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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.

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:

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

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:

$$W_f = ltw_e + l^2 t\beta w_p \tag{2}$$

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:

$$w_f = \frac{W_f}{lt} = w_e + l\beta w_p \tag{3}$$

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:

$$3t \le l \le \min(W/3, 2r_p) \tag{4}$$

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 of the films. Two different notch geometries can be used for the EWF test (Mai et al. [16]), i.e., a Single Edge Notched Tension (SENT) specimen and a Deep Double Edge Notched (DDENT) specimen, but recently the DDENT specimen has been more commonly used due to the symmetry of crack propagation and the simplicity of process zone formation. The most recent ESIS protocol has recommended the DDENT specimen as a standard specimen.

As a modified test procedure, five different ligament sizes were selected (3, 5, 7, 9, and 11 mm), and four specimens were tested for each ligament length. In Fig. 1, the geometry of the test specimen is shown. The EWF test is designed to correlate the tear property as measured by the Elmendorf tear test; therefore, the test speed was selected as 0.5 m/s. In the Elmendorf test, the test speed varies during the test due to the pendulum drop. This has been estimated to be 0.2–0.7 m/s (Gupta et al. [17]). Therefore, an average speed of 0.5 m/s is used for the Elmendorf test. The gauge length was 60 mm and the test temperature was the ambient temperature (23 °C).

3. Experimental results

In Table 1, the mechanical properties of the tested blown films are shown. Some reports (Lu et al. [18], Wu et al. [19], Plumley et al. [20]) have attempted to correlate tear with the strain hardening modulus concept of the tie-chain theory (Huang and Brown [21]). However, there was no clear conclusion regarding the correlation between them. As shown in Table 1, tear properties are not correlated with the strain hardening modulus due to a complex crack propagation mechanism that accompanies the process zone in front of the crack tip. The strain hardening modulus is calculated from a modified rubber elasticity theory (Howard [22]). Based on the modified rubber elasticity theory, the true stress that is applied to thin films can be expressed as follows:

$$\sigma_{tr} = \sigma_0 + G(T)\left\{\lambda^2 - \frac{1}{\lambda}\right\} \tag{5}$$

where λ is the draw ratio and G is the strain hardening modulus, which is a function of the temperature.

Fig. 2 depicts two actual load-displacement curves from MD and CD tests for LLDPE-1. As the ligament size increased, both the maximum load and the maximum elongation increased. Therefore, the total work of fracture, which is calculated as the area under the curve, also increased. Small differences of 5–14% were observed in the maximum loads for a given ligament size for MD and CD cracks; however, there were large changes in the maximum elongation and compliance after the maximum load. The former is mainly related to the resistance to yield initiation between notches, and the latter is related to the large elongation of the test specimen.

In most cases, there are considerable differences in the load-displacement curves for MD and CD especially for films with a density of 0.940 g/cm^3. Large differences in the Elmendorf tear for MD and CD test data were also supported by the EWF test data. As shown in Table 1, a comparison of films with a density of 0.920 and films with a density of 0.940 shows a very small value for the MD/CD tear ratio (~0.04) for HDPE films; however, the 0.920-density films have much higher values in the 0.3–0.6 range for this same ratio.

To explain the overall tear performance of films, one must consider some important factors such as the intrinsic tear resistance, which is mainly related to the initiation of tear, and the formation of microcrazes or voids in the process zone in front of a crack tip. As described by the theory of the EWF test, the intrinsic tear resistance is explained by EWF, i.e., the y-intercept of the fitted curve of the energy–ligament diagram, while the whitening zone effect can be explained by the non-essential work of fracture (NEWF), i.e., the slope of the energy–ligament diagram.

In Fig. 3(a), the EWF test results are shown for MD cracks. These results reveal large differences depending on the density of film. Films with a density of 0.940, such as HDPE-1 and HDPE-2, have much lower slopes than films with a density of 0.920, such as LLDPE-1, LLDPE-2, and LLDPE-3. These low slopes are directly related to energy dissipation rather than the intrinsic fracture toughness of the films, i.e., the formation of microcracks and/or microvoids during crack propagation. Such an energy dissipation mechanism helps to achieve very high values for tear. Therefore, even though high-density polyethylene films show high strength, tear values in MD cracks are very low due to the lack of an energy dissipation mechanism, i.e., the lack of toughness.

In Fig. 3(b), the variability (R-squared) of the statistical fit that is obtained from the EWF test data is compared with the coefficient of variation (CV) that is obtained from the Elmendorf tear. The CV can be defined as follows:

$$CV = \frac{\text{Standard deviation}}{\text{Average}} \tag{6}$$

For films with the same density, the values of the statistical variability that are obtained from the EWF test and the Elmendorf tear test are very similar. Surprisingly, among films with a density of 0.920, LLDPE- 3A shows very consistent data for both tests, but LLDPE-1 shows less consistent data. If the density is higher, the statistical stability decreases especially for the EWF test. Both these

