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New fracture characterization in polymer miniature specimens based on the essential work of fracture

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ABSTRACT: The fracture characterization under plane-stress conditions in polymer sheets in recent decades has usually been done through the application of the essential work of fracture (EWF) method. However, when deeply double-edged, notched tensile standard specimens cannot be obtained, the use of alternative small pieces, such as prenotched miniature specimens, could be a viable solution. This is why we examined the new fracture characterization in polymer-prenotched small punch test (SPT) specimens in this study. With the results that we obtained, the feasibility of using prenotched SPT specimens for evaluating the EWF parameters and their correspondence with the results from standard specimens were established. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 42837.

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INTRODUCTION

One technique that has been widely used in recent decades to assess the fracture properties in thin polymer plates under plane-stress conditions is the essential work of fracture (EWF or W_e) method.[1–4] This method, developed by Broberg[5,6] for metals and subsequently applied to polymers by Mai and Cotterell,[7,8] proposes that the energy consumed in ductile tearing failure might be divided into two terms. The first of these, *essential work,* refers to the energy needed to create the new fracture surfaces. The second, *nonessential or plastic work* (W_p), corresponds to the energy involved in more general plastic deformation, which is geometrically dependent. The experimental part of EWF is essentially based on the test of different specimens, in which deeply double-edged, notched tensile (DDEN-T) specimens are usually used. These specimens can be machined directly from a polymer sheet or manufactured by injection or molding techniques. However, when these standard specimens cannot be obtained because material is limited, as is often the case in injected components or thermowelded bonding areas, the use of alternative small pieces, such as prenotched miniature specimens, can be a viable solution.

In this study, the small punch test (SPT) was used on the selected specimens. This test basically consists of the deformation of a miniature specimen ($10 \times 10 \times 0.5$ mm^3), whose edges were firmly gripped by a die with a high-strength punch. In recent decades, SPT has been used by a great number of researchers to obtain mechanical and fracture properties when the material was limited,[9–14] but very few researchers have used prenotched SPT specimens.[15,16] The experimental setup can be found in the CEN code of practice for SPT.[17]

With the results obtained from this research, the feasibility of using prenotched SPT specimens for evaluating the EWF parameters and its correspondence with the results obtained from standard specimens (DDEN-T) was established.

EXPERIMENTAL

Material and Standard Fracture Characterization

As discussed previously, the EWF method postulates that the total work of fracture (W_f) in ductile tearing failure can be calculated from the area of the force–displacement curve and divided into two terms: W_e and W_p. These terms can be expressed as a function of the specimen ligament, as shown in eq. (1) and rewritten into specific terms in eq. (2):

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

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

where w_e is the specific essential work, w_p is the specific plastic work, t is the specimen thickness, L is the ligament length, and β is the shape factor related to the form of the outer plastic dissipation zone.[18] Thus, eq. (2) allows the specific work of fracture (w_f) to be plotted as a function of L, where w_e and βw_p can be determined by the intercept with the w_f axis for $L = 0$, and the slope can obtained by its linear regression.

