrogen, then breaking open with a TMI impactor. The  $J$ -integral value for the three-point bend specimen with an  $S/W$  ratio of 4 is given by the following equation:

$$J = 2 \cdot U/B \cdot b \quad (1)$$

where  $U$  is the input energy, the area under the load vs. the displacement curve;  $B$ , the specimen thickness; and  $b$ , the ligament length. In the E813-81 method,  $J_c$ , the  $J$  value at the onset of crack propagation is determined by the intersection of the  $R$ -curve and the blunting line, which is defined by the following equation:

$$J = 2 \cdot \sigma_y \cdot \Delta a \quad (2)$$

The  $\sigma_y$  is the uniaxial yield stress and  $\Delta a$  is the crack growth length. Parallel to the blunting line and at an offset of 0.15 and 1.5 mm the minimum and maximum crack extension lines are drawn, respectively. In the E813-87 method, instead of a bilinear fit, the  $J$ - $R$  curve is fitted to a power law by the following form:

$$J = C_1 \cdot \Delta a^{C_2} \quad (3)$$

The critical  $J$  value,  $J_c$ , is now at the intersection of the power law and the line by the following equation:

$$J = 2 \cdot \sigma_y \cdot \Delta a - 0.4 \sigma_y \quad (4)$$

In this construction,  $J_c$  represents the  $J$  value necessary to grow the crack an additional 0.2 mm. The size criterion for the plane-strain suggested by ASTM in terms of  $J$  can be expressed by the following equation:

$$B, b > 25(J_c/\sigma_y) \quad (5)$$

where  $\sigma_y$  is the yield strength of HIPS (20 MPa).

## RESULTS AND DISCUSSION

### Fractographic Studies

Figure 1(a) shows a typical HIPS fracture surface ( $B = 10$  mm), where the crack growth length (between lines A and B) is nearly constant from the center to the skin of the specimen. A less defined crack-tip stress-whitening zone can be seen (between lines B and C), which is considered as the partially damaged precrack zone. Figure 1(b)–(d) shows the detailed SEM microscopic features of the crack growth, the stress whitening, and the undamaged zones. The crack growth zone [Fig. 1(b)] shows the characterization of localized shear yielding. The stress-whitening zone [Fig. 1(c)] reveals interior microscopic cracks beneath the fracture surface indicative of precrack damage through multiple crazes. The undamaged zone [Fig. 1(d)] shows typically the brittle fracture with flakelike structure.

### $J$ Data from ASTM E813-81 Method

In this paper, same-set data obtained from the multiple-specimen technique has been used in the E813-81, E813-87, and hysteresis methods. Table I summarizes all the data for the HIPS with  $B = 10$  mm.

Figure 2 illustrates the load-displacement curves from three different thickness specimens. The load maximum is increased with the increase of the specimen thickness, as would be expected. The crack initiations, defined as abrupt rising of crack growth length ( $\Delta a$ ) or the hysteresis energy, locate close but before the load maxima. Figure 3 shows the plots of  $J$ -integral values against crack growth lengths. The crack tip blunting line is drawn according to eq. (2). The  $R$ -line was determined by a linear equation of the regression of  $J$  on  $\Delta a$  by using only those data points that meet the criterion as shown in Figure 3. The  $J_c$ 's obtained from the intersection of the  $R$ -lines and the blunting line are essentially independent on specimen thickness. When the  $J$  values were determined at the intersection of the resistance curve with the  $y$ -axis as recommended by Narisawa and Takemori,<sup>14</sup> the  $J_c$ 's obtained were slightly lower (10–15%), as would be expected. However, the thinner specimen ( $B = 10$  mm) has a higher  $dJ/d\Delta a$  value than that of the thicker specimens ( $B = 12.5$  and 15 mm). The value of  $dJ/d\Delta a$  can be considered as the resistance of a material to stable crack extension. Paris et al.<sup>32</sup> showed that the resistance of a material to sudden unstable cracking after the commencement of stable cracking can be characterized by using the value of  $dJ/d\Delta a$ :

$$Tm = \frac{E}{\sigma_y^2} \frac{dJ}{d\Delta a} \quad (6)$$

$Tm$  is a nondimensional parameter called the material tearing modulus. Although the thicknesses of all three specimens are significantly higher than the size criteria suggested by the ASTM Standards according to eq. (5), the thinnest specimen still shows better resistance to stable crack extension.

### $J$ -Integral from ASTM E813-87 Method

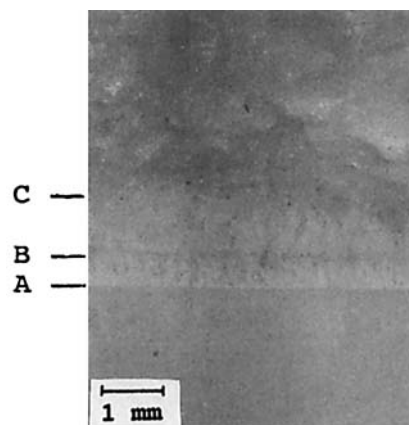
Plots of  $J$ -integral values vs. crack growth lengths for the three specimen sizes are shown in Figure 4. The power law regression of the data within the exclusion lines (0.15 and 1.5 mm) gave the following equations:

for  $B = 10$  mm,

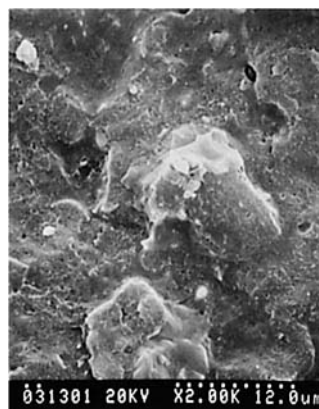
$$J = 189 \times (\Delta a \times 10^{-3})^{0.454} \quad (7)$$

for  $B = 12.5$  mm,

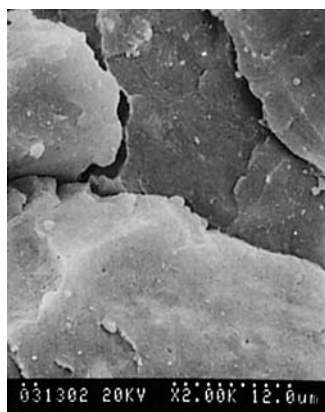
$$J = 184 \times (\Delta a \times 10^{-3})^{0.464} \quad (8)$$



