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Plane Stress Fracture Toughness of Unplasticized PVC Material Determined by the Essential Work of Fracture (EWF) Approach

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Abstract: Essential work of fracture (EWF) approach was used to evaluate the fracture toughness of uPVC film. It was found that the specific essential work of fracture, (w_e) is independent of specimen width, specimen gauge length, loading rate and test temperature, but dependent on the geometry of the test specimens. Test temperature and geometry were the only testing parameters affecting the specific non-essential work of fracture (βw_p) in a very significant way. This approach has proved to be capable of determining toughness and to illustrate the crack grow from DENT specimen. This difference was confirmed by the high ductility and the development of the necking zone at the crack tip under two different conditions (Plan strain and plane stress). The present work is aimed at studying the response and ligament length effects on the fracture behaviour of a amorphous polyvinyl chloride - Pipe. The evaluation of toughness under plane stress conditions was performed by this method. The results are examined and discussed in terms of recent developments.

Key words: Fracture mechanics · EWF · uPVC · DENT

INTRODUCTION

Linear Elastic Fracture Mechanics (LEFM) approach is often used to characterise fractures that occur at nominal stresses well below the uniaxial tensile yield stress of a material. Under this condition, plastic flow at the tip of the crack is intimately associated with a fracture process which is brittle in nature. A single fracture parameter such as the Critical Stress Intensity Factor, K_{Ic} or the Critical Strain Energy Release Rate, G_{Ic} have been found to be sufficient to characterise this type of fracture at its critical condition. However, the LEFM approach cannot be adopted in characterising the failure of ductile and toughened polymers, where a large plastic zone often exists at the tip of the crack and, much of the plastic flow work dissipated in this zone is not directly associated with the fracture process. For ductile materials, two approaches have been used in order to characterise the fracture behaviour, namely, the essential work of fracture (EWF) and the J-integral.

EWF approach has recently gained popularity due to its experimental simplicity. This approach which was proposed by Broberg [1] assumes that the non-elastic region at the tip of a crack may be divided into two regions: an inner region where the fracture process takes place and the outer region where the plastic deformation takes place. The total work of fracture can then be partitioned into two components: work that is ex-pended in the inner fracture process zone to form a neck and subsequent tearing and the work which is consumed by various deformation mechanisms in the surrounding outer plastic deformation zone. The former is referred to as "Essential Work of Fracture" and the latter as "Non-Essential Work of Fracture". The method has been used to study the fracture behaviour of wide range of materials such as metals [2-4], polymer films [5-12] and papers [13] under plane-stress conditions. Studies on these materials indicate that the method provides a useful means by which frac-ture toughness can be determined.

In this study, EWF approach is used to determine the fracture toughness of uPVC. The effects of specimen geometry and loading rate on EWF parameters for uPVC are investigated in detail.

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EWF Concept

Theory: The measurement of fracture toughness of uPVC materials is generally more difficult. To test the validity of the EWF method, the fracture mechanics principles were employed to evaluate fracture toughness material in large scale plasticity.

In the case of brittle fracture of polymer, the total work of fracture W_f is associated with the fracture line around the crack. The initiation of crack can be described by the critical energy G_c or the critical intensity K_c. However, for ductile polymer such as uPVC, the total work of fracture is a constant of the material. For this case Broberg [1] proposes a material presenting plasticity to separate the non elastic region at the crack tip into two distinct regions: The internal zone IFPZ (Fracture Process Zone) and the external zone OPDZ (Outer Process Zone). Alone work dissipated in the IFPZ allow to describe the intrinsic behaviour of material, while the work dissipated in the OPDZ is a function of the sample used and the type of solicitation.

The EWF concept originates fracture from the 70s from Broberg's unified theory of [1, 13–15]. Accordingly, stable crack growth is due to an increasing work input in an autonomous (term of Broberg in Ref. [1]) inner region, is "filtered" through the gradually increasing action of the dissipative work in the neighboring region. Thus, the total work of fracture includes both the dissipative work in the outer "plastic" zone and the essential one in the inner autonomous zone. The latter is called the fracture process zone and the essential work of fracture represents a material property (toughness). By contrast, the non-essential or "plastic" work is a geometry-depended parameter. The attribute "plastic" may suggest that irreversible deformation takes place in the outer fracture zone. As shown later, this holds for thin, ductile metals, for which the EWF technique was originally developed [16], but not for polymers [17]. The pioneering role in the extension of the EWF to polymers should be assigned to Mai and coworkers [5, 7, 15].

