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The essential work of plane-stress ductile fracture of poly(ether-ether ketone) thermoplastic

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The total work of fracture in a ductile material is not a material constant and the linear elastic fracture mechanics is not appropriate. Only the work performed per unit area in the fracture process zone, called the specific essential work of fracture, is a material constant for a given specimen thickness. The results of an experimental investigation on the essential work of fracture of a crystalline and a non-crystalline poly(ether-ether ketone) (PEEK) films are reported. Single-edge notched specimens were used to determine the specific essential work by extrapolating the straight-line relationship between the specific work of fracture and ligament length to zero ligament length. In this way, the specific essential work of fracture for the crystalline PEEK film of thickness 0.1 mm was measured to be 65.02 kJ m^{-2} and for the non-crystalline film of thickness 0.25 mm was measured as 62.71 kJ m^{-2}. Advancing crack opening displacements (COD) have also been analysed and the specific essential work of fracture calculated from the COD values compared extremely well with those results obtained from the intercept of specific work of fracture versus ligament length.

1. Introduction

In brittle materials, the plastic flow at the tip of the crack is intimately associated with the fracture process which is brittle in nature. A single fracture parameter such as the critical stress intensity factor, K_c, or the critical strain energy release rate, G_c, is sufficient to characterize this fracture at its critical condition. However, because fracture processes are controlled by the crack tip stresses and strains, and the states of triaxial stresses near the crack tip are influenced greatly by the specimen size, the fracture parameter, K_c is expected to vary with the size of the specimen used. To achieve this state of stress the specimen thickness, B, must exceed some multiple of the plastic zone size at the tip of the crack, i.e. $B \geqslant 15r_p$. This limitation on the specimen size forms the basis of the minimum test-piece size requirements of the ASTM E-399 standard for valid determination of $K_c(K_{Ic})$ which is given by [1]

$$a, B, W - a \geqslant 2.5\left(\frac{K_c}{\sigma_y}\right)^2 \qquad (1)$$

where W is the specimen width, a is the crack length and σ_y is the uniaxial yield stress of the material. These size requirements have been successfully used to predict the transition from a plane-stress to plane strain fracture in polymers (e.g. [2, 3]). In ductile materials, thin sheet polymers in particular, the plastic zone of the advancing crack tip is large and much of the plastic flow at the crack tip is not directly involved in the fracture process. Broberg [4] suggested that the total work of fracture may be considered as being made of two components: one associated with plastic work which is considered to be the non-essential work of fracture, and the other associated with initiation of instability and regarded as essential work of fracture. The latter may be regarded as a material property characterizing fracture under plane-stress conditions. Following the Broberg idea, it was proposed [5–8] that the total specific work of fracture, or the work of fracture per unit ligament area, w_f, may be written as

$$w_f = \frac{W_f}{L} = w_e + \beta L w_p \qquad (2)$$

where w_e is the specific essential work of fracture, w_p is the specific plastic work of fracture, L is the ligament length and β is a shape factor which describes the size of the plastic zone. It has been demonstrated by Mai and Cottrell [6–8] and more recently by Paton and Hashemi [9] that plane stress fracture in polymers can be characterized by the fracture parameter, w_e.

This paper reports the results of an experimental investigation into the essential work of fracture of a crystalline and a non-crystalline poly(ether-ether ketone) film of nominal thicknesses in the range 0.1–0.265 mm. A comparison is also made between the experimentally measured values of w_e and the values estimated based on the crack opening displacement (COD) of the advancing crack tip.

2. Essential work of fracture and experimental procedure

Cotterell and Reddell [5] have shown that the deep edge notched tension specimen is the most appropriate to determine the essential work of fracture in thin sheet metals. When such a specimen yields completely before crack initiation, the plastic region is confined entirely to a circular area about the ligament as shown in Fig. 1. By partitioning the work of fracture into two parts (work that goes into the end region, W_e, and the work that goes into the outer region, W_p), the total work of fracture may be written as

$$W_f = W_e + W_p \quad (3)$$

The essential work of fracture is proportional to the ligament length, L, and the non-essential work in the rest of the plastic region is proportional to L^2, i.e. we may write

