



Evaluation of the tear properties of polyethylene blown films using the essential work of fracture concept

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ABSTRACT

In the case of very thin materials such as blown films, the applied stress state in front of the crack tip is normally a plane stress condition, and the deformation around the crack tip due to the remote stress is very large. However, current standard test methods for quantifying the fracture toughness of thin films, such as the Elmendorf tear test, cannot explain or represent the tear characteristics accurately. The common way of interpreting the test results from the Elmendorf tear test is to develop an empirical correlation and then compare the average values. In this paper, essential work of fracture (EWF) tests for five commercial polyethylene (PE) blown films have been conducted, and the fundamentals of their tear properties based on fracture mechanics have been studied. The results from the EWF test are interpreted based on two important parameters, i.e., the essential work of fracture (W_e) and the non-essential work of fracture (W_p). Further, the relationship between these parameters and the current standard Elmendorf tear test is shown.

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1. Introduction

Tear is one of the most critical mechanical properties of polymeric films. However, unlike most other standards of mechanical testing, the current standards for tear testing are generally not adequate with regard to the concept of fracture mechanics. The most well-known tear test, which is defined as per the ASTM standard, is the Elmendorf tear test (ASTM D1922 [1]). This test was originally developed in the paper industry and subsequently adopted by the plastics industry to obtain practical evaluations of the fracture toughness for stable crack propagation in a simple manner. However, the Elmendorf tear test is purely empirical and pseudo-quantitative. The test is also non-intrinsic and therefore, cannot yield fracture mechanics parameters for engineering design (Casellas et al. [2], Marzinsky et al. [3], Wu and Sehanobish [4]). Moreover, it is also well-known that the results from the Elmendorf tear test are commonly unreliable statistically. The best way of interpreting the results from the Elmendorf tear test in terms of fracture mechanics parameters is to develop an empirical correlation and compare the resulting values with those from a well-defined tear test.

In the case of very thin materials such as films, the applied stress state in front of the crack tip is normally a plane stress condition, and the deformation around the crack tip due to remote stresses (e.g., tensile stress, tears, etc.) is usually very large. Therefore, for ductile thin films such as polyethylene (PE), large-scale yielding can occur in front of the crack tip. The tearing process of ductile films is very similar to the tensile process because of the large deformation in the direction of loading (Chang et al. [5]). Due to the large plastic deformation of thin PE films during the tear test, well-known fracture mechanics parameters for linear elastic fracture mechanics (LEFM), such as the stress intensity factor (SIF) and the energy release rate (ERR), cannot be used to quantify the fracture toughness of such films. For large-scale yielding, nonlinear fracture mechanics parameters based on irreversible energy dissipation should be introduced, and in that sense, the crack opening displacement (COD) and J-integral can be potential candidates for this role (Eason et al. [6]). However, methods of testing for these fracture parameters are well defined under the plane strain condition. Hence, additional efforts are needed to use these parameters to obtain the fracture toughness and tear characteristics of thin ductile films. In addition, two components of the overall fracture process, viz., fraction initiation and crack propagation, are very important to understand the tear characteristics, but the Elmendorf tear test cannot distinguish them. Hence, an alternative test based on fracture mechanics such

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as the Essential Work of Fracture (EWF) (Cotterell and Reddel [7]) test can be considered to analyze the fundamentals of the tear process. Even though some fundamental aspects are to be considered such as the transition between the plane stress and plane strain conditions, this EWF testing method can be used effectively for industrial testing as well as academic testing. Moreover, a more detailed investigation of the process zone, which is a major factor in the EWF testing method, and crack propagation behavior can be undertaken through crack layer (CL) theory (Chudnovsky [8]).

Though the EWF test is designed for an in-plane tear (mode I), it can be used to analyze an out-of-plane tear (mode III), as with an Elmendorf tear, if the test film is ductile enough. If an out-of-plane tear is applied to very ductile film, the loading direction with respect to the notch of the film rotates immediately due to the localized ductile deformation around the notch tip (Chang et al. [9], Isherwood and Williams [10]). As Chang et al. [9] found from their experimental study, the formation of the process zone with large plastic deformation prevented the mode III out-of-plane fracture, and the film twisted 90° along the loading direction and failed in an in-plane tear (mode I), instead. In this case, it is reasonable to analyze the tear properties of films through a notched specimen with a tensile test such as the EWF test.

In this paper, EWF tests for five polyethylene blown films are conducted, and the fundamentals of the tear properties are studied. The tear performance, in both the machine direction (MD) and the cross direction (CD), of the blown PE films studied is explained in terms of the components of the EWF test. The results of the industrial standard tear test, i.e., the Elmendorf tear test, are compared with those of the components of the EWF test to understand the proper empirical relationship between the Elmendorf tear test and the EWF test.

