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The application of the essential work of fracture methodology to the plane strain fracture of ABS 3-point bend specimens

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Abstract

The applicability of the EWF methodology to 3-point bend (SEB) specimens under conditions other than plane stress has been assessed experimentally. Different fracture conditions, pure plane strain and plane strain/plane stress transition, were obtained by varying the specimen thickness and testing temperature (20 and 80 °C). Post-mortem fracture surfaces appeared always completely stress-whitened, indicating ductile fracture. The load–line displacement plots are similar over a well-defined range of ligament lengths for which the application of the EWF methodology was in principle possible. Nevertheless, in experiments conducted at room temperature, crack growth was observed to initiate before maximum load and complete ligament yielding. This behaviour was confirmed through plastic collapse analyses. A critical ligament length was found, over which the total specific work of fracture was dominated by edge effects. Below this critical ligament length, EWF methodology was still applicable and it was possible to extrapolate reliable w_{Ie} values.

Keywords: Essential work of fracture applicability; ABS; Plane stress–plane strain regime

1. Introduction

The essential work of fracture method (EWF) is a sound methodology to characterize the fracture toughness of polymers films, ductile metals, paper sheets and fibrous composites under plane stress conditions [1–6]. The simplicity of the EWF approach is the main reason why the method has gained so much popularity in recent years for evaluation of fracture toughness of ductile polymers as a simpler alternative to *J*-integral analysis. The experimental measurement of the EWF is fairly easy since it simply consists of the determination of the total fracture energy of several samples differing in initial ligament length, and the linear regression of these data. In contrast with the *J*-approach, the EWF does not involve the detection of the onset of cracking and the interruption of the test.

It is of interest in many cases to characterize the fracture toughness under plane strain conditions and to extend the EWF methodology to conditions other than plane stress. This topic has been extensively studied during recent years with results published on the applicability of the EWF to the plane stress/plane strain transition and pure plane strain regimes [2,7–9] and high-rate impact testing [10–13]. The EWF methodology can be applied to conditions other than pure plane stress, provided the specimen ligament is fully yielded at initiation in geometrically similar specimens. Under these conditions, the specific EWF is a material constant and independent of the specimen geometry, but not necessarily independent of thickness. However, whether the requirements have been completely satisfied has not always been strictly demonstrated.

The present work examines the applicability of the EWF methodology to ABS SEB specimens of different thickness at 20 and 80 °C under quasi-static loading conditions.

2. The essential work of fracture methodology

When yielding precedes the fracture of a specimen and

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slow crack growth, though the total specific fracture work is not a material constant, there is an inner process region, where the specific work is a constant [14]. The work in this inner region has been termed the essential work, W_e, and the work in the shielding outer process region, the non-essential work, W_p, these two components can be separated by a series of experiments on geometrically similar specimens [1].

The applicability of the EWF methodology relies on the following conditions and assumptions: (1) the ligament should completely yield prior to fracture initiation; (2) the essential fracture work W_e inside the inner fracture process zone is proportional to the ligament length, l; and (3) the plastic work W_p in the outer process zone should be proportional to the square of the ligament length, l^2. Thus, the total work of fracture W_f can be written as:

$$W_f = W_e + W_p \tag{1}$$

Dividing Eq. (1) by the ligament area, lB, (where B is specimen thickness), yields [1]

$$w_f = w_e + \beta w_p l \tag{2}$$

in which w_f is the specific fracture work, w_p is the specific plastic work and β is the geometrical shape factor for the outer plastic zone. When plane stress conditions prevail for all ligament lengths, it is further assumed that w_e is a constant dependent on thickness. Hence, the essential work of fracture can be separated from the non-essential.