$$W_f = LBw_e + L^2B\beta w_p \quad (4)$$

where w_e is the specific essential work of fracture and is defined as essential work in the specimen with a unit thickness and unit ligament, and βw_p is the non-essential work, defined as the plastic work in a specimen with unit thickness and unit ligament length. β is a shape factor depending on the size and the geometry of the plastic zone. Therefore, the total specific work of fracture, w_f, according to Equation 4 may be defined as

$$w_f = \frac{W_f}{LB} = w_e + L\beta w_p \quad (5)$$

Thus, if the specific work of fracture, w_f, is plotted against the ligament length, L, a straight line should be obtained with a positive intercept giving the specific essential work, w_e, as shown schematically in Fig. 2. The slope of this line gives βw_p which is a measure of the non-essential specific work term and may be inferred that when βw_p approaches zero, the fracture process will be accompanied by plastic work

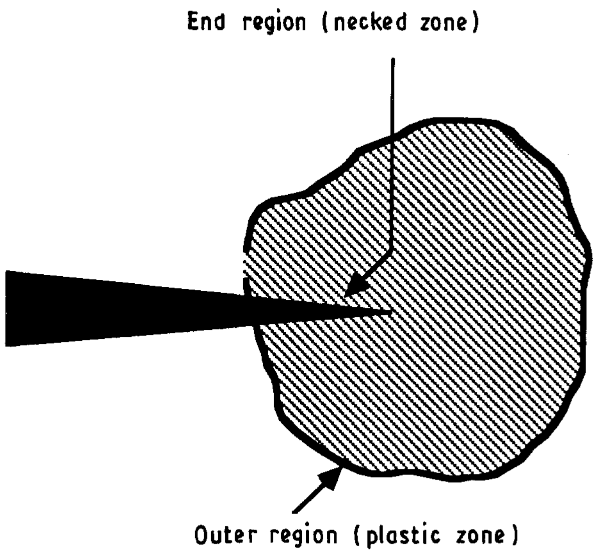


Figure 1 Crack tip deformation zone in a ductile material.

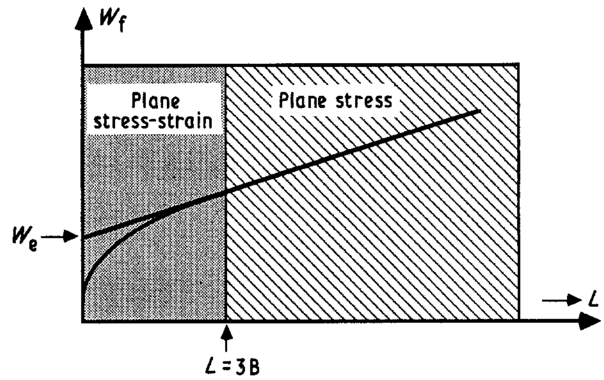


Figure 2 Schematic representation of the total specific fracture work versus ligament length showing plane stress and plane stress–strain regions.

contribution confined to the necking process zone only.

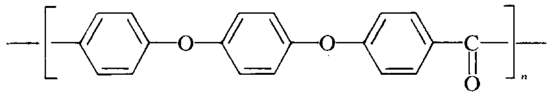
For Equation 5 to yield a straight-line relationship between w_f and L, the ligament must be in a state of pure plane stress and the fracture occurs after complete yielding of the ligament (because only under pure plane stress state are w_e, w_p and β all independent of the ligament length). This imposes upper and lower limits on the ligament length. Cotterell and Reddell [5] suggested that the upper limit is determined by the size of the plastic zone ahead of a crack tip in a large sheet, unless necking occurs at the large length/thickness ratio. It is considered that the ligament length should not be larger than the plastic region. The lower limit is governed by the sheet thickness and is of the order of $3B$–$5B$. Thus using the linear elastic fracture mechanics for the upper limit, the boundaries of the ligament length should be in the range of

$$\frac{L}{\pi}\left(\frac{K_c}{\sigma_y}\right)^2 > L \geqslant 3B \quad (6)$$

where K_c is the plane stress fracture toughness and σ_y is the yield stress. For samples with ligament lengths smaller than $3B$, there is a fracture transition from plane stress to plane strain and when the ligament length approaches zero a fully plane strain fracture is obtained. In the mixed mode stress state, because of the increasing plastic flow constraint with decreasing ligament length, w_f decreases as shown schematically in Fig. 2, and a linear relationship between w_f and L does not necessarily occur.