As expressed above, the total work of fracture (W_f) can be partitioned into two components; (i) the essential work of fracture (W_e) consumed in the inner fracture process zone (IFPZ) to create new surface and (ii) the non-essential (or plastic) work (W_p) performed in the outer "plastic" defor- mation zone (OPDZ) - Fig. 1.

The total work of fracture (W_f), calculated from the area of the Load–displacement curves is given by Equation (1):

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

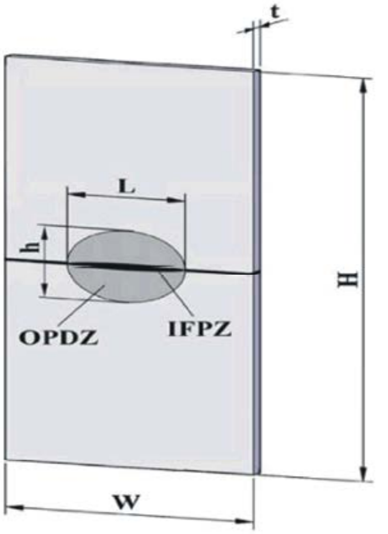


Fig. 1: Schematic diagram of process zone in ductile fracture specimen

Table 1: Technical specifications

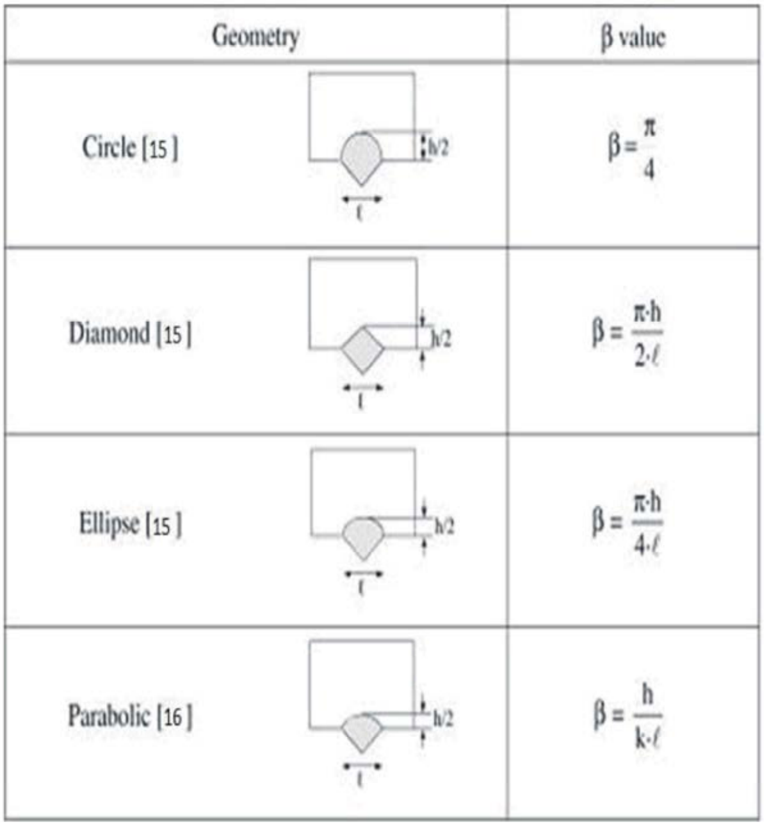
Characteristic	Specification	Method
Density	1036 Kg/m^3	ISO 1183
Index of melt flow rate	0.2 g/10min	ISO 1133
Viscat-softening temperature	75°C	ISO 306

Assuming that both zones are within the ligament of the specimen (cf. Fig. 1), Equation (1) can be rewritten into the specific terms (Equations (2) and (3)):

$$W_f = w_e \,.\, Lt + \beta w_p \,.\, L^2 t \qquad (2)$$

$$w_f = w_e + \beta L w_p \qquad (3)$$

where L is the ligament length, t is the specimen thickness and β is the shape factor related to the form of the outer plastic dissipation zone. Accordingly w_e and w_p are surface and volume-related, respectively. Equation (3) provides the basis for data reduction: data on the specific work of fracture $w_f$determined on specimens with varying ligaments are plotted as a function of the ligament length L, such that w_e and βw_p are given, respectively, by intercept on the w_f axis for L = 0 and the slope obtained by a the linear regression. Then, w_p can be explicitly deduced for some shapes of the outer plastic zone with known β given by Fig. 2 for different OPDZ geometries and relationship with the β parameter [18,19]. Note that in the outer plastic dissipation zone crazing, voiding (continuity/discontinuity-type events), shear deformation (isotropy/anisotropy-type events) and their combination may occur.



