PLANE STRESS FRACTURE TOUGHNESS OF DUCTILE POLYMERIC FILMS: EFFECT OF STRAIN RATE ON THE ESSENTIAL WORK OF FRACTURE PARAMETERS

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ABSTRACT

This communication reports on the effects of strain rate on the plane stress fracture toughness of various ductile polymeric films (LLDPE-co-But, PP, PA6, and PET) assessed by the essential work of fracture approach. Testing rates have been varied from 1 mm/min up to 3 m/s by a tensile tester and an instrumented tensile impact device. A general trend of the specific essential work of fracture values as a function of the strain rate is not evident since the experimental data do not follow a monotonic trend. Nevertheless, the yielding (initiation) and necking/tearing (propagation) components of the specific essential work of fracture show a well defined rate dependence. In particular the specific essential work of fracture component related to crack initiation is increasing, while the specific essential work of fracture component related to crack propagation is decreasing with strain rate.

1 INTRODUCTION

Linear Elastic Fracture Mechanics (LEFM) approach to evaluation of materials fracture toughness is based on the assumption that all energy dissipation is associated with the fracture process and the deformation which occurs is linearly elastic. Application of LEFM to polymeric materials requires linear load-displacement behaviour and very localized plastic deformation at the crack tip. Moreover LEFM tests are usually conducted on relatively thick specimens because an high transverse constrain is often assumed to provide a minimum toughness value (Williams [1]). At a present, the requirements for determining K_C and G_C values for plastics are well defined in testing standards such as ISO 13586 [2], and ASTM D5045. In practice, these standards requires that i) specimens are sufficiently thick to assure plane-strain conditions, ii) the non-linearity is within a specific (5%) reduction in the slope of the load-displacement curves, and iii) the extension of the plastic zone is small with respect to overall specimens size. This last condition is satisfied when the radius of plastic zone is much smaller (about 50 times) than specimens thickness (B), crack length (a), and ligament length (W-a), and hence the following size criteria must be satisfied:

$$B, a, (W-a) > 2.5\frac{K_Q}{\sigma_y} \quad . \tag{1}$$

where K_Q is a conditional K_C value and σ_y is the yield stress of the material.

All such conditions are not satisfied for ductile polymeric films, whose fracture is generally preceded by large plastic deformations under plane stress conditions, and, consequently, LEFM cannot be used for measuring their fracture toughness. Other methods such as J-integral and the essential work of fracture (EWF) have overcome the limitation of LEFM and should be used instead.

Aim of this work is to investigate the fracture behaviour of several ductile polymeric films by the EWF in order to assess the effects of testing rate on their fracture parameters.

2 THEORETICAL BACKGROUND

The EWF approach is based on the Broberg's suggestion (Broberg [3]) that the energy associated with fracture can be partitioned into two parts: one is specific to the fracture of the material and, as such, is a material parameter; the second is related to plastic deformations and depends upon the geometry. This idea has been further developed by Cotterell and Reddel for metals (Cotterell [4]) and, more recently, extensively applied to the fracture characterization of ductile polymers (Clutton [5]). The principle of the technique is to measure the load-displacement curves of a series of notched specimens having various different ligament lengths, ensuring that plasticity in the ligament is fully developed before fracture occurs. In such cases, it is possible to partition the total work of fracture (W_f) into a part dissipated for creating new fracture surfaces (W_e) and a part dissipated in plastically deforming a volume of material surrounding the crack (W_p). W_e is proportional to the fracture area, while W_p is proportional the volume of the outer region:

$$W_f = W_e + W_p = w_e Lt + w_p \beta L^2 t \ . \quad (2)$$

where L is the ligament length, t is the sheet thickness and β is a shape factor associated with the dimension of the plastic zone. Normalizing by the specimens cross section (Lt), we obtain:

$$w_f = \frac{W_f}{L\,t} = w_e + \beta\, w_p L \ . \quad (3)$$

From eqn (3) it follows that the specific work of fracture w_e may be determined from a graph of the specific total work of fracture w_f plotted against L.

