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The use of deeply double edge notched small punch specimens for the determination of the essential work of fracture (EWF) parameters in polymer sheets

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ABSTRACT

In recent decades, one of the most widely used techniques to characterize the fracture properties of polymer sheets under plane stress conditions has been the essential work of fracture (EWF). This method allows the testing of different pre-cracked specimens although those most commonly tested are the deeply double edge notched tensile specimens (DDEN-T). However, in situations in which the access to the material is limited, e.g. in service-exposed components, the use of smaller specimens is proposed: deeply double edge notched small punch specimens (DDEN-SP). In this paper the EWF theory is applied to the miniature test in order to obtain fracture parameters, and the viability of the method is discussed. These results are also compared to those obtained from standard specimens (DDEN-T).

1. Introduction

The essential work of fracture (EWF) is a method originally proposed by Broberg [1,2] in the seventies for metals and alloys. Subsequently, Mai [3,4] extended this technique for polymer characterization. In recent decades, EWF has been widely and successfully used to evaluate fracture properties in polymer sheets under plane stress conditions. For laboratory analysis of the EWF, the tested specimens are usually the deeply double edge notched tensile specimens (DDEN-T) [5,6].

The foundation of the EWF method is to divide the energy that has been consumed during ductile fracture of pre-cracked specimens, (W_f), into two terms: the essential work (W_e) and the plastic work (W_p). The former, W_e, represents the energy required to create the new fracture surfaces, which can be related to the inner fracture process zone IFPZ (Fig. 1). The latter, W_p, is a non-essential work as it comprises the energy employed in general plastic deformation and dissipation process, depending on the geometry of the deformed region. This plastic work is thus related to the outer process dissipation zone OPDZ (Fig. 1). Both terms are a function of the specimen ligament as expressed in Eq. (1). Hence, they are usually divided by the ligament section ($L \cdot t$) in order to use the specific work terms, (w_f, w_e and w_p), as shown in Eq. (2),

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

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

where t is the specimen thickness, L is the ligament length and β is the shape factor corresponding to the geometry of the outer plastic dissipation zone [7]. The term w_e is equivalent to the fracture toughness. For polymer films, the advantage of the EWF method compared to the J-Integral procedure is, in many cases, its experimental simplicity.

Different specimens are tested in order to empirically obtain EWF parameters and energies, especially the deeply double edge notched tensile (DDEN-T) type. These specimens are machined directly from a polymer sheet or are manufactured by injection or moulding techniques. However, sometimes the available polymer raw material or sheets are not large enough or the material access is physically restricted, e.g. in injected components or thermowelded bonding areas. In these cases, standard specimens cannot be obtained and smaller samples must be tested. For this purpose, the alternative use of deeply double edge notched small punch (DDEN-SP) specimens is proposed in this paper.

Within this new approach of EWF, the use of miniature notched specimens does not allow tensile conventional tests to be carried out, thus requiring the Small Punch Test (SPT). Miniature specimens tested with the SPT, whose dimensions are $10 \times 10 \times 0.5$ mm, are deformed by a high strength punch.

Although the Small Punch Test has been used in numerous studies with the objective of mechanically characterizing a

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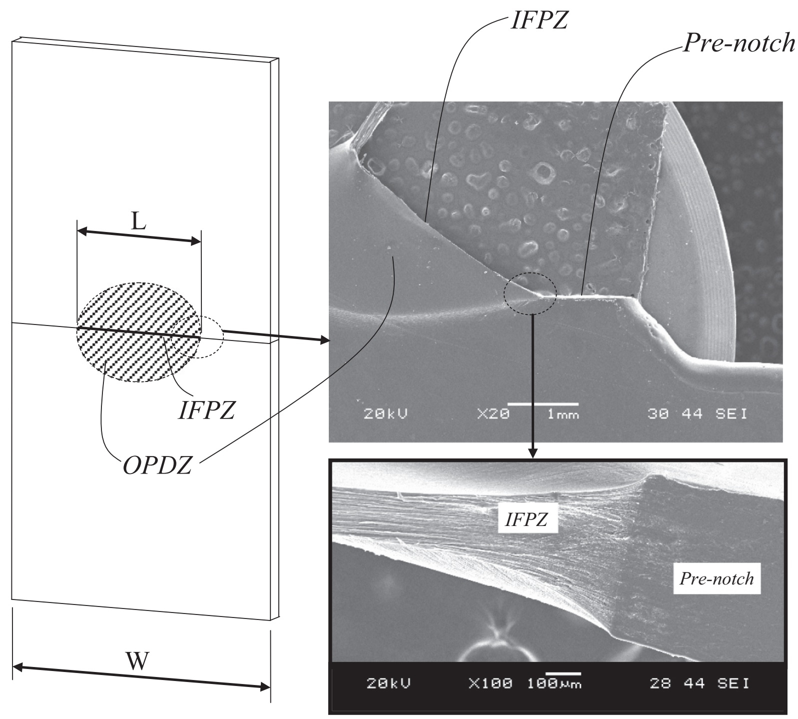

