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Effects of Thickness, Deformation Rate and Energy Partitioning on the Work of Fracture Parameters of uPVC Films

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Summary

Unplasticised poly(vinyl chloride) (uPVC) films have been tested using the essential work of fracture (EWF) method. Influence of loading rate and film thickness on the tensile properties and work of fracture parameters was evaluated. In addition, energy partition analyses were carried out applying two different approaches ("yielding" and "initiation"), which differ in the treatment of the stored elastic energy. Results showed less effect of the film thickness and deformation rate (<100 mm/min) on the EWF terms. On the other hand, the specific essential work of fracture (w_e) at high load rate (1.2 m/s) approached the yielding-related term ($w_{e,y}$) obtained at static loading rates (<100 mm/min).

Introduction

The Essential Work of Fracture (EWF) method, originally proposed by Cotterell and Reddel [1] after Broberg's work [2], has proved to be a useful tool to characterise the fracture of thin sheets of ductile materials including metals [3] and polymers ([4-9] and references therein). This method proposes the division of the total work of fracture (W_f) of a deeply double edge notched tensile (DDENT) specimen (fig.1) into two terms, named essential work of fracture (W_e) and non essential work of fracture or plastic work (W_p). The first one is a surface-related term and is associated with the energy required to create two new surfaces. W_e is therefore proportional to the ligament section $(l \cdot t)$ where l is the ligament length and t is the thickness (fig.1). The plastic work is related with the energy involved in the outer zone of the fracture and is proportional to the volume of the plastically deformed zone $(\beta \cdot l^2 \cdot t)$. β is a factor which depends on the shape of the plastic zone.

$$W_f = W_e + W_p = w_e \cdot l \cdot t + \beta w_p \cdot l^2 \cdot t \tag{1}$$

Rewriting equation (1) using the specific terms, thus dividing by $l \cdot t$, we obtain that the specific work of fracture w_f is a linear function of the ligament length:

$$w_f = w_e + \beta \cdot w_p \cdot l \tag{2}$$

By numerical integration of the load-displacement (L-d) curves (see Fig.2-*I*), the work of fracture (W_f) of the specimens at different ligament lengths can be determined.

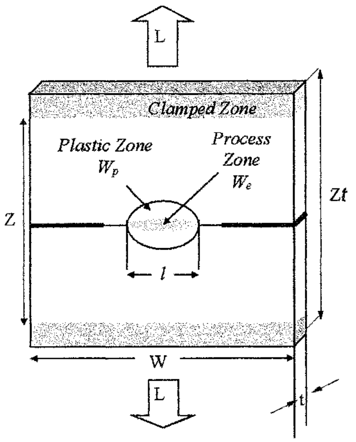

Fig. 1. DDENT specimen and its dimensions:
Thin film W=50mm Z=50mm Zt=75 mm t=0,25mm
Thick film: W=50mm Z=50mm Zt=75 mm t=0,50mm
Impact film: W=15mm Z=50mm Zt=80 mm t=0,25mm

Then, the specific terms, viz. specific essential work of fracture (w_e) and the plastic term (βw_p) can be determined experimentally by a linear regression drawn for the w_f versus l curves. Many works show that the essential work of fracture, w_e is a material property independent on the test geometry for a given thickness and temperature [4-6]. The non essential work, W_p depends, however, on the shape of the plastic zone surrounding the process zone.

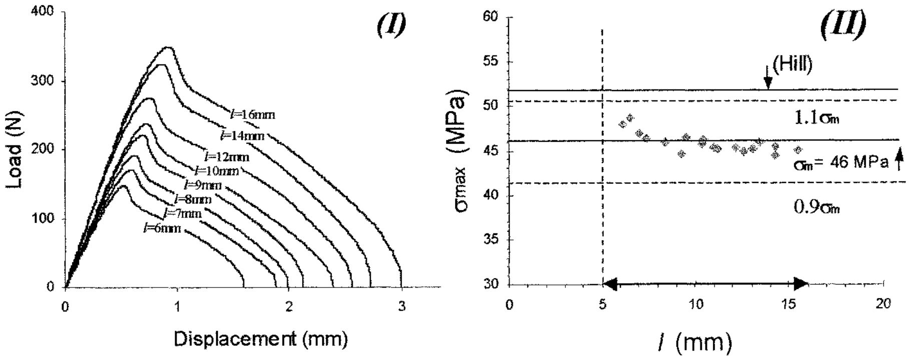

Fig 2. Self-similarity of the Load-Displacement curves (*I*) and the state of stress (*II*) showing aplication of Hill criterion, taken from a series of fracture test of DDENT specimens with different ligament lengths . The EWF method is in this case applicable in this range of l (t = 0,5 mm; crosshead speed was 1mm/min).