Following an approach recently proposed by Karger-Kocsis et al. (Karger-Kocsis [6]) and successfully applied by this research group on PET (Pegoretti [7]), the total work of fracture W_f can be partitioned into two components: i) the work W_y for yielding of the ligament region; ii) the work W_{nt} for necking and subsequent tearing of the ligament region:

$$W_f = W_y + W_{nt} \ . \quad (4)$$

This energy partition is usually done by considering W_y as the energy under the load-displacement curve up to the maximum load, and W_{nt} as the energy from the maximum load up to final fracture. Similarly to Eq. (3), the variation of the specific terms w_y and w_{nt} with the ligament length can be expressed as:

$$w_y = \frac{W_y}{B\,L} = w_{e,y} + \beta_y\, w_{p,y}\, L \ ; \qquad w_{nt} = \frac{W_{nt}}{B\,L} = w_{e,nt} + \beta_{nt}\, w_{p,nt}\, L \ . \quad (5)$$

where $w_{e,y}$ and $w_{e,nt}$ represent the yielding and the necking/tearing components of the specific essential work of fracture, respectively, and $\beta_y w_{p,y}$ and $\beta_{nt} w_{p,nt}$ are the yielding and the necking/tearing related parts of the specific non-essential work of fracture, respectively.

3 EXPERIMENTAL

In this study, four different semicrystalline polymeric cast films were used, and namely: a poly(ethylene terephthalate) (PET, DuPont – Mylar, thickness t=52 μm), a nylon-6 (PA6, SNIA, t=45 μm), a polypropylene (PP, Basell – EP1X35AF, t=75 μm), and a linear low-density-polyethylene/butene copolymer (LLDPE-*co*-But, Polimeri Europa, t=50 μm).

Rectangular coupons having width of 50 mm (24 mm for impact test) and length of 90 mm (grip distance 50 mm) were cut such that their longitudinal axis was parallel to the machine direction of the extruded film. Coupons were then razor notched to obtain double edge notched tension (DENT) specimens with ligament length in the range from 5 to 20 mm.
Tensile tests at low to intermediate displacement rates (from 1 mm/min up to 500 mm/min) were performed by an Instron tensile tester model 4502 equipped with a 1 kN load cell. Tests at higher displacement rates of 1 m/s (60000 mm/min) and 3 m/s (180000 mm/min) were carried out under impact conditions by an instrumented CEAST impact pendulum in the tensile configuration. All tests have been performed at room temperature.

3 RESULTS AND DISCUSSION

The total specific work fracture (w_f) values have been obtained by evaluation of the area under the load-displacement curves of DENT specimens loaded at various rates. In all cases, a similarity in the shape of the load-displacement traces for a sample consisting of specimens with a range of ligaments can be observed. For example, the load-displacement curves obtained for LLDPE-*co*-But at various loading rates are reported in Fig. 1.