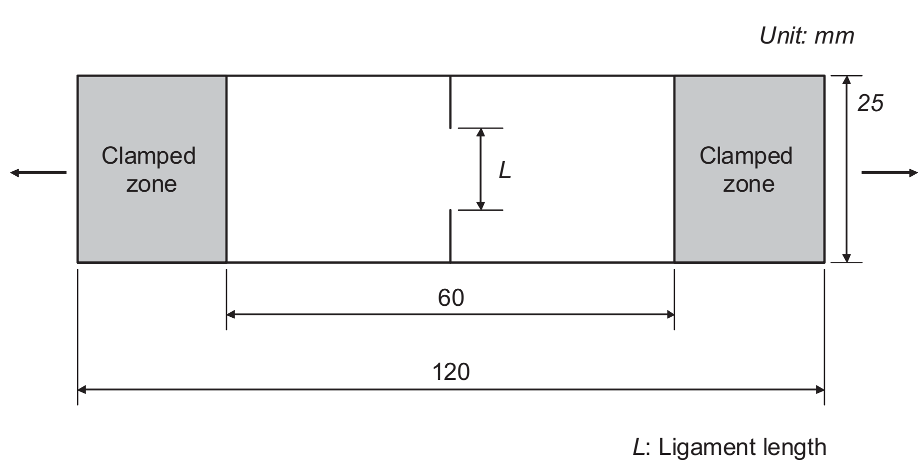


Fig. 1. Specimen geometry of EWF test specimen.

Table 1
Mechanical properties of tested blown films.

Films	Direction	*I*2	Density (g/cc)	Yield stress (MPa)	Elongation to Break (%)	Ultimate stress (MPa)	Strain Hardening Modulus (MPa)	Strain Hardening modulus ratio (CD/MD)	Intrinsic Elmendorf tear (g/μm)	Elmendorf tear (g/μm)	MD/CD tear ratio
LLDPE-1	MD	1.006	0.921	12.8	775	47.2	16.9	0.573	23.1	11.81	0.367
	CD			14.1	487	62.0	9.67			32.20	
LLDPE-2	MD	0.835	0.921	12.6	744	47.6	17.3	0.534	20.1	9.02	0.320
	CD			11.9	455	54.6	9.21			28.19	
LLDPE-3	MD	1.089	0.920	16.3	706	83.9	26.8	0.678	15.1	11.22	0.640
	CD			18.1	518	86.6	18.2			17.52	
HDPE-1	MD	1.146	0.940	32.5	835	63.4	15.9	0.611	4.4	1.06	0.043
	CD			28.4	489	67.4	9.69			24.69	
HDPE-2	MD	1.258	0.940	32.9	714	52.5	15.4	0.619	6.3	1.57	0.039
	CD			28.3	494	61.1	9.53			39.92	

observations are related to the formation of a haze band – if such a band appears or is larger, the variability is greater. This result indicates that crystallization during the blown film process is inherently a less reproducible process in the sense that the effects of processing on the molecules, including the way in which the ligaments are made, have greater implications for the crystallization process. Compared to the results shown in Fig. 3(a) for CD cracks, all films exhibit much higher slopes under MD cracks, as shown in Fig. 4(a). The values of the variability of the Elmendorf tear and EWF are also equal or lower for the MD direction, as shown in Fig. 4(b).

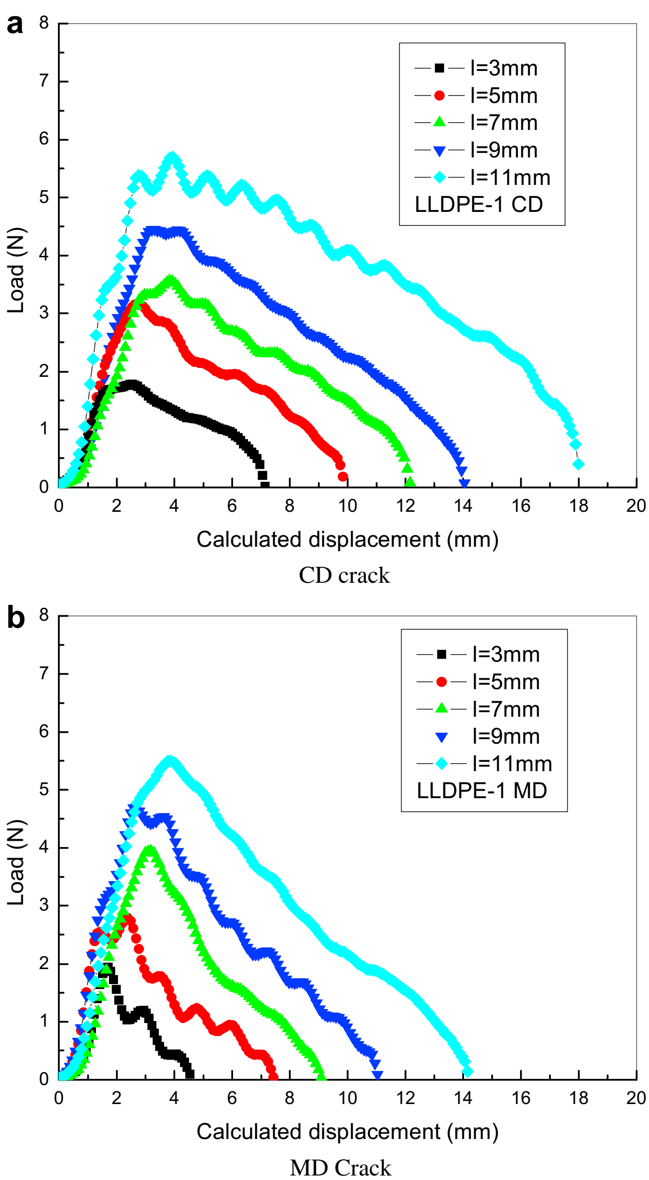


Fig. 2. Comparison of EWF test results of MD and CD crack for LLDPE-1.