There are some requirements that must be satisfied in order to apply properly the EWF method. Firstly, there must be steady crack propagation through the yielded ligament of the specimen (ductile fracture). Secondly, the fracture of all specimens tested should occur in analogous mode. This can be checked looking at the self-similarity of the L-d curves obtained during the fracture tests (fig. 2-*I*). Finally, all the specimens must be in the same state of stress during fracture. According to the ESIS protocol, this can be verified if the maximum stress (σ_{max}) value obtained for each ligament length fall in the range of $0.9\sigma_m$ – $1.1\sigma_m$ being σ_m the mean (σ_{max}) value (fig 2-*II*). Hill's criterion [10] can be used to assure whether plane stress or mixed plane stress/plane strain conditions prevail.

Energy partitioning

It has been proposed that by splitting the total work of fracture is possible to obtain a critical plane-strain EWF value representing the toughness of the material [11] (and references therein). The related energy partitioning separates the total work of fracture in two components, viz. yielding- and necking-related terms and adopts for them the EWF data reduction. However, there are different criteria on how to perform the energy partition. Two different approaches can be found in literature:

a) "Yielding Work": Energy partitioning at the maximum load [12, 13] (see fig.3-*I*). The total work of fracture W_f is separated in two components: $W_{f,y}$ (work for yielding of the ligament area) and $W_{f,n}$ (work of fracture for subsequent necking and tearing).

$$w_f = w_{f,y} + w_{f,n} = (w_{e,y} + \beta w_{p,y} \cdot l) + (w_{e,n} + \beta w_{p,n} \cdot l) \qquad \textbf{(3)}$$

b) "Initiation Work": Applied until now only to isotactic polypropylene homopolymer [14]. The energy partition criterion is taken after necking of the ligament area (see fig. 3-*II*). The total work of fracture W_f is separated in two components: W_I (irreversible initiation process involving yielding, necking and crack-tip blunting) and W_{II} (crack propagation and extended necking in the plastic zone). In this method the absorbed elastic energy in the necked specimen is supposed to be released during the W_{II} process, and it is not included in the initiation work

$$w_f = w_{f,I} + w_{f,II} = (w_{e,I} + \beta w_{p,I} \cdot l) + (w_{e,II} + \beta w_{p,II} \cdot l) \qquad \textbf{(4)}$$

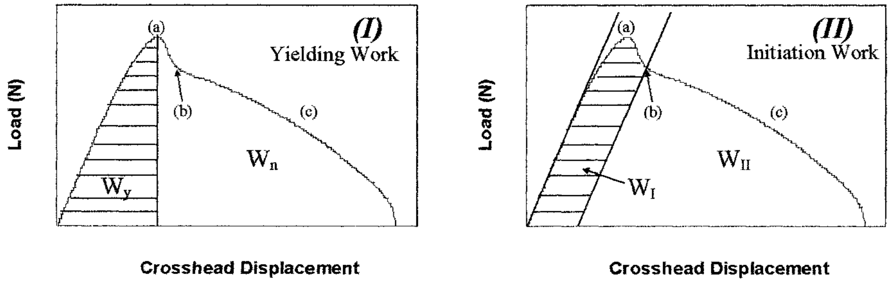

Fig 3. Load–displacement curve obtained with a DDENT specimen. Point (a) corresponds to maximum load where ligament necking starts and it is completed in point (b). Afterwards, there is steady crack propagation and extensive necking in plastic zone until final rupture of the specimen.

In the present work, the toughness of extruded unplasticised PVC (uPVC) films was assessed by the EWF method. Tests were performed at different crosshead speeds on uPVC films of various thickness. The above two criteria for energy partitioning were applied and the outcome discussed.

Experimental

The unplasticized PVC (uPVC) sheets were extruded from a proprietary PVC formulation developed for rigid films and sheets. The recipe contained emulsion-type PVC (K value=60 according to ISO 1628-2) and less than 5 wt.% ethylen/vinylacetate copolymer (EVA) as major components. The presence of the latter was proved by Fourier-transform infrared spectroscopy (FTIR) which revealed a strong absorption band at 1730 cm^{-1}. Dynamic Mechanical Thermal Analysis (DMTA) performed under sinusoidal tensile loading (10 Hz at a heating rate of 1°C/min) showed two relaxation peaks: one at T=-60°C (β-relaxation transition) and a more pronounced one at T=94°C. This last peak, attributed to glass transition temperature of uPVC, displays a shoulder at T=100 °C that could be assigned to the melting temperature of the EVA. The uPVC sheets were available as transparent extruded ribbons of 75mm width in two thicknesses (250 and 500 μm).

