THE ESSENTIAL WORK OF FRACTURE OF POLYOLEFINIC FILMS

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Fracture behaviour of different thickness polypropylene films and sheets was studied using the Essential Work of Fracture (EWF) method following the ESIS protocol, as an alternative to LEFM and EPFM, which are not suitable for the characterisation of ductile films. The specific essential work of fracture, w_e, and the plastic work of fracture, βw_p, were determined. The w_e value was considered as a toughness measurement, independent of the sample geometry. The influence of the thickness, t, and the rate of testing, v, on w_e and βw_p, was studied on polypropylene (PP) films and sheets with a Deep Double Edge Notched Tension geometry.

INTRODUCTION

An experimental method, called the Essential Work of Fracture (EWF) and developed by Mai and Cotterell (1) following the Broberg's theoretical idea (2), is being increasingly used for the determination of toughness on polymeric films and sheets (3-6). Theoretically, the toughness values obtained do not depend on the specimen geometry, but can be influenced by different parameters. The aim of this work is to compare the toughness of different composition propylene-ethylene copolymers. In this paper, a preliminary investigation is presented, where this technique is applied on an homopolymer polypropylene to evaluate the influence of the test speed (v) and the thickness (t) on the EWF toughness parameters.

THEORY

Broberg (1) postulated that the total fracture energy (W_f) of a notched specimen during a tensile test could be divided into two terms, called the Essential and Non-Essential Work of Fracture (W_e and W_p respectively). The first item is related to the instability on the crack tip (where the real fracture process occurs) and is proportional to the ligament section (lt),

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Effect of the crosshead speed

The Fig. 2 shows the w_f vs. l values of specimens tested at 2, 20 and 100 mm/min. Filled symbols correspond to specimens tested in plane stress conditions, while open symbols refer to values obtained in a mixed-mode state (between plane stress and plane strain). The distinction between the points obtained in each stress state has been done following the Hill's analysis. Plotting σ_{net} vs. l it can be seen that the stress state transition occurs for a ligament length value of $l^* \approx 6$mm. The regression lines of the plane stress data give us the w_e and βw_p values, which are listed in Table 1. From the results, it seems that both w_e and βw_p values decrease as the test rate is increased, indicating that the material is tougher at lower speeds, according to the viscoelastic nature of polymers.

TABLE 1- Fracture data obtained varying the test rate and the thickness.

t (μm)	v(mm)	w_e (kJ/m^2)	βw_p (MJ/m^3)	$2r_p$ (mm)
100	2	53.5	10.16	32.4
100	20	51.1	9.44	24.2
100	100	48.9	9.40	18.1
38	2	74.3	11.98	55.6
500	2	41.8	10.87	21.3
1000	2	25.3	10.32	12.05

Effect of the thickness

The specific fracture work against the ligament length diagram for different thickness DDENT specimens is showed in Fig. 3. Again, the plot of σ_{net} vs. l (Fig. 4) is used to separate data obtained in each stress state. Two remarks can be done. Firstly, the plane stress points do not lay exactly on the value predicted by Hill: while the film data are very close to $1.15\sigma_y$, the sheet values do not fulfil so well the prediction, laying rather below it. Secondly, there is not an exact l^* value at which the transition occurs, as the growth of the σ_{net} when l is reduced is not very marked (Fig. 4). However, both Fig. 3 and 4 diagrams allow us to situate a transition at $l^* \approx 5$mm for films and $l^* \approx 6$mm for sheets (in Fig. 3, it can be observed that the mixed-mode data are found to be situated under the regression lines, what is helpful to situate l^*). Obviously, this value is rather far from the $l^*=(3\text{-}5)t$ suggested by the ESIS (6), but other works (3, 4) have already found similar l^* values. For the thickest specimens, it can be seen that the value of $2r_p$ is rather below the other maximum ligament size criterion, W/3, and thus, according to equation 3 the points of longest ligament length should not be considered for the regression line calculation. However, the σ_{net} vs. l diagram shows that the values corresponding to $l>12$ mm have the same stress level, and therefore a similar behaviour, than those situated between $l^*<l<12$mm, despite the ligament is not fully yielded when necking starts. Otherwise, it is important to consider that for different reasons equation 4 may not be very accurate (it may be highly dependent on the plastic zone shape, and on the E value determination method), as suggested by Hashemi (5).

With the plane stress data, the regression lines have been calculated (results are listed in Table 1). A high dependence of w_e on the thickness has been obtained, as the toughness of the 38μm films is about three times the toughness of the 1mm sheets. Although the specimens (Type IV). The stress and strain values at maximum load (σ_y, ε_y) as well as the Young`s modulus (E) were evaluated.