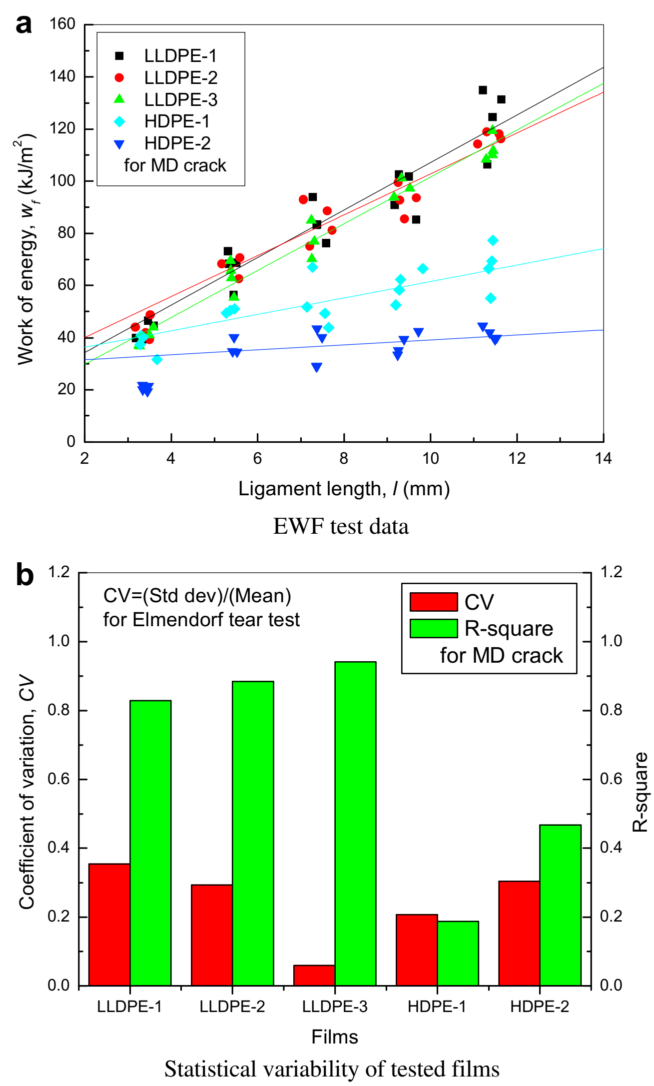
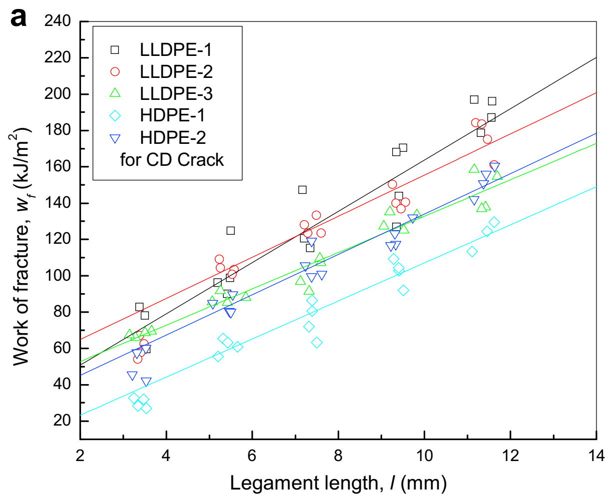
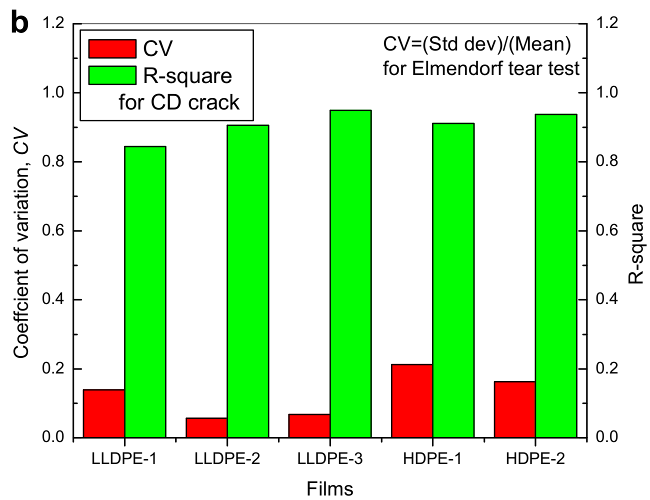


Fig. 3. EWF test data for MD crack for all tested films.