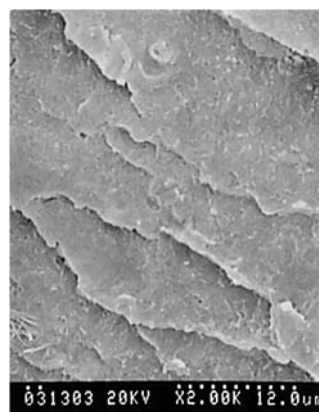
1a. Fracture with various zones



1b. Crack growth zone, between lines A and B



1c. Stress whitening zone, between lines B and C



1d. Undamaged zone, above line C

**Figure 1** Fracture surface for HIPS;  $B = 10$  mm: (a) fracture with various zones; (b) crack growth zone, between lines A and B; (c) stress-whitening zone, between lines B and C; (d) undamaged zone, above line C.

for  $B = 15$  mm,

$$J = 94 \times (\Delta\alpha \times 10^{-3})^{0.382} \quad (9)$$

The  $J_c$ 's (Table II) were determined from the intersections of the 0.2 mm offset line and these power regression curves. Validation of the  $J_c$ 's were evaluated using the size criterion expressed in eq. (5). For the HIPS employed in this study, the minimum  $b$  and  $B$  required to satisfy the criterion are between 5.4 and 6.2 mm. The thinnest specimen,  $B = 10$  mm, has a slightly higher  $J_c$  value but the difference is within experimental error. In direct comparison be-

tween these two ASTM methods,  $J_c$  values from the E813-87 method are about 20% higher than those from the E813-81 method. Only very limited comparative  $J_c$  data between E813-81 and E813-87 on polymeric materials have been reported. We found that the  $J_c$ 's from E813-87 for the elastomer-modified polycarbonates,<sup>29</sup> ABS,<sup>30</sup> and PC/ABS blend<sup>31</sup> are from 20 to 100% higher than those from E813-81. The  $J_c$  value obtained from the E813-87 method is generally greater than that from the E813-81 method for polymeric materials. If the 0.2 mm offset line specified in E813-87 is being reset at 0.1 mm and the rest of the procedures are unchanged,

**Table I Summarized  $J$  Data for HIPS ( $B = 10$  mm)**

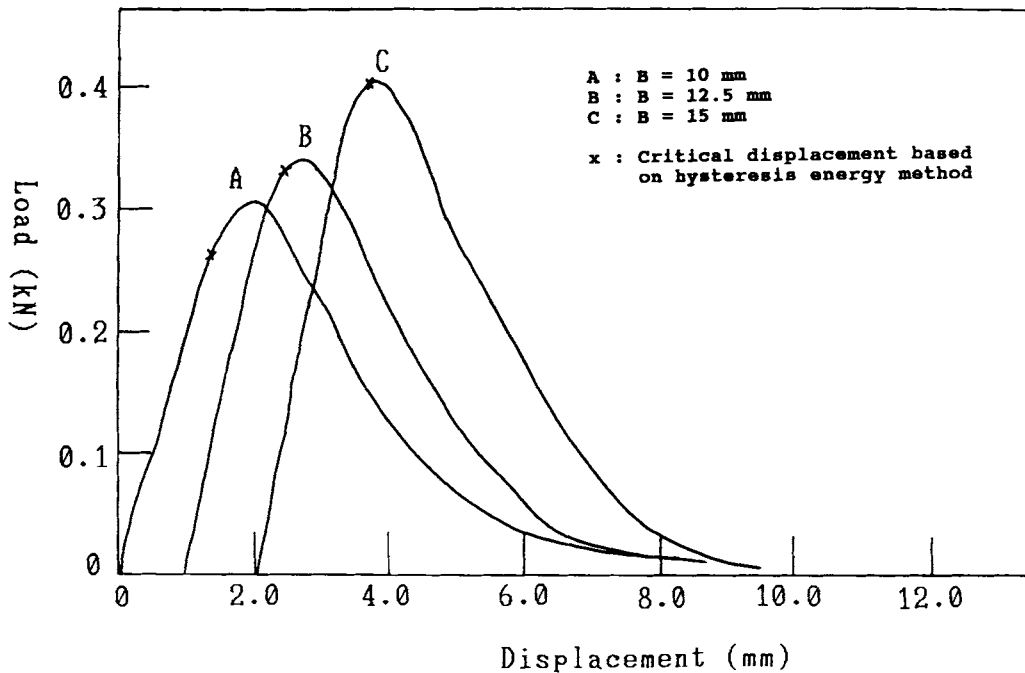
$D$ (mm)	$U$ (joule)	$J$ (kj/m <sup>2</sup> )	Hysteresis Ratio	Hysteresis ( $E$ , joule)	$\Delta a$ (mm)
0.6	0.032	0.64	0.096	0.003	0.024
0.7	0.042	0.84	0.088	0.004	0.028
0.8	0.055	1.10	0.087	0.005	0.035
0.9	0.067	1.33	0.110	0.007	0.040
1.0	0.074	1.48	0.105	0.008	0.048
1.1	0.116	2.32	0.110	0.013	0.080
1.25	0.144	2.88	0.144	0.020	0.120
1.3	0.148	2.96	0.157	0.023	0.130
1.4	0.163	3.26	0.190	0.031	0.150
1.5	0.209	4.18	0.245	0.051	0.220
1.6	0.223	4.46	0.250	0.056	0.300
1.75	0.284	5.68	0.350	0.099	0.400
1.9	0.338	6.76	0.380	0.128	0.600
2.0	0.358	7.16	0.410	0.147	0.760
2.3	0.400	8.00	0.580	0.232	1.000

the resultant  $J_c$  values obtained are now comparable to the results from the E813-81 method as shown in Table II. After all, the 0.2 mm offset line suggested in the E813-87 method is only an arbitrarily selected value used to define the  $J$  value to grow the crack by an additional 0.2 mm. Such a 0.2 mm offset line definition may be appropriate for most metals, but it appears higher than the results from E813-81 for

most polymeric materials based on the limited available information.