When the ligament l is large, a situation that is usually given by the condition

$$l \geq (3-5)B, \tag{3}$$

and the thickness, B, is small

$$B \ll 25 w_e/\sigma_y \tag{4}$$

where σ_y is the yield strength, the fracture is plane stress. In this case, the specific essential work of fracture is dependent on the thickness. On the other hand, if the thickness B is large

$$> B \geq l$$
$$\geq 25 w_e/\sigma_y \tag{5}$$

the fracture is plane strain and the specific essential work has its plane strain value w_{Ie} [1,2,8,15,16]. The specific work of fracture variation with ligament length has two forms shown schematically in Fig. 1. If the two conditions for plane stress fracture given by Eqs. (3) and (4) are satisfied before the ligament ceases to yield completely before fracture initiation, then a transition from plane strain to plane stress is seen as shown in Fig. 1(a). In this case, the extrapolation to zero ligament length to zero is uncertain and both linear and power curve fitting have been proposed [7–9]. However, if the ligament ceases to be yielded completely before the conditions given in Eq. (5) are violated, then Fig. 1(b) applies. In this case, it is argued that since the deformation is similar, the extrapolation should be linear and the specific essential work is the plane strain value [17,18].

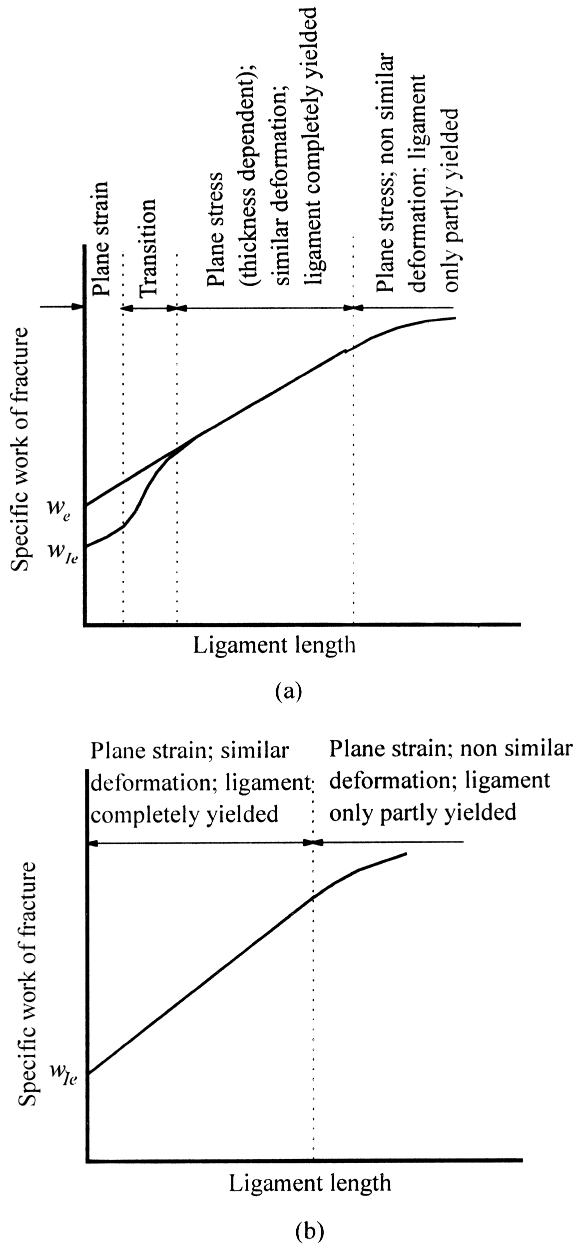

Fig. 1. Sketch showing the variation of the total specific work of fracture with ligament length and the plane stress and plane strain regions. (a) Deformation transition from plane strain to plane stress before ligament ceases to be completely yielded. (b) Ligament ceases to be completely yielded before transition from plane strain to plane stress.