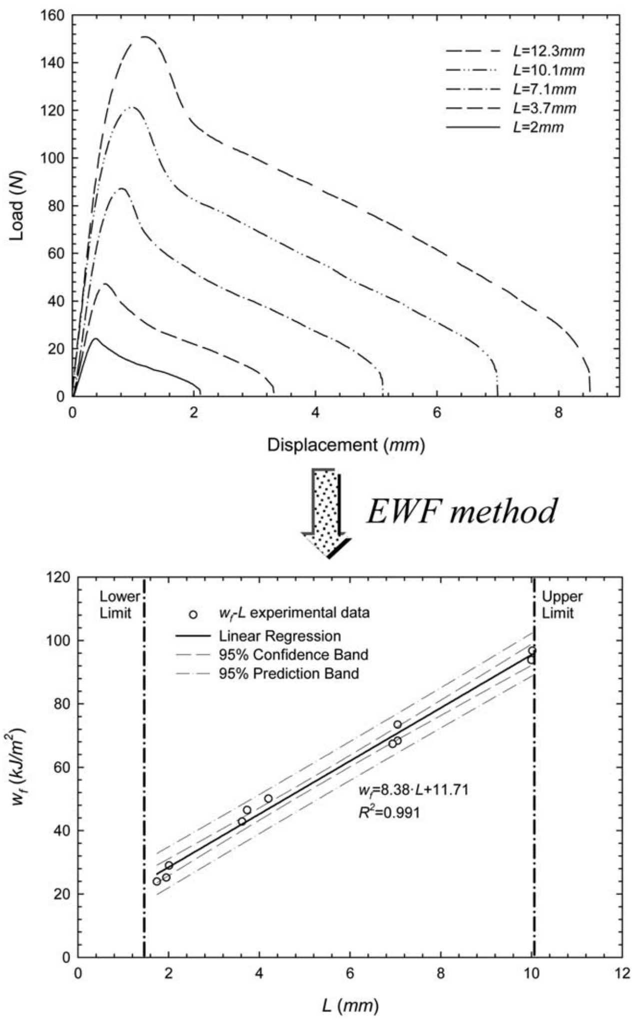

Figure 1. EWF method for the DDEN-T specimens.

The following requirements should be met before the EWF method is applied to assess toughness:[19] full ligament yielding before crack initiation, the prevalence of plane-stress conditions, and self-similar load–displacement curves. Nevertheless, Bárány *et al.*,[18] in their reviewed research, suggested that the latter is the only prerequisite (*sine qua non*) that must be met for the successful application of the EWF method.

Generally, the EWF method is applied to polymer films or thin polymer sheets (<2 mm). Specifically for this study, an EPLAK® by KARTON Company thermoplastic bulk polypropylene copolymer with an initial extruded sheet thickness of 0.465 mm and with a theoretical weight of 0.92 g/cm^3 was selected.

To assess the toughness of the analyzed polypropylene, DDEN-T specimens with a width (W) of 30 mm were cut with a laser from the polypropylene sheet, and in all of them, the notches were sharpened with a razor blade. To ensure the plane-stress conditions of the specimens, their L was varied in the range usually used in the EWF method: $L \geq (3-5)t$ for the lower bound and $L < W/3$ for the upper bound.[18]

Figure 1 shows some of the load–displacement curves that we obtained. It was clear that all of them had a similar shape, so it was possible to apply the EWF method. The shape of the load–displacement curve was verified in all of the tested specimens, and those with a different shape to that shown in Figure 1 were discarded. In the same figure, w_f is plotted as a function of L, and as was expected, the data formed a straight line, where w_e was 11.71 kJ/m^2, and the slope βw_p was 8.38. The correlation coefficient value obtained was $R^2 = 0.991$, so we considered the fit to be very good.[20]

EWF for the Prenotched SPT Specimens

As mentioned previously, the determination of the feasibility of applying the EWF method to prenotched SPT specimens was the focus of this research. Miniature specimens (10 × 10 mm^2) were cut from the polypropylene sheet and prenotched with a razor blade. The longitudinal prenotching used on the specimens was of the non-through-thickness cracklike flaw type, from the midpoint on one side of the specimen to the midpoint on the other, as shown in Figure 2. The notch was generated in one step by placing the razor blade perpendicularly through the midpoint of the specimen and applying a light pressure to create the prenotch. The depth was controlled by the placement of a few calibrated sheets on both sides of the specimen to ensure that the razor blade did not cut deeper than it should.

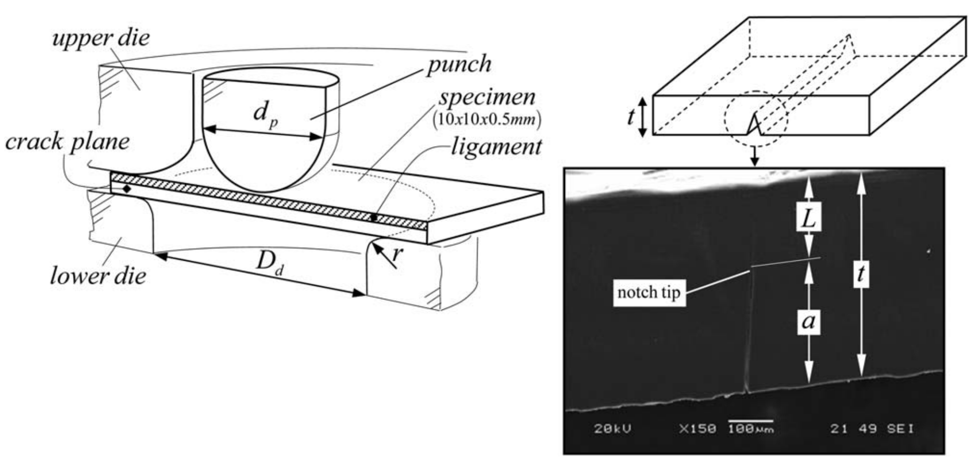

Figure 2. SPT device and prenotched small punch specimen.

