STRAIN RATE DEPENDENCE OF THE ANISOTROPIC FRACTURE TOUGHNESS OF RUBBER MODIFIED POLYPROPYLENE FILMS

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ABSTRACT

A rubber modified cast polypropylene film has been tested by the essential work of fracture method to assess the effect of material orientation on the fracture toughness. The tests have been performed under different quasi-static rates, in order to analyze the strain rate effects on the material toughness: impact rates were also considered, but results are still at a preliminary stage. Results indicate a marked anisotropy with higher essential work of fracture values for cracks propagating transversally to the extrusion direction. Fracture toughness in both direction is substantially independent of testing speed up to 500 mm/min and markedly decreases under impact conditions. Furthermore, the specific essential work of fracture was partitioned into two terms, one representing the specific work for yielding up to the onset of fracture, and another term related to the specific work for subsequent necking and tearing. Scanning electron microscopy observations have been conducted to reveal fracture surfaces morphology.

1 INTRODUCTION

The dispersion of a second phase is often used to achieve improvements in the impact properties of engineering polymers. The role of the second phase is usually to promote initiation and development of matrix plastic deformation. Rubber modified polymers usually displays a typical ductile behaviour generally exhibited at low strain rates or at high temperatures by the unmodified materials (Béguelein, Ph. et al. [1]). The viscoelastic nature of thermoplastic polymers accounts for a dependence of the properties on temperature and strain rate, and therefore also modified polymers can exhibit a transition to a brittle behaviour at high deformation speed. Besides, technological transformation processes can develop material orientations that strongly affect the mechanical properties of semicrystalline thermoplastics, due to the micromorphology of the materials, orientation of polymer chains and the existence of residual stresses (Yokoyama et al. [2]).

Aim of this work is to determine how strain rate can affect the material properties of an anisotropic polymeric film in the directions parallel and perpendicular to the extrusion direction. Due to the inherent ductility of rubber modified polymers, an elastoplastic fracture mechanics approach was applied, the essential work of fracture (EWF) method, that seems to be the most appropriate technique to obtain fracture parameters for polymeric films (Maspoch et al. [3]).

2 THEORETICAL BACKGROUND

The EWF method, originally proposed by Cottrell and Reddel after Broberg's work, is based on the assumption that total fracture energy, W_f, can be separated into two terms: one, named essential work of fracture, W_e, is related to the energy to create two new surfaces, in what is called process zone; the other, the non-essential work of fracture, or plastic work, W_p, corresponds to the energy dissipated in the surrounding deformation zone (Fig. 1a). Since the first term it's a surface related term, while the other is a volumetric contribution, from the total fracture energy specific essential and non essential work of fracture, respectively w_e and w_p, can be derived following the equation:

$$W_f = W_e + W_p = w_e \cdot (L \cdot t) + \beta w_p \cdot (L^2 \cdot t) \quad (1)$$

where t represents thickness, L the ligament length, and β a factor which depends on the shape of the plastic zone. Dividing eqn. (1) by the ligament surface (L·t), we obtain that the specific work of fracture, w_f, is a linear function of the ligament length:

$$w_f = w_e + \beta \cdot w_p \cdot L \quad (2)$$

and therefore the essential and non essential work of fracture parameters can be experimentally determined as the intercept and the slope of the linear regression of the specific work of fracture values measured for different ligament lengths, respectively.

Following an approach recently proposed by Karger-Kocsis et al. [4] and successfully applied by this research group on PET (Pegoretti et al. [5]), the total work of fracture was partitioned into two components: i) the work for yielding the ligament region W_y, estimated as the energy up to the maximum load point; ii) the work for necking and subsequent tearing of the ligament region, W_{nt}, representing the work spent from the yield point until the specimen breaks, and therefore the crack propagation energy. Applying relationships similar to eqns. (1,2), specific essential and non-essential work for the yielding and necking/tearing processes can be as:

$$w_y = w_{e,y} + \beta \cdot w_{p,y} \cdot L \quad (3)$$

$$w_{nt} = w_{e,nt} + \beta \cdot w_{p,nt} \cdot L \quad (4)$$

and therefore the essential and non essential work of fracture can be divided in these sub-terms, as:

$$w_e = w_{e,y} + w_{e,nt} \quad (5)$$

$$\beta \cdot w_p = \beta \cdot w_{p,nt} + \beta \cdot w_{p,nt}. \quad (6)$$

3 EXPERIMENTAL

3.1 Materials

The material, kindly supplied by MG Lavorazioni Materie Plastiche SpA (Vicenza-Italy) as A4 foils, is a rubber modified polypropylene-polyethylene block copolymer, with 10-12% PE content and a 4-5% rubber content. The material, commercialized under the trade name of P88, is a cast film with an average thickness of about 80μm. The processing conditions develop anisotropic features in the films: different mechanical properties are thus found in directions parallel (II) and perpendicular (⊥) to extrusion (Tab. 1).