Geometry	β value
Circle [15]	$\beta = \frac{\pi}{4}$
Diamond [15]	$\beta = \frac{\pi \cdot h}{2 \cdot \ell}$
Ellipse [15]	$\beta = \frac{\pi \cdot h}{4 \cdot \ell}$
Parabolic [16]	$\beta = \frac{h}{k \cdot \ell}$

Fig. 2: OPDZ geometries and relationship with the β parameter

Experimental Procedure: This study was conducted on commercial unplasticized PVC – pipe extruded material form having an outer diameter of 200 mm, a length of 400 mm and a thickness of 2mm, supplied by TUBEX Company. The characteristics of the raw materials are given in Table 1.

Specimens were cut directly from the pipes in longitudinal extrusion direction and machined. The dimensions of the tested specimens are shown in Fig. 3-a. The uPVC mechanical properties were determined from standard uniaxial tensile test (ISO 8256) at room temperature and at a crosshead speed of 1mm/min, using a universal testing machine equipped with extensometer Fig. 3-b. The standard NF ISO 8256 specimen configuration was used in the uniaxial tests, although no standard procedures for performing high-speed tensile tests on plastic materials exist to date. The straight gauge section has a length of 10 mm and a width of 4 mm. The nominal thickness of the specimen is 18 mm.

The specimens used to fracture testing are Double Edge Notched Tension DENT'. They were machined directly from the pipe, so as to have a thickness lower than of the pipe. Notching was performed by saw cutting. The notch depth was chosen according to ESIS protocol standards recommendations [20].

Using a series for DENT specimens with identical dimensions but varying ligament length. It has been recommended that the ligament length range for plane stress determination of the EWF approach as:

$$3t < L < \min(2R_p; W/3) \quad (4)$$

where W is the width of the DENT specimen and R_p is the plastic radius.

The fracture testing method under tensile solicitation was conducted at constant displacement rate for all specimens at 23°C as a basic test condition. Testing was carried in an Zwick - 1100 test machine, especially designed for polymer characterization and equipped with a 2 kN load cell. In the ideal case DENT specimen is commonly used and recommended to characterise toughness of polymer by the essential work of fracture "EWF" approach.