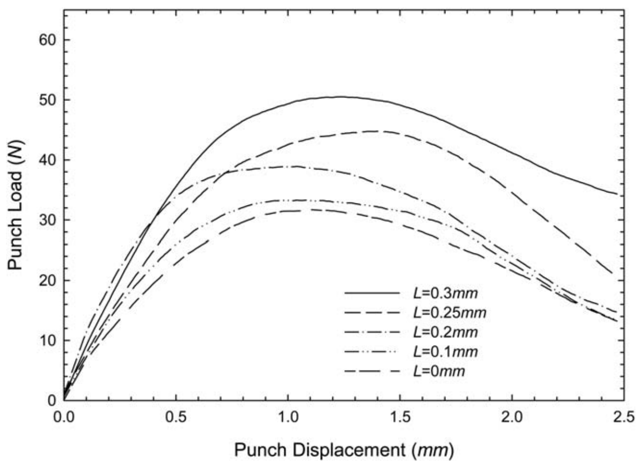

Figure 3. Load–displacement curves for the P–SPT specimens.

As shown in Figure 2, it was clear that the prenotch was sufficiently sharp (<15 μm) for applying the EWF method.[20] Prenotched SPT specimens with different crack depths (*a*s) were used. Although the range of the notch length varied between $a = 0$ and $a = t$, it was necessary to set upper and lower bounds, similar to those established for DDEN-T specimens, for the remaining *L*. To define these limits, different aspects, such as the shape of the crack propagation, the shape of the load–displacement SPT curves, and the tendency of the w_f results against the prenotch length, had to be taken into account.

Once the prenotch was achieved, the SPT specimens could be tested. The tests were conducted at room temperature with a punch diameter of 2.5 mm, the punch drop rate was 0.5 mm/min, and the hole in the lower die had a diameter of 4 mm and a fillet radius of 0.5 mm. For each specimen, a load–displacement curve was obtained, from which the area under the curve was calculated corresponding to W_f.

RESULTS AND DISCUSSION

Figure 3 shows the load–displacement curves for some of the prenotched SPT specimens corresponding to different *L*s. It was clear that when *L* was greater than 0.2 mm, the curve shape was different from those with lower *L* values. In addition, when the

