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For what kind of polymer is the toughness assessment by the essential work concept straightforward?

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SUMMARY

The essential work of fracture (EWF) concept seems to be a proper and easy way to determine the inherent fracture behavior of ductile polymers. Unfortunately, all experiments reported until now were performed on polymers which did not meet the basic requirement of this fracture mechanical approach, viz. full ligament yielding prior to onset of crack growth. This problem often resulted in wrong conclusions and useless discussions on the specimen preparation, including notching techniques. By using tensile-loaded deeply double-edge notched (DDEN-T) specimens of amorphous copolyesters (aCOP) it was demonstrated that they are, in fact, the optimum choice to push forward the EWF concept for ductile polymers. Full ligament yielding before crack growth was evidenced by infrared thermographic (IT) frames taken during the loading of the DDEN-T specimens. The yielding "marked" with a load-drop in the corresponding load-displacement curves, enabled to split both the specific essential and non-essential work of fracture into their contribution terms: yielding and necking incl. fracture, respectively. It was argued that this EWF approach is most straightforward for the toughness description of such amorphous polymers that undergo necking by (multiple) shear banding without considerable strain-hardening, as aCOPs do.

1. INTRODUCTION

Determination of fracture toughness of ductile polymers by concepts of the non-linear fracture mechanics (denoted also as ductile, elastoplastic or post-yield fracture mechanics) represents an great challenge nowadays. One of their most promising approaches is the essential work of fracture (EWF) theory ([1-6] and references within), originally proposed by Broberg [7].

The EWF concept, which differentiates between the essential (W_e, required to fracture the polymer in its process zone) and non-essential or plastic work (W_p, consumed by various deformation mechanisms in the plastic zone), as indicated in Figure 1. The total work of fracture (W_f) is composed of the two above terms:

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

Taking into consideration that W_e is surface-, whereas W_p is volume-related, W_f can be given by the related specific work parameters (i.e. we and wp,respectively):

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

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

where l is the ligament length, t is the thickness of the specimen and β is a shape factor related to the form of the plastic zone.

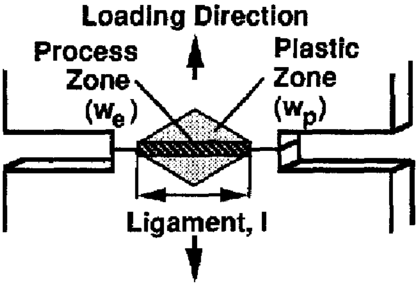

Figure 1
Process and plastic zones in a DDEN-T specimen, schematically

Based on Equation 3 w_e can be easily determined by reading the ordinate intercept of the linear plot w_f vs l. This is exactly the beauty with this method. In contrary to the toughness determination by the J-integral [2,4,6,8-9] where the partially loaded specimens should be broken up to visualize the crack advance (Δa) needed to construct the J_R curve (J vs Δa curve) from which the critical value (J_c) can be derived, in case of the EWF w_e, representing a material parameter, can be read simply from the ordinate intersection of the linear plot according to Equation 3.

It should be kept in mind that for the reliable application of the EWF the ligament should has been yielded prior to the onset of crack growth. According to the authors knowledge this requirement was never met until now; none of the load-displacement (F-x) curves displayed in the literature (e.g.[1,4,9-11]) shows any yielding prior to tearing. Yielding should be discernible in the related F-x curves as clearly as for example the onset of necking in a standard tensile test, should not be? Can this requirement fulfilled at all, and if yes, how does the present state of knowledge with the EWF method change?

The author believes that reports disputing whether or not w_e is a material parameter [12] and round-robin tests [13] that fail to yield the expected results are simply related to an improper selection of the polymers investigated.

Objectives of this work were: i) to show how efficient the EWF approach is when adopted for the right polymer, and ii) to point out by which properties the ideal polymer is characterized.

2.EXPERIMENTALS

Sheets with different thickness of amorphous copolyesters (aCOPs) under the tradename Eastar® PETG 6763 (furtheron PETG) and Eastar® PCTG 5445 (not included in this paper) available commercially from Eastman Chemical Co. (Kingsport,TN,USA) were used in this work.
For the EWF study double deeply edge-notched tensile (DDEN-T) specimens with a width of 35 and clamped length of 70 mm were selected and loaded with a crosshead rate v= 1mm/min at room temperature (RT). The free ligament length (l) was set in the range l=5 to 20 mm. At every ligament at least 3 specimens were investigated. Data reduction (cf.Equation 3) followed the recommendations of the ESIS TC-4 group [13].
Development of the plastic zone (cf. Figure 1) was followed by infrared thermography (IT, Hughes, Portland, OR, USA). IT was aimed to map of the relative temperature rise in the ligament region. Further details to the experimental section can be taken from our other works [14-15].

