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The essential work of fracture of a thermoplastic elastomer

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Abstract

This paper presents the fracture behaviour of a thermoplastic elastomer, HYTREL 5556. Since with this material it is not possible to successfully apply the LEFM nor the EPFM, it has been studied by following the ESIS protocol for determining the essential work of fracture in plane stress and extended for mixed-mode conditions, which should give a material constant, independent of the sample geometry. DDENT specimens were used in two different thickness, and results showed that the essential works of fracture in plane stress and mixed-mode were the same for both thickness for this material.

Introduction

The material studied comes from the Du Pont company. It shows typical elastomers behaviour, but it can be transformed as the same as a thermoplastic. As its properties make it very useful for high mechanical performance applications, it seems interesting to characterise the fracture of this material with a single parameter. According to the linear elastic fracture mechanics (LEFM), the fracture toughness may be represented in terms of $\mathbf{K}_c$, the critical stress-intensity factor, or $\mathbf{G}_c$, the critical strain-energy release rate, but these can only be used for brittle materials whose plastic zone in the crack tip is small enough compared to the specimen dimensions. As ductile polymers with an important plastic zone are involved, the limit of small scale yielding is violated. It makes the use of K_C or G_C inadequate, even at low temperatures (tests carried out on HYTREL 5556 confirm this fact). Another approach, the J-integral technique, has been adopted to overcome this difficulty as an alternative to the LEFM. However, the extremely high deformations attained during the tests without crack propagation also made this method inappropriate.

Essential Work of Fracture

A recently developed method that seems adequate for this kind of material is the essential work of fracture measurement. Broberg (1) suggested that when a ductile material which contains a crack is loaded, the plastic deformation takes place in an outer zone

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surrounding the real crack process region. Thus, the total fracture work $\mathbf{W_f}$ may be divided into two terms. The former is called the essential work of fracture $\mathbf{W_e}$ and is associated with the instability created in the vicinity of the crack tip. The latter is associated with the material yielding and is called the non-essential work of fracture $\mathbf{W_p}$ (the plastic deformation does not contribute to the crack extension). For a given thickness, only the essential work of fracture is a characteristic property of the fracture behaviour of ductile materials. The non-essential work of fracture depends on the shape of the plastic area. In a tensile test, the total work of fracture can be written as

$$(1) \qquad W_f = W_e + W_p = w_e lt + w_p \beta l^2 t$$

where $\mathbf{w_e}$ is the specific essential work of fracture, $\mathbf{w_p}$ is the specific non-essential work of fracture, **l** is the ligament length, **t** is the specimen width and **β** is a dimensionless factor that describes the plastic zone size.

The specific work of fracture or the work of fracture per unit ligament area is

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

The plot of the specific work as a function of the ligament length should be a linear relation $w_f = f(l)$, whose crossing with the Y-axis gives the specific essential work of fracture $\mathbf{w_e}$, and the slope, $\mathbf{\beta w_p}$.

However, to preserve the validity of equation (2) the ligament must be in a plane stress state, for which $\mathbf{w_e}$ and $\mathbf{\beta w_p}$ are independent of **l**. This condition sets up limits on the ligament length. To prevent side effects on the specimen, **l** must be smaller than **W/3**. Moreover to maintain a plane stress state the ligament must be long enough compared to the specimen thickness (l>3t). Thus the next relation must be verified:

$$(3) \qquad \frac{W}{3} > l > 3t$$

Several authors have developed experimental approaches in order to evaluate the essential work of fracture in plane stress mode (2-4). Although the essential work of fracture can be determined with any specimen geometry (5), it is usual to test deeply double edge notched tension (DDENT) samples (Fig. 1). In this study, essential work tests have been carried out following the ESIS protocol (6) for plane-stress conditions. For the mixed-mode region, a value has been found following the method proposed by Wu and Mai (7). Saleemi and Nairn (8) have developed an experimental procedure to determine $\mathbf{w_e}$ in a pure plane strain state, that should be the same as J_{IC}.

Experimental

Material

The material was supplied in the form of sheets (75mm x 120mm x t) of two different thickness, t (3.2 and 2 mm), which were mechanised to obtain the specimens. HYTREL is a thermoplastic elastomer composed of a polybutylen terephtalate crystalline phase (A) and a polyether glycol amorphous phase (B). The properties of the material depend on the proportion of each phase. The A-phase units are situated on the extremities of the B-phase chains in a triblock configuration. Glass transition temperature (Tg) of each phase are Tg_A=80°C and Tg_B= -40°C.