3. Experimental procedure

Experiments were conducted on a commercial acrylonitrile–butadiene–styrene terpolymer, Lustran ABS-740 manufactured by General Electric. Pellets were compression moulded into thick plates at 200 °C and 4.3 MPa and then rapidly cooled with running water. The plates were

Table 1
Material properties

T (°C)	E (MPa)	σ_y (MPa)
20	1625	42
80	900	22

then annealed in an oven for 3 h at 90 °C to release residual stresses generated during moulding. Samples for subsequent mechanical characterization were machined from the plates. Mechanical tests were carried out in an Instron 4467. Tangent elastic modulus, E, and yield stress, σ_y (taken at maximum of load–displacement trace), were determined by uniaxial tension tests on dumb-bell shaped specimens at strain rates comparable to those at fracture initiation in the notch bending tests (Table 1). The initial bending nominal strain rate, $\dot{\varepsilon}$, was estimated from the displacement rate, $\dot{v}$, in the bend tests assuming that the strain is linear across the notched section using the relationship

$$\dot{\varepsilon} = \frac{6W}{S^2}\dot{v} \tag{6}$$

where S is the span of the bend test.

Fracture characterization was performed on single-notched specimens deformed in 3-point bending. The specimen span, S, and width, W, were kept constant at 56 and 14 mm, respectively. Specimens of 7 mm thick were tested at 20 and 80 °C; also specimens of 4 mm thick were tested at 80 °C. Sharp notches were introduced with a razor blade with a tip radius of 0.13 μm. A V-notch 1 mm deep was machined at the compression side opposite to the sharp notch to avoid excessive plastic hinging. Tests were performed at constant crosshead speed of 2 mm/min. The specimens were bent until complete failure and the total work of fracture was calculated from the integration of the load versus displacement data. Two test temperatures were used; 20 and 80 °C.

4. Results and discussion

Load–displacement curves for 7 mm thick specimens tested at 20 °C and for 4 and 7 mm thick tested at 80 °C, corrected for indentation effects [19], are shown in Fig. 2(a–c). Slip line theory gives a limit load for a rigid-plastic material in terms of the plane strain yield strength ($1.155\sigma_y$). The maximum load normalised by the specimen thickness, B, and the yield strength, σ_y, is compared with the slip-line field solution obtained by Wu et al. [20] in Fig. 3. For specimens tested at 80 °C, the normalised maximum load is either equal to the slip line field solution or only a little less indicating that the ligament was probably completely yielded before crack initiation. However, the normalised maximum load for the specimens tested at 20 °C is significantly less than the slip-line field solution indicating that the ligaments had not been yielded completely