EWF test data



Statistical variability of tested films

Fig. 4. EWF test data for CD crack for all tested films.

In Table 2, the results from the EWF test are shown. "Reliable points" in Table 2 mean the data that can be used for a linear regression, assuming plane stress conditions. Regarding the analysis of data from EWF tests, it is well-known that the linear relationship between the total work of energy and the ligament size is invalid as the ligament size is smaller than a critical value, which refers to the transition from the plane stress condition to the plane strain condition (Mai and Cotterell [23]). For example, in the case of HDPE-2 with MD cracks, the data obtained from specimens with ligaments of 3 mm do not correspond to 'Reliable points,' which can be confirmed by statistical data analysis. The EWF is determined as the y-intercept of the load-displacement curve by extrapolation of the linear portion (from Figs. 3 and 4). According to previous studies (Wu and Mai [24], Mai and Powell [25], Chan and Williams [26]), EWF can be directly related to the fracture toughness, J_k, of the film; hence, EWF is the main fracture parameter of films. Due to the very large plastic deformation of the notch tip before crack initiation, conventional standard tests based on fracture mechanics for measuring the fracture toughness, as with the critical stress intensity factor (K_{Ic}) and J-integral (J_{Ic}), which are developed for the plane strain condition, are not applicable for ductile films. Moreover, the measured fracture toughness under the plane stress condition that is obtained from conventional approaches is not a material parameter as it is severely affected by the specimen thickness and ligament size. Hence, it can be thought that EWF tests can be simple and effective for quantifying the fracture toughness of ductile films.

According to the calculated EWF values, LLDPE-2 (24.4 KJ/m^2 for MD and 42.3 KJ/m^2 for CD) shows a higher EWF value when compared with LLDPE-1 (16.1 KJ/m^2 for MD and 22.5 KJ/m^2 for CD) or LLDPE-3 (18.4 KJ/m^2 for MD and 30.1 KJ/m^2 for CD). According to the Elmendorf tear data, LLDPE-1 should be the toughest film. The EWF value cannot explain the differences in the tear values. Two higher-density films, HDPE-1 and HDPE-2, also show inconsistent EWF values when compared to the tear values. Gupta et al. [17] proposed that EWF can be a good way of explaining tear properties for polyethylenes with different comonomers such as octene, hexane, and butene, but that may also be because they manifest a very distinct difference in tear values under similar failure mechanisms. If the failure mechanisms differ due to differences in the composition, molecular weight, or density, EWF alone cannot be used for comparing the overall tear properties. We will return to this later in this paper.

Depending on the film properties, such as the ductility and orientation, very distinct differences can be observed after the EWF test. If the film is very ductile, plastic deformation (observed as whitening) can be identified from the undeformed film (as shown in Fig. 5(a)). However, if the film is not ductile, no area of whitening is visible due to the brittleness of the film (as shown in Fig. 5(b)). Furthermore, in the case of ductile films, during the EWF test, symmetrical crack propagation (a large elongation of the process zone) is observed (as in the triangular shape of the process zone) followed by large blunting of the two notch tips, which is shown in Fig. 5(a). However, as shown in Fig. 5(b), due to the lack of ductility in the crack direction, the PZ cannot be fully developed before final fracture. Hence, some individual PZ wakes are observed without a triangular PZ.

Table 2
Summary of EWF test data.

Films	Direction	Elmendorf tear (g/μm)	R-square	Slope (MJ/m3)	β	EWF (kJ/m3)	NEWF (MJ/m3)	Normalized EWF[a]	Normalized slope[a]
LLDPE-1	MD	11.81	0.83	9.11	0.047	16.1	193.3	0.71	0.65
	CD	32.20	0.84	14.12	0.114	22.5	123.7	1.00	1.00
LLDPE-2	MD	9.02	0.88	7.84	0.054	24.4	145.4	1.08	0.56
	CD	28.19	0.91	11.32	0.096	42.3	117.9	1.87	0.80
LLDPE-3	MD	11.22	0.94	8.29	0.062	18.4	134.3	0.81	0.59
	CD	17.52	0.95	10.29	0.094	30.1	109.0	1.34	0.73
HDPE-1	MD	1.06	0.19	0.95	N/A	29.6	N/A	1.31	0.07
	CD	24.69	0.91	10.48	0.055	2.3	190.0	0.10	0.74
HDPE-2	MD	1.57	0.47	2.89	N/A	33.2	N/A	1.47	0.20
	CD	39.92	0.94	11.11	0.077	22.9	144.3	1.02	0.79

[a] Normalized by LLDPE-1 CD data.