In general, HYTREL materials have an exceptional stiffness and resilience, high strength to creep, to fatigue and to impact loadings, low temperature flexibility, preservation of properties at high temperature and great resistance to acids and solvents. In this study

HYTREL 5556 was used, which is the grade with the best set of properties, summarised in Table 1 (9).

Test procedure

To measure the essential work of fracture in plane stress conditions, $\mathbf{w}_e$, tests were carried out using DDENT specimens (Fig. 1), as established in the ESIS protocol. The distance between the grips must be great enough to preserve the geometry of the plastic zone. The sizes of samples were 75(W) x 60(L) x t mm.

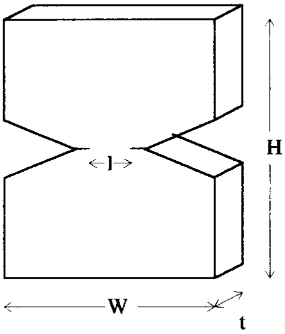

Figure 1 : DDENT Specimen

For each set at least 20 specimens were tested with ligament length obeying ESIS(6) conditions represented in Table 2. With this distribution more values were obtained for short ligament lengths and thus a more precise evaluation of $\mathbf{w}_e$. Moreover, 16 other specimens were prepared for mixed-mode conditions ($l<3t$).

The V-notches were perfectly symmetrical, and further extended with a fresh sharp blade for at least 1mm in order to obtain the ligament length desired ($0.5<l<25$mm), while taking care of keeping a good alignment.

Table 1: HYTREL 5556 main properties.

Flex.Modulus (MPa) (-40°C)	760
(23°C)	207
(100°C)	110
Impact Strength (J/m) (-40°C)	170
(23°C)	i.r.*
Melt Temperature (°C)	203
Glass transition temp.(°C)	-18
Density (g/cm^2)	1.2
Hardness (Shore D)	55

Table 2: Ligament length experimental conditions (in plane stress mode).

ligament length		Min. number
Max.	Min.	of samples
0.33 W	0.27 W	2
0.27 W	0.20 W	3
0.20 W	0.13 W	5
0.13 W	3 t	10

* incomplete rupture

Fracture tests were carried out at room temperature and constant crosshead rate (2W/75=2mm/min) until total failure of the specimens on an universal testing machine. The load vs. displacement curves were recorded, and the energy absorbed calculated by curves computer integration. The ligament length and the plastic zone size were evaluated with a travelling optical microscope.

Verifications

(a) The maximal stress in the net section ($\sigma_{net}=P_m/lt$) was calculated from the value of the maximal load during the tensile test and plotted against l. The plasticity theory postulated by Hill (10) predicts that the maximal stress in the net section of a DDENT sample is **$1.15\sigma_y$** in pure plane stress state (where σ_y is the material yield strength), and **$2.97\sigma_y$** in pure plane strain state.

(b) For each specimen the necked zone around the crack was microscopically observed to obtain a value of **h** (the half of the maximal height of this zone in the load direction). Two measures per face of each broken piece were taken (thus 8 per specimen) and averaged. The **h** vs. **l** diagram gives a straight line whose slope is equal to **$4\beta/\pi$** in the case of an elliptical yielded zone (the case of HYTREL) and **2β** for a diamond-shaped zone. The non-essential work of fracture w_p can be determined from this last result and the w_f-l diagram slope. Another approach to calculate β is by plotting the volume of the necked zone (V_p) as a function of l^2t, that represents the ideal yielded zone volume. As the definition of β is the ratio between V_p and l^2t, the slope of this plot gives its value. For an elliptical necked region, V_p is obtained with the expression

(4) $$V_p = \pi\frac{hlt}{4}$$

Results and discussion

Two sets of different thickness specimens were tested. For each set w_e was determined in plane stress state (ESIS method), and in mixed-mode state (Wu and Mai method (8)).

Set I: t=3.2mm

Fig. 2 shows the plot of the specific work of fracture (w_f) as a function of ligament length (l). The dash vertical line on l=3t=9.6mm separates mixed-mode and plane stress states. Linear fits are done in both stress state regions to obtain the value of w_e, by extrapolating to the Y-axis intersect, and βw_p, from the slope of the line. These results are shown in Table 3.

In order to verify the results obtained, the maximal stress in the net section (σ_{net}) vs ligament length diagram is drawn (Fig. 3). It shows the plane stress/mixed-mode transition according to Hill's theory (10) for DDENT configuration. To find the value of σ_y, tensile tests on 10 unnotched specimens were carried out at the same crosshead rate (2 mm/min), obtaining a mean value of 15.88 MPa. Thus, $1.15\sigma_y = 18.26$ MPa, and $2.97\sigma_y = 47.16$ MPa. As can be seen in Fig. 3, the transition between the two stress states seems to start at slightly lower ligament lengths than 3t=9.6mm. However, in this study it was considered that the transition occurred at l=3t agreeing with the ESIS protocol (6) (this consideration seems to be confirmed by the curve in Fig.2).