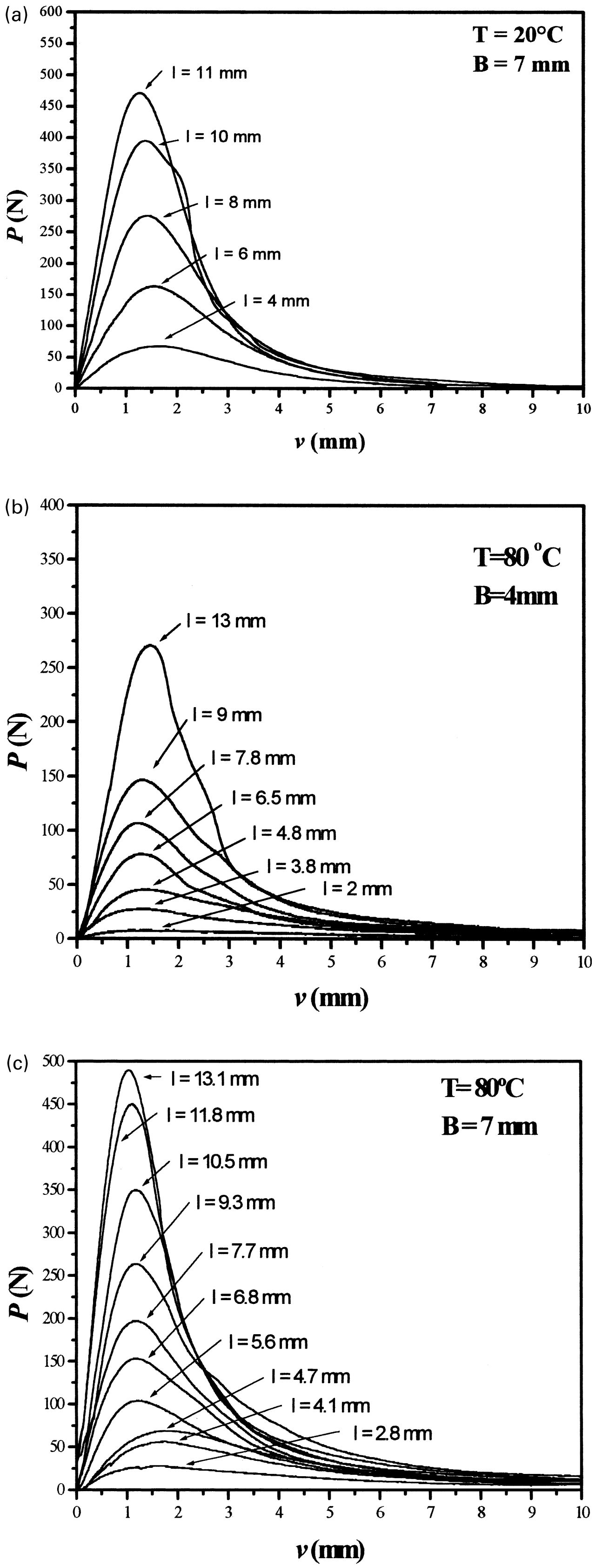

Fig. 2. Load versus displacement curves: (a) thickness $B = 7$ mm, temperature 20 °C; (b) thickness $B = 4$ mm, temperature 80 °C; (c) thickness $B = 7$ mm, temperature 80 °C.

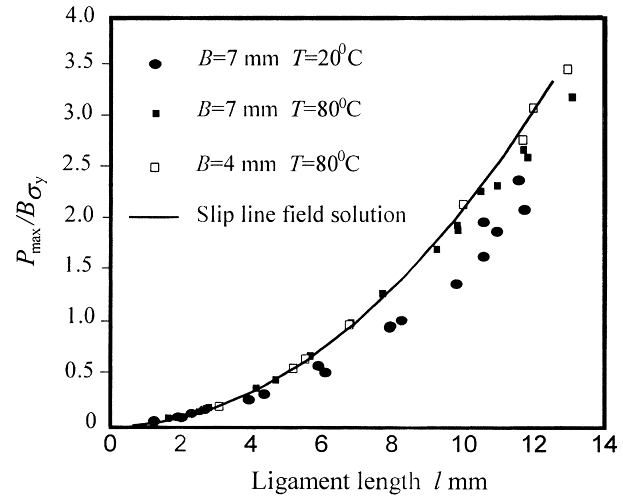

Fig. 3. Maximum normalised load as a function of ligament length.

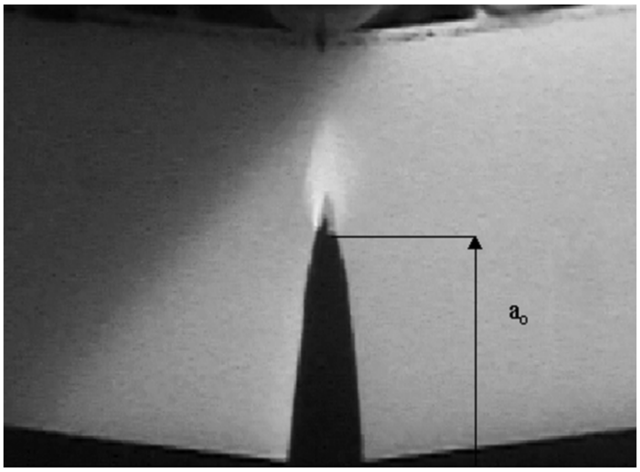

Fig. 4. The whitened zone in a specimen tested at 20 °C.