2.1. Materials

In the present study poly(ether-ether ketone) material, trade name PEEK, was used as received. PEEK is a relatively a new aromatic polymer and has a chemical structure of the form



PEEK has a glass transition temperature of 143 °C and a melting point of 334 °C. This implies a high-temperature performance but also a high-temperature melt. The maximum achievable crystallinity of PEEK is about 48% but more typical values are less than 30% [10].

Two grades of PEEK film material were received; "Stabar" XK300 film, a crystalline grade of PEEK of nominal thickness 0.1 mm; "Stabar" K200 film, a non-crystalline grade of PEEK of nominal thicknesses 0.25 and 0.265 mm.

2.2. Fracture tests

To measure the essential work of fracture, w_e, tests were carried out using the single-edge notched tension (SENT) specimens of dimensions, $W = 25$ mm and $Z = 80$ mm as shown in Fig. 3. Crack length varied from 4–22 mm giving a/W ratios in the range 0.16–0.88. The initial notches were prepared by slowly pushing the fresh edge of a razor blade into the material. The razor blade was mounted on a laboratory attachment so that penetration could be controlled carefully. The notch measurement was done using a travelling microscope.

After notching, specimens were fractured at room temperature on an Instron testing machine at a constant crosshead rate of 1 mm min^{-1} and the load/displacement trace for each specimen was recorded. Typical load–displacement traces are shown in Fig. 4. The areas under the load/displacement traces were measured using a planometer.

2.3. Tensile tests

Tensile yield stress measurements were also made at a constant crosshead rate of 1 mm min^{-1} using dumb-bell shaped specimens. The load–time plot for each specimen was recorded and the yield stress calculated from the maximum load and the original cross-sectional area of the specimen. From these tests, tensile yield stress values of 80 and 62 MPa were determined for XK300 and K200, respectively.

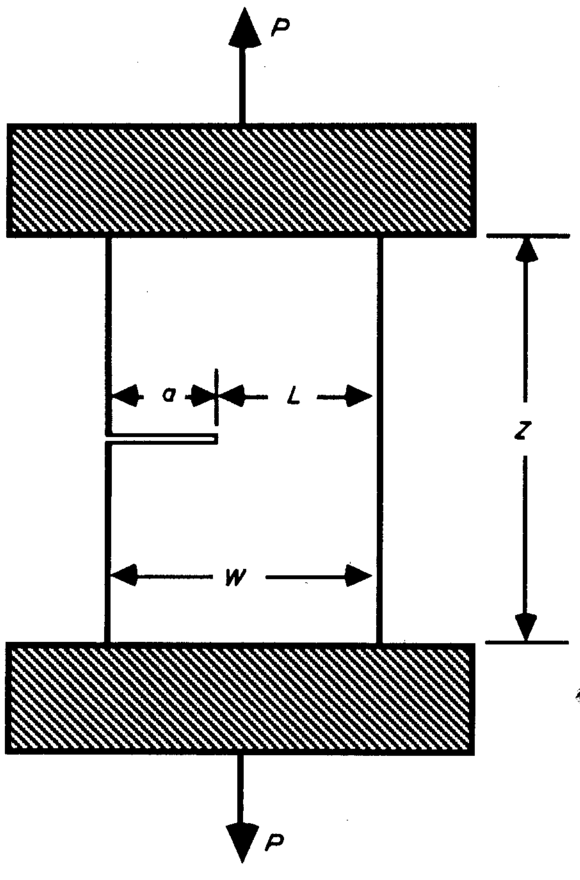


Figure 3 Specimen configuration: $Z = 80$ mm, $W = 25$ mm.

