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On the plane-strain essential work of fracture of polymer sheets

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Summary

The essential work of fracture (EWF) is the most straightforward method to assess the toughness of ductile polymer films and sheets in which per se plane-stress conditions prevail. The interest is focused, however, on the determination of the plane-strain fracture toughness being a material parameter. It was demonstrated that the plane-strain essential work of fracture (determined in dynamic tensile impact tests) agreed well with that of the yielding-related specific essential work of fracture concluded from static mechanical tests for an amorphous copolyester sheet. This agreement still held when the plane-strain essential work of fracture derived by considering the experimental data in the plane-stress/plane-strain transition range (laying below the lower threshold ligament for which a linear regression was adopted) for a thicker sheet of the same polymer has been considered.

Introduction

The essential work of fracture (EWF) theory ([1-2] and references therein) splits the total energy required to fracture a precracked specimen in two components: the essential (W_e) and the non-essential or plastic work of fracture (W_p), respectively. The first term is needed to fracture the polymer in the process zone and thus generate new surfaces. W_p is the actual work consumed in the outer plastic region where various energy dissipation mechanisms take place. The total fracture energy, W_f, calculated from the area of the force-displacement curves, can thus be expressed by:

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

Considering the surface- and volume-dependence of the constituent terms, Equation 1 can be rewritten into the specific terms:

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

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

where: 1 is the ligament length, t is the specimen thickness and β is a shape factor related to the form of the plastic zone. Based on Equation 3, we can be estimated from the interception of the linear regression of the plot of w_f vs 1 with the w_f-axis [1-2]. The EWF is working excellently for polymer films and sheets as demonstrated in numerous works [1-8 and references therein].

Deeply double-edge notched specimens (DDEN-T) cut of amorphous (co)polyesters [7-10], poly(butylene terephthalate) [11], polycarbonate [12], PVC [13] and polypropylene [14-15] during static tensile loading failed by full ligament yielding preceding the necking and tearing process. The load drop observed between yielding and necking allowed us to partition between the specific work of fracture required for yielding (w_y) and for necking+tearing (w_n), respectively [2,7-10]. As a consequence the data reduction indicated in Equations 1-3 are changing for:

$$w_f=w_{f,y}+w_{f,n}=w_e+\beta w_p l \qquad (4)$$

$$w_{f,y}=w_{e,y}+\beta' w_{p,y} l \qquad (5)$$

$$w_{f,n}=w_{e,n}+\beta'' w_{p,n} l \qquad (6)$$

Note that this energy partitioning, introduced by the author's group, has been proved by other research groups in the meantime [11-13,15]. There are some strong arguments that $w_{e,y}$ is a material parameter. First, $w_{e,y}$ is independent on the molecular mass [7] at least in a molecular mass range where the entanglement network is fully developed. Second, $w_{e,y}$ did not depend on the deformation (strain) rate at least under static conditions [2,16]. Recall that all aforementioned findings are related to amorphous copolyesters in which complete ligament yielding preceded the necking+tearing process. On the other hand, major interest of the fracture mechanical characterization is to determine the critical plane-strain value which represents the inherent toughness of the polymer (denoted further on by $w_{e,IC}$, where IC is means the critical value under mode I type loading). It was supposed that $w_{e,y}\approx w_{e,IC}$, however with less experimental evidence [2,17]. $W_{e,IC}$ can be experimentally determined if one can find those experimental conditions for a given polymer under which it fractures ductilely along the full ligament without forming, however, a plastic zone. Note that these conditions can be achieved by tensile impact tests, which is – surprisingly – less explored by using the EWF method [18]. Accordingly, the objectives of this work were: i) to show that the EWF approach can be adopted for the tensile impact of a suitable polymer and its outcome is the plane-strain essential work of fracture, and ii) to point out that this value agrees well with the yielding-related specific essential work of fracture term derived from static loading.

Experimentals

DDEN-T specimens of amorphous copolyester sheets of Eastar® PCTG 5445 (Eastman Chemical Co.,Kingsport,TN,USA) were used. Characteristics of this PCTG material were given in our earlier papers [16-17].

The width, overall and clamped length of the DDEN-T specimens were 15, 80 and 40 mm. The width was limited by the clamping unit of the instrumented impact pendulum (Ceast, Pianezza, Italy). Dynamic loading of the DDEN-T specimens occurred at an incident speed of 1.2 m/s (set in order to reduce the "smearing" effect of dynamic oscillations) at room temperature. The energy of the striker was 7.5 and 15 J, respectively. The free ligament length (1) of the DDEN-T specimens was in the range 1≈2 to ≈14 mm. During data reduction the energy up to maximum load was equaled with the yielding-related work - cf. Equation 5. The broken surface of the DDEN-T specimens was inspected in scanning electron microscopy (Jeol 6300, Jeol, Tokyo, Japan) after gold sputtering.