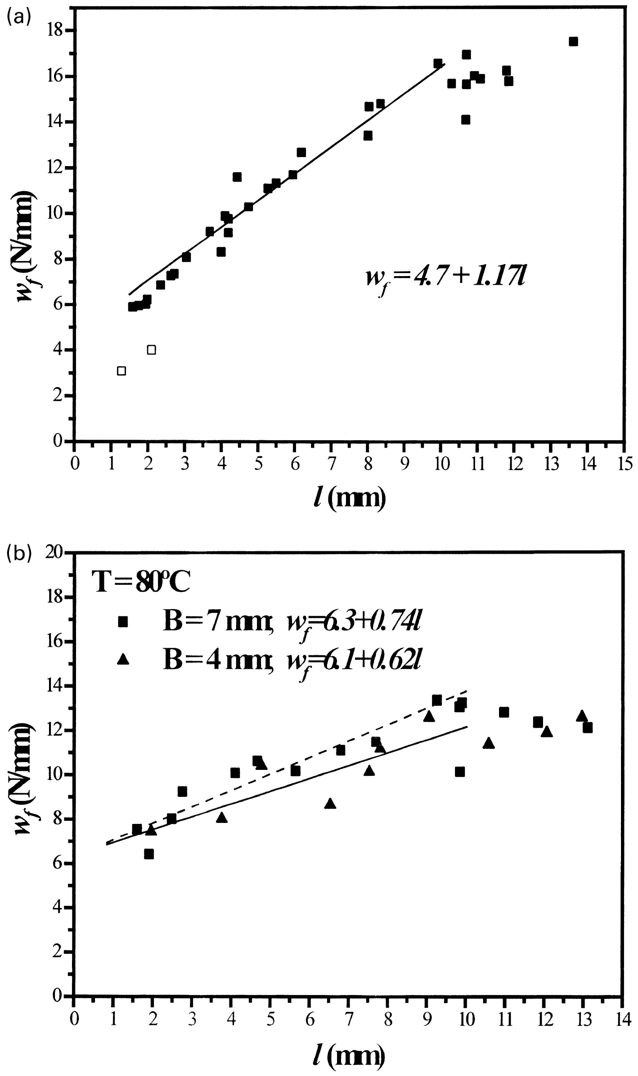

Fig. 5. Specific work of fracture as a function of ligament length: (a) thickness $B = 7$ mm, temperature 20 °C; (b) thickness $B = 4$ and 7 mm, temperature 80 °C.

before crack initiation. Since true similarity can only be achieved if the ligament is completely yielded, fracture initiation at 20 °C was studied with a video camera. Fig. 4 shows a specimen, where the fracture has just been initiated. The whitened zone at the crack tip indicates a region, where the polymer has cavitated under the high hydrostatic tensile stress. The whitened zone does not spread into the compression zone, but that would not be expected. So Fig. 4 indicates extensive yielding, but cannot be used to decide whether the ligament has completely yielded. Provided the ligament is completely yielded during most of the crack propagation, the effect on the total work of fracture is slight.

The total specific work of fracture was evaluated from the curves in Fig. 2(a–c) and is plotted against ligament length for the two temperatures in Fig. 5(a–b). When the notch depth is less than $0.18W$, slip-line field solutions show that yielding is not confined to the ligament, but also extends to the notched surface [21]. Consequently, there is no similarity in the deformation for large ligaments. For ligaments less than 10 mm, which corresponds to a notched depth $0.21W$, the specific fracture work-ligament data fall roughly on a straight line. The percentage error in the specific fracture work is inversely proportional to the ligament length and thus the possible error for very small ligaments is high. All the data points for $l < 10$ mm, except for the two represented by open symbols for very small ligaments, Fig. 5(a) seems to lie on trend lines. The best straight lines have been fitted to the specific fracture work-ligament data points for $l < 10$ mm, except these two. Although the correlation coefficient 0.97 is relatively high for the results shown in Fig. 2(a), the points seem to lie on a curve rather than a straight line. A slightly better fit to a straight line is obtained, if only the points from ligaments is less than 7 mm. The correlation coefficient is 0.98 and the intercept gives $w_{Ie} = 3.42$ kJ/m^2. There is little reason to reject the points for the ligaments between 7 and 10 mm. All the points for the test at 20 °C lie below the slip line theory in Fig. 3 except for ligaments less than 3 mm. However, the probability that the ligament is completely yielded is greater