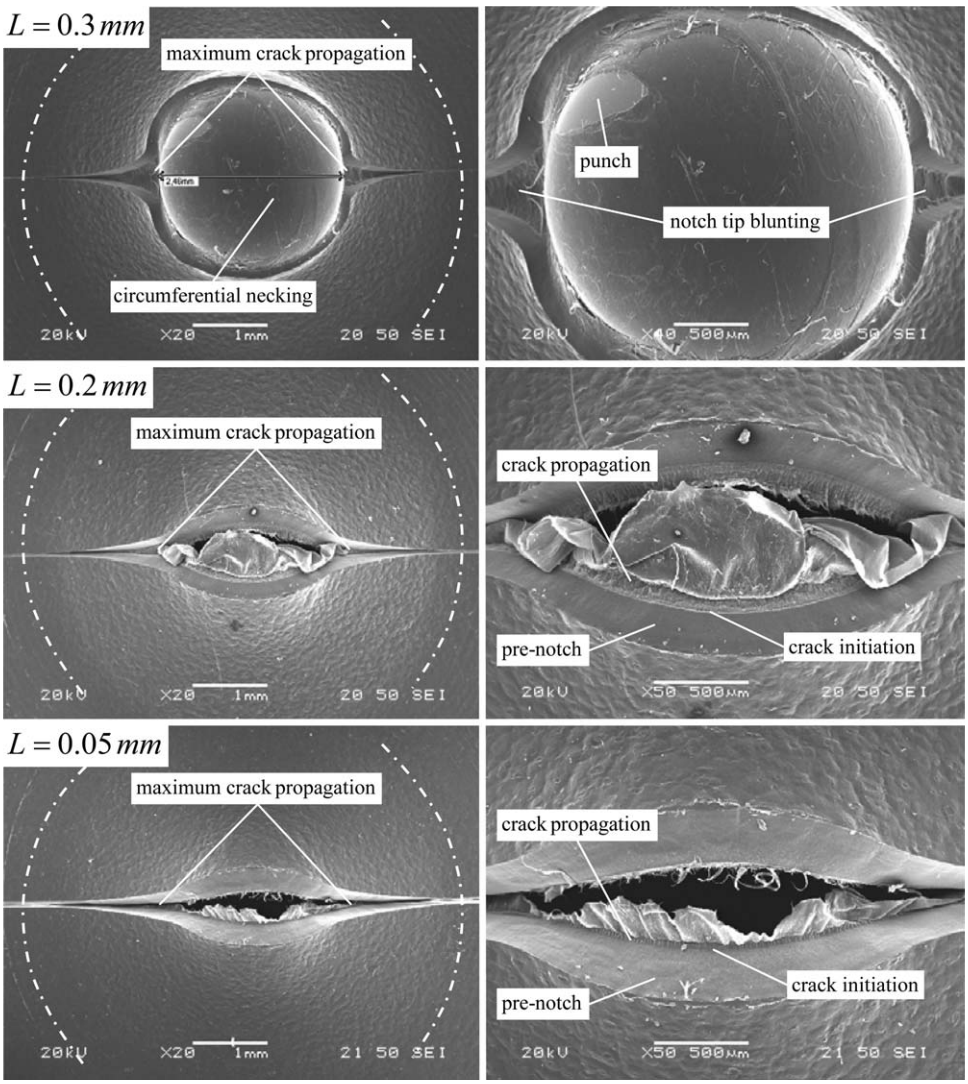

Figure 4. SPT specimens.

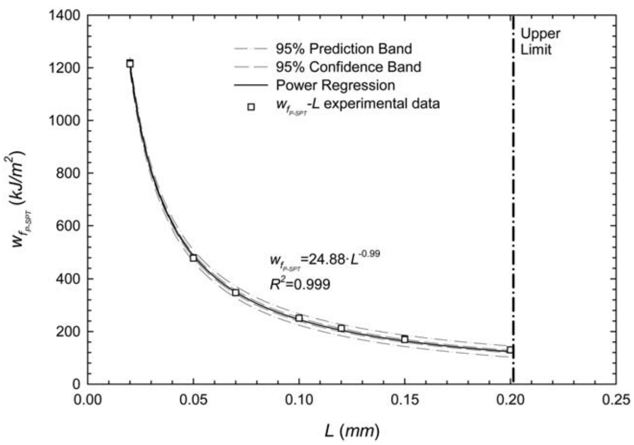

Figure 5. w_f versus L for the P–SPT specimens.

failure in the SPT specimens was analyzed (Figure 4), it was possible to identify two failure modes. The first corresponded to specimens with an L greater than 0.2 mm and, in some cases, those with L values between 0.1 and 0.2 mm where the crack did not propagate perfectly through the thickness because of a slight circumferential necking, which prevented the punch from passing through the specimen. The second took place after crack propagation in the plane that contained the notch. As shown in Figure 4, the crack propagation stopped before reaching the embedded area of the specimen because the crack had already grown sufficiently for the punch to push through two halves of the specimen. This was taken as a reference point in determining the ligament width so that it was equal to 2.5 mm in all of the specimens.