Results and Discussions

Figure 1 evidences that the DDEN-T specimens of PCTG failed ductilely after full ligament yielding due to tensile impact. The ductile fracture is well recognizable on SEM pictures taken on the fracture surface of the DDEN-T specimens - cf. Figure 2.

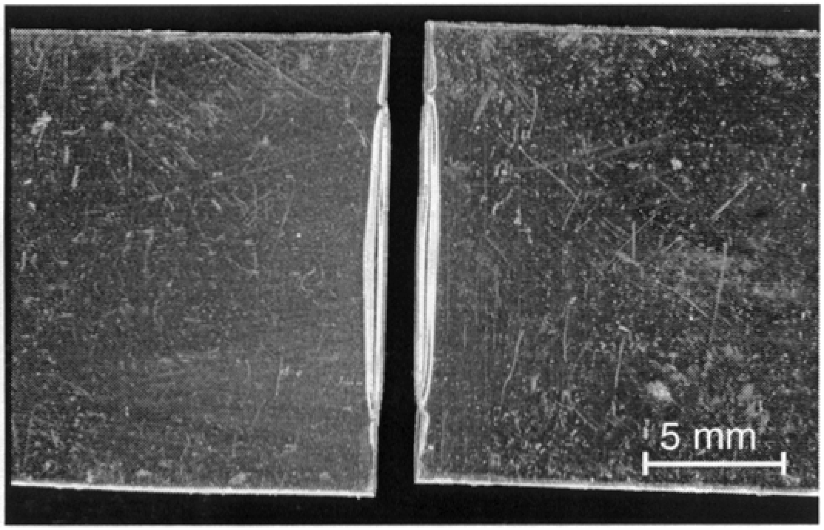

Fig. 1 Broken halves of a DDEN-T specimen of PCTG with 1≈10 mm after tensile impact

The plastic zone formed owing to tensile impact is highly constrained, as expected. So, the plastic zone, the boundaries of which are colinear with the fracture surface, is almost negligible – cf. Figure 1. This is opposed to the static tests where a well developed plastic zone of diamond or elliptical shape appeared [2,7,16-17]. A negligible plastic zone means that we and we,y should be closely matched.

The w_f vs 1 (Equation 3) and $w_{f,y}$ vs 1 (Equation 5) correlations are depicted in Figure 3. Table 1 collates the w_e and $w_{e,y}$ terms determined both under static and dynamic (present work) conditions. Recall that the $w_{e,IC}$ value determined in a thicker PCTG sheet (ca. 3 mm) by presuming a linear relationship between the experimental w_f vs 1 data, laying below the lower threshold ligament value, was 17.5 kJ m^{-2} [17].

Note that in this region mixed plane stress/plane strain conditions are accommodated. It is interesting to note, that researchers usually disregard this range although it may be used to derive the plane-strain term, i.e. $w_{e,IC}$, they are mostly interested in. The real problem is that the data reduction for this mixed mode range is not known, due to which the reader may find very peculiar curve forms [20]. Nevertheless, for the data in