Fig. 4 and Fig. 5 are plotted to evaluate the value of β. The results are shown in Table 4 as β_1 (plane stress)and β_2 (mixed-mode) for the *h vs. l* method and β_1' (plane stress) and β_2' (mixed-mode) for *necked zone volume* method.

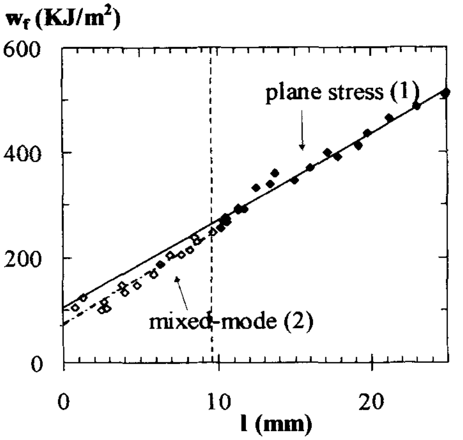

Fig.2. w_f *as a function of* l *for Set I (t=3.2mm). The lines are the best linear fits for plane stress (filled symbols) and mixed-mode (open symbols) regions.*

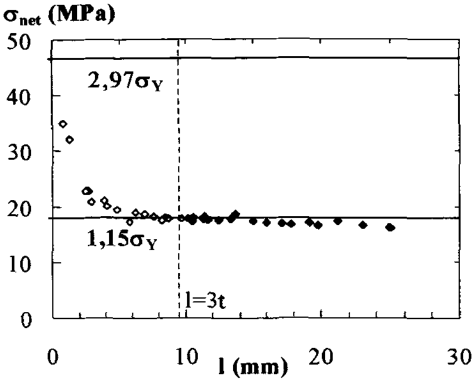

Fig.3. σ_{net} vs l *for Set I (t=3.2mm). Data in plane stress (filled symbols) and mixed-mode (open symbols) regions are separated by the vertical line at l=3t.*

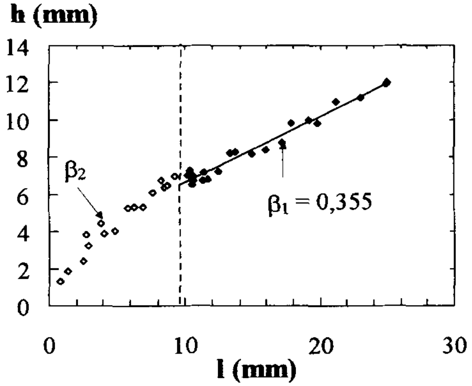

Fig.4. h *vs.* l *plot for Set I (t=3.2mm). The solid line is the best linear fit with plane stress data (filled symbols). The slope is* $4\beta/\pi$.

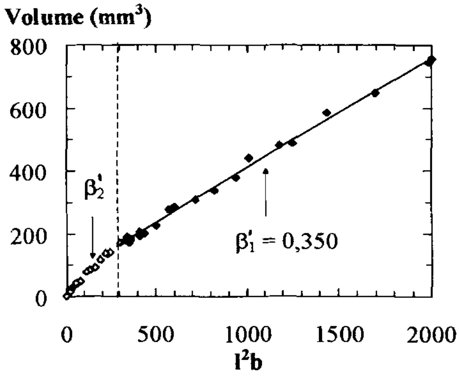

Fig.5. V_p *vs.* l^2t *Set I (t=3.2mm). The solid line is the best linear fit with plane stress data (filled symbols). Slope gives* β.

Set II: t=2mm

The w_e and βw_p values (Table 3) are calculated from linear fits on Fig. 6. Transition from the mixed-mode to plane stress state is situated at $l=3t=6mm$, which is clearly shown by the σ_{net} vs. l diagram (Fig. 7). It again agrees with the plasticity theory predictions (10). Fig. 8 and Fig. 9 are plotted in order to know the value of β, and the results are shown in Table 4.

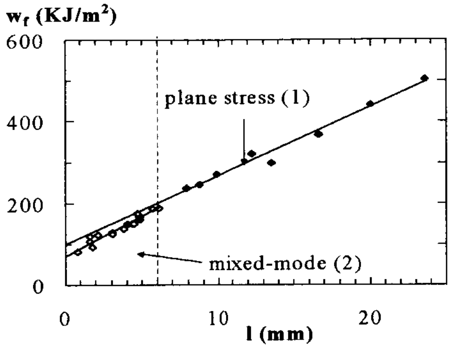

Fig.6. . w_f as a function of l for Set II (t=2mm). The lines are the best linear fits for plane stress (filled symbols) and mixed-mode (open symbols) regions.