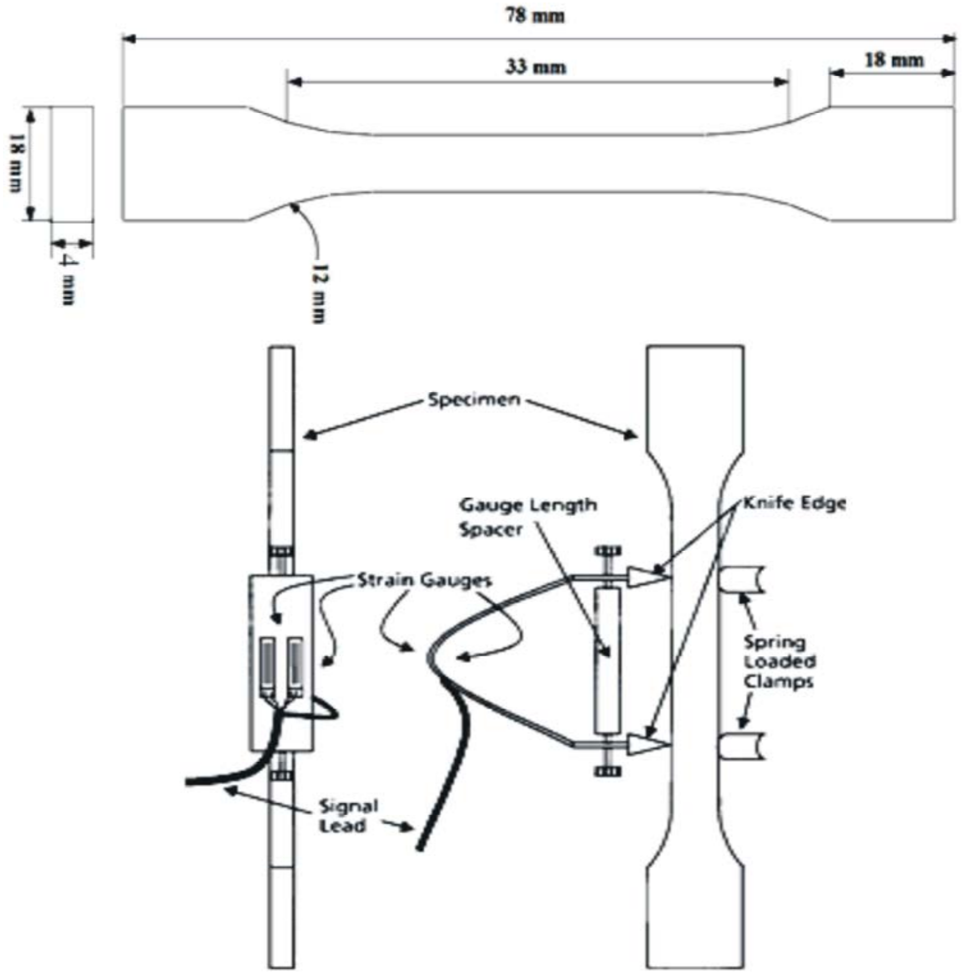


Fig. 3: Sample geometries tested in tension
a) The NF ISO 8256 specimen dimensions (thickness=18mm)
b) Schematic of a clip on strain gauge extensometer

RESULTS AND DISCUSSION

The typical load-displacement curves obtained for DENT specimen with various ligament lengths are reporting in Fig. 4. It is remarked the same behaviour with similar shapes of curves for each size of the ligament, i.e the development of the plastic zone FPZ and the onset of crack growth; witch was influenced by the ligament length and which indicates that the fracture mode is independent of the ligament length. Note that the plastic zone has an elliptical shape.

The different steps of evolution of uPVC material during the test are shown in Fig. 4.

The procedure to follow of decomposition of the total work of fracture 'W_f' and to determine 'W_e' is to vary the size of the ligament in stress plane conditions. In all cases, it is clear that the specimen undergoes ductile fracture.

It is observed a linear elastic behaviour between 'I and II', an increasingly stable of load vs displacement; followed by the non-linear part until the maximum load 'III' which explains the beginning of blunting at the crack tip. After yielding it is remarked that load decreased rapidly up to 'IV', the plastic zones meet each other and necking start. After that, crack starts to grow as a function of ligaments and the necking zone until fracture of the sample 'V'. Load and displacement for each specimen depend on the ligament length.

The EWF technique is valid over a range of ligament length. Several approaches have been defined by many writers [3] stated that '$L < W/3$'. Other authors [21, 22] extend this criterion in formulating the following condition in equation (4).

The total work of fracture can be calculated as a function of 'L' from the area under the load–displacement curve.