3. Results and discussion

3.1. Experimental determination of essential work of fracture

As shown in Fig. 4, under the testing conditions employed, these grades of PEEK material did not fail in a brittle manner. All of the specimens exhibited ductile failure with gross yielding and so that no K_c criterion could be considered. The presence of the plane-stress deformation was apparent by the contraction of the specimen surfaces. Slow crack growth was observed in all the specimens and the onset of slow crack growth (crack initiation) always occurred after crack tip blunting. In all the tests crack initiated before the maximum load was reached and grew stably beyond the maximum load by ductile tearing under plane stress conditions as the load dropped to zero. When the maximum load was reached the ligament was grossly yielded. From the areas under the load–displacement diagrams the specific work of fracture, w_f, was calculated and plotted against the ligament length, L, as shown in Figs 5–7. It is evident from the figures that

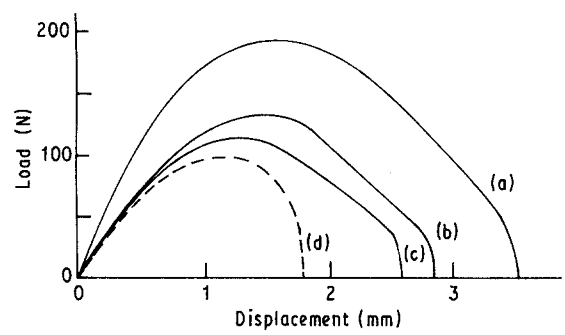


Figure 4 Typical load–displacement curves for (———) K200 ($B = 0.265$ mm) and (– – –) XK300 ($B = 0.1$ mm). L: (a) 14.26 mm, (b) 11.96 mm, (c) 10.01 mm, (d) 8.32 mm (e) 16.07 mm.

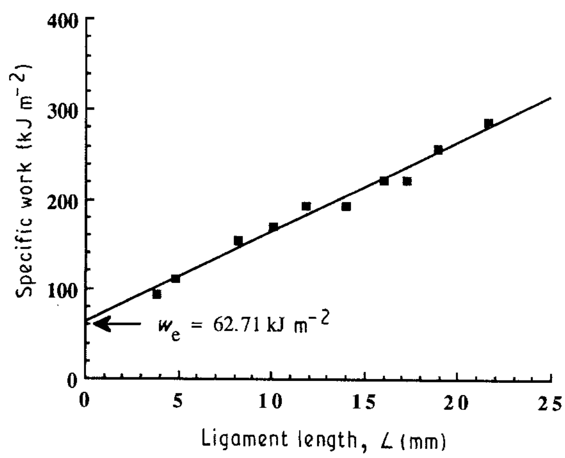


Figure 5 The specific work of fracture for K200 as a function of the ligament length ($B = 0.250$ mm). The line drawn is the best fit with the equation $w_f = 62.71 + 10.09\ L$.

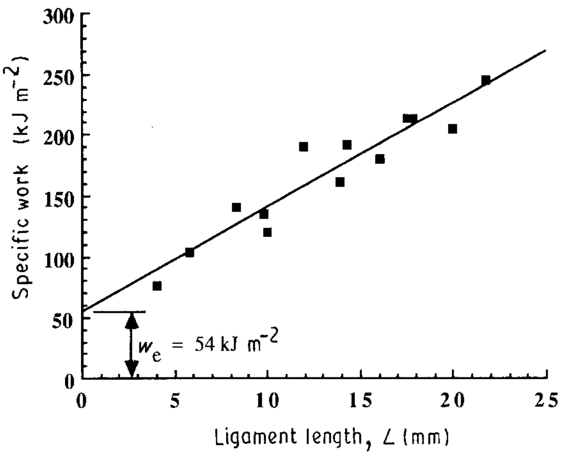


Figure 6 The specific work of fracture K200 as a function of the ligament length (B = 0.265 mm). The line drawn is the best fit with the equation w_f = 54.0 + 8.63 L.

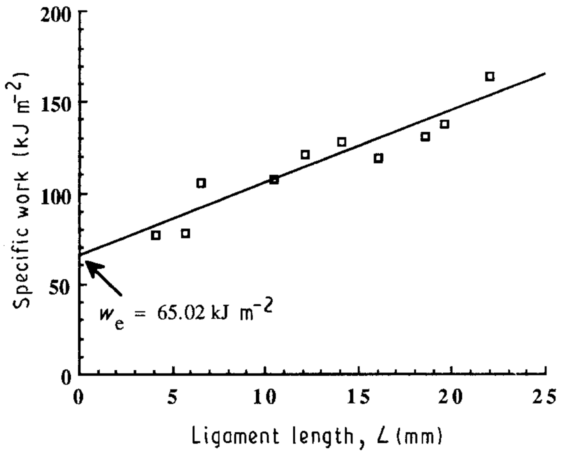


Figure 7 The specific work of fracture for XK300 as a function of the ligament length (B = 0.1 mm). The line drawn is the best fit with the equation w_f = 65.02 + 4.0 L.