3.RESULTS

Fracture Behavior

Figure 2 depicts the F-x curves of DDENT-T specimens at various ligaments for PETG. It is very striking that the F-x curves at different ligament length are similar to one another, which is essential for adopting the EWF theory. A much more important phenomenon in respect to the F-x curves is, however, related to a load drop that "marks" where yielding (onset of necking) takes place. At this point the whole ligament yields instantenously, that is evidenced by IT pictures (see later). This full ligament yielding is followed by a necking stage up to the final fracture, as shown by Figure 2.

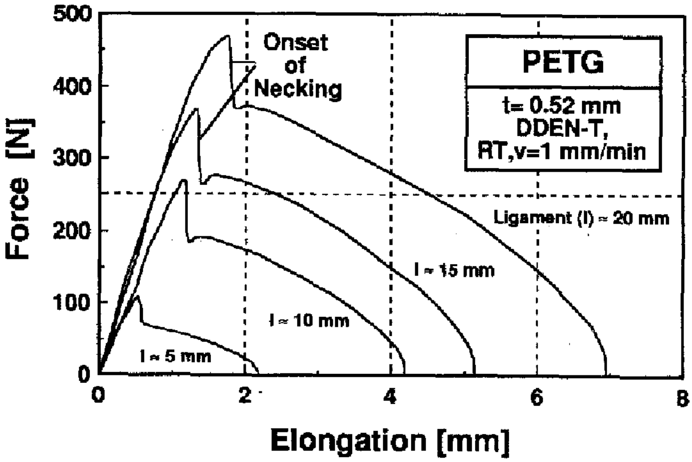

Figure 2 Comparison of the F-x curves of DDEN-T specimens at different ligament lengths for PETG

Figure 3 depicts the w_f vs l curves for the DDENT specimens of PETG. w_f was computed from the area beneath the F-x curves registered (cf. Figure 2).
According to Equation 3, the essential work of fracture (w_e) was read from the intercept of the linear regression line with the ordinate. Figure 3 contains also the slope value (βw_p; cf. Equation 3) and the correlation coefficient of the related regression line. The well-marked yielding in the F-x curves of COPs allows us to distinguish between the specific work of fracture required for yielding (w_y) and that consumed by necking and fracture (w_n). This feature is of utmost importance in order to get a deeper understanding of the EWF approach and to elaborate estimation procedures (based e.g. on usual tensile characteristics) for its terms, viz w_e and w_p.

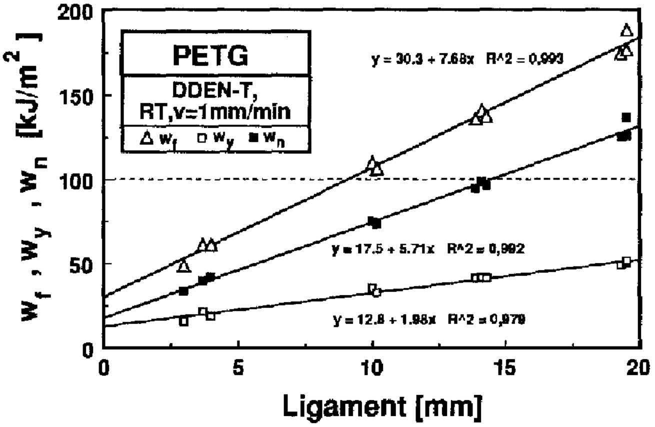

Figure 3
w_f and its contributing terms (w_y and w_n) vs l for the DDEN-T specimens of PETG

Failure Behavior

IT frames taken during loading (cf. Figure 4) have shown, in fact, for the full ligament yielding at the load drop (cf. Figure 2). The temperature rises due to the instantenous yielding up to about 5°C in case of PETG (picture A in Figure 4b). The serial IT pictures in Figures 4b show the development of the temperature field in the ligament area, and thus indicate the formation of the plastic zone (cf. Figure 1) in the necking stage. The cursor points 1 to 4 on the IT frames were positioned as follows:
1- showing the reference temperature;
2,3 - at the necking borderline in the upper and lower parts of the DDEN-T specimens, respectively, and
4 - in the mid ligament range or at hottest spot.
The IT frames before final breakage of the specimens imply for the presence of a shallow, diamond-like plastic zone.
The IT technique is a valuable tool not only to demonstrate the ligament yielding, but also to compute the the plastic work from the slope of w_f vs l (i.e βw_p; cf. Figure 3) explicitely [14-15]. Furthermore, the author believes that

IT may be an alternative and direct way for the determination of the essential work of fracture.