Table 2
Essential work of fracture parameters

T (°C)	B (mm)	w_{Ie} (kJ/m^2)	B_{min} (mm)	Correlation coefficient, R^2
20	7	3.4–4.7	2.8	0.98, 0.97
80	7	6.3	7.1	0.94
80	4	6.1	6.9	0.84

if the ligament is smaller, so that the value for the specific essential work fracture given by including ligament length's less than 7 mm may be more accurate. The values of the intercept, which are interpreted as the specific essential work of plane strain fracture obtained from the intercepts in Fig. 2, are given in Table 2 together with the correlation coefficients. There is more scatter in the results at 80 °C and the correlation coefficients are lower, but a straight line fit seems reasonable.

The minimum specimen thickness for plane strain according to Eq. (4) is also given in Table 2. The specimen thicknesses are greater than the minimum value except for the 4 mm thick specimens tested at 80 °C. Since the intercept for the 4 mm thick specimen is virtually the same as that for the 7 mm thick specimens, the restriction placed by Eq. (4) is, in this case, too severe. However, in general Eq. (4) is a good guide to the minimum thickness for plane strain. The minimum B/l used in the linear fit was 0.4 and 0.7 for the 4 and 7 mm thick specimens, respectively, which are close to the recommended value of 1.0 for plane strain testing. Thus in these tests, the fracture is plane strain or near plane strain at initiation. It is therefore not surprising that the specific work of fracture is a linear function of the ligament length, if $l/W < 0.82$ because, there is similarity in the deformation which is under plane strain (or nearly so in the case of the 4 mm thick specimens tested at 80 °C) during both initiation and propagation.

5. Concluding remarks

The EWF concept was applied to ABS thick 3-point bend specimens. The condition of yielding of the full ligament prior to crack propagation was not always achieved, compromising the methodology applicability. This anomaly was checked by limit load analysis and observation of the stress whitened region. Since the deformation was plane strain, or very near plane strain, and the total work of fracture was a reasonably linear function of the ligament length, the fact that the ligament may not have been completely yielded at initiation does not seem to have affected the results significantly. The results at 20 °C illustrate one of the frustrating problems with the essential work of fracture concept that the intercept is sensitive to the cut offs applied to the raw data. Consequently, the value of the essential work at 20 °C is in the range 3.4–4.7 kJ/m^2 with the actual value probably nearer to the bottom limit than the top.

The toughness of ABS reaches a maximum at a rubber content of 28% [23], which is close to the rubber content of ABS-740 (23%). The values for J_{Id} obtained by Lach et al. [22] (approximately 13 kJ/m^2 at 20 °C and 11 kJ/m^2 at 80 °C, maximum 15 kJ/m^2 at 30 °C) are much higher than those obtained here for w_{Ie}. However, there is a wide range of quoted values, which depend significantly on the J Standard used. For example Riccò et al. [23], for room temperature tests on an ABS containing 18% rubber, quote 3.85 kJ/m^2 for J_{Ic} measured using the 1981 Standard. The results obtained by Bernal et al. [24] on ABS-740 manufactured by Monsanto (an ABS with different Young's modulus and yield strength to the ABS manufactured by General Electric used in this work) had considerable scatter; they quoted values of J_{Ic} of 5 and 3.4 kJ/m^2 at 20 and 80 °C, respectively. On the contrary to previous results, the results obtained in this paper indicate that the toughness at 80 °C is greater than that at 20 °C. Conclusive comparison of the present results to those previously quoted is difficult because of some uncertainty in the value of the essential work of fracture at 20 °C and a large range of values for J_{Ic} in the literature.

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