**$J$ -Integral by the Hysteresis Method**

The hysteresis energy defined in this paper is the energy difference between the input and the recovery in cyclic loading and unloading processes that may



**Figure 2** Complete load-displacement curves for HIPS with various thicknesses.

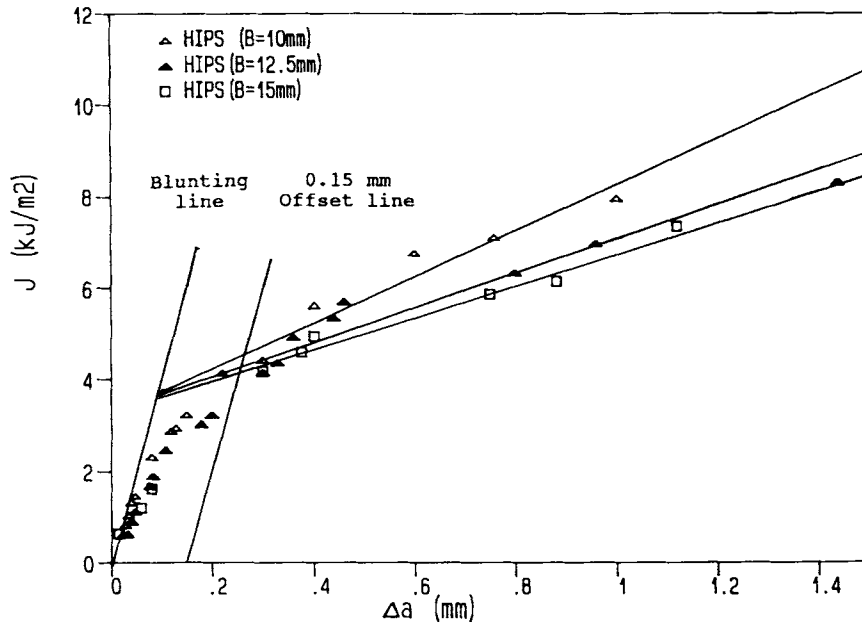


Figure 3  $J$ -integral curves according to ASTM E813-81.

be included during crack blunting or crack growth. The close relation between the precrack hysteresis and the corresponding ductile-brittle transition behavior of polycarbonate and polyacetal has been previously reported.<sup>33,34</sup> In our previous paper, we proposed a new approach to obtain  $J_c$  by assuming the  $J$  value at the beginning of a steep rising of the hysteresis energy under a constant rate of a displacement-controlled loading as the critical  $J$  value.<sup>28</sup> Since the measurement of crack growth length is no longer necessary by this approach, this

proposed hysteresis method is relatively simple. The  $J_c$  values of HIPS obtained by using this hysteresis method were very close to the results from the modified E813-81 method<sup>14</sup> by neglecting the crack blunting line (Table II). In direct comparison with the results from the ASTM E813-81 and E813-87 methods, the  $J_c$ 's obtained from this hysteresis method are about 15 and 30% lower, respectively. The experimentally measured hysteresis energy is believed to be higher than the true hysteresis energy at the starting point of unloading because of the

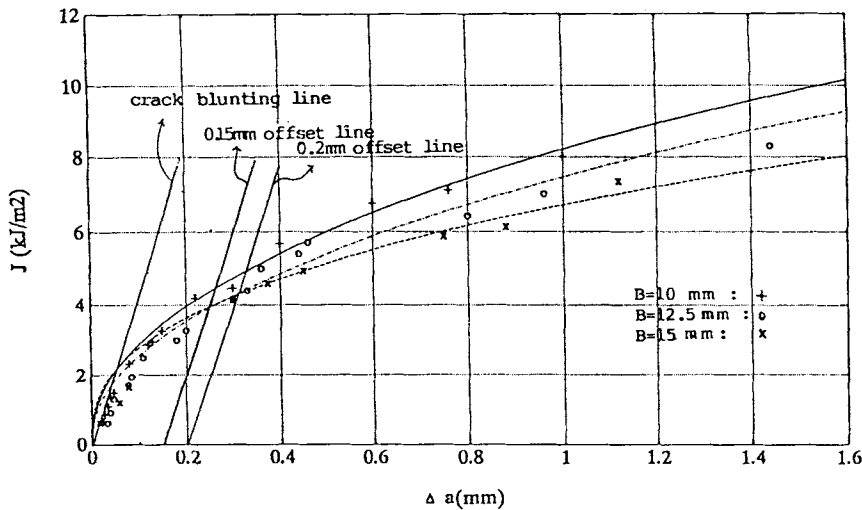


Figure 4  $J$ -integral curves according to ASTM E813-87.