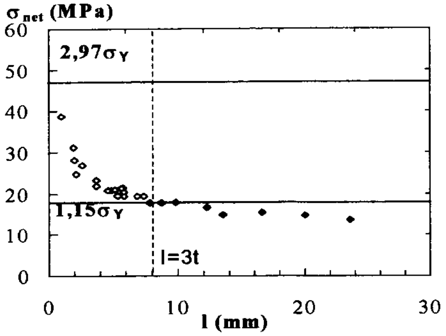

Fig.7. σ_{net} vs. l for Set II (t=2mm). Data in plane stress (filled symbols) and mixed-mode (open symbols) regions are separated by the vertical line at l =3t.

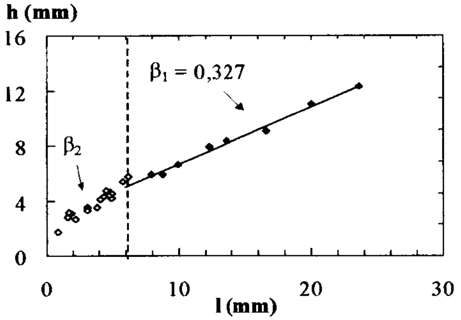

Fig.8. h vs. l for Set II (t=2mm). The solid line is the best linear fit with plane stress data (filled symbols). The slope is $4\beta/\pi$.

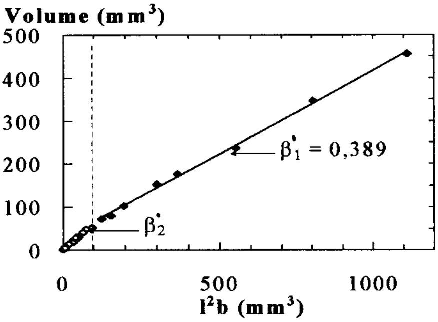

Fig.9. V_p against l^2b for Set II (t=2mm). The solid line is the best linear fit with plane stress data (filled symbols). The slope is β.

TABLE 3. Results of w_e and βw_p for both sets and for each stress state.

	SET I		SET II	
stress mode	mixed-mode	**plane stress**	mixed-mode	**plane stress**
w_e (KJ/m²)	73.0	**104.5**	71.8	**99.6**
βw_p (mJ/mm³)	17.8	16.8	19.3	16.8

TABLE 4. Values of β and w_p calculated according to each method for plane stress state.

METHOD		SET I	SET II
h vs. l	β_1	0.355	0.327
	w_p (mJ/mm³)	44.7	51.4
necked zone volume	β'_1	0.350	0.389
	w'_p (mJ/mm³)	48.0	43.2

The values of specific essential work of fracture in plane stress state (Table 3) are roughly the same for both thickness studied (**w_e**=104.5 KJ/m^2 for t=3.2mm and **w_e**=99.6 KJ/m^2 for t=2mm). In mixed-mode, values of essential work are also very similar (**w_e**=73.0 KJ/m^2 for t=3.2mm and **w_e**=71.8 KJ/m^2 for t=2mm). Thus, it would seem that **w_e** in both stress states is not sensitive to specimen thickness for this elastomer. We can also note that both mixed-mode values are rather lower than the plane stress ones, as could be expected.

Table 4 shows the non-essential specific work of fracture calculated by taking the values β_1 and β'_1 which are roughly equivalent. According to the results, both methods employed to obtain the shape factor and thus **w_p** in plane stress seem to be valid.

In the mixed-mode region, the non-essential specific work of fracture is more difficult to evaluate. Even if the slope β**w_p** seems to be approximately constant (Fig.2 and 6), from the **h** vs. **l** plot it may be observed that the shape factor β_2 increases as **l** is reduced. Thus, no rigorous value of **w_p** may be given for this stress state.

Conclusions

In this study, it has been demonstrated that, for this material, the essential work of fracture is a property independent of the sample thickness (in the range studied) in plane stress and mixed-mode states.

An alternative method to that proposed in the ESIS protocol for determining β in plane stress was successfully used.

It was observed that the shape factor in the mixed-mode region (β_2) depends on the ligament length. Consequently, no reliable evaluation of the non-essential specific work is possible in this region.

This essential work of fracture analysis shows that it is possible to obtain fracture parameters for elastomeric materials.

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