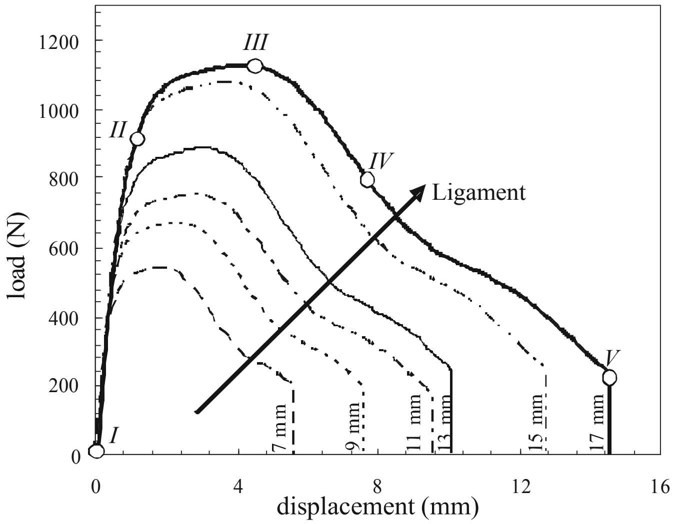


Fig. 4: Typical load - displacement curves for DENT specimen

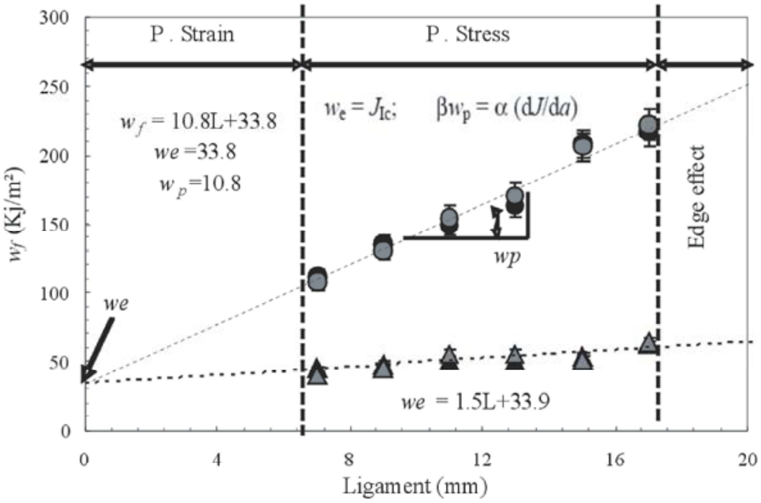


Fig. 5: Schematic representation of specific work of fracture as a function of ligament length

From there, knowing the thickness and length of the initial ligament, the total work of fracture per unit area 'w_f' is determined for each size of the ligament. Then for a specific range of ligaments, it is possible to trace w_f according to L. The right slope is βw_p and the intercept is we.

A typical curve of wf as a function of L is shown in Fig. 5. To verify the validity of the criteria cited previously, it exceeding the valid range of the equation (4). it is remarked a curve being linear and increased. It can be seen that in plane stress two regions, It is clear that for a ligament in the range of validity, we found a w_e= 33 KJ/m^2 which is close of 'J_{IC}'. While in plane strain exists dispersion, however, this dispersion is reasonable given that the ligament length is too small. It can be said with some certainty that the initiation w_e and propagation βw_p parameters in plane stress depend on ligament length 'L'. The parameter "β"is already determined by equation (5).

$$\beta = \frac{\pi h}{4L} \tag{5}$$

Finally, to verify the validity of EWF criteria, the identification of the limit load 'P_{Max}' to maximum load allow to find the result from Hill's analysis on the DENT specimen [23]. This hypothesis states that rupture occurs after the limit load. The maximum average load in the ligament σm is defined as the ratio between maximum load and the initial ligament surface:

$$\sigma_m = \frac{P_{max}}{L,t} = a.\sigma_y \tag{6}$$

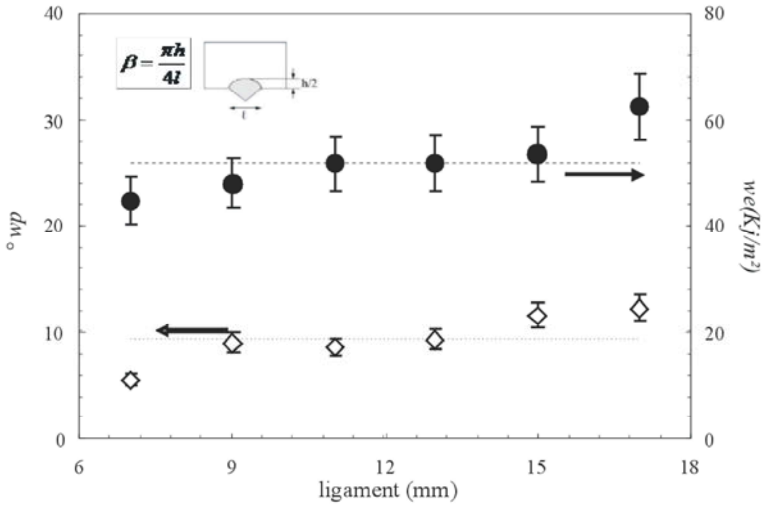


Fig. 6: Evolution of σ_{Max} as a function of ligament

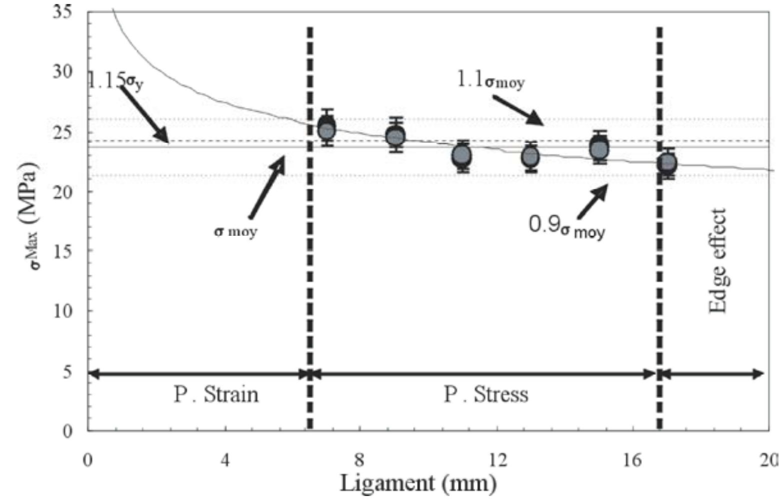


Fig. 7: Ligament dependence of specific essential (w_e) and non-essential (w_p) work of fracture parameters

With a: confinement ratio
σ_m for the DENT specimen geometry to be given by 1.15 σ_y. In addition to Hill's criteria, it is considered useful to apply an average value of σ_{max} denoted by σ_m.

There applies the criterion that any essential work data, for which $\sigma_{max} > 0.9\sigma m$ and $\sigma_{max} < 1.1\sigma_m$ be rejected from the determination of w_e. We remark for all data located in the range of validity between L_{min} and L_{max}, that the values of σ_m are in the range Fig. 6.

The essential work of fracture (w_e) and the non-essential term (βw_p) shows a smooth increase as a function of ligament length Fig. 7. However, when their β-values are considered and w_p is calculated, this trend seems to be constant for the ligament length range for plane stress. It must be recalled the nature of this polymer could give rise to uncertainties in βw_p or β determinations. Even so, the increasing trends seem to be related to the progressively lower homogeneous necking capability of the uPVC. Each specific work of fracture is believed to contain an essential term that is independent of the ligament length and a nonessential term that is proportional to the ligament length. It can be seen that as the ligament rises the specific essential work of fracture term (w_e) slightly increases from: 40 kJ/m^2 at 7mm to 60 kJ/m^2 at 17mm. On the other hand, the specific non-essential parameter (βw_p) lightly increases with ligament and then stabilizes.

It is important to observe that the ligament range explored is in the interval recommended in equation (4) recommended by ESIS.

The amorphous uPVC is a very ductile polymer whatever the loading conditions are: i.e., un-notched and notched tensile tests. In such a case even uPVC is a ductile material at room temperature Fig. 8-a.