for a given material and a given specimen thickness, B, all the experimental data lie on a straight line which can be back-extrapolated to give the specific essential work of fracture, w_e. It must be noted that because the ligament length in all the tests was greater than $3B$ the ligament was always in a state of plane stress. Table I gives values for w_e and βw_p for the two materials. It is evident from Table I that the essential work of fracture increases with decreasing specimen thickness. The specific non-essential work term, βw_p, also increases with decreasing thickness. This result can be correlated to the difference in the experimental load–displacement curves where for a given ligament length, the specimen thickness of 0.25 mm showed a larger amount of plastic flow whereas the specimen thickness of 0.265 mm exhibited less plastic flow around the ligament length.

Another interesting feature of the data is the difference in the values of the essential work of fracture for the crystalline and non-crystalline materials. Although a direct comparison cannot be made because of different thicknesses (for the crystalline PEEK 0.1 mm and for the non-crystalline PEEK 0.25 and 0.265 mm), nevertheless it is evident that the crystalline material with a smaller thickness has more or less the same w_e value as that of the non-crystalline material having larger thicknesses. Therefore, it could be expected that for the same specimen thickness the essential work of fracture for the crystalline PEEK will be smaller than that of the non-crystalline PEEK material. Furthermore, a much smaller βw_p term for the crystalline material is indicative of a much smaller amount of plastic flow around the ligament length in this material compared to that of the non-crystalline material.

3.2. Estimated values of the essential work of fracture from the crack opening displacement (COD) of the advancing crack tip

Another method of calculating the essential work of fracture is via the crack opening displacement (COD) of the advancing crack tip. By plotting the ultimate elongation, δ, against the ligament length, L, and extrapolating to zero ligament length [11], the COD value of the advancing crack tip was determined as shown in Figs 8–10. Because the shape of the load–displacement diagrams was approximately parabolic, the work of fracture, W_f, may be written as

$$W_f = \frac{2}{3} P_{max} \delta \qquad (7)$$

where P_{max} is the maximum load. According to Hill [12], maximum load is a linear function of the ligament length and the relationship between the maximum load and ligament length may be expressed as

$$P_{max} = \gamma L B \sigma_y \qquad (8)$$

where σ_y is tensile yield stress and $\gamma = 2/3^{\frac{1}{2}}$.

When the maximum load for crystalline and non-crystalline PEEK material was plotted against

TABLE I Fracture data for SENT specimens

Material	Thickness (mm)	Yield stress (MPa)	w_e (kJ m^{-2})	Slope (βw_p) (NJ m^{-3})
K200	0.265	62	54.01	8.63
	0.250	62	62.71	10.09
XK300	0.100	80	65.02	4.00

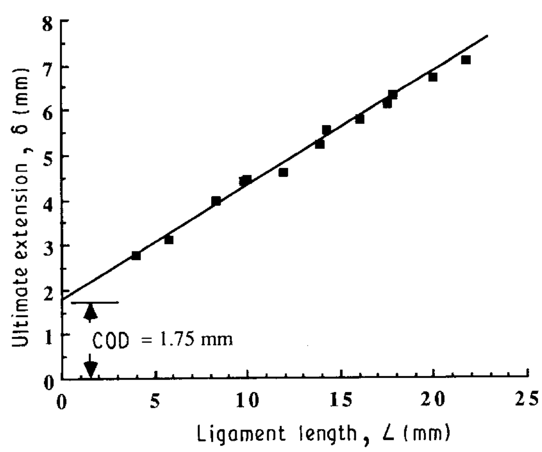


Figure 8 Ultimate extension against ligament length for K200 (B = 0.265 mm). The line drawn is the best fit with the equation δ = 1.75 + 0.258 L.