Fig. 1. Deeply double edge notched tensile specimen.

material sample of small dimensions [8–11], few of these studies have considered pre-notched SPT specimens [12,13]. The experimental procedure and the required equipment are described in the CEN code of practice for small punch testing [14].

Recently, in previous research papers [15,16], in order to characterize the fracture properties of polymer sheets under plane stress conditions, there has been an attempt to establish the viability of applying the EWF method in pre-notched miniature polymer specimens. Despite the good results obtained, selecting a miniature specimen resembling that of a DDEN-T was found to be appropriate. Consequently, the objective of this paper is to analyse whether the DDEN-SP specimens are useful for the assessment of fracture material properties by means of EWF or not. A possible correlation with those results from standard specimens (DDEN-T) is also discussed.

2. Materials and EWF for DDEN-T specimens

The EWF technique as mentioned above proposes that the total work of fracture (W_f) consumed during ductile tearing can be obtained by calculating the area of the load-displacement curve and then be separated into the essential and plastic terms (W_e and W_p). Hence it is possible to plot the specific work of fracture w_f as a function of the ligament length L according to Eq. (2). Fitting this expression by means of a linear regression, w_e represents the intercept of the line with the vertical axis at $L = 0$ while $\beta \cdot w_p$ might be determined as the slope of the fitted line.

To assure that the EWF theory can be applied for toughness determination, a number of requirements must first be met [17]: (i) the ligament must fully yield before crack initiation, (ii) plane stress conditions must prevail and (iii) the condition of self-similar load-displacement curves must be achieved (self-similarity is related to the shape of the curves although the size depends on the ligament length). Despite this, in their research on EWF [7] Bárány et al. point out that the third one, self-similarity between curves, is the only really necessary condition that should be fulfilled for the successful application of EWF.

Generally, the EWF method is applied to the characterization of polymer sheets of little thickness ($t < 2$ mm). In the present study, the selected material is an amorphous polyethylene terephthalate (A-PET) manufactured by extrusion, type A-B-A 100% (layers A of 100% virgin material and layer B of recovered materials) whose theoretical weight is 1.33 gr/cm^3 and with an initial extruded sheet thickness of 0.492 mm.

DDEN-T specimens with a width of $W = 30$ mm were obtained by means of laser cutting from the previously extruded A-PET sheets in such a way that both edges are notched with the purpose of obtaining a toughness value for this selected material. Both edge notches in every DDEN-T specimen were sharpened with a razor blade. Considering that the specimen width is reduced by different notch sizes, the ligament length must vary in such a way that the plane stress conditions are maintained. Thus, the range employed in the EWF method is limited by a maximum ligament of $L \geqslant 3 \cdot t$ and a minimum of $L < W/3$ [7]. All DDEN-T tests were performed at room temperature.

The mechanical behaviour of the selected A-PET in the DDENT-T test might be observed in the load-displacement curves plotted in Fig. 2 for different ligament lengths. A shape similarity between the different curves is clearly confirmed, thus the EWF method might be applied. Moreover, a ductility level (D_L) was proposed by Gamez-Perez [18] as expressed in Eq. (3), where d_r is the displacement at rupture, with the aim of rationalizing different fracture behaviours. This ductility level is examined in the performed tests, and it is found that D_L takes different values but always within the range between 0.15 and 1; these values lead to classifying the fracture as post-yielding behaviour in which the EWF method is completely applicable [18]. As a consequence, it can be assured that the selected A-PET material is suitable for the application of EWF.

$$D_L = d_r/L \tag{3}$$

After a visual comparison between all of the performed tests, those specimens in which the load-displacement curve has a considerably different shape are not considered as valid results. Once the abnormal curves are discarded, w_f is obtained and plotted as a

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