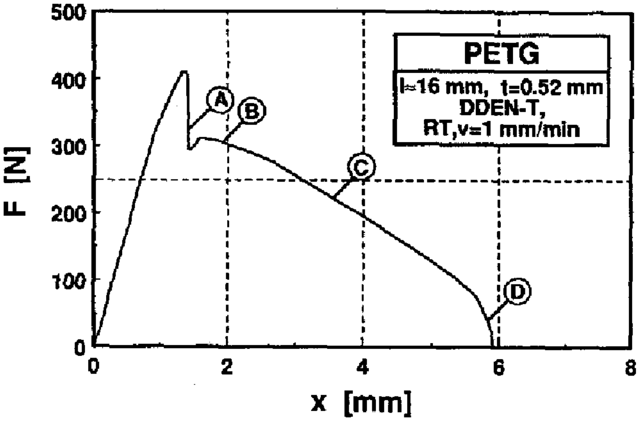

Figure 4a
F-x curve of a DDEN-T specimen (l≈16 mm) of PETG

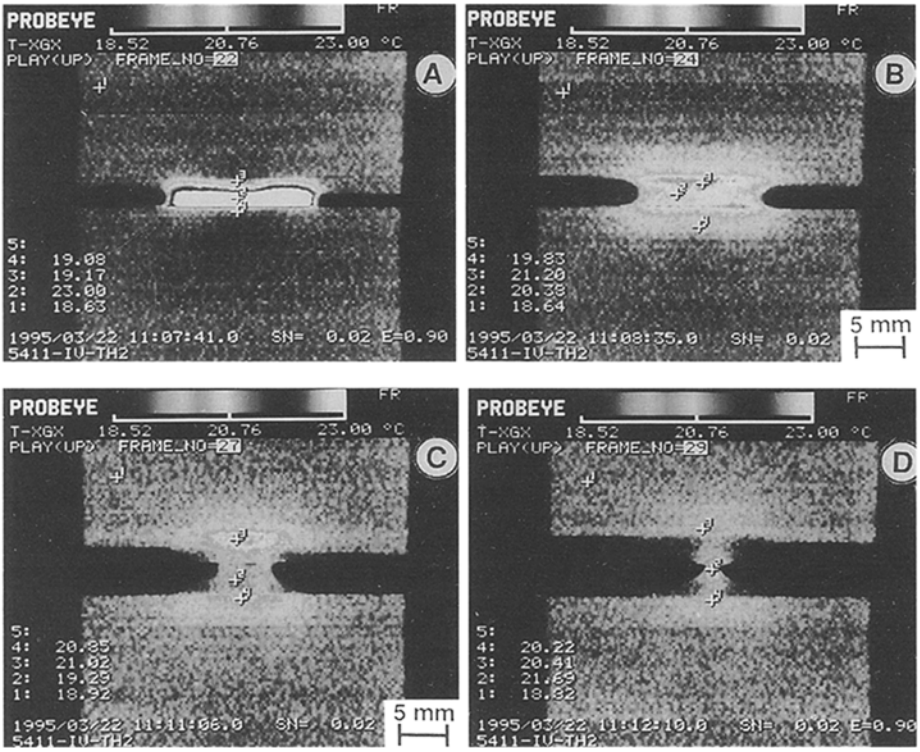

Figure 4b
Serial IT frames taken during loading of the specimen in Figure 4a
Note: taking position (i.e. A,B,C and D) of the IT frames is indicated in the F-x curve in Figure 4a

4. DISCUSSION

Characteristics of the Ideal Polymer for EWF

It is obvious that the right polymer for plane-stress EWF should be amorphous, because the yield stress (σ_y) of amorphous polymers is considerably lower than that of semicrystalline grades. This is an essential prerequisite of matching the criterion: full ligament yielding prior to crack growth. A further problem with semicrystalline polymers is that their yielding is always superimposed to crack growth [14].