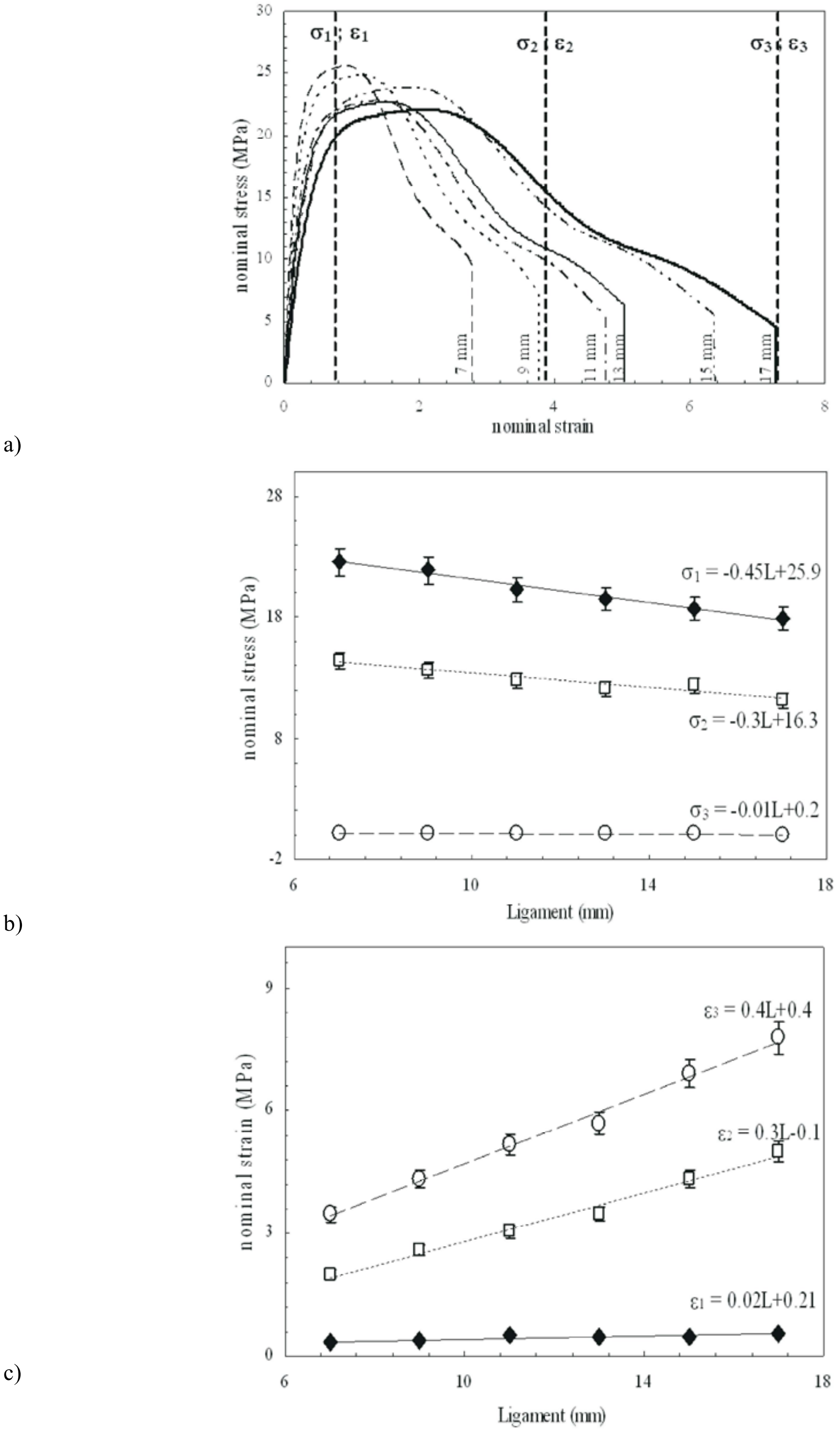


Fig. 8: Tensile properties of uPVC for notched samples DENT:
a) nominal stress–strain curve, b) evolution of yield stress stage, c) evolution of yield strain stage

It is remarked ultimate properties in tension for DENT samples. The only visible effect is a decrease in various stages of yield stress and strain due to the rubber content. In the example, Fig. 8-b and 8-c shows the evolution of these magnitudes (σ_1; ε_1 - σ_2; ε_2 - σ_3; ε_3). So, the increasing/decreasing trends in terms of stress/strain seem to be related to the progressive increase ligament of the uPVC.

CONCLUSION

Plastic deformation and necking of uPVC under tensile loading were investigated using uniaxial tension and DENT tests. Results from the uniaxial tension tests suggest that the neck development of the uPVC can be divided in neck inception and neck propagation, respectively, with fracture occurring only at the end of the neck propagation stage.

Ligament effects on the fracture behaviour of DENT samples of amorphous uPVC – pipe have been investigated by the EWF approach. Results showed that the specific essential work of fracture term, w_e, was scarcely affected by both ligaments (in the range from 7 to 17 mm). A marked increase of the specific essential work of fracture parameter occurred only under tensile conditions (displacement rate of 1 m/min). On the other hand, the specific non-essential parameter, βw_p, gradually increased with loading over the whole experimental range. The neck development of the DENT tests was similar, except that the crack growth was involved in both stages of the neck development.

The study also observed two interesting phenomena in the DENT tests. One is an increasing energy throughout the whole fracture process, despite two distinctively different stages of the neck development. The other is a constant fraction of the specific non-essential parameter under total ligament length, which is independent of the original ligament length used in the study.