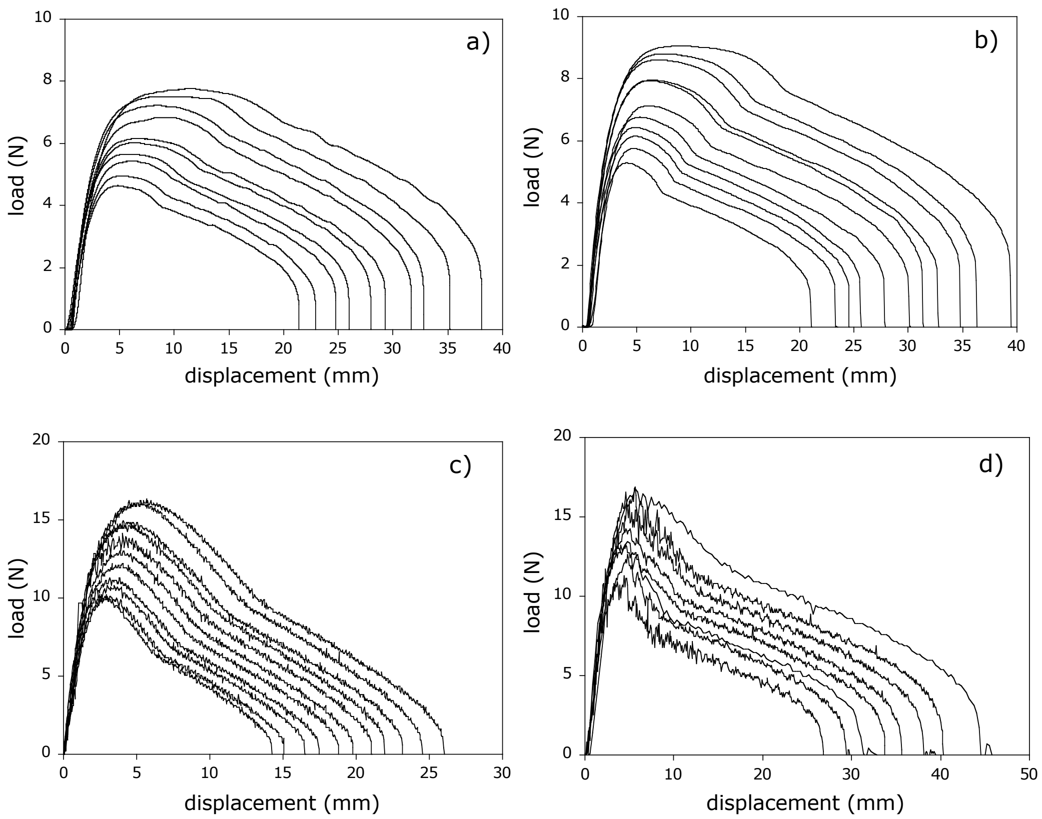

Figure 1: Load-displacement traces of LLDPE-*co*-But DENT specimens with various ligament lengths tested at a) V= 10 mm/min, b) 100 mm/min, c) 1 m/s, and d) 3 m/s.

It is interesting to observe that even under impact conditions the quality of the load-displacement signal is sufficiently stable, and that the obtained curves show a certain self-similarity.

The area under the load-displacement curves normalized to the specimen ligament cross-section represents the total specific work of fracture. In general w_f values resulted to be linearly dependent on the ligament length, as reported in Figure 2 for LLDPE-*co*-But.

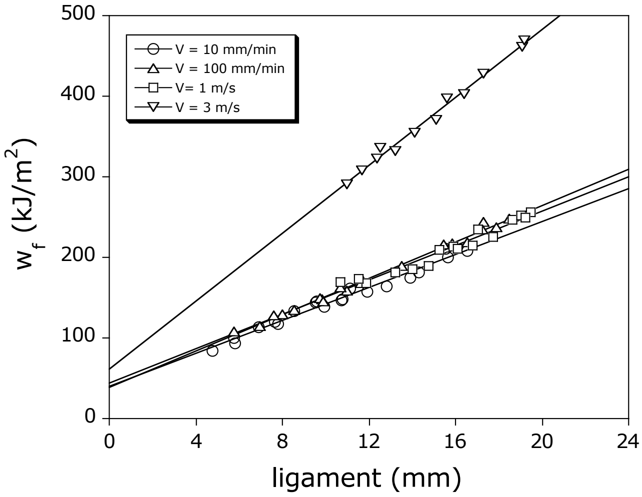

Figure 2: Specific work of fracture versus ligament length data for LLDPE-*co*-But specimens loaded at various displacement rates.

The specific essential work of fracture (w_e) is then derived from the "best fit" linear regression analysis of the data as the intercepts of the line at zero ligament length, while its slope represents the specific non-essential work of fracture (βw_p). In Tab. 1 the specific essential work of fracture values obtained at various loading rates are reported for the materials under investigation.

Table 1: specific essential work of fracture values.

	w_e (kJ/m^2)			
V (mm/min)	LLDPE-*co*-But	PP	PA6	PET
10	40.1	44.0	43.8	40.2
100	38.9	41.9	40.7	39.4
60000	44.6	26.9	53.2	63.7
180000	61.6	50.9	53.4	--

It is quite evident that the data reported in Tab. 1 do not permit to establish a clear trend of the specific essential work of fracture values as a function of the strain rate.

The total specific work of fracture can be partitioned into two components: the energy under the load-displacement curve up to the maximum load (W_y), and the energy from the maximum load up to final fracture (W_{nt}). The first term is related to the yielding of the ligament region and to the crack initiation processes, while the second term is clearly related to the energy dissipation during the crack propagation process. These quantities can be plotted as a function of the ligament length, and the intercepts of the linear regression lines ($w_{e,y}$ and $w_{e,nt}$) represent the yielding and the necking/tearing components of the specific essential work of fracture.