**Table II Summarized  $J$  Data from Three Methods**

	$B$ (mm)		
	10	12.5	15
ASTM E813-81 method			
$J_c$ (kJ/m <sup>2</sup> )	3.8	3.7	3.6
$dJ/d\Delta a$ (MPa)	5.0	3.7	3.5
$J$ at $\Delta a = 1$ mm, kJ/m <sup>2</sup>	8.0 <sup>a</sup>	6.7 <sup>a</sup>	6.2 <sup>a</sup>
ASTM E813-81 by neglecting the blunting line $J_c$ (kJ/m <sup>2</sup> )	3.21	3.24	3.24
ASTM E813-87 method $J_c$ (kJ/m <sup>2</sup> )	4.9	4.3	4.3
ASTM E8123-87 with 0.1 mm offset line $J_c$ (kJ/m <sup>2</sup> )	3.8	3.3	3.5
Hysteresis energy method $J_c$ (kJ/m <sup>2</sup> )	3.3	3.2	3.0

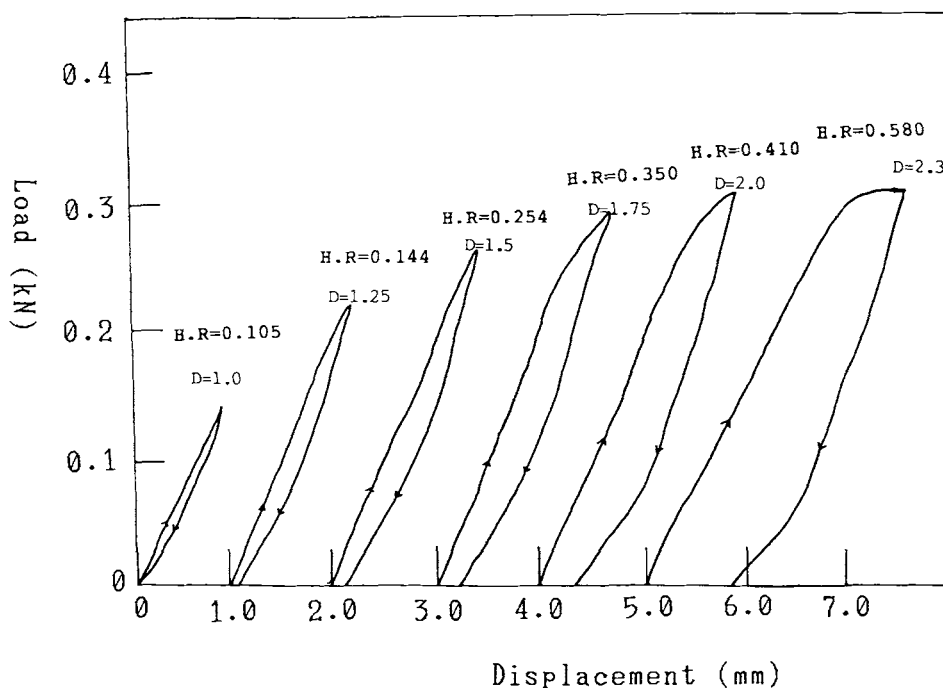
<sup>a</sup> Data estimated from the  $R$  lines of Figure 3.

time-dependent nature of polymers. It is impossible to obtain the true hysteresis energy at the end point of loading.

Figure 5 illustrates the hysteresis loops and their corresponding hysteresis ratios at various stages of displacements for the HIPS with  $B = 10$  mm. Both

the hysteresis ratio and the permanent displacement increase with the increase of loading displacement, especially near the transition range of crack initiation (between 1.25 and 1.5 mm). Figure 6 shows the plots of hysteresis ratios vs. displacements for the three thickness specimens, and the critical displacements for  $B = 10, 12.5,$  and  $15$  mm are 1.20, 1.45, and 1.59 mm, respectively. Figure 7 shows the plot of displacement vs. the corresponding hysteresis energy for the specimen  $B = 10$  mm, where the blunting line was constructed without using the three data points near the transition range and the critical displacement of 1.35 mm was obtained. Figures 8 and 9 are the similar plots with the specimen thickness of  $B = 12.5$  and  $15$  mm, and the corresponding critical displacements of 1.54 and 1.72 mm were obtained, respectively. The  $J_c$ 's determined from the latter (hysteresis energy) are higher than the former (hysteresis ratio) because of higher critical displacements, and our previous paper<sup>28</sup> employed the latter. For the purpose of direct comparison, a similar plot of the displacement vs. the crack growth length is shown in Figure 10 and the critical displacements of 1.36, 1.63, and 1.73 for  $B = 10, 12.5,$  and  $15$  mm were obtained, respectively.

By comparing the critical displacement results from these three methods, the hysteresis energy method and crack growth length method are better matched. Therefore, we decided to employ the hys-



**Figure 5** Hysteresis loops at various stages of displacements for HIPS;  $B = 10$  mm.

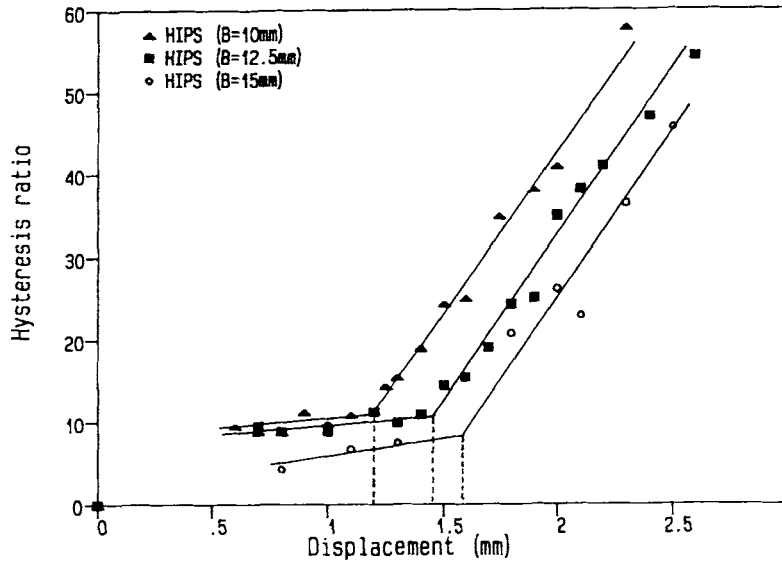


Figure 6 Critical displacements determined by hysteresis ratio.