Fracture Tests

DDENT specimens were prepared by cutting the films and sheets into rectangular coupons of width and gauge length of 60mm. Initial notches were made perpendicularly to the traction direction with a fresh razor blade mounted on a laboratory attachment designed for this purpose, obtaining for each set at least 20 specimens with ligament lengths varying between 1 and 20mm with the distribution recommended by the ESIS protocol (7). The ligament lengths were measured before the test using a travelling microscope. The influence of the test rate was investigated on 100μm thick specimens at 2, 20 and 100mm/min, while the thickness dependence was evaluated on the 38, 100, 500, 1000 and 3000μm thick specimens at 2mm/min, all at room temperature.

RESULTS AND DISCUSSION

Fracture Behaviour

For films and thinner sheets (0.5 and 1mm) the fracture of DDENT specimens was completely stable (at 2mm/min), obtaining load vs. displacement diagrams like those shown in Fig.1. The 3mm sheets fracture was unstable after reaching the maximum load at this same speed (this behaviour was also observed on 1mm sheets when they were tested at 20mm/min). As the behaviour of the thicker sheets was not ductile, the EWF approach has not been applied to them.

It can be observed that the shape of the Fig.1 curves is practically identical for the different initial ligament lengths, indicating that the fracture mode seems to be independent of ligament length. These curves have been obtained with 100μm DDENT specimens of different ligament lengths at 2mm/min. The ligament area was observed during the test with a microscope equipped with a camera: until the maximum load (A), the high stresses concentrated on the notch tips generate two plastic zones that grow in opposite directions as the load increases. At the maximum load, the plastic zones meet each other (the whole ligament is yielded) and subsequent necking starts on the crack tips, producing a marked load drop until the whole ligament is necked (B). This occurs very rapidly and, at this moment, the crack starts to grow across the necked zone (C) until fracture occurs (D). However, not all the DDENT specimens had the same behaviour. From the ligament observation during the tests, it followed that the ligament is not fully deformed plastically when the crack starts to grow on thicker sheets with the longest ligaments (l>12mm). From the maximum load of these curves, the value of σ_{net} was calculated for each specimen in order to verify the Hill's prediction. For this purpose, the σ_{net} vs. l diagram was plotted, and the data position was compared with the $1.15\sigma_y$ value. In each case, the σ_y used was obtained at the same test rate and with the same thickness as that of the DDENT specimens tests.

while the second one is associated to the plastic work, and considered proportional to the plastic zone volume ($\beta l^2 t$):

$$W_f = W_e + W_p = w_e lt + w_p \beta l^2 t \tag{1}$$

where w_e is the Specific Essential Work of Fracture (per surface unit), w_p is the Non-Essential Specific Work of Fracture (per volume unit), l is the ligament length and β a shape-factor of the plastic zone. Dividing this equation by the ligament section, we have:

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

which is the equation of a line whose Y-axis intercept and slope are w_e and βw_p respectively when w_f is plotted as a function of l. Theoretically, only w_e is geometry independent and therefore a material parameter. Following the ESIS protocol of EWF (7), two restrictions must be satisfied for the validity of the EWF theory. Firstly, the minimum ligament length must ensure that the specimen is tested in plane stress conditions (it is usually considered that this occurs when l is greater than three to five times the thickness). However, the verification of the l/t ratio for which the transition of plane stress to mixed mode conditions occurs may be verified by plotting the maximum net stress obtained during the DDENT specimens tests (σ_{net}) against their initial ligament length. Following the Hill's predictions (8), the pure plane stress solicitation of a DDENT specimen gives a σ_{net} value of $1.15\sigma_y$, which raises to $2.97\sigma_y$ in pure plane strain conditions. Secondly, the maximum l value must keep the specimen out from edge effects, and must also ensure that the ligament is fully yielded before the crack propagation. For these purposes, the ligament length must satisfy:

$$l < \min(W/3, 2r_p) \tag{3}$$

where W is the specimen's width and $2r_p$ is the plastic zone size generated by the crack tip:

$$2r_p = (\pi/8)(Ew_e/\sigma_y^2) \tag{4}$$

EXPERIMENTAL

Material

The material used in this study was an homopolymer polypropylene film grade (Escorene 4563F1) from Exxon. The material was received as non-oriented films of 38 and 100μm thick, and in form of granulates, which were transformed by compression moulding into 0.5, 1 and 3mm thick sheets.

Tensile Tests

The tensile tests were carried out on an universal testing machine at different crosshead speeds of 2, 20 and 100mm/min at room temperature. The specimens were cut from the films and sheets with a normalised die, obtaining ASTM-D638 standard dumbbell dispersion (and consequently the experimental error) is quite important, the tendency of a growth of w_e as the thickness is reduced can be confirmed for this material. The influence of t on the plastic work item, βw_p, is less clear, and we can only say that for a same transformation method (extrusion or compression) it slightly decreases with an increase of the thickness, thus suggesting that the transformation method influence should be studied.