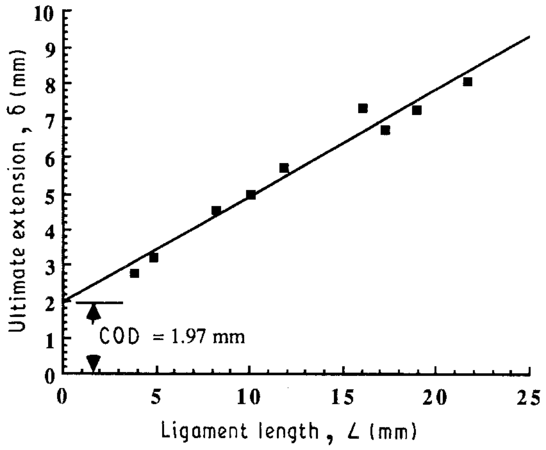


Figure 9 Ultimate extension against ligament length for K200 ($B = 0.25$ mm). The line drawn is the best fit with equation: $\delta = 1.97 + 0.29\ L$.

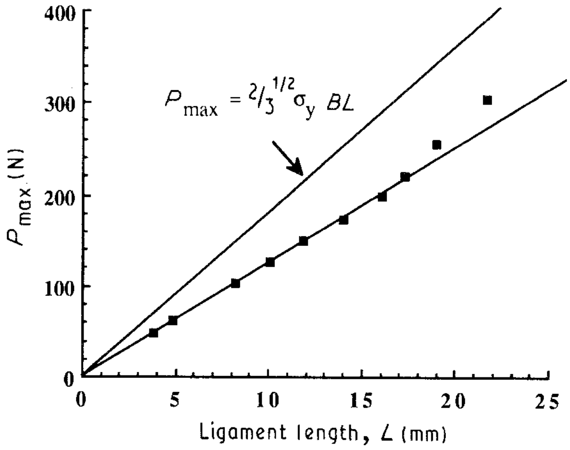


Figure 12 Maximum load as a function of ligament length for K200 ($B = 0.25$ mm).

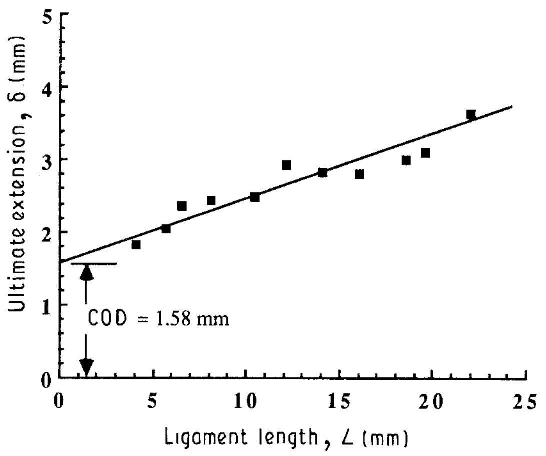


Figure 10 Ultimate extension against ligament length for XK300 ($B = 0.1$ mm). The line drawn is the best fit with the equation: $\delta = 1.587 + 0.092\ L$.

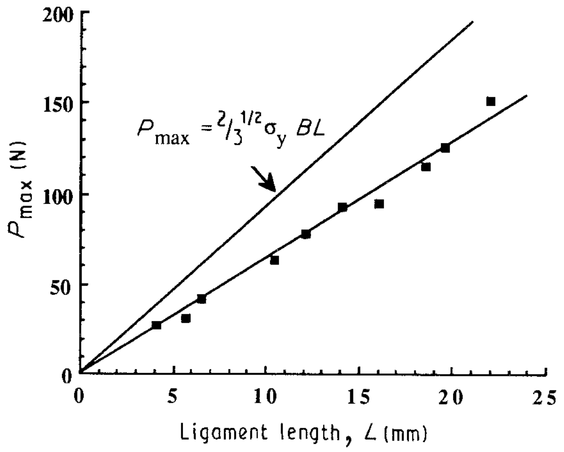


Figure 13 Maximum load as a function of ligament length for XK300 ($B = 0.1$ mm).