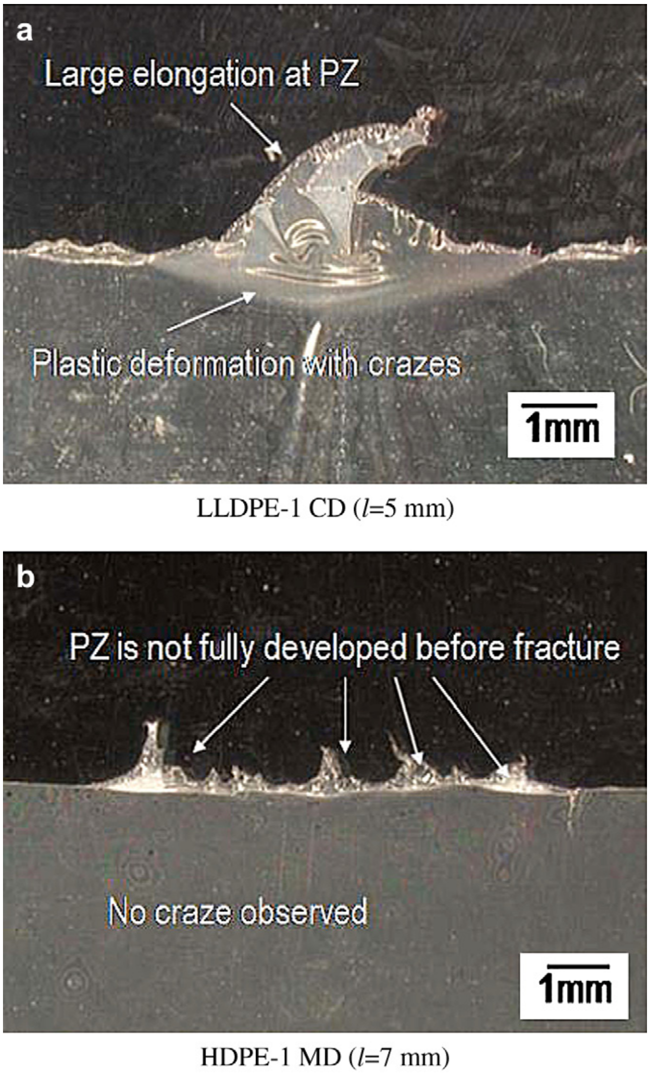


Fig. 5. Typical image of the process zone after EWF test.

Arguably, whitening surrounding a largely elongated PZ may represent recrystallization with stress thinning (Ferrer-Balas et al. [27]) or the formation of microcrazes and/or microvoids (Wu et al. [28]). Therefore, if the failed film has a distinct whitening area, the crack resistance might be increasing during crack propagation. In addition, one of the main concerns when a DDENT specimen is used is the symmetry regarding failure, but it is observed that most specimens after EWF tests failed reasonably symmetrically.

From Eq. (3), the geometric factor, β, can be calculated and the result is shown in Table 3. β should be constant for all ligament sizes, but consistent values were not found due to the large amount of shrinkage after fracture. For MD cracks of films with a density of 0.940, the shrinkage was so severe that the values from Eq. (3) were neither reliable nor measurable. For this sample, β was determined as the ratio between the PZ height and the ligament size. The determination of β for different geometries, which is defined by the ESIS protocol, is also shown in Table 3. A larger β indicates that microcrazes and/or microvoids in the PZ are more distinct and broad. NEWF that is shown in Table 2 represents the amount of energy dissipation in the outer PZ.

4. Discussion

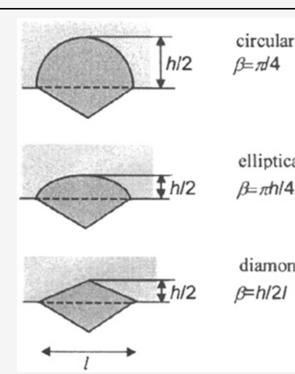
In Fig. 6, EWF and the slope of the tested films are shown. For MD cracks, unexpectedly high EWF values are calculated for two films (HDPE-1 and HDPE-2) with a density of 0.940. In contrast, these two films show the lowest slopes. For CD cracks, LLDPE-2 and LLDPE-3 show high EWF values, but HDPE-1 has a very low EWF value. Regarding the slopes of the CD cracks, LLDPE-1 ranks the highest followed by LLDPE-2 and HDPE-2, while HDPE-1 and LLDPE-3 both show relatively low slopes. But, the variation in the observed slopes of CD cracks is not that much different compared to that for MD cracks.

In Fig. 7, the calculated results of NEWF and the geometric factor, β, are shown. The measurement of β for the MD cracks for the two films with a density of 0.940 is not possible due to the lack of formation of a whitening zone. This means that film extension is not uniform, and no visible microcrazes and/or microvoids surround the crack path (recall Fig. 5(b)). In Fig. 7(a), LLDPE-1 shows the highest value for NEWF, and LLDPE-2 and LLDPE-3 show similar values for MD cracks. For CD cracks, the very same tendency is observed for NEWF, but the two films with a density of 0.940 show higher NEWF values when compared to films with a density of 0.920. The β value for films with a density of 0.940 is not high when compared to that for films with a density of 0.920. This may be explained by the orientation and microcrazing mechanism of films. In Fig. 7(b), the geometric factor, β, of films with a density of 0.940 is small, as described above.