teresis energy method to determine the critical displacement and  $J_c$ . This hysteresis method used to determine the critical displacement and  $J_c$  is actually equivalent to the crack growth length method by following the abrupt rise of the crack growth length except that the tedious measurements of crack growth lengths are not required. The major difficulty in this hysteresis method is the selection of valid data points to construct the bilinear lines. We decided to exclude the data points, if present, in the transition range in the blunting line con-

struction, as demonstrated in Figure 7. The definition of crack initiation is the beginning of a crack-tip extension when the crack blunting can no longer sustain the applied stress. So the critical  $J$  value based on the steep rising of either the hysteresis or the crack growth length can be considered as a physical event of crack initiation rather than as an arbitrary engineering parameter (E813-87) or as a theoretical predicted crack blunting equation (E813-81). The initiation based on the blunting-line approach (E813-81) can be considered as a physical

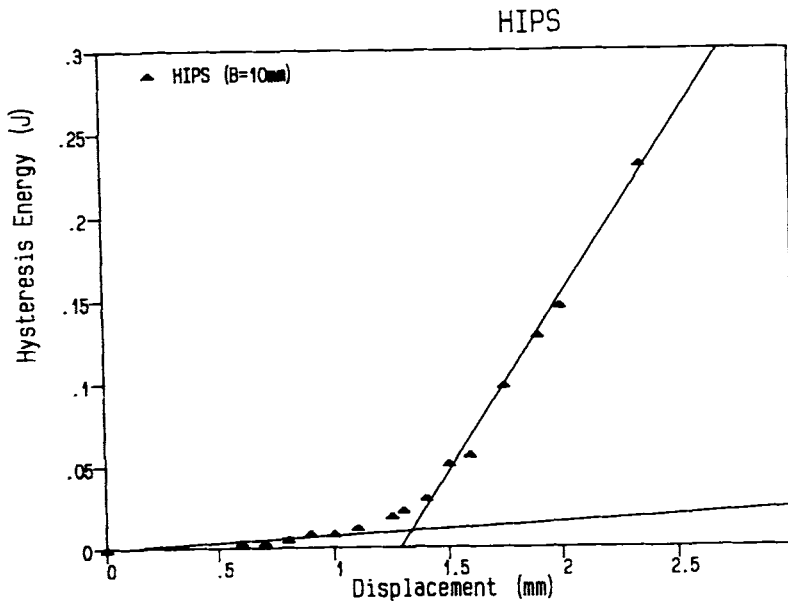


Figure 7 Critical displacement determined by hysteresis energy for HIPS;  $B = 10$  mm.



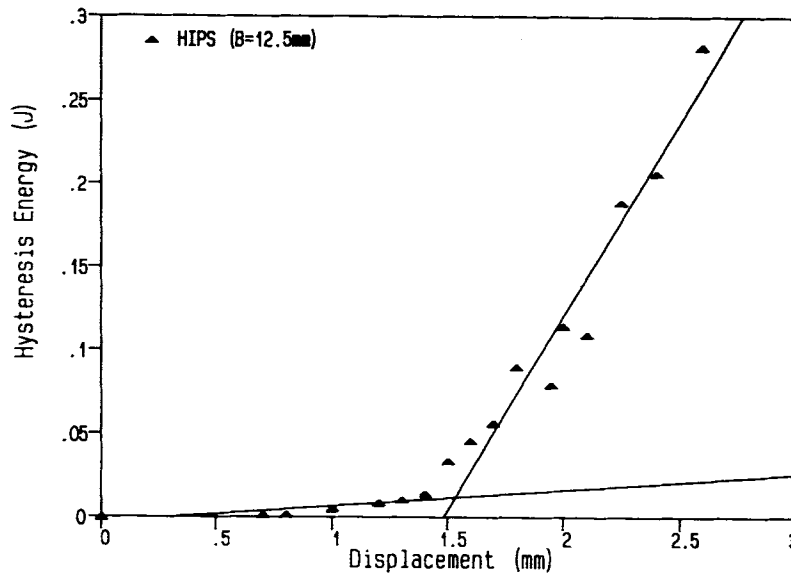


Figure 8 Critical displacement determined by hysteresis energy for HIPS;  $B = 12.5$  mm.

event; however, it is based only on the assumption that the crack tip follows the ideal crack-opening displacement (COD) theory.

The crack-initiation phenomenon is highly complicated and varied with types of polymers employed. The way of  $J_c$  determination from the E813-81 method tends to force the fracture behavior of essentially all the materials into a predetermined fashion. Therefore, the deviation from the true  $J_c$  for crack initiation in the E813-81 method may vary from material to material depending on how the real

crack-blunting phenomenon deviating from the theoretically predicted blunting-line equation.

Figure 11 demonstrates the first step in determining the  $J_c$  value by plotting the curve of displacements vs.  $J$  values. As soon as the critical displacement is determined by one of the three possible methods mentioned above, hysteresis ratio, hysteresis energy, or crack growth length,  $J_c$  can be determined readily. The critical displacements and the corresponding  $J$  values obtained from these three different methods are shown in Table III. Since the