CONCLUSION

The deep double-edge notched tension specimens have been successfully used for determining w_e and βw_p. The influence of the test rate seems to be very low, although both values decrease slightly as the speed increases. The most important result of this work is that the toughness (w_e) of this material is highly dependent on the thickness. This dependence is so high that, firstly, w_e is reduced by 3 when the thickness changes from 38μm to 1mm, and, secondly, the fracture behaviour of notched specimens is completely modified when the thickness changes from 1 to 3mm, varying from ductile to fragile failure. Another observation is that the transition of plane stress to mixed-mode occurs at a ligament length value that is rather independent of the specimen thickness, and therefore the suggested criterion of l^*=(3-5)t is not fulfilled.

SYMBOLS USED

β = shape factor of the plastic zone
E = Young's Modulus (MPa)
l = ligament length (mm)
σ_y = yield stress (defined as the maximum) of a tensile test (MPa)
σ_{net} = net stress of a DDENT specimen test (max. load divided by ligament section) (Mpa)
t = thickness (μm)
W = specimen width
w_e = specific essential work of fracture (kJ/m^2)
w_p = specific non-essential or plastic work of fracture (kJ/m^2)
$2r_p$ = plastic zone size (mm)

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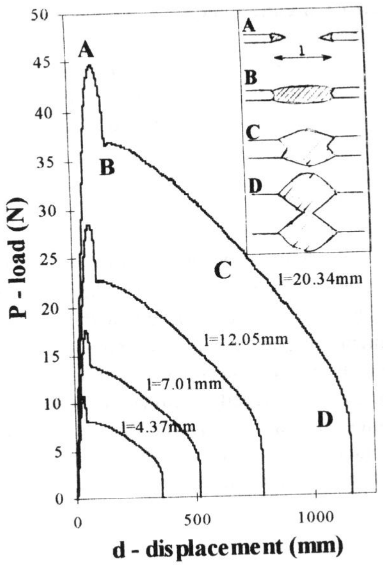

Figure 1. Curves obtained on different ligament length DDENT specimens.

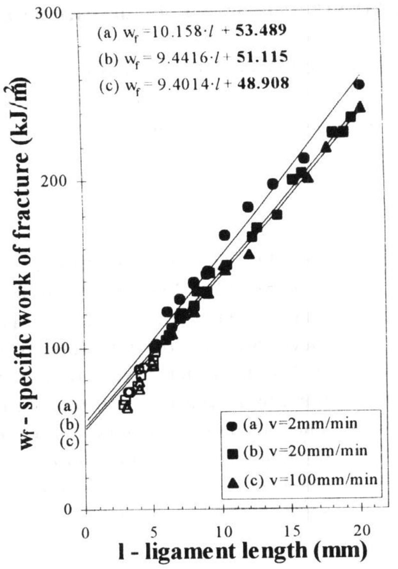

Figure 2. Specific work of fracture against ligament length for three test speeds.

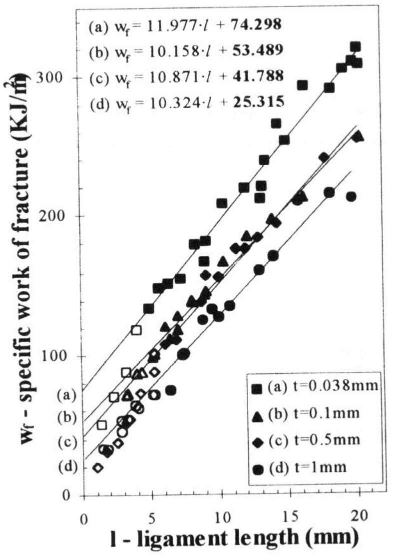

Figure 3. Specific work against ligament length with four different thickness.

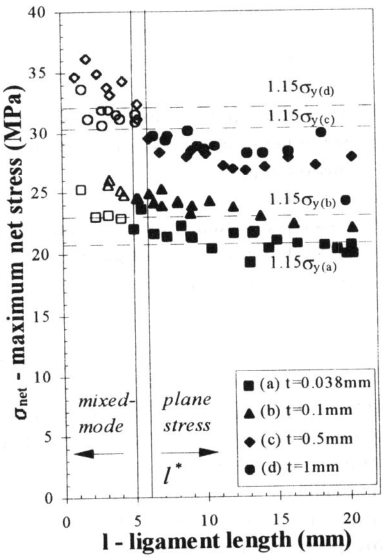

Figure 4. Verification of the stress mode transition following Hill's analysis.