To confirm the EWF test method to quantify the tear properties of the films, it is very important to find a correlation between the Elmendorf tear and a certain parameter that is obtained from the EWF test. As described earlier in the introduction of this paper, EWF

Table 3

Films	Direction	Type	l=3	l=7	l=9	Beta
LLDPE-1	MD	E	0.053	0.044	0.045	0.047
	CD	E	0.131	0.095	0.108	0.111
LLDPE-2	MD	E	0.061	0.054	0.048	0.054
	CD	E	0.093	0.097	0.099	0.096
LLDPE-3	MD	E	0.065	0.059	0.056	0.060
	CD	E	0.103	0.092	0.088	0.094
HDPE-1	MD	U	N/A	N/A	N/A	N/A
	CD	E	0.055	0.054	0.057	0.055
HDPE-2	MD	U	N/A	N/A	N/A	N/A
	CD	E	0.080	0.071	0.078	0.077



is important for explaining the intrinsic fracture resistance. To explain a proper mechanism for tear, the major mechanism governing the tear process should be understood. A comparison of the reported values for EWF and the slope in Fig. 6 and a consideration of the ligament size and units according to Eq. (3) reveal that the portion of the second term (slope) is an order of magnitude larger than that of the first term (EWF), especially for films with a density of 0.920. Therefore, it can be ascertained that the overall tear can be mainly controlled not by EWF but by the slope. But, this still depends on the relative magnitudes of the two terms in Eq. (3). If a certain film has a very high EWF or very low slope, the main mechanism of tear or EWF may be changed from the second term (slope) to the first term (EWF).

As a result, the concept of competition between EWF and the slope can be confirmed if the relationship between the Elmendorf tear (the overall tear property) and parameters from the EWF test is established. In Fig. 8(a), the correlation between the Elmendorf tear and EWF is shown. As explained in the previous paragraph, no correlation between them is visible. But two different trends may be observed for MD and CD tears. In the case of films with a density of 0.920, EWF of the CD tear and the measured Elmendorf CD tear are both always higher than the corresponding MD measures. On the contrary, in the case of films with a density of 0.940, EWF of the MD tear is higher than the EWF of the CD tear.

In Fig. 8(b), an important correlation is shown for the Elmendorf tear and the slope of the EWF plot. Due to the large effect of the slope (NEWF for a portion of Eq. (3)) on the overall fracture energy, there is a strong correlation between them especially for high-tear films. In the case of HDPE-1 MD cracks and HDPE-2 MD cracks, the correlation may not be important because of the low value of the second term of Eq. (3), which can be explained by Fig. 3(a). Karger-Kocsis and Czigany [29] reported that the out-of-plane type deformation (mode III) in the trouser tear test results in markedly lower w_e and higher w_p values than those obtained by in-plain (mode I) tests on DDENT specimens. Thus, even though w_e that is obtained from DDENT specimens is relatively high (as with MD cracks for HDPE-1 and HDPE-2), the contribution of EWF may be less for a tear test, such as the Elmendorf tear test. That can be another factor for determining the total energy of tear.

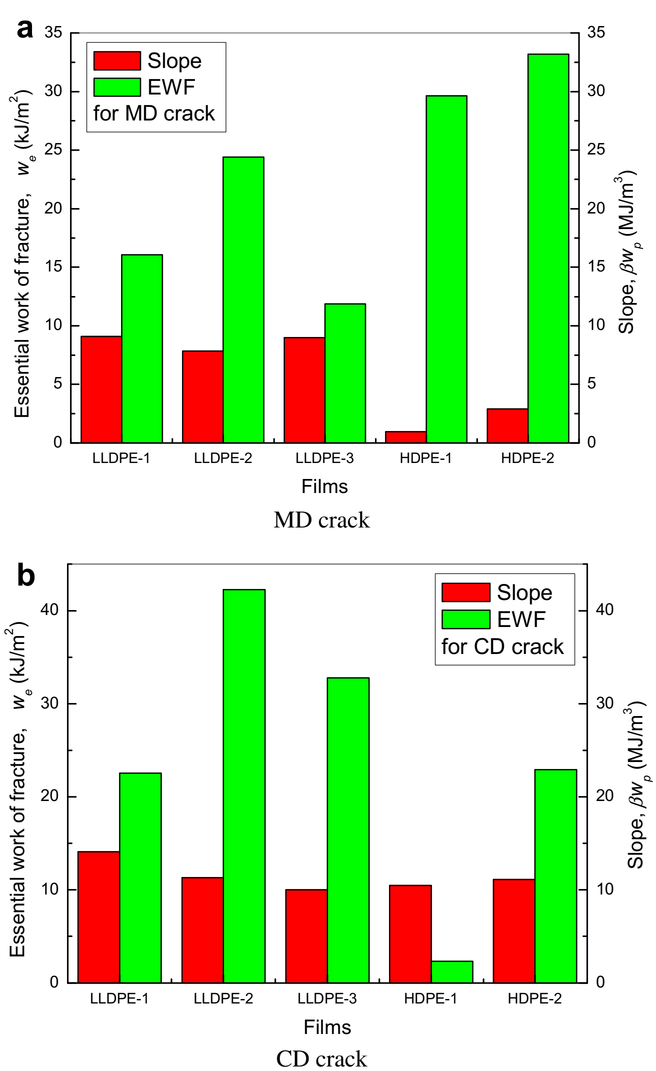


Fig. 6. EWF test results for MD and CD cracks.