DMTA test revealed a main peak in the tan δ thermogram at about 5°C, related to glass transition of the polypropylene matrix, and a second peak at about -50°C, due to the added rubber.

Table 1: Some mechanical properties of P88 films in the direction parallel (II) and perpendicular (⊥)to the extrusion direction, from laboratory experiments and producer data sheets(*).

	II direction	**⊥ direction**
Young modulus (MPa)	910	840
Yield Stress (MPa)	26.8	22.7
Elmendorf Tearing resistance*(mN)	450	4000

3.2 Test methods

Fracture tests were carried out following the ESIS protocol of EWF (ESIS-TC4 [6]). DENT specimens were prepared by cutting A4 sheets of P88 into rectangular coupons in direction parallel to the extrusion direction (called TD, to remind that crack propagates transversally to the extrusion direction) and perpendicular (called MD) (Fig. 1b). Initial notches were made perpendicularly to the load direction with a fresh razor blade, and 25 specimens for each test were obtained, with the geometry reported in Figure 1a, and ligament length varying between 6mm and 14mm; ligament lengths were measured before the tests by an optical microscope.

Tests were performed with the dynamometer Instron Mod. 4502, at different displacement rates, V (1mm/min; 10mm/min; 100mm/min; 500mm/min). Temperature was kept constant at 25°C by means of a thermostatic cell Instron Mod. SFL 3119-409. The load vs. displacement curves were recorded, and the energy was calculated by their integration.

Impact tests were performed at room temperature at 1 m/s by an instrumented CEAST tensile impact pendulum on specimen with a width of 24 mm, but with the same ligament range; quasi static tests on this specimens showed that a different specimen width did not influence the fracture parameters. These tests are however at a preliminary stage and thus results have to be cautiously regarded.

3.3 SEM Micrograph

SEM observations were carried out on P88 specimens to have information about fracture surfaces by a Cambridge Stereoscan 200 scanning electron microscope. Samples were cooled in liquid nitrogen and here cut in a brittle manner in directions perpendicular (TD) and parallel (MD) to the extrusion direction. Specimen were then treated in n-Hexane at 50°C for 1h to evidence the rubber presence.

4 RESULTS AND DISCUSSION

Mechanical tests at different displacement speeds led to the stress vs. displacement curves reported on Fig.2. All curves show a pronounced maximum, corresponding to the yielding of the material, followed by a drop related to necking and subsequent tearing. The maximum stress increases for both samples as the test speed increase (inset of Fig. 2), and TD samples always revealed higher stresses. At the same time, extents of the necking/tearing stage becomes progressively smaller at higher rates, but their regular behavior confirm a stable crack propagation, as reported in other works on rubber modified polymer (Béguelin et al. [1]).

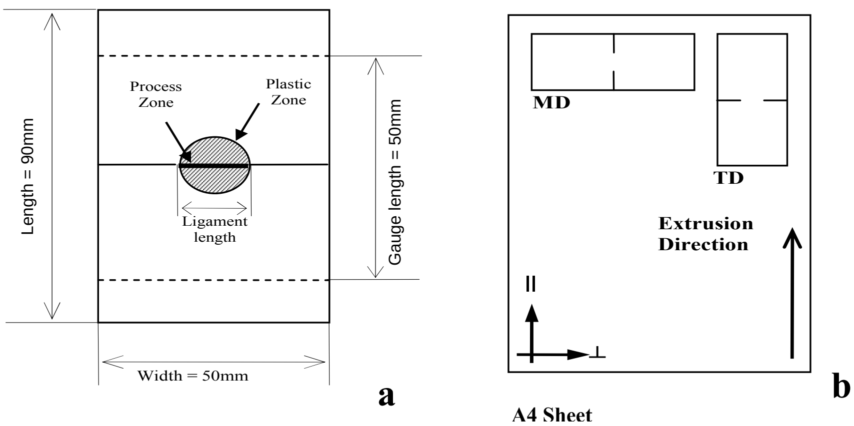

Figure 1: Geometry (a) and orientation (b) of specimens used for the EWF method.