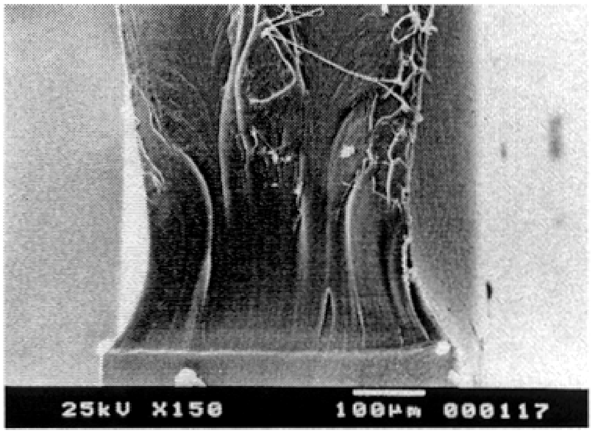

Fig. 2 Ductile fracture surface of a DDEN-T specimen of PCTG

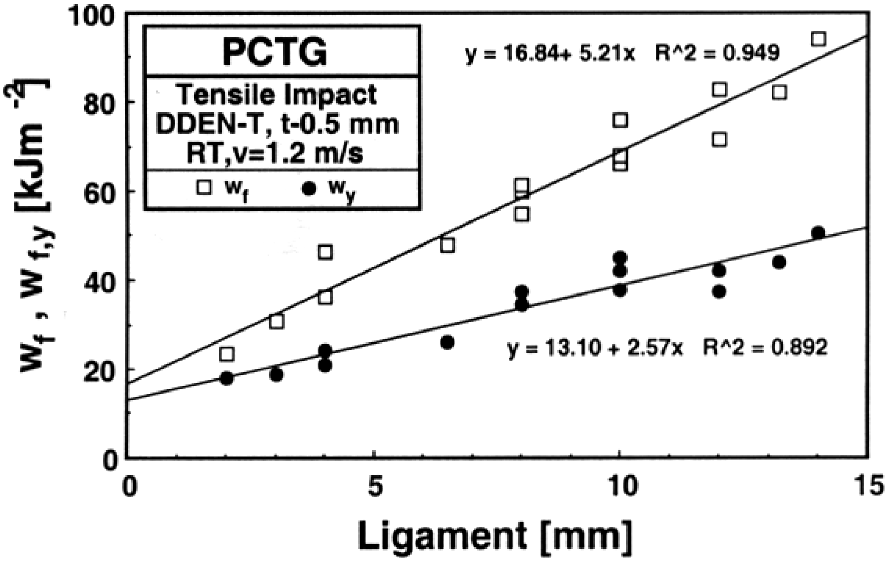

Fig. 3 w_f and $w_{f,y}$ vs l traces for tensile impacted DDEN-T specimens of PCTG

this range either power [21-22] or linear curve fitting [17,23] were proposed. Considering the fact that the EWF terms listed in Table 1 may underlay a rather large scatter, viz. ±25% when considering the 95% confidence limits [17], the data in Table 1 support the working hypothesis: the yielding-related essential work of fracture ($w_{e,y}$) under static mechanical loading agrees with that of the critical plane strain value ($w_{e,IC}$) determined under dynamic conditions.

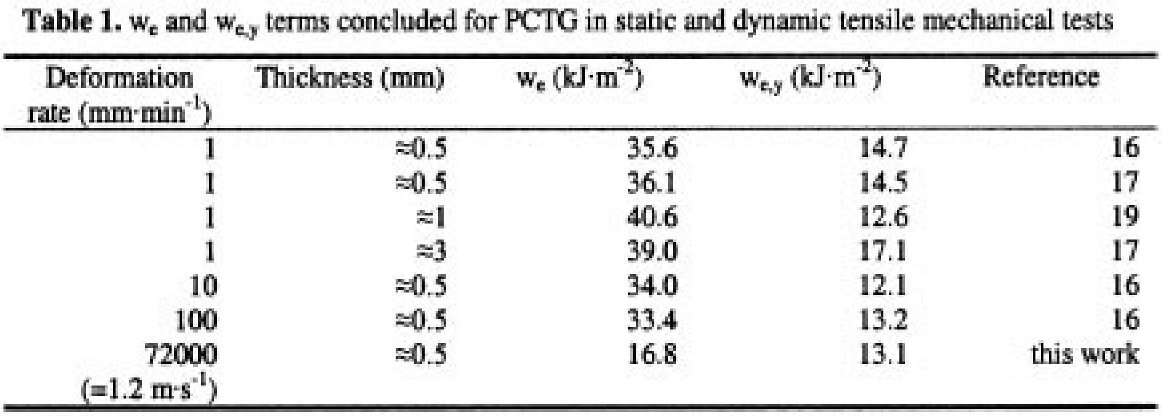

Table 1. w_e and $w_{e,y}$ terms concluded for PCTG in static and dynamic tensile mechanical tests

Deformation rate ($mm \cdot min^{-1}$)	Thickness (mm)	w_e ($kJ \cdot m^{-2}$)	$w_{e,y}$ ($kJ \cdot m^{-2}$)	Reference
1	≈0.5	35.6	14.7	16
1	≈0.5	36.1	14.5	17
1	≈1	40.6	12.6	19
1	≈3	39.0	17.1	17
10	≈0.5	34.0	12.1	16
100	≈0.5	33.4	13.2	16
72000 (=1.2 $m \cdot s^{-1}$)	≈0.5	16.8	13.1	this work

Conclusions

The plane-strain essential work of fracture ($w_{e,IC}$) value of an amorphous copolyester was determined experimentally in tensile impact loading (deformation rate=1.2 m/s) using deeply double-edge notched tensile (DDEN-T) specimens. Major arguments that the dynamic value represents plane-strain toughness are as follows: the fracture surface is fully ductile, the plastic zone developed is very limited, and as a consequence the specific yielding-related and overall work of fracture values are closely matched with one another. $w_{e,IC}$ was comparable with that of the yielding-related specific work of fracture ($w_{e,y}$) determined under static loading conditions (v=1 to 100 mm/min), According to the presented approach the plane-strain essential work of fracture can be approximated by the yielding-related plane-stress value. As the latter can be easy determined under static loading in sheets and films, whereas the plane-strain value is hardly assessable in most cases, the proposed approach is of high practical relevance.

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