In the literature there are EWF results on amorphous polymers, such as polycarbonate (PC) [9,16] and polyethyleneterephthalate (aPET) [11], available; what is wrong with them? Both under plane-stress and plane-strain conditions of the EWF concept the ideal polymer should be prone for shear deformation [17]. This failure is neither characteristic for PC, nor for aPET, but fortunately this is exactly the dominating failure mode in aCOPs. For example, the onset of necking in a dummbbell specimen of aCOP is always induced by a well localized shear band being inclined under 45° to the loading direction (Figure 5). The neck propagation is given by multiple shear band formation without pronounced strain-hardening. (Recall that above difference was made between shear banding and diffuse shear yielding).

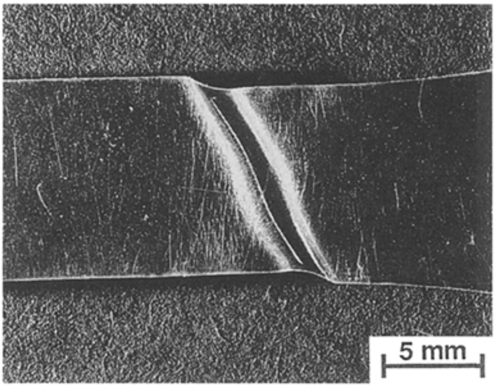

Figure 5
Necking onset by shear banding in a tensile loaded dumbbell (loading direction: horizontal)

Impact on the State of Knowledge with EWF

Let us first consider the usual size criteria of the EWF tests. The validity range of the EWF is generally given by [2-3,6,10-11,14]

$$(3\text{–}5)t \le l \le \min\left(\frac{B}{3} \text{ or } 2r_p\right) \tag{4}$$

where B is the width of the specimen (35 mm in our case) and $2r_p$ is the size of the plastic zone:

$$2r_p = \frac{1}{\pi} \cdot \frac{E w_e}{\sigma_y^2} \tag{5}$$

The plastic zone calculated by inserting the following data measured on PETG: E=2.3 GPa, w_e=30 kJ/m^2 and σ_y=50 MPa,

yielded $2r_p \approx 9$ mm. This size is similar to the alternative criterion, i.e. $B/3 \approx 12$ mm, of the upper threshold.
Based on the self-similarity of the F-x curves in the ligament range l= 5 to 20 mm (later extended even for l=30 mm), one can claim, however, that both criteria for the upper validity range are definitely too conservative in this case. Not only the upper, but also the lower threshold value can be, however,more precisely defined when aCOPs are used.

The other aspect is related to the thickness depedence of w_e. Right now it is generally accepted that w_e is a material parameter at least for a given specimen thickness (e.g. [10,16]). The latter restriction is, however, not obvious. Taking into account that in a given specimen thickness range still plane-stress condition is prevailing: why does a thickness dependence exist?
It was found that w_e is constant, in fact, for a considerably broad thickness range for aCOPs. This is an important new finding at which the rationale behind should be carefully analyzed.

5. CONCLUSIONS

The plane-stress ductile fracture behavior of amorphous copolyesters (COPs) was studied by the essential work of fracture (EWF) method using deeply double-edge notched tensile (DDEN-T) specimens. Based on this study the following conclusions may be drawn:

i- amorphous COPs are likely the ideal polymers for the approval of the EWF concept, since they undergo full ligament yielding prior to the onset of crack growth (which is a prerequisite of the EWF approach).

ii- due to the clear indication for yielding in the load-displacement curve (well discernible load drop in the F-x curve), the contributing terms of both specific essential and non-essential work of fracture, given by yielding and subsequent necking and fracture, respectively, can be determined separately.

iii- based on the failure characteristics of aCOPs,it was suggested that failure onset in the most suitable polymers for the EWF tests occurs via localized shear banding. The following necking process of the specimen, controlled by multiple shear banding that turns into diffuse shear yielding, should not result, however, in considerable strain-hardening. The latter criterion can be reached by amorphous polymers with no tendency to strain-induced crystallization.

It can be prophecied that further investigations with aCOPs (or other polymers of similar characteristics) may yield a breakthrough in the application of the EWF theory for the toughness description of ductile polymers.

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