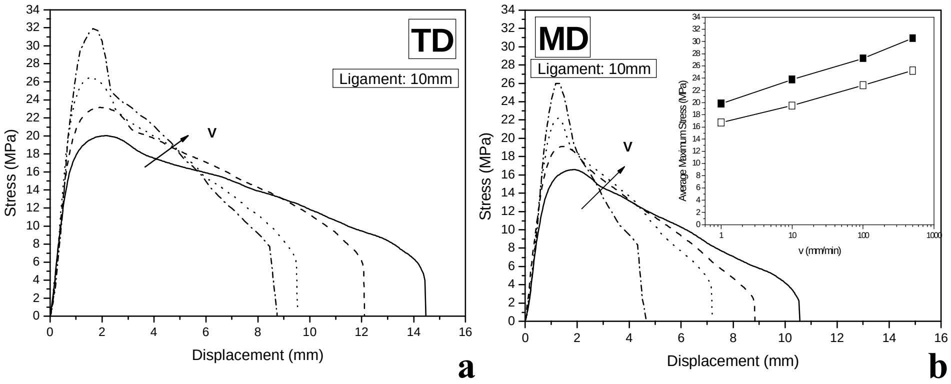

Figure 2: Stress versus displacement curves measured on TD (a) and MD (b) specimens (Ligament ≈10mm)at different test speed, V (—1mm/min; –––10mm/min; ····· 100mm/min; –·–·– 500mm/min;); in the inset: test rate dependence of average maximum stress for TD (■) and MD (□) samples with ligament between 6 and 14mm.

Data reduction in accordance to the ESIS protocol for the EWF method led to the plots represented in the inset of Fig.3. TD samples showed higher specific work of fracture values than MD ones, but in both cases the main effect of test speed, V, is a decrease of the slope of specific work of fracture vs. ligament curves, while the intercepts of the curves remain almost unaffected.

Fig. 3 shows the values of the specific essential and non essential work of fracture at various displacement rates. TD samples showed a higher fracture toughness than the MD ones, in accordance to the higher Elmendorf resistance observed perpendicularly to the extrusion direction.

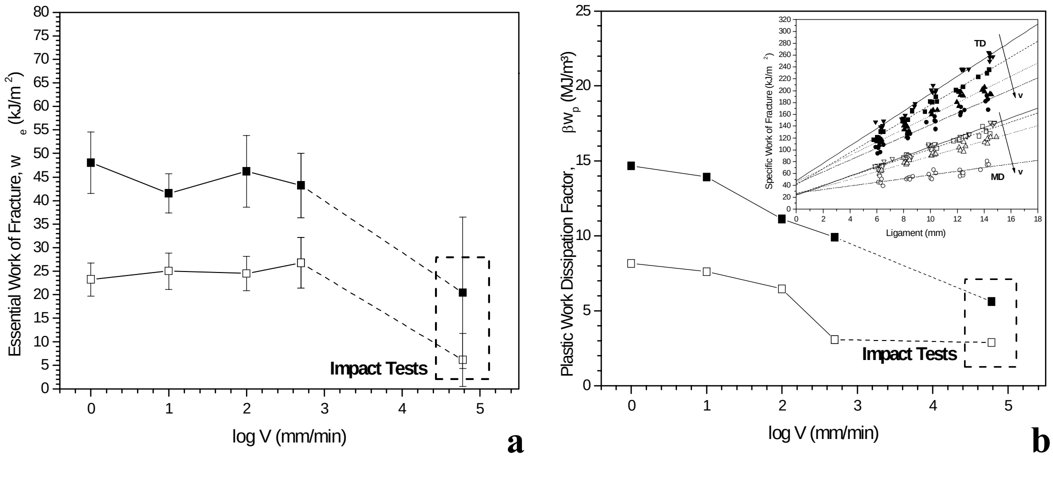

Figure 3: Test speed dependence of specific essential (a; w_e) and non essential (b; βw_p) work of fracture on polypropylene TD (■) and MD (□) specimens; in the inset: speed test dependence of the work of fracture versus ligament length curves in the quasi static tests (test speed, V, varying between 1mm/min and 500mm/min).

Quasi-static test rates (up to 500 mm/min) practically do not affect the w_e values, and a ductile-to-brittle transition it's observed only at impact test rate (1m/s) (Fig.3a). Non essential work of fracture decreases as test rate increases, showing a transition behavior for the impact tests, more evident for the less tough MD samples (Fig.3b).

Partition of the essential work of fracture in the yielding and necking/tearing components indicates that the crack propagation stage accounts for the main part of the total fracture energy at this temperature and for all the quasi-static test speeds (Fig.5), as found by Béguelin et al. [1]. The yielding component of the essential work of fracture remains almost unaffected by the test rate in TD samples, but shows a slight increase for the MD samples, where, on the other hand, the necking/tearing parts remains constant. The non essential work of fracture partition still shows that the necking/tearing stage is responsible of the main part on the plastic dissipation parameters; a transition to lower values as the test speed increases is still observed.