2. Experimental method and materials

2.1. Essential work of fracture

The concept of EWF was proposed in detail by Cotterell and Reddel [7], who suggested that the total work of fracture, W_f , which is dissipated in a precracked body, could be separated by the work that is consumed in two distinct process zones, viz., the inner and outer regions of the overall process zone. This method of work partitioning gives rise to the essential work of fracture, W_e , and non-essential work of fracture, W_p , respectively. The essential work of fracture represents the work at the end region in the vicinity of the crack tip that initiates the crack. The non-essential work of fracture represents the work at the outer region that is responsible for the plastic deformation of the material following crack initiation and propagation. Therefore, the total work of fracture can be formulated as follows:

$$W_f = W_e + W_p \quad (1)$$

The essential work is proportional to the ligament size, l , if it is assumed that the specific essential work of fracture, w_e , remains constant. The non-essential work of fracture, W_p , in the rest of the plastic region is proportional to the square of the ligament size, l^2 . Hence, the total work of fracture can be written as:

$$W_f = ltw_e + l^2t\beta w_p \quad (2)$$

where t is the thickness of the specimen, and β is the shape factor that is based on the specimen geometry and size of the process zone. Therefore, the total specific work of fracture, w_f , can be defined by normalizing the thickness of the specimen and the ligament size as follows:

$$w_f = \frac{W_f}{lt} = w_e + l\beta w_p \quad (3)$$

The specific total work of fracture is a linear function of the ligament size of the specimen. If the specific total work of fracture is plotted vs. the ligament size, the two main parameters, i.e., the intercept with the Y-axis, w_e , and the slope of the curve fitted line, βw_p , can yield the resistance of the direct fracture process and the energy dissipation from the process zone during the fracture process. The former is closely related to the fracture toughness of the film, and the latter is closely related to the ductility of the film. According to the general approach of the EWF test, the specific essential work of fracture is the major point of interest, but the non-essential work of fracture is important if the tested film is very ductile.

Even though some researchers such as Saleemi and Narin [11] have successfully applied the EWF concept to specimens with the plane strain condition, the EWF test is practically applicable to specimens with the plane stress condition due to the effect of the ductility and the distinct formation of the process zone. Hence, to avoid the plane strain-plane stress transition region, the ligament should be larger than three times the specimen thickness. In addition, it is recommended that one keeps the maximum ligament size smaller than one-third of the specimen width. Therefore, the following ligament criterion is proposed:

$$3t \leq l \leq \min(W/3, 2r_p) \quad (4)$$

where W is the specimen width, and r_p is the size of the plastic zone. However, this recommendation is too strict especially for very thin and ductile films; so, the actual range of the ligament size for applying the EWF test should be based on the linear region of the plot between the specific work of fracture and the ligament size.

Another way of checking the plane stress condition is to use the classic Hill's criterion (Hill [12]), which is also recommended by the European Structural Integrity Society (ESIS) protocol. The measurement of the peak load, $P_{\max}$, during each test allows the maximum net section stress, σ_{net} , to be calculated. According to Hill's criterion, the net section stress should be smaller than 1.15 times the yield stress, σ_y , which is obtained by the uniaxial tensile test. Using such criteria, the EWF test methodology is improved, though some technical issues should be addressed further (Poon et al. [13], Williams and Rink [14]).

2.2. Materials and test setup

Test samples are selected from polyethylene resin-based blown films. Three of these are LLDPE films (density of ~ 0.920 g/cc) and two of them are HDPE films (density of ~ 0.940 g/cc). The melt index (I2) for all films is approximately 1.

All the films were blown using a 64.5 mm smooth-bore, single-screw extruder having an aspect ratio (L/D) of 25:1 and fitted with a six-inch-diameter blown film die using external cooling air with a temperature of 10 °C and without internal bubble cooling. A screen pack comprised of 20, 40, 60, 80, and 20 mesh screens in that order was used. Films representing relatively high machine-direction orientations were made using a Davis-Standard barrier screw (DSB II). A barrel profile of 190.6/204.4/176.7/135.0/135.0 °C with downstream equipment at 221.1 °C delivered a melt temperature of between 203.9 and 230.6 °C, depending on the resin. The extrusion rate was 85.3 kg/h through a Sano die with a die gap of 2.8 mm and BUR of 2.0 to provide a final film thickness of 0.0254 mm. The frost line height was maintained at 711.2 mm.

The EWF test is designed based on the ESIS protocol [15], but the specimen geometry was slightly modified due to the thin thickness

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