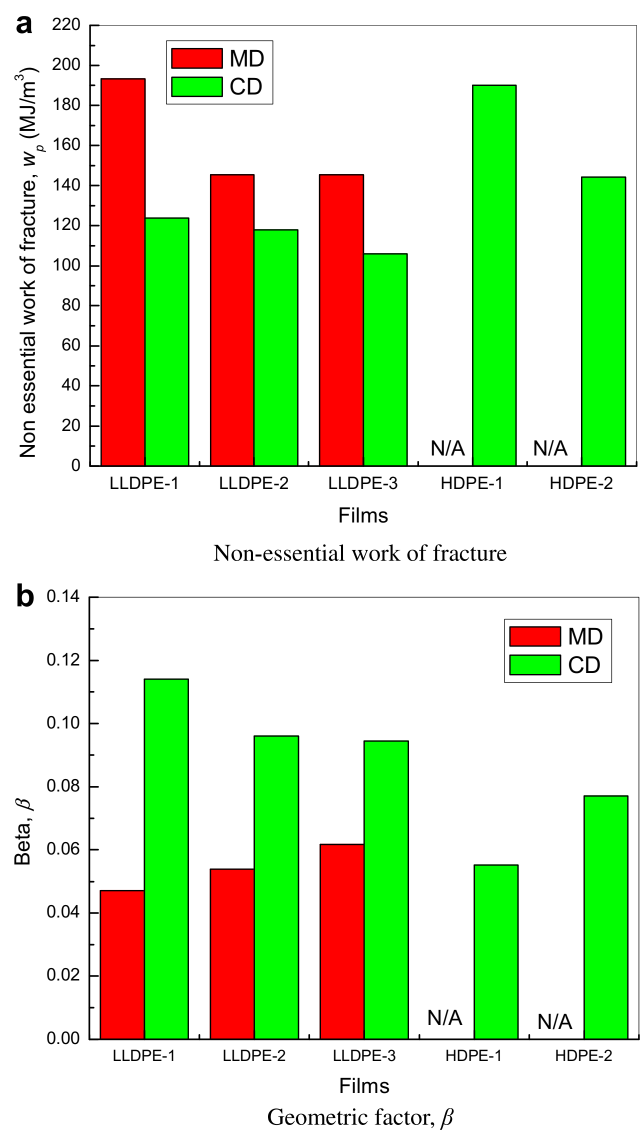


Fig. 7. Calculated NEWF and geometric factor, β.

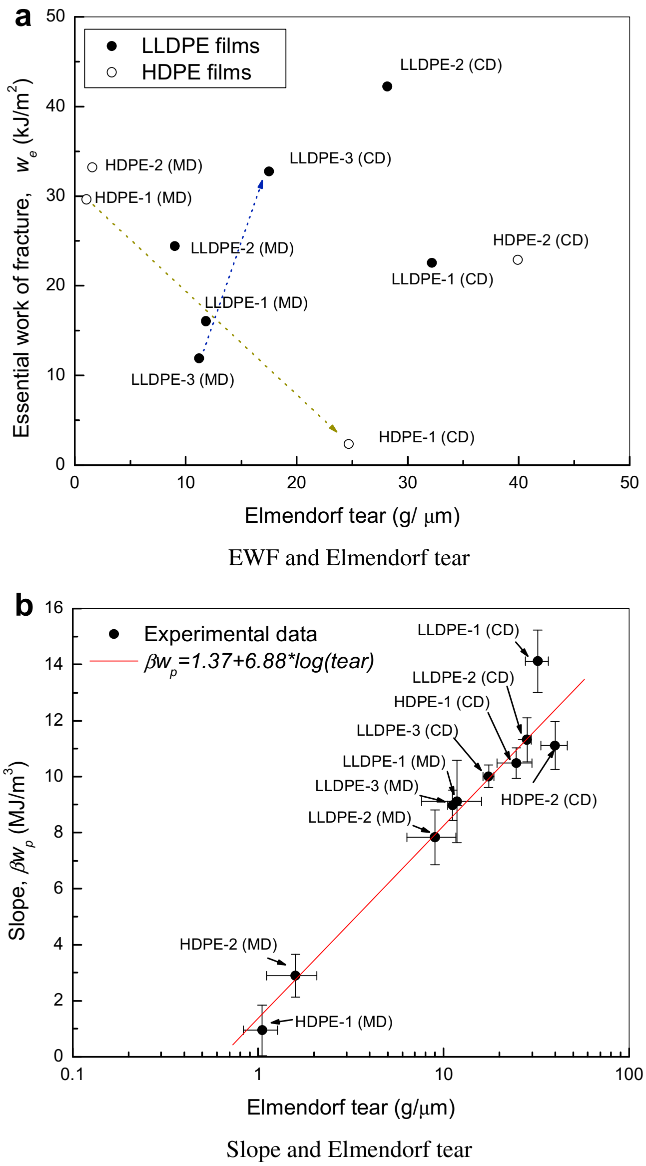


Fig. 8. Correlation between each term in Equation (3) and Elmendorf tear.