The SEM pictures reported in Fig.5 were taken on fracture surfaces perpendicular to the load direction for both the specimens orientations; film was fractured in a brittle manner after cooling in liquid nitrogen. Fracture surfaces perpendicularly to the extrusion direction, i.e. TD samples, revealed the presence of holes on their surfaces as consequence of rubber dissolution by the treatment in n-Hexane (Fig.5a). In opposition to the large extent of rubber on these surfaces, MD samples, whose ligament is parallel to the extrusion direction, do not show any detail related to rubber presence.

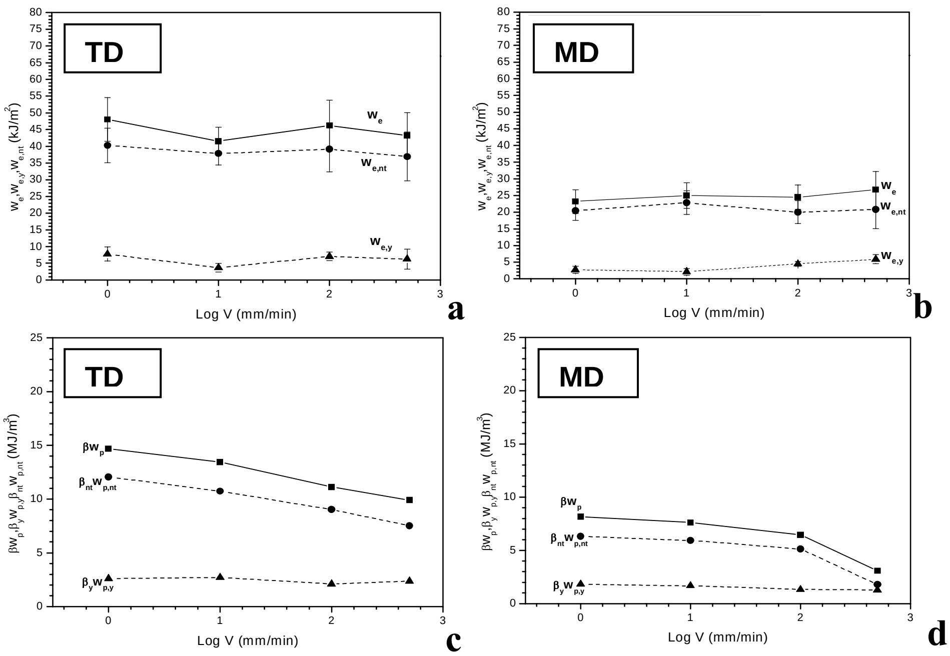

Figure 4: Test speed dependence of specific essential (a: TD; b: MD) and non essential (c: TD; d: MD) work of fracture (■), and their partition in yielding (▲) and necking/tearing (■) related components.

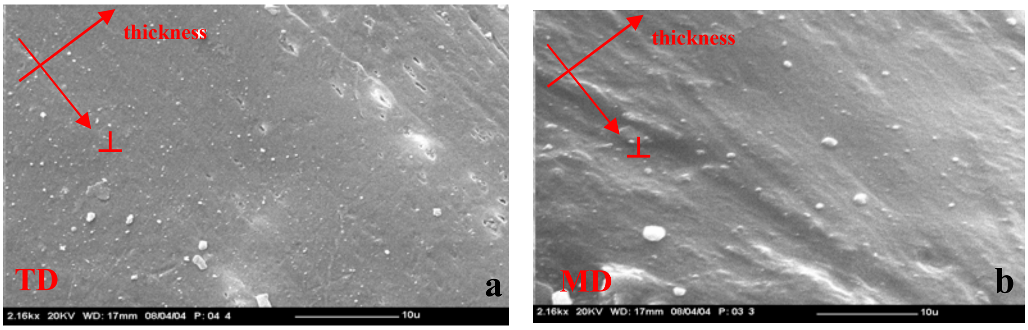

Figure 5: SEM of the fracture surfaces of TD (a) and MD (b) specimens.

5 CONCLUSIONS

Fracture toughness at various strain rates was measured in the directions perpendicular and parallel to the extrusion direction in a rubber modified polypropylene (PP) film. Samples showed higher mechanical features when tested along the extrusion direction, with ligaments lying perpendicularly to this direction. On this specimens no relevant strain rate effect was revealed for the essential work of fracture, and only under impact rates a transition to a brittle behavior was found; this ductile behaviour for quasi-static test speeds was consistent with the presence of rubber particles on the ligament surface. Anyhow the slope of the specific work of fracture vs. ligament curves, and therefore the non essential work of fracture, show a progressive decrease at higher strain rate, and relevant effects are shown still in the quasi-static range of test speed. On the other hand, the absence of rubber inclusions in the fracture plane for samples with ligaments parallel to the extrusion direction, is suggesting that crack propagate between rubber particles, thus explaining the low crack resistance in this direction.

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