Test Procedures

EWF tests using DDENT specimens (fig.1) were performed according to the ESIS recommended procedure [9] at both static (1, 10 and 100 mm/min) and dynamic conditions. The impact rates were achieved using a CEAST instrumented pendulum (hammer mass = 2.19 kg and incident speed = 1.2 m/s) without considering inertial effects. For comparison purposes, high-speed tensile tests were also done on an MTS high-rate servo hydraulic test system finding good agreement with the pendulum results. The w_f values were obtained from the resultant load-displacement curves. Tensile tests (ASTM type IV specimens) were carried out to apply the Hill criterion, as recommended in [9]. All tests were performed at room temperature (23°C).

Results and Discussion

Fig. 4 shows typical load-displacement (L-d) curves obtained during testing of DDENT specimens of similar ligament at different crosshead speeds. In all cases, the assumptions required to apply the EWF methodology were met except for impact testing of the thicker film, which showed brittle behaviour. Consequently, the EWF method could not be applied to the thick film at impact rate.

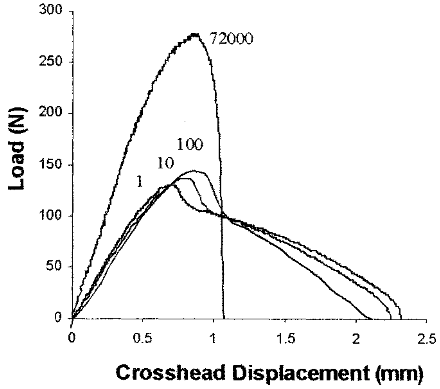

Fig. 4. Load-dislacement curves obtained at 1, 10, 100 and 72000 (1,2 m/s) mm/min loading rates (t =0.25 mm and ligament length l = 11 mm.)

The ligament length range considered in EWF tests has been chosen regarding the self-similarity of the L-d curves and verifying the presence of plane stress conditions in all cases. For static and dynamic tensile loading the ligament length interval of the DDENT specimens was set at *5mm*< l <*16mm* and *5mm*< l <*12mm*, respectively.
The resulting w_f vs. l diagrams are represented in Fig. 5. The EWF values obtained are summarized in Table 1 and Table 2.

Effect of thickness and loading rate

In general, the effects of specimen thickness and loading rate on the EWF values remain unclear as they vary with the type of the polymer. In some cases, increasing loading rate slightly reduced the plastic term because of the viscoelastic nature of the polymer. At the same time a minimal variations in w_e was observed [5]. In other cases, [4, 6] the value of the plastic term increased with the deformation rate while w_e again remained constant. Ching et al. [16] found that the w_e decreased with the testing speed and the plastic term remained constant. Consequently, hardly any prediction can be given on how the EWF values change with the testing (strain) rate.

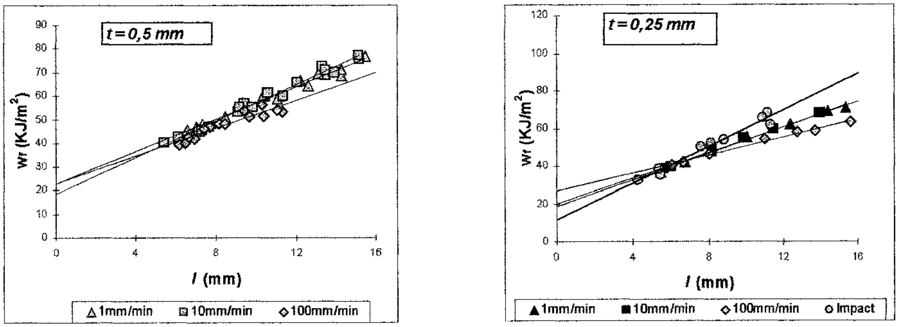

Fig. 5. Diagrams of w_f vs. l of the fractured specimens, showing fairly good linear regressions.

In our case, considering the work of fracture parameters under static loading rates (1, 10 and 100 mm/min) for the uPVC sheets at both thicknesses, a significant reduction in the βw_p term can only be observed at 100 mm/min deformation rate. The results obtained for the specific essential work of fracture, w_e, do not show a clear tendency. This can be attributed to experimental errors, especially at higher crosshead rates.
Although Arkhireyeva and Hashemi [13] have recently found a dependence of w_e as a function of thickness (0.15 - 0.4 mm) for a uPVC sheets, we did not obtain similar results. The presence of EVA impact modifier may be responsible for this discrepancy

Energy partitioning

Both energy-partitioning methods were applied to the data obtained during the EWF tests. The calculated parameters are shown in table 1.