5. Conclusion

In this paper, the EWF test was carried out on five sets of blown polyethylene thin films to better understand their tear characteristics based on fracture mechanics. EWF tests yield two types of information, EWF and NEWF (or slope) for crack behavior. Some important conclusions can be drawn from this.

(1) The load-displacement curves obtained from DENT specimens are similar to the ligament increases. EWF is the intrinsic material parameter for a given thickness, and corresponds to the critical *J*-integral (J_{Ic}) that is based on mathematical similarity.
(2) The slope of the EWF test yields the reduction of compliance during crack propagation. NEWF is the concentration of energy dissipation.
(3) All CD and MD crack propagations for films with a density of 0.920 are consistent with the shape ratio, β, for the PZ and ligaments. However, for MD crack propagation in films with a density of 0.940, no craze zone is observed in the vicinity of crack propagation (almost zero beta).
(4) The accuracy of the EWF test (*R*-squared) has the same trend as that of the Elmendorf tear test (in terms of the coefficient of variation), and it may depend on the geometry of the specimen, process conditions, notch symmetry, etc. Although the EWF value is important to explain the intrinsic fracture toughness of material, the actual energy consumption including crack propagation is controlled by NEWF and beta, as the ligament elongates. The EWF values for CD cracks are larger than those for MD cracks for films with a density of 0.920, but the opposite trend is observed for films with a density of 0.940. The most important conclusion is that for all films, there is a good correlation between the slope and the Elmendorf tear that is observed at the semi-log scale.

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References

[1] ASTM Standard D1922. ASTM International; 1999.
[2] Casellas JJ, Frontini PM, Carella JM. Journal of Applied Polymer Science 1999;74:781–96.
[3] Marzinsky CN, Lustiger A, Ling S. In: Proceedings of SPE/ANTEC 99 1999: 2463–7.
[4] Wu S, Sehanobish K. In: Proceedings of SPE/ANTEC 04 2004: 3991–3995.
[5] Chang AC, Chum SP, Hiltner A, Baer E. Polymer 2002;43:6515–26.
[6] Eason T, Bradley WL, Dawson M. In: Proceedings of SPE/ANTEC 99 1999: 3453–7.
[7] Cotterell B, Reddel JK. International Journal of Fracture 1977;13(3):267–77.
[8] Chudnovsky A. Crack layer theory, NASA contractor report 174634. NASA Lewis Research Center; 1984.
[9] Chang AC, Inge T, Tau L, Hiltner A, Baer E. Polymer Engineering and Science 2002;42(11):2202–12.
[10] Isherwood DP, Williams JG. Engineering Fracture Mechanics 1978;10:887–95.
[11] Saleemi AS, Narin JA. Polymer Engineering and Science 1990;30(4):211–8.
[12] Hill R. Journal of the Mechanics and Physics of Solids 1952;1952(1):19–30.
[13] Poon WKY, Ching ECY, Cheng CY, Li RKY. Polymer Testing 2001;20:395–401.
[14] Williams JG, Rink M. Engineering Fracture Mechanics 2007;74:1009–17.
[15] ESIS TC-4. Essential work of fracture test protocol version 6 2000.
[16] Mai YW, Cotterell B, Horlyck R, Vigna G. Polymer Science and Engineering 1987;27(11):804–9.
[17] Gupta P, Wilkes GL, Sukhadia AM, Krishnaswamy RK, Mansfield T. Polymer 2005;46:8819–37.
[18] Lu J, Sue HJ, Rieker TP. Polymer 2001;42:4635–46.
[19] Wu S, Bosnyak C, Faul D, Tau L, Huang Y. In: Proceedings of SPE/ANTEC 2001: 2001.
[20] Plumley TA, Sehanobish K, Patel RM, Lai SY, Chum SP, Knight GW. In: Proceedings of SPE/ANTEC 1995:1995.
[21] Huang YL, Brown N. Journal of Polymer Science: Part B. Polymer Physics 1991;29:129–37.
[22] Howard RN. Macromolecules 1993;26:5860–9.
[23] Mai YW, Cotterell B. International Journal of Fracture 1986;32:105–25.
[24] Wu J, Mai YW. In: Proceedings of SPE/ANTEC 95 1995; 1738–42.
[25] Mai YW, Powell P. Journal of Polymer Science: Part B. Polymer Physics 1991;29:785–93.
[26] Chan WYF, Williams JG. Polymer 1994;35:1666–72.
[27] Ferrer-Balas D, Maspoch ML, Martinez AB, Ching E, Li RKY, Mai YW. Polymer 2001;42:2665–74.
[28] Wu S, deGroot W, Davidock D, Juarez V. In: Proceedings of SPE/ANTEC 2006: 571–5.
[29] Karger-Kocsis J, Czigany T. Polymer 1996;37(12):2433–8.