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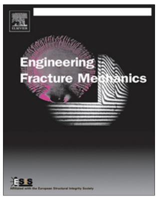

The post-yield fracture of a ductile polymer film: Notch quality, essential work of fracture, crack tip opening displacement, and J-integral

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ABSTRACT

Double edge notched tension (DENT) specimens of a polyethylene terephthalate (PET) film were tested in an universal testing machine, measuring the displacements and the ligament lengths with a digital image correlation (DIC) system. With these data the essential work of fracture (EWF), crack tip opening displacement (CTOD), and the J-integral fracture methods were compared. The specimens were tested in mode I under plane stress conditions, verifying that the crack always propagated through a fully yielded ligament. It has been proved that w_e, the specific essential work of fracture was the specific energy just up to crack initiation and has the same value that J-integral at crack initiation, J_o. The relationship of these parameters with the CTOD was also shown. The influence of the notch quality on the fracture behaviour when the specimens were sharpened by two different methods, femtosecond laser ablation or by razor blade sliding, has also been analysed in detail.

1. Introduction

The ability of polymers to be shaped in practically any form makes possible to obtain films which are mainly used in the packaging and agriculture market segments that accounts for a 39.6% and 4.3% of the plastic global demand, respectively.

The classical tests for determining the mechanical properties of polymer films are well established and standardized, but this is not the case for the fracture properties.

The linear elastic fracture mechanics (LEFM) approach is used to study fractures occurring at nominal stresses well below the material yield stress. The main hypothesis of LEFM considers that the dissipated energy is confined in a small area near the crack tip (small scale yielding), and the fracture is brittle, without extensive deformation.

The LEFM approach is not applicable when the plasticity around the crack tip becomes too large; in those cases the elastic plastic fracture mechanics (EPFM) apply and CTOD and J-integral are appropriate methods to characterize fracture. When the crack propagation occurs through a highly deformed and yielded material then the post-yield fracture mechanics (PYFM) can also be applied and the EWF is the most suitable method. For ductile polymers where crack propagation occurs through a fully yielded ligament, the EWF, the CTOD, and the J-integral are commonly used.

The EWF is gaining acceptance to characterize the plane stress toughness of ductile polymer films in mode I, basically using the double edge notched tension (DENT) configuration. The widespread use of the EWF technique is due to the apparent simple DENT specimen preparation and the simple testing.

The specific work of fracture, w_e, becomes an inherent material parameter only if the ligament fully yields before the crack initiation.

In a previous work [1] carried out on an EPBC (ethylene-propylene block copolymer) material where the ligament was completely yielded before the onset of crack initiation, it was concluded that the specific work of fracture was the energy per unit of ligament area just up to crack initiation, that is, an initiation value. This conclusion drives to the question of whether this value is equivalent to J_o in plane stress conditions, because both parameters have the same physical meaning. According to Mai et al. [2] the essential work of fracture is equivalent to the J-integral at initiation, J_o. Although good numerical agreement

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Nomenclature

a	crack length	β	geometrical shape factor related to the OPZ
cte	constant	ν	poisson's ratio
CTOD	crack tip opening displacement	$CTOD_c$	CTOD value at the onset of crack propagation
d	displacement	d_i	displacement at the onset of crack initiation
DENT	double edge notched tension specimen	d_r	displacement at specimen rupture
DIC	digital image correlation system	l_i	ligament length measured during the test
E	elastic modulus	l_o	initial ligament length
EPBC	ethylene-propylene block copolymer	l_{we}	ligament length at d_i
EPFM	elastic plastic fracture mechanics approach	J_o	J-integral value at crack initiation
EWF	essential work of fracture approach	r_p	plastic zone radius
IPZ	inner process zone	w_e	specific work of fracture
J	J-integral	W_e	essential work of fracture
LEFM	linear elastic fracture mechanics approach	w_f	specific total energy
OPZ	outer process zone	W_f	total energy
P	load of tail curves extracted from load records	w_p	specific non-essential work of fracture
PET	polyethylene terephthalate	W_p	plastic work or non-essential work of fracture
PYFM	post-yield fracture mechanics approach	Δa_b	increment of crack length at blunting
t	specimen thickness	σ_{fs}	engineering flow stress
U	energy dissipated in fracture of the specimen	σ_i	stress at the onset of crack initiation
W	specimen width	σ_n	nominal stress
Z	specimen height	σ_y	uniaxial tensile yield stress
α	propagation contribution to the extension		

has been usually found between w_e and J_o, it is still questioned whether w_e represents or not an initiation value. This equivalence between w_e and J_o has been apparently assumed in several articles either in an explicit manner [3–6], or in an implicit way [7–12]. It should be mentioned that there is only one unique clear evidence that w_e is an initiation value, as has been demonstrated in a previous work on an EPBC film [1].

One of the aims of the present work is to find additional evidence that w_e is an initiation value and therefore study the relationships between w_e, J_o and CTOD. For this reason a polyethylene terephthalate (PET) film, having very different mechanical behaviour than the previously studied EPBC, was used here. Moreover, the fracture toughness parameters have been determined on the same test data and on the same DENT specimens.

Another question which is still pendant in the EWF method are the variations of the w_e values found by different laboratories. Bárány et al. [13] in his review on the EWF summarized the w_e values found by different authors for different polymers. The range for PET films was between 35 and 80 kJ/m^2. Martinez et al. [14] observed significant differences in the w_e values when the specimens were sharpened using the femtosecond laser ablation technique or by the classical razor blade sliding method. The latter providing much higher values than the former one. These differences were explained by the presence of plastically deformed material accumulated at the tip of the razor blade sharpened notches in contrast to the almost negligible plastic deformation existing at the tip of the femtolaser sharpened specimens. The differences in the w_e values were attributed to differences in the notch quality produced. Therefore another aim of this work is to investigate in detail the effect of the notch quality on the fracture behaviour.

2. Background

The common approaches for toughness assessment in ductile polymers includes the J-integral, the crack tip opening displacement, and the essential work of fracture. The theoretical principles and key assumptions of these methods are summarized in the following sections.

2.1. Essential work of fracture

The EWF method was firstly proposed by Cotterell and Reddell [15] after Broberg's work on stable crack growth [16]. The EWF theory is based on the hypothesis that the total energy, W_f, involved in the ductile fracture of a precracked specimen can be separated in two terms.

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

where W_e, the essential work of fracture, accounts for the energy necessary to generate new crack surfaces while W_p is called the plastic work or the non-essential work of fracture and includes all the other components of energy dissipated in the fracture process.

The EWF concept establishes that the process zone can be divided into an inner process zone (IPZ) where the fracture process actually occurs and an outer process zone (OPZ) (Fig. 1). Thus, W_e is proportional to the IPZ area while W_p is proportional to the volume of the OPZ. Using these considerations, Eq. (1) can be rewritten in specific terms as follows

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

where l_o is the ligament length, t is the specimen thickness and β is a factor related to the shape of the OPZ.

It is possible to assess Eq. (2) by performing a series of tests on DENT specimens with different ligament lengths and plotting the specific total work of fracture, w_f, values as a function of their ligament lengths. A simple linear 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. References [13,17] contain a detailed description of the EWF methodology.

In the EWF analysis the following key assumptions are taken:

(a) The ligament length is fully yielded prior to the onset of crack propagation. Full ligament yielding must show a load drop in the related load-displacement curves