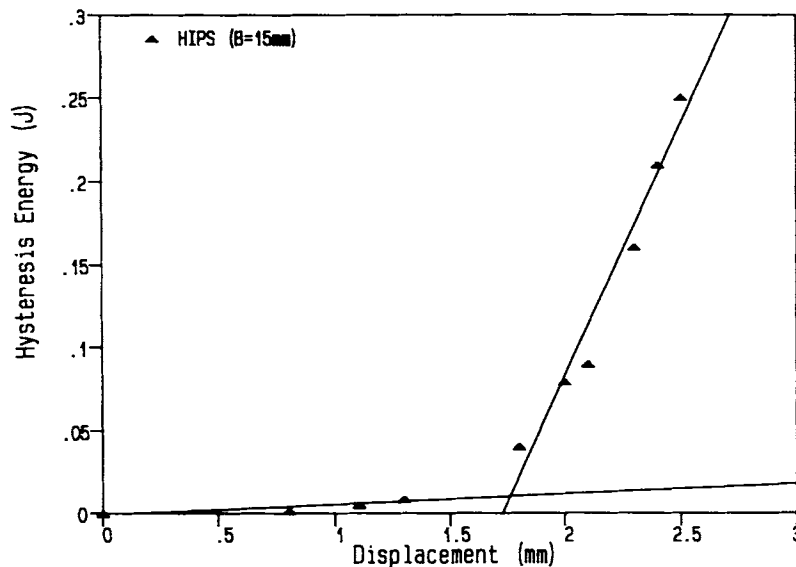


Figure 9 Critical displacement determined by hysteresis energy for HIPS;  $B = 15$  mm.

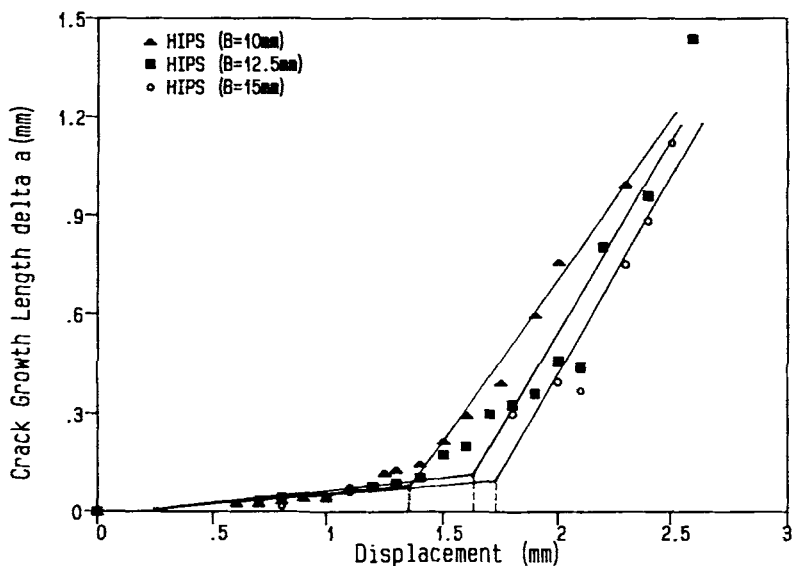


Figure 10 Critical displacements determined by crack growth length.

$J$  values or the critical displacements evaluated from the crack growth length match the results from the hysteresis energy better than do the results from the hysteresis ratio, we therefore prefer the hysteresis-energy approach in the  $J_c$  determination. Figures 12 and 13 demonstrate that the  $J_c$  determination by this hysteresis energy method can be carried out by combining these two plots into one. Figure 14 shows the plots of crack-growth length vs. hysteresis energy from all three thickness specimens. The linear relation between  $\Delta a$  and hysteresis energy ob-

served is quite interesting and this is why the critical displacements obtained by the crack growth length and by the hysteresis energy are about the same. This result indicates that the rate of hysteresis energy increase per unit area of the newly created surfaces ( $B \times 2\Delta a$ ) for the thinner specimen is higher than the thicker specimen (Table III).

If we assume the hysteresis energy due to the creation of unit area of new surface is equal, other types of energy dissipations such as crazes, plasticity, and rubber debonding must be higher for the thinner

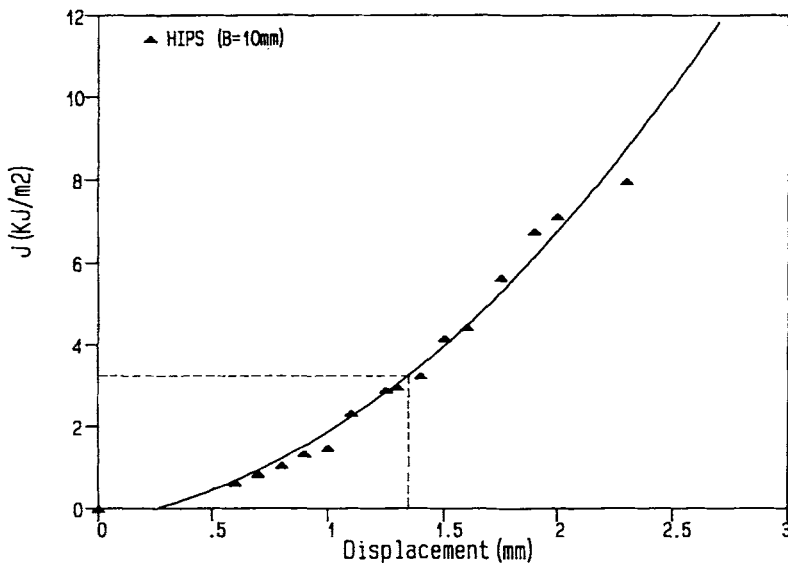


Figure 11 Determination of  $J_c$  from the  $J$  vs. displacement curve and the known critical displacement for HIPS;  $B = 10$  mm.