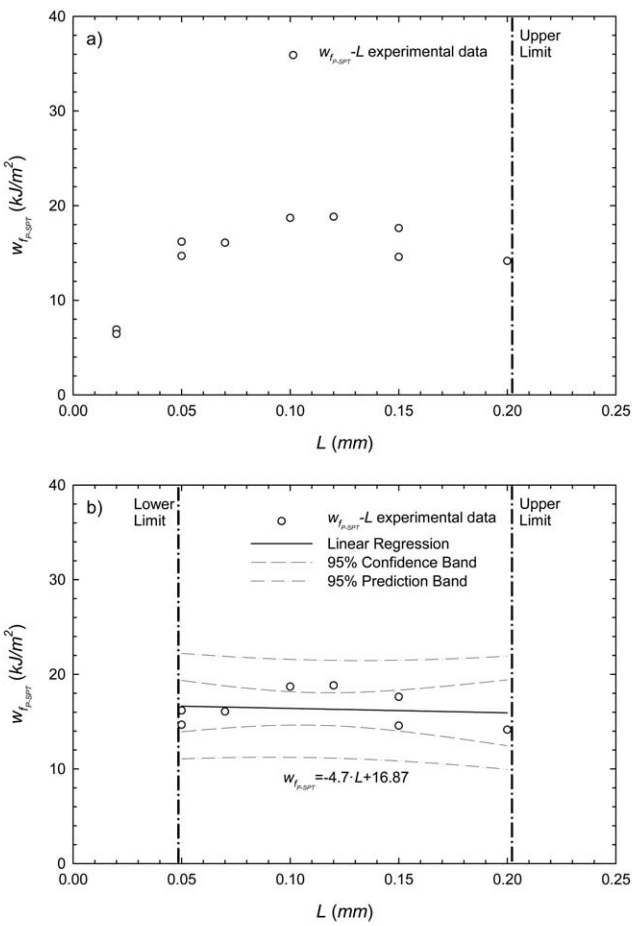

Figure 6. EWF method for the P–SPT specimens.

This second failure mode was necessary to determine w_f; this indicated that the specimens without this specific failure mode should not be used in the estimation of w_f. With this in mind, the upper limit of the w_f–L data could be set to an L value greater than 0.2 mm. Figure 5 shows the w_f values obtained as a function of L, in which the data fit perfectly with a power law.

Unfortunately, the power law data representation in the DDEN-T specimens is not well accepted by the EWF community.[18] However, in this case, the prenotched SPT (P–SPT) specimens did not show the same behavior as the DDEN-T specimens when L approached zero. In a DDEN-T specimen, when L was 0, the load–displacement curve approached zero ($W_f = 0$) because the specimen was separated into two halves, and the force during the test was zero. However, in a P–SPT specimen, when L was 0, the load–displacement curve did not approach zero (Figure 3) because the punch had to plastically deform the two halves of the specimen to pass through them to complete the test.

It was necessary to subtract the W_f fixed value corresponding to the P–SPT specimen with an L of 0 from each specimen's W_f value to ensure that the P–SPT specimens resembled DDEN-T specimen behavior when L was 0. In Figure 6(a), which shows the w_f–L data obtained, one can see that for low L values, the w_f values decreased significantly. The same thing happened in the DDEN-T specimens, so the lower bound could be set to $L = 0.05$ mm. A linear regression with values between the upper and lower limits was performed [Figure 6(b)], in which the intercept on the w_f axis for $L = 0$ was $w_{eP-SPT} = 16.87$ kJ/m^2 and the slope was $\beta w_{pP-SPT} = -4.7$. These values were compared with $w_e = 11.71$ kJ/m^2 and $\beta w_p = 8.38$ from the DDEN-T specimens, respectively. First, the value of w_{eP-SPT} was slightly higher than that of w_e; this could be justified because when the specimen failure did not occur completely in mode I, such as in the P–SPT specimens, the w_e value increased by more than a factor of two.[21] Second, the slope value was much lower because part of the specimen W_p was subtracted to achieve a linear regression of the results.

CONCLUSIONS

In this article, we have demonstrated that the EWF method can be applied to prenotched miniature specimens. This is because the basic principles for the application of the method, the most important of which is the self-similar load–displacement curves, are met. Apart from that, the upper and lower limits for L of the P–SPT specimens were established. Although the P–SPT specimen failure mode was not reached completely in mode I, the specific EWF term w_{eP-SPT} could be compared with that obtained in the DDEN-T specimens w_e. To conclude, we found that the w_{eP-SPT} value was slightly higher than the w_e value for the analyzed polypropylene polymer. Obviously, to extend this conclusion to other polymers, more research is required. However, this study can be viewed as a necessary initial step in the determination of the specific EWF from miniature specimens when there is not enough material to perform standard tests.

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