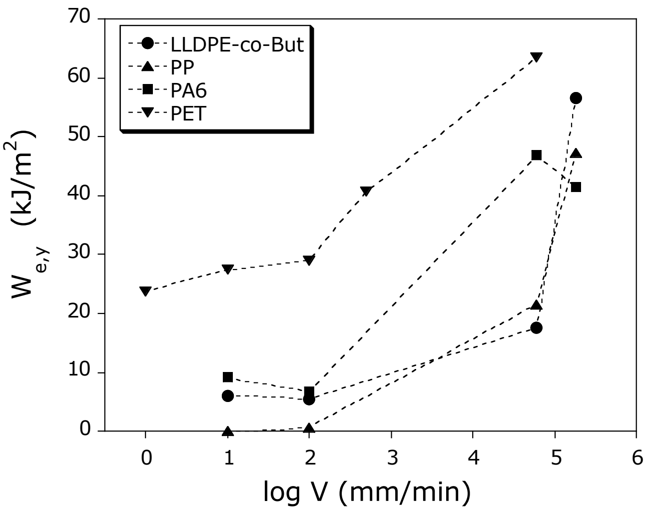

Figure 3: Yielding component of the specific essential work of fracture versus displacement rate for LLDPE-*co*-But, PP, PA6 and PET specimens.

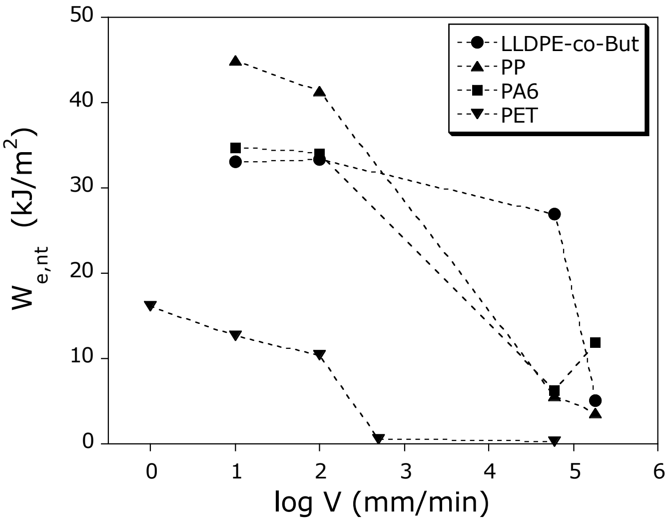

Figure 4: Necking/tearing component of the specific essential work of fracture versus displacement rate for LLDPE-*co*-But, PP, PA6 and PET specimens.

As evidenced in Fig. 3, it is quite interesting to observe that for all the investigated materials the yielding related component of the specific essential work of fracture is increasing when testing rate increases. On the other hand, the necking/tearing component of the specific essential work of fracture is decreasing with testing rate. This means that the specific work of fracture, that represents the energy expended in the inner process zone to create the fracture surfaces, is given by the sum of two contributes that are both affected by the testing rate but with opposite trends. This could explain the non-monotonic trend of the specific work of fracture values observed as a function of the testing rate. On the basis of experimental data reported in Figs. 3 and 4 it can be concluded that as the testing rate increases the specific energy required for crack initiation ($w_{e,y}$) increases while specific energy required for crack propagation ($w_{e,nt}$) decreases. Moreover it is worthwhile to observe that the transition in both $w_{e,y}$ and $w_{e,nt}$ curves occurs at different displacement rates depending on the material. In particular, even if it is difficult to exactly quantify this trend, there is a tendency for this critical rate to increase as the material glass transition increases, i.e. in the following order: LLDPE-co-But (T_g at about -120 °C), PP (T_g at about -10 °C), PA6 (T_g at about 50 °C), and PET (T_g at about 80 °C).

4 CONCLUSIONS

The plane strain fracture toughness of four polymeric films (LLDPE-*co*-But, PP, PA6 and PET) have been investigated by the essential work of fracture approach. Fracture behaviour of double edge notched specimens have been evaluated in tension over a wide range of displacement rates from 1 mm/min up to 3 m/s (impact conditions). The specific essential work of fracture values do not show a monotonic trend as a function of the strain rate. By partitioning the total specific work of fracture energy into a yielding related (W_y) and a necking/tearing (W_{nt}) related component, the specific terms $w_{e,y}$ and $w_{e,nt}$ can be obtained, that represent the yielding and the necking/tearing related components of the specific essential work of fracture, respectively. These terms resulted to be significantly rate dependent: in particular the specific essential work of fracture component related to crack initiation is increasing, while the specific essential work of fracture component related to crack propagation is decreasing with strain rate.

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