**Table III Critical Displacements ( $D_c$ ) Determination by Hysteresis Energy, Hysteresis Ratio, and Crack Growth Length for HIPS with  $B = 10, 12.5,$  and  $15$  mm**

	$B$ (mm)		
	10	12.5	15
By hysteresis energy			
$D_c$ (mm)	1.35	1.54	1.72
$J_c$ (kJ/m <sup>2</sup> )	3.30	3.18	3.01
$D_c$ , by hysteresis ratio,			
$D_c$ (mm)	1.20	1.45	1.59
$J_c$ (kJ/m <sup>2</sup> )	2.64	2.77	2.28
By crack growth length			
$D_c$ (mm)	1.36	1.63	1.73
$J_c$ (kJ/m <sup>2</sup> )	3.31	3.53	3.02
(Hysteresis energy) / $2B \cdot \Delta a$ (kJ/m <sup>2</sup> )	11.5	9.2	7.7

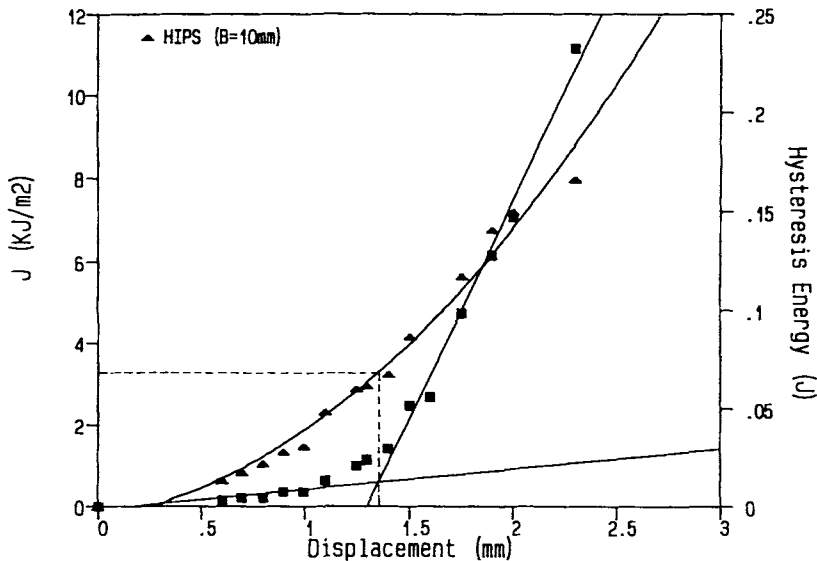
specimen. The thinner specimen has a relatively higher constituent of plane-stress, and more energy consumed in various dissipation processes is expected. The correspondingly higher value of  $dJ/d\Delta a$  (and  $T_m$ ) for the thinner specimen than for the thicker specimen obtained provides more evidence (Table II).

**Further Discussion**

The competition between crazes and general yielding (around the vicinity of crack tip) will determine the occurrence of material crack blunting proposed by

Tung<sup>26</sup> that is able to provide a partial answer to the controversy on crack blunting. Some materials with relatively lower crazing stress, classified by Tung<sup>26</sup> as the toughened semiductile linear amorphous polymers, tend to suppress the crack tip blunting through general yielding and, therefore, the  $J_c$  from the E813-81 is slightly overestimated. Some materials with relatively lower yield stress, classified as semiductile linear amorphous polymers, general yielding in the plastic zone take places and blunts the crack tip. Our previous report<sup>28</sup> on the elastomer-modified polycarbonates did show the occurrence of crack blunting. Polycarbonate, with lower yield stress relative to craze stress, is known for its easy-to-yield-than-to-craze feature<sup>35</sup> and the elastomer-modified PC also shows general yielding rather than crazes.<sup>36</sup> The nature of the matrix is more important in dictating the mode of the failure mechanism and certainly not all the toughened polymers are in favor of crazes as defined by Tung.<sup>26</sup>

Calculation of  $J$  values using eq. (1) in E813 methods is rather straightforward; however, the validity of eq. (1) applying in polymeric materials may still face yet another challenge in the future when more research data are available. At present time, arguments are concentrated mostly on how to define the critical  $J$  value to be more suitable and meaningful from the engineering viewpoint. ASTM E813-87, a modified version of E813-81, indeed removes some of the questions about the validity of the blunting-line equation, but its excessively higher  $J_c$  value relative to the E813-81 method in most polymeric materials may cause great concern in terms



**Figure 12** Determination of  $J_c$  for HIPS;  $B = 10$  mm.

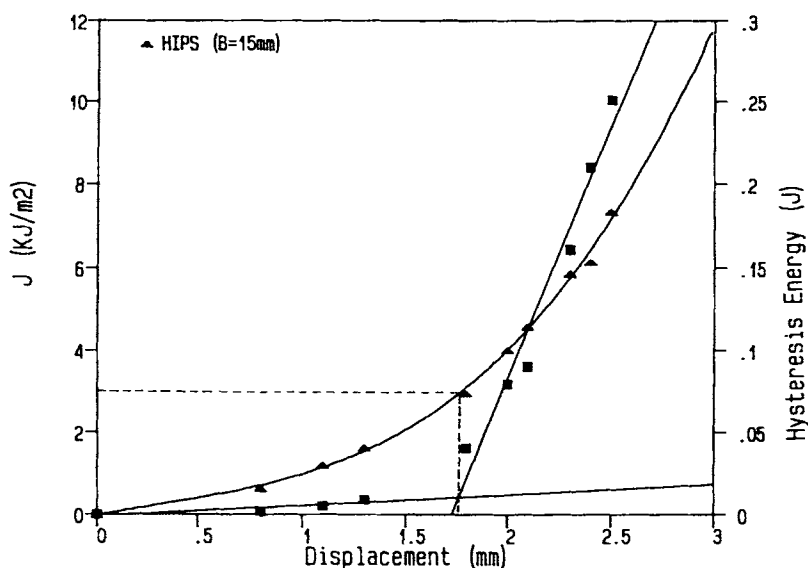


Figure 13 Determination of  $J_c$  for HIPS;  $B = 15$  mm.

of practical engineering design. In the four polymeric systems we have studied including PC,<sup>28,29</sup> ABS,<sup>30</sup> PC/ABS blend,<sup>31</sup> and HIPS, the  $J_c$ 's obtained according to the E813-87 method are from 20 to 100% higher than those obtained from the E813-81 method. Huang<sup>16</sup> reported that the  $J_c$  of the rubber-toughened nylon 6/6 was 15 kJ/m<sup>2</sup> from E813-81 and 38 kJ/m<sup>2</sup> from E813-87. Such tremendous discrepancy in  $J_c$  obtained from these two ASTM methods certainly will puzzle many engineering designers as to which one to choose.

The suggested 0.1 mm offset line for the E813-87 method can match the results close to the E813-81 method for most polymeric materials. For many metals and alloy steels, the two methods of analysis (i.e., E813-81 and E813-87) do not give very different  $J_c$  results. Direct application of these  $J$ -integral measurement techniques to characterize fracture toughness for ductile polymers is problematic as already pointed out by several investigators.<sup>14-16</sup> In addition to the question of the crack-blunting equation, many polymer-related properties such as vis-

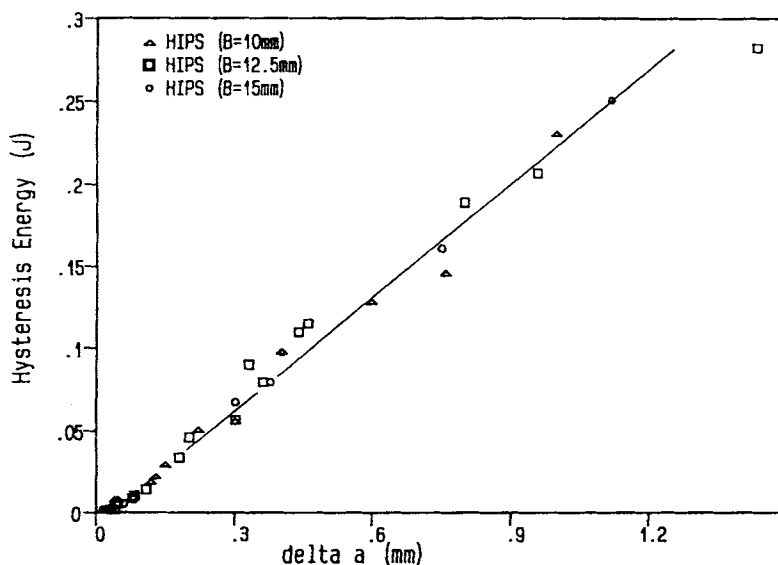


Figure 14 Relation between crack growth length and corresponding hysteresis energy for HIPS;  $B = 10, 12.5, \text{ and } 15$  mm.

coelasticity, plasticity, craze, rubber cavitation, and rubber debonding may also contribute to the observed difference. Essentially all the above-mentioned properties, by different degrees, relate to the hysteresis (loss) phenomenon.

Relatively little attention has been addressed to the subject of hysteresis in fracture mechanics and fracture behavior. Chudnovsky et al. described this irreversible deformation event in terms of a large zone of transformed material in their proposed crack-layer theory.<sup>21-25</sup> In this paper, we try to avoid the issue of  $J$  value calculation and concentrate on the subject of a better defined  $J_c$ . The implication of the abrupt sudden rising of the hysteresis ratio or the hysteresis energy due to crack initiation has its foundation as a physical event. The sudden increase of the hysteresis can be attributed to the potential energy release due to the crack extension and new surfaces formed. The  $J_c$  obtained from the hysteresis energy method (not the hysteresis ratio) is either close or slightly lower than that from the E813-81 method but significantly lower than that from the E813-87 method. Therefore, we believe that the E813-81 method, based on the theoretically predicted crack blunting line equation, may slightly deviate from the true  $J_c$  (in terms of onset of initiation) but that it is still more realistic than the E813-87. Huang<sup>16</sup> felt the E813-87 approach to be more promising than the E813-81 based on the smaller variability between laboratories, but failed to address the problems of the excessively higher  $J_c$  values.

Combining Tung's proposal<sup>26</sup> and the results from our studies, the controversy on crack blunting seems a little clearer now. Mass yielding around the vicinity of the crack tip dominates the failure mechanism for the elastomer-modified PC and crack blunting occurs as predicted by the crack blunting line equation. Therefore, the  $J_c$  values obtained from the standard E813-81 are comparable to the hysteresis energy method<sup>28</sup> and believed to be valid. HIPS is known for the multiple crazes failure mechanism and the standard E813-81 method is slightly overestimated by using the blunting line. When the  $J_c$  determination was carried out by neglecting the crack blunting line as shown in Table II,  $J_c$  values obtained were in the same range as the results from the hysteresis energy method. Therefore, this hysteresis method actually inherently adjusts for any effect arising from the crack blunting. Whether these two ASTM E813 Standards are appropriate for polymers still requires more investigation.  $J_c$  defined by using this proposed hysteresis approach is simple experimentally and avoids the blunting-line controversy.

## CONCLUSIONS

Three different  $J$ -integral methods, E813-81, E813-87, and the hysteresis, have been used to characterize the toughness of HIPS with different thicknesses. The  $J_c$  values were highest from the E813-87 method, followed by the E813-81 method, then by the hysteresis method. The modified version of the E813-81 method by neglecting the crack blunting line resulted in as close results as those of the hysteresis method. The original E813-81 method, predicting the formation of crack blunting, is applicable for polymers in that mass yielding is the dominant failure mechanism, such as for elastomer-modified polycarbonates. The modified version of E813-81 by neglecting the crack blunting is more appropriate for polymers known for crazes as the main failure mechanism, such as for HIPS. The original E813-87 method, using the 0.2 mm offset line, results in excessively high  $J_c$  values for most polymeric materials. The modified E813-87 method, using the 0.1 mm offset line, will give a more reasonable  $J_c$  value and still maintain the advantage of smaller variability. The proposed hysteresis method inherently adjusts for the occurrence of crack blunting and thus avoids the controversy of the blunting line issue. Besides, it is simple without the requirement of the tedious crack growth length measurement.

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