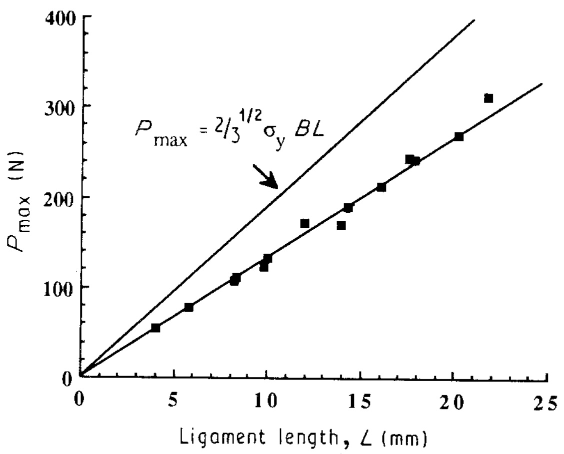


Figure 11 Maximum load as a function of ligament length for K200 ($B = 0.265$ mm).

ligament length, the result lay on a straight line passing through the origin as shown in Figs 11–13. Also shown in the figures is the maximum load predicted by Equation 8 with $\gamma = 2/3^{\frac{1}{2}}$ and, clearly, in all the tests the maximum load falls well below the value predicted by Hill. This is because Hill's analysis was for a rigid plastic material that forms a neck, whereas there was a

TABLE II Fracture data for SENT specimens

Material	Thickness (mm)	COD (mm)	Slope ($\gamma B \sigma_y$) (10^3 N m^{-1})	γ (kJ m^{-3})
K200	0.265	1.75	13.30	0.81
	0.250	1.97	12.62	0.81
XK300	0.100	1.58	06.41	0.80

diffuse yield region in the present tests. Table II gives a summary of the results attainable from figures. It is interesting to note that from tests performed here, a constant value of 0.81 is obtained for γ compared with the value of $2/3^{\frac{1}{2}}$ (= 1.15) suggested by Hill [12].

By substituting Equation 8 into Equation 7 we have

$$W_f = \frac{2}{3} \gamma L B \sigma_y \delta \qquad (9)$$

Now by substituting Equation 5 into Equation 9 and rearranging, we obtain an expression for the ultimate elongation, δ, in terms of the ligament length, L

$$\delta = \frac{3}{2 \gamma \sigma_y} (w_e + L \beta w_p) \qquad (10)$$

The COD of the advancing crack tip may now be determined from Equation 8 by putting $\delta = \text{COD}$

TABLE III Fracture data for SENT specimens

Material	Thickness (mm)	COD (mm)	w_e ($kJ\,m^{-2}$)	
			Eq. 5	Eq. 12
K200	0.265	1.75	54.0	58.50
	0.250	1.97	62.71	66.20
XK300	0.100	1.58	65.02	67.50

when $L = 0$ (see figures), i.e.

$$\mathrm{COD} = \frac{3}{2\gamma\sigma_y} w_e \tag{11}$$

Alternatively we may write

$$w_e = \frac{2\gamma\sigma_y}{3}(\mathrm{COD}) \tag{12}$$

Using the data of Table II, the specific essential work of fracture may be computed from Equation 12. As shown in Table III, the specific essential work values calculated from the above equation compare extremely well with those results obtained from the intercept of the plot of w_f versus L.

Finally, substituting the value of 0.8 for γ in Equation 12 we obtain a general expression for w_e in terms of COD for the PEEK material

$$w_e = 0.533\,\sigma_y\,(\mathrm{COD}) \tag{13}$$

4. Conclusion

The single-edge notched tension specimens have been successfully used for determining the specific essential work of fracture, w_e, of both crystalline and non-crystalline PEEK materials. It was found that the essential work of fracture was dependent upon the specimen thickness. For the crystalline PEEK material of thickness 0.1 mm, values of the specific essential work of fracture and the advancing COD at the crack tip were, $w_e = 65.02\ kJ\,m^{-2}$, COD = 1.58 mm, $\beta w_p = 4.0\ MJ\,m^{-3}$. On the other hand for non-crystalline PEEK material of thickness 0.25 mm we obtained $w_e = 62.71\ kJ\,m^{-2}$, COD = 1.97 mm, $\beta w_p = 10.09\ MJ\,m^{-3}$. These values suggested that the crystalline PEEK is less ductile than the non-crystalline material. Results also supported the idea of estimating the specific essential work of fracture form the crack opening displacement of the advancing crack tip. For PEEK material a good estimate of w_e can be made from crack opening displacement using the relationship $w_e = 0.533\ \sigma_y$ (COD).

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