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Test Method

The fracture testing of ductile polymer films: Effect of the specimen notching

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ABSTRACT

The fracture of a ductile polymer film, a heterophase ethylene-propylene block copolymer, has been studied, combining a range of characterisation methods in an attempt to provide a better understanding of the intricate details that play an important role in the repeatability and reproducibility of the essential work of fracture test. The experimental factors that have a strong influence on the resulting parameters are clearly explained, with particular attention to the effect of the quality of the notches, the non-collinearity of the two edge notches in double edge notched tension specimens, and the lack of alignment of the specimen with the load axis once it is mounted on the load train. Furthermore, the influence of these experimental factors on the registered stress-displacement curves is also studied, and a criterion and the method for separating non-valid specimens are established.

1. Introduction

Polymer films are used in a wide variety of applications. Their toughness is often a basic requisite to meet some industry needs.

The Linear Elastic Fracture Mechanics (LEFM) approach is used to study fractures occurring at nominal stresses well below the material yield stress. The dissipated energy is confined in a small area near the crack tip, and the fracture is brittle. The LEFM approach is not applicable when the plasticity around the crack tip becomes large; in those cases the Elastic Plastic Fracture Mechanics (EPFM) is applied. When the crack propagation occurs through a highly deformed and yielded material then Post-Yield Fracture Mechanics can also be applied and the Essential Work of Fracture (EWF) is a suitable methodology.

The EWF approach has become very popular to characterise fracture of polymer films and is increasingly used due to its apparent simple preparation and easy testing. The EWF characterises the plane stress toughness in mode I, generally using the double edge notched tension (DENT) configuration for the specimens.

In spite of the apparent simplicity of the EWF test, some aspects of the validity of this technique remain controversial; there are intricate details that seem to play an important role in the repeatability and reproducibility of the test. This problem has been and still is a topic of much debate, and these questions indicate that the EWF procedure is not yet sufficiently well-defined to be standardised. Some of the aspects of the test validity are related to the specimen manufacture, particularly the quality of the notches.

Two sets of specimens have been prepared, the first one sharpened by the femtosecond laser ablation technique, and the second one sharpened by the classical razor blade sliding technique. These two sets of specimens have been characterised by combining the EWF, J-integral, and crack tip opening displacement (CTOD) methods in an attempt to provide a better understanding of the EWF fracture approach for characterising the fracture toughness of a ductile polymer film. The connection between the quality of the notches and the shape and size of the registered stress-displacement curves has been established. This was done in order to find a criterion and a method to eliminate non-valid specimens. Furthermore, it has been studied in detail how the size and shape of the stress-displacement curves are related to the EWF fracture parameters.

The effect on the stress-displacement curves of specimens with non-collinear notches, specimens with different quality between the two edge notches, and specimens having a lack of alignment with the load axis once mounted on the testing machine grips have

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been also studied.

Moreover, there is a limited understanding of the polymers to which the EWF approach can be applicable. The EWF approach has been successfully applied to polymers that undergo necking before crack propagation. However, there is some controversy over the applicability of the EWF approach to heterophase polymers, which can deform by other mechanisms. For this reason, a very ductile grade of an ethylene-propylene block copolymer (EPBC), which is prone to plastic deformation and thus problematic for the notch sharpening, was tested.

The main objective of this work is to contribute to a better understanding and to clarify some of the controversial factors involved in the EWF test.

2. The EWF approach

2.1. The EWF concept

The EWF approach [1] is based on the hypothesis that the total energy involved during the ductile fracture of a pre-cracked specimen (W_f) can be separated into two terms.

$$W_f = W_e + W_p \tag{1}$$

where W_e, the essential work of fracture, represents the energy required for the creation of two new surfaces during the crack propagation, whereas the second term, W_p, is called the plastic work or the non-essential work of fracture and collects all other sources of energy produced throughout the fracture process. The term W_e is considered to be proportional to the area of the Fracture Process Zone (FPZ) while W_p is proportional to the volume of the Outer Plastic Zone (OPZ). These zones are schematised in Fig. 1 for a DENT specimen.

Rewriting Eq. (1) using specific terms,

$$w_f = \frac{W_f}{l_o g t} = w_e + \beta w_p \cdot l_o \tag{2}$$

where t is the specimen thickness, l_o is the original ligament length and β is a factor that depends on the shape of the OPZ.

It is possible to assess Eq. (2) by performing a series of tests on specimens with different ligament lengths, and subsequently plotting the specific total work of fracture values, w_f, as a function of their ligament lengths. A simple regression analysis of this plot shows that the specific essential work of fracture, w_e, and the specific non-essential work of fracture, βw_p, are the intercept for a zero ligament length and the slope of the linear regression line, respectively.

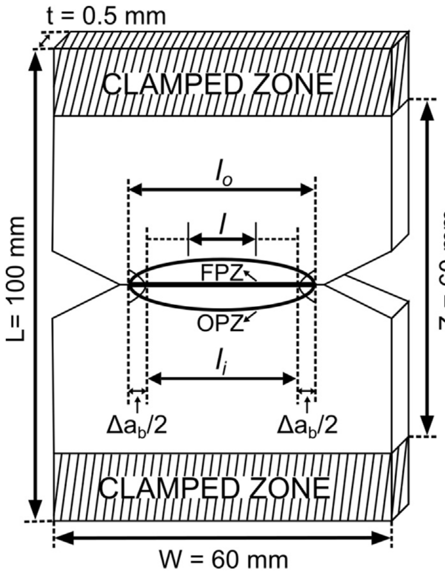

Fig. 1. DENT specimen geometry.

The value which represents the toughness, namely, w_e, is an inherent material parameter only if the ligament yields fully before the onset of crack propagation.

2.2. Key assumptions

In the EWF analysis, the following three basic key assumptions are made:

a) The l_o is fully yielded prior to the onset of crack propagation.

In a DENT specimen, it could be estimated that l_o will be completely yielded prior to the onset of crack propagation if it is less than twice the size of the plastic zone radius, r_p. Under plane stress conditions, for a linear plastic zone

$$2r_p = \frac{\pi}{8}\left(\frac{E w_e}{\sigma_y^2}\right) \tag{3}$$

and for a circular plastic zone

$$2r_p = \frac{E w_e}{\pi \sigma_y^2} \tag{4}$$

where E is the elastic modulus and σ_y is the uniaxial yield stress.

Although having $l_o \le 2r_p$ is a reasonable size criterion, it appears to be too restrictive.

b) Fracture occurs under plane stress conditions.

As polymer films have a thickness of less than 1 mm, a practical lower limit of 5 mm for l_o has been accepted when preparing DENT specimens to be properly handled. The upper limit for l_o requires full-ligament yielding before crack propagation. Hence, l_o has to be less than twice r_p in DENT specimens.

Another upper limit is given by the relationship:

$$l_o \le \frac{W}{3} \tag{5}$$

where W is the specimen width. This last condition is necessary to prevent edge effects.

c) Good quality notches.

Good quality means identical and repetitive sharp notches without plastic deformation in front of the notch tip. This requirement guarantees self-similar load-displacement and ligament length-displacement curves for the tested specimens [2,3].

The notch sharpening is of critical importance in obtaining good results [4–6]. The larger notch tip radius or plastic deformation, the higher w_e values.

2.3. Other considerations

When the key assumptions are satisfied, w_e is the specific energy just before crack initiation. That is, an initiation value which coincides with the J-integral value at initiation, J_o [2].