Method "Yielding Work": $w_{e,y}$; $\beta w_{p,y}$; $w_{e,n}$; $\beta w_{p,n}$
Method "Initiation Work": $w_{e,I}$; $\beta w_{p,I}$; $w_{e,II}$; $\beta w_{p,II}$

Data in table 1 show that with increasing testing rate $w_{e,y}$ and w_{eI} behave differently. While $w_{e,y}$ remained more or less constant, $w_{e,I}$ increased. This is due to the fact that the elastic energy stored in the specimens are considered differently by the above energy partition methods. In the case of the "Initiation Work" method, the increase of $w_{e,I}$ indicates that at low crosshead speeds more absorbed elastic energy is available to be released during the propagation process ($W_{f,II}$ in Fig 3). At higher rates more elastic energy is consumed during necking, which belongs to the initiation process ($W_{f,I}$). This reasoning is best shown in Fig. 6.

Table 1. EWF values obtained for PVC with different thickness and crosshead speed. The confidences have been determined as the standard deviation in linear regression analysis.

	1 mm/min		10 mm/min		100 mm/min	
	W_e	βW_p	W_e	βW_p	W_e	βW_p
t=0.5mm						
W_f	22.71 ± 1.40	3.43 ± 0.13	18.50 ± 1.34	3.85 ± 0.12	22.9 ± 2.8	2.95 ± 0.32
$W_{f,y}$	7.87 ± 0.47	1.09 ± 0.04	6.43 ± 1.50	1.70 ± 0.14	8.3 ± 2.3	1.89 ± 0.21
$W_{f,n}$	14.84 ± 1.35	2.35 ± 0.12	12.06 ± 1.87	2.16 ± 0.17	17.2 ± 4.2	0.72 ± 0.48
$W_{f,I}$	3.91 ± 0.58	0.98 ± 0.05	6.31 ± 1.76	1.53 ± 0.16	15.7 ± 1.7	1.09 ± 0.16
$W_{f,II}$	18.71 ± 1.49	2.46 ± 0.14	12.19 ± 2.22	2.33 ± 0.21	7.7 ± 3.5	1.77 ± 0.41
t=0.25mm						
W_f	18.94 ± 1.41	3.49 ± 0.13	20.36 ± 1.33	3.38 ± 0.12	26.6 ± 1.3	2.40 ± 0.11
$W_{f,y}$	6.61 ± 0.82	1.14 ± 0.07	10.14 ± 0.53	1.18 ± 0.05	10.8 ± 3.7	1.57 ± 0.33
$W_{f,n}$	12.78 ± 0.99	2.35 ± 0.09	20.23 ± 0.89	2.20 ± 0.02	15.8 ± 4.1	0.83 ± 0.37
$W_{f,I}$	2.48 ± 0.78	1.09 ± 0.07	6.85 ± 0.24	1.34 ± 0.01	10.2 ± 2.5	1.63 ± 0.22
$W_{f,II}$	16.47 ± 1.75	2.38 ± 0.16	13.51 ± 1.35	2.04 ± 0.12	16.4 ± 2.8	0.77 ± 0.25

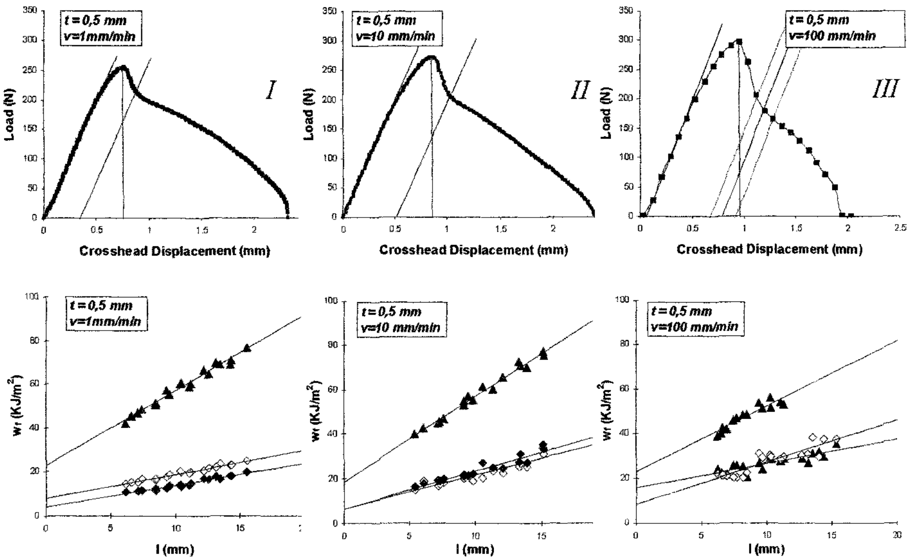

Fig 6. Energy partition methods and their results for *l*=11mm and different loading rates: ◆ represents the values obtained with the