REFERENCES

1. Broberg, K.B., 1968. Critical review of some theories in fracture mechanics. International Journal of Fracture Mechanic, 4: 11-18.
2. Arkhireyeva, A., S. Hashemi and M. O'Brien, 1999. Factors affecting work of fracture of uPVC film. Journal of Material Science, 34: 5961-5974.
3. Cotterell, B. and J.K. Reddell, 1977. The essential work of plane stress ductile fracture. International Journal of Fracture, 13: 267-277.
4. Cotterell, B. and Y.W. Mai, 1982. Plane stress ductile fracture. Advanced Fracture Research. (Fracture 81), Cannes, France, 4: 1683-1695
5. Mai, Y.W. and P. Powell, 1991. Essential work of fracture and J-integral measurements for ductile polymers. Journal of Polymer Science Polymer Physics Edition, 29: 785-793.
6. Mai, Y.W., B. Cotterell, R. Horlyck and G. Vigna, 1987. The essential work of plane stress ductile fracture of linear polyethylenes. Polymer Engineering & Science, 27: 804-809.
7. Mai, Y.W. and B. Cotterell, 1986. On the essential work of ductile fracture in polymers. International Journal of Fracture, 32: 105-125.
8. Mai, Y.W. and B. Cotterell, 1980. Effects of prestrain on plane stress ductile fracture in Alpha-Brass. Journal of Materials Science, 15: 2296-2306.
9. Hashemi, S. and J.G. Williams, 2000. Temperature dependence of essential and non-essential work of fracture parameters for polycarbonate film. Plastic, Rubber and Composites, 29(6): 294-302.
10. Hashemi, S., 2002. Fracture of polybutylene terephthalate (PBT) films. Journal of Polymer, 43: 4033-4041.
11. Arkhireyeva, A. and S. Hashemi, 2002. fracture behaviour of polyethylene naphthalate (PEN). Journal of Polymer, 43: 289-300.
12. Broberg, K.B., 197). Crack-growth criteria in nonlinear fracture mechanics. Journal of the Mechanics and Physics of Solids, 19(6): 407-418.
13. Mai, Y.W., H. He, R. Leung and R.S. Seth, 1995. In “Int. Fract. Mech. Vol. 26 STP1256,” edited by W. G. Reuter *et al*. ASTM, Philadelphia, pp: 587.
14. Broberg, K.B., 1975. On stable crack growth. Journal of the Mechanics and Physics of Solids, 23: 215-37.
15. Mai, Y.W., S.C. Wong and X.H. Chen, 2000. Application of fracture mechan-ics for characterization of toughness of polymer blends. In: Paul DR, Bucknall CB, editors. Polymer blends: formulations and perfor-mance, Vol 2. New York: Wiley, pp: 17-58.
16. Mai, Y.W. and B. Cotterell, 1984. The essential work of fracture for tearing of ductile metals. International Journal of Fracture, 24: 229-36.
17. Karger-Kocsis, J., 2000. Microstructural and molecular dependence of the work of fracture parameters in semicrystalline and amorphous polymer systems. In: Williams G, Pavan A, editors. Fracture of polymers, composites and adhesives, Vol 27. Oxford: Elsevier and ESIS Publ, pp: 213-30.

18. Gray, A., 1993. Testing protocol for essential work of fracture, ESIS, editor. European Structural Integrity Society (ESIS) - TC4.
19. Ferrer-Balas, D., M.L. Maspoch, A.B. Martinez and O.O. Santana, 2001. Influence of annealing on the microstructural, tensile and fracture properties of polypropylenefilms. J. Polymer, 42(4): 1697-705.
20. Moore, D.R., A. Pavan and J.G. Williams. Eds, ESIS. (2001). Fracture mechanics testing methods for polymers, adhesives and composites. In. 28 Elsevier, Amsterdam, Publication, pp: 177-195.
21. Chan, W.Y.F. and J.G. Williams, 1994. Determination of the fracture toughness of polymeric films by the essential work method. Journal of Polymer, 35: 1666-1672.
22. Saleemi, A.S. and J.A. Nairn, 1990. The plane-strain essential work of fracture as a measure of the fracture toughness of ductile polymers. Journal of Applied Polymer Science, pp: 30-211.
23. Hill, R.H., 1952. On the discontinuous plastic states with special reference to localized necking in thin sheet. Journal of the Mechanics and Physics of Solids, 1: 19-30.