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Plane strain Essential Work of Fracture in SENB geometry at low and high strain rates of PC/ABS blends

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Abstract

The fracture parameters of PC/ABS blends rich in PC were determined both at high and low strain rate. The criteria postulated by LEFM (K_{IC} and G_{IC}) and EPFM (J_{IC}) were used and compared to the plane strain Essential Work of Fracture (We) using the SENB geometry. The results showed the relationships predicted between them. The ABS shows a reinforcing effect, both at high and low strain rate, until 15 % by weight of terpolymer. The expected fracture parameter variations with the increase of the strain rate were observed until 10 % by weight of ABS. From 15 % and on, except for PC-40, there is no change, suggesting an important modification of the ductile-brittle transition and/or a lower notch's sensitivity. The abnormal behaviour of the blend containing 40 % by weight of ABS could be attributed to the coalescent morphology obtained. The EWF concept is suggested as an alternative method or, at least, as a preliminary analysis of ductile fracture systems.

Introduction

A quantitative study on some polymer system's fracture presents certain problems since the same material may exhibit a wide range of behaviour depending of the stress/strain conditions applied. By one side, may show brittle characteristics associated to a linear relation between stress and strain and if there is some deviation, the "plastic zone" generated could be neglected if its small enough compared to the specimen dimensions. In those cases the Tensional (**K_C**) and the Energetic (**G_C**) criteria, suggested by the Linear Elastic Fracture Mechanics (**LEFM**), are applied.

The situation gets more complicated when the same material, in one set of test conditions - i.e. lowering the strain rate applied, presents an extensive plastic zone in the crack tip during its propagation, associated with ductile fracture. The parameters postulated by the Elasto-Plastic Fracture Mechanics (**EPFM**) are required, which in the case of plastic materials, the critical value of the J-integral (**J_C**) is the most used one. Some aspects of the method used still remain controversial.

First, the definition of a "critical" value, **J_C**: as an initiation value, like in the method suggested by ASTM E813-81; or as a simple definition with engineering design purpose like in ASTM E813-89 and the modifications proposed in 1991 by ESIS.

Secondly, the use of the "crack tip blunting line" concept ($J = 2\Delta a\sigma_y$), like in ductile metals, is questioned. According to *Narisawa and Takemori* [1] this concept does not describe properly the crack tip blunting process on plastic materials. They suggest a

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crack extension determination further than the limits proposed in the standards mentioned before. In this case a J value of "real" initiation (**J_o**) is obtained.

Another problem comes at high strain rates (impact) test when, technically, the totally "controlled and monitored" crack extension measurements are difficult. In this case an easier analysis could be applied: *The Essential Work of Fracture* (**EWF**).

Essential work of fracture (EWF)

Initially, the EWF concept was developed for metals but recently it has been used on plastic materials, specifically on polymeric films. The idea, postulated by Broberg, is based on the fact that when a ductile solid containing a crack is loaded, the plastic deformation takes place in an outer zone surrounding the real crack or fracture process zone [2,3].

Thus, the Total Work of Fracture (**W_f**) is expressed as the sum of an Essential Work component (**W_e**) dissipated in the formation, deformation and rupture of the zone preceding the crack, and a Non-essential (**W_{ne}**) component dissipated in the external zone which depends on the volume of the necked zone. Thus, the specific total fracture work (ω_f) can be expressed as:

(1) $$\omega_f = \omega_e + \beta\omega_p(B(w-a))$$

where ω_e and ω_p are the Essential Work of Fracture per unit of ligament length and the Non-essential or Plastic Work per volume unit respectively. β is the shape factor describing the plastic zone size. B, w and a are the specimen thickness, width and initial crack length respectively. When ω_f vs. (w-a) is plotted and a linear regression applied, at least when an appreciable plastic deformation is generated, the Y-axis intercept gives ω_e and the slope $\beta\omega_p$.

For a valid analysis by this model ω_e, ω_p and β must be independent of the ligament length, which is satisfied when the generated stress state is unique and uniform. In this case the necked zone area (A_{dzp}) follow the relation [3]:

(2) $$A_{zd} = \beta(w-a)^2$$

The **EWF** analysis has been used with Deeply Double Edge Notched Tension (DDENT) samples, so that a uniform ***plane stress*** condition can be satisfied, with low requirements on sample dimensions [4]. Nevertheless, *Priest and Holmes* [5] have applied this concept in a wide range of specimen geometries, at high and low strain rate, to characterise the ductile fracture of linepipe steel. They reported a plane stress ω_e value independent of the sample geometry used.

Whereas the ω_e determined in the conditions described before may be a useful property, the main interest of the fracture behaviour remains in the ***plane strain*** state, where fracture conditions are more severe. In this case ω_e could be related to the Energetic parameters proposed by **LEFM (G_C)** and **EPFM (J_C)**.

ω_e and J-integral critical value (J_c) correlation

Considering that the J-integral variation with stable crack extension in the small extension region could be expressed by [1]:

(3) $$J = Jc + \left(\frac{dJ}{da}\right)\Delta a$$

Mai and Cotterell [6] suggested a "term by term" comparison between equations (1) and (3). Their comparison is based on the similar sense of the vectorial equation components postulated by Rice for the J-Integral definition [7] and the derived one for the EWF [6]. Thus:

(4) $$J = \omega_f \quad ; \quad \beta\omega_p = \alpha\frac{dJ}{da} \quad ; \quad \omega_e = Jc$$

where α is a constant depending on the specimen geometry.
The geometrical conditions for a ***plane strain*** state can be extrapolated from those used for the application of the J-Integral concept using SENB specimens, with a/w between 0.4 and 0.6 [8]. Thus:

(5) $$B, (w\text{-}a), a > 25(\omega_e/\sigma_y)$$

Experiments on several ductile polymers using the J approach and the EWF analysis have supported these relations [2,3].

ω_e and G_c correlation

For systems which do not present an important plastic deformation during fracture, ω_p is almost 0, therefore the second item of equation (1) could be neglected. In this case the energy wasted in the crack opening process (U_f) can be formulated using the Critical Crack Tip Opening Displacement concept **(CTOD)**:

(6) $$U_f = CTOD * \sigma_c[B(w-a)]$$

Taking σ_c as the stress at crack initiation and considering the equivalence between **CTOD** and **G_{IC}** criteria, we have:

(7) $$G_{IC} = \lambda * CTOD * \sigma_c$$

According to *Brown and Srawley* [9], λ must be 2 in order to make valid comparisons with LEFM, thus:

(8) $$\frac{2U_f}{B(w-a)} = G_{IC}$$

Comparing with equation (1), in which the plastic term is neglected, we have:

(9) $$2\omega_f = 2\omega_e = G_{IC}$$

The main objective of the present study, is to evaluate the applicability of the ***plane strain*** **Essential Work of Fracture** concept in SENB geometry, both at high and low strain rates, on Polycarbonate (PC)/Acrylonitrile-Butadiene-Styrene (ABS) terpolymer blends in the PC rich range.

Experimental

The blends were prepared in an injection machine ($T_{injection}$= 280°C) employing a Bisphenol A Polycarbonate (PC) (MFI = 12,35 g/10 min at 300°C/1,2 kg) and an Acrylonitrile-Butadiene-Styrene (ABS) "Core Shell" terpolymer (MFI = 22,25 g/10 min at 220°C/10 kg) containing 24% by weight of Styrene-Acrylonitrile copolymer (SAN) and 6% by weight of Butadiene. The blend's range composition in weight basis were: PC/ABS: 95/5, 90/10, 85/15, 80/20, and 60/40. Along this paper the following terminology will be used: **PC-X**, with **X** representing the ABS by weight proportion of the blend.

All the tests were carried out at room temperature (22 ± 2 °C) on prismatic bars (6 x 13 x 65 mm) with SENB geometry. The sharpening of the mechanised V notches was made by pressing the root of the notches with a fresh razor blade.

G_{IC} was determined following the EGF 1990 protocol [10] with the multiple specimen technique, varying the normalised crack lengths (a/w) from 0.27 to 0.57. The J-integral initiation values (**J_o**) were determined following the methodology suggested by *Narisawa and Takemori* [1] using at least 15 specimens with a/w = 0.5. In the **EWF** tests the same geometry and a/w range as in the **LEFM** tests were used.

The high strain rate determinations were done in an instrumented impact Charpy equipment with an effective impactor mass of 2.508 kg, a distance between the supports of 50.8 mm and a velocity at the impact moment of 1.06 ± 0.02m/s ($\approx$ 150 s^{-1}) which produced the minimal dynamics effects in our tests.

The low strain rate tests were carried out in a universal testing machine in the three point bending configuration, with a crosshead speed of 1mm/min. (0.03 min^{-1}), and a span of 50.8 mm between the supports.

The amount of energy absorbed in all tests was calculated by computational integration of the Load-Load point displacement plots. In each case, use was made of the methodology for energy correction by indentation as described in [10].

The observed whitening zone area, associated to the plastic deformation, was quantified using the equation of the ellipsis area:

$$A_{dpz} = \pi xy \qquad (10)$$

with the major axis (x) been the ligament length (w-a) and the minor axis (y) the averaged whitening zone height of the zone taken as the sum of the height from each broken half at the midway of the ligament length. In all the cases the measurements were carried out on perpendicular slides from the fracture surface plane of the central zone, and viewed, each side, on an optical travelling microscope.

Results

Shape factor (β) determination

The parameters obtained from the linear fits of the Log A_{pdz} vs Log (w-a) plots for each blend composition both at high and low strain rates are summarised in Table 1. It is noted that there is a very good fit, with a slope near to 2 as was predicted in equation 2. This fact suggests that the shape factor (β) of the plastically deformed area does not depend on the ligament length for this specimen geometry, so it could be expected that the graphic representation of equation 1 would be linear.

Fracture parameters at low strain rate (0.03 min^{-1}):

Figure 1 shows the ω_f vs. (w-a) plots used for the determination of ω_e and $\beta\omega_p$. The results are shown in Table 2 together with the J_o and dJ/da (slope of the linear fit of de J-Δa as indicated by ASTM E813-81) determined at the same strain rate. An excellent approach among both "initiation" parameters (ω_e and **J_o**) can be observed, therefore the proposed relationships (equation 4) seems to be correct for the geometry employed.

Attention must be paid to the parameters obtained in PC. The observed slope from the ω_f vs. (w-a) plots was very small (almost 0), indicating a plastic work or a "non-essential" work practically negligible. This situation suggests that the system has a linear-elastic behaviour, so the relation 9 should be applied. The value obtained not only verifies the dimensional requirements (equation 5) but is coherent with the values reported by *Kinloch* (3.7 kJ/m^2) [11] and *Williams* (3.5 kJ/m^2) [12] at similar test conditions, taking into account the possible differences concerning Young's modulus and molecular weight.

Table 1: Linear fit parameters for the Log (A_{dpz}) vs. Log (w-a) plots. r^2: Correlation coefficient.

	150 s^{-1}			0.03 min-1		
Blend	Slope	r^2	β	Slope	r^2	β
PC-5	----	----	----	1.918	0.9813	0.3170
PC-10	----	----	----	2.036	0.9617	0.2549
PC-15	1.963	0.9950	0.2049	2.034	0.9930	0.2261
PC-20	1.987	0.9779	0.1649	2.060	0.9952	0.2252
PC-40	----	----	----	2.088	0.9626	0.2249
100	2.060	0.9779	0.1284	1.977	0.9346	0.1648

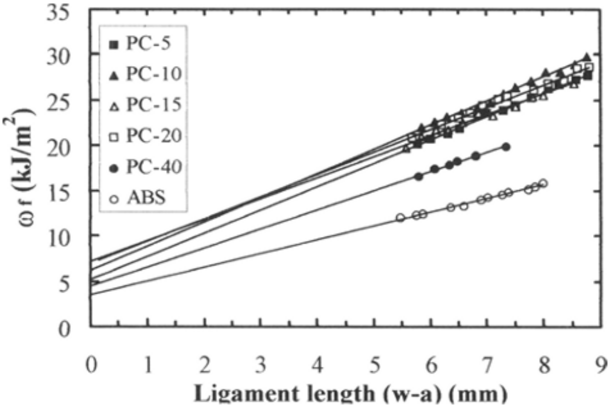

Figure 1: ω_f vs. (w-a) plots at 0.03 min^{-1}.

Table 2: ω_e, $\beta\omega_p$, J_o and **dJ/da** at 0.03 min^{-1}. r^2: Correlation coefficient (**): is the $2\omega_e$ value. (*) calculated by equation 5.

Blend	ω_e (kJ/m^2)	$\beta\omega_p$ (kJ/m^{2}mm)	r^2	ω_p (kJ/m^{2}mm)	J_0 (kJ/m^2)	dJ/da (kJ/m^{2}mm)	B,(w-a),a (mm)*
PC	3.02**	0.0987	0.9906	-----	-----	-----	1.31
PC-5	5.53	2.5269	0.9958	7.97	5.55	10.136	2.18
PC-10	6.75	2.5864	0.9915	10.15	6.75	13.628	3.06
PC-15	7.26	2.4197	0.9920	10.70	7.21	14.581	3.46
PC-20	6.69	2.5035	0.9923	11.12	6.65	14.890	3.14
PC-40	3.69	2.2271	0.9874	9.90	3.70	14.519	1.86
ABS	2.97	1.599	0.9936	9.70	2.95	12.059	2.16

Fracture parameters at high strain rates (150 s^{-1}):

As it was expected, the slopes of the ω_f vs. (w-a) plots for the systems with brittle fracture (PC, PC-5 and PC-10) were practically zero. Table 3 shows the critical energetic LEFM parameter in plane strain state (**G_{IC}**) for the compositions which allow its application, and the ω_e values to all of them. The relationship observed between them is nearly 2, in accordance with the relation derived previously (equation 9).

The plane strain state geometrical requirements (equation 5) were calculated considering the *yield stress* (σ_y) estimated at 150 s^{-1} by applying the Eyring model [13] with the values obtained in tensile tests made at crosshead speeds between 1 and 500 mm/min. As can be seen all compositions fulfil these requirements.

The blends PC-15, PC-20 and the ABS reported reasonable values in ***plane strain*** state conditions. Thus, these values can be interpreted as the critical energy realised for the crack propagation in a stable way equivalent to a **J_o** value.

For PC-40 the Load-Time curve obtained showed an initial linear part until the maximum load, followed by a sudden drop and a characteristic "ductile" propagation (Figure 2). In this case the maximum load level reached in the initial part of the curve has been used as the characteristic point. As can be noted, a correlation between ω_e and **G_{IC}** is observed.

Discussion

Results validation

The evidence obtained by applying the **Slipline Field Theory** in SENB geometry and determining **J_o** to all the blend composition values [14], indicate that the crack propagates before the plastic collapse (maximum load registered), which wouldn't validates the use of the Essential Work of Fracture concept in our systems.

Nevertheless, *Hashemi and O'Brien* [15] applied satisfactorily this concept in *Polyether Ether Ketone* (PEEK) DDENT films, where crack propagates before the maximum load. When the maximum load was reached, the ligament length presented a considerable extent of plastic deformation, as in our case.

Keeping in mind this situation, and the fact that there was a very good graphical fitting between our experimental data and the equation 1, and that the ω_e and **J_o** values were similar, it can be affirmed that, at least concerning the PC/ABS blend range studied and the geometry used, the Essential Work of Fracture analysis could be valid.

Table 3: ω_e, $\beta\omega_p$ and **G_{IC}** at 150 s^{-1}. (*) From the energy at maximum load in the initial linear zone of the Load-Time curve.

Blend	ω_e (kJ/m^2)	$\beta\omega_p$ (kJ/m^2.mm)	ω_p (kJ/m^2.mm)	G_{IC} (kJ/m^2)	B, (w-a), a (mm)
PC	1.10	-----	-----	2.20	0.72
PC-5	1.46	-----	-----	2.90	1.07
PC-10	2.12	-----	-----	4.20	1.58
PC-15	7.23	1.9698	9.61	----	2.65
PC-20	6.63	2.4472	14.84	----	3.06
PC-40	2.78*	-----	-----	5.50*	2.20
ABS	3.12	2.1060	16.41	----	3.47

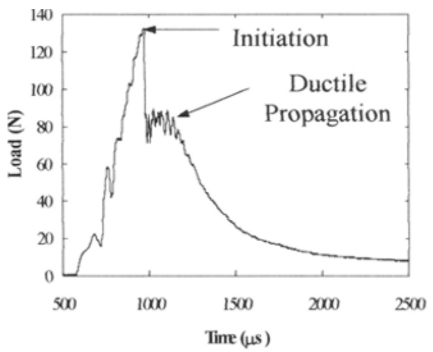

Figure 2: Load-Time curve obtained by Instrumented Charpy Impact Test for the blend PC-40.

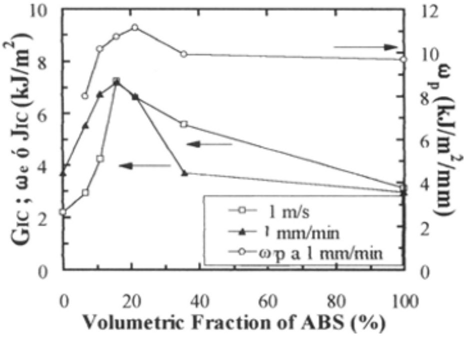

Figure 3: Variation of the fracture parameters with the composition's blend (% by weight of ABS).

It must be noted that in order to make the linear fits in the plots ω_f vs. (w-a), the selected ligament lengths range (w-a) was the one where the geometry was "mechanically stable", i.e. the plots of Total Fracture Energy by unit thickness (U_f/B) vs.(w-a) was linear.

According to *Williams* [16] in highly ductile systems the geometry will be mechanically unstable when the total fracture energy (U_f) increases suddenly as a consequence of an instability in the crack propagation. In these cases the plots U_f/B vs (w-a) present important deviations from linear behaviour, and usually occur at two extreme regions:

a) At very large (w-a): attributed to the decreased stress concentration due to a large amount of plastic deformation around the small initial crack. This situation correlates to a/w smaller than 0.26 in a SENB geometry.

b) At extremely small (w-a): attributed to the insufficient space around the crack tip for the plastic deformation.

General behaviour of blends

The tendencies obtained in the range of blend compositions (Figure 3), show an increase in the critical energy for crack propagation until PC-15, for both strain rates. The ABS reinforcing effects seems to lose effectiveness when it reaches 40% by weight in the blend where a drop of the value under the expected limits is seen. This could be attributed to the coalescent morphology obtained [14] which causes a non-uniform stress distribution between the phases lowering the mechanical effectiveness of the blend.

While between 15 and 20% of ABS there is a decrease on the energy consumed for crack initiation, a Non-essential Work of Fracture (ω_p) increase is observed. It could be related with an increase of the value dJ/da associated to the propagation resistance of the crack [17]. Both observations reveal a higher work for the crack propagation rather than initiation concerning this composition.

Comparing the energy consumed for crack initiation (ω_e or J_o) at high strain rates with those at low strain rates, the compositions poorer in ABS contents (PC, PC-5 and PC-10) show a decrease when strain rate is increased, as a consequence of the viscoelastic nature of the systems. From 15% of ABS and on (except for blends PC-40) it was observed that variations caused by a strain rate increase were not noticeable, suggesting that the notch's sensibility, compared to the others systems, is lower and/or that the ductile-brittle transition suffers an important modification.

The increase observed in the energetic parameter (ω_e or G_{IC}) at impact rates ($\approx 150\ s^{-1}$) compared to the low strain rates ($0.03\ min^{-1}$) for PC-40 may be related to the morphologic situation. Probably the adiabatic heating, as a consequence of the low heat capacity inherent to the polymerics systems and the high crack's propagation rate, could be more effective than in the other blends in the decrease of the local yield stress of the susceptible phase (ABS), raising the amount of energy required for the crack propagation.

Conclusion

At a first sight the geometric conditions used violate the dimensional requirements for an accurate application of the EWF analysis. Nevertheless, since the necked zone shows the expected dependence with the ligament length and the similarity of the values obtained with the values estimated by the application of the traditional methods (G_{IC} and J_O), it can be considered that the results obtained are valid. Thus, it is offered an alternative way of evaluating crack parameters when LEFM can not be applied and the J0 criteria present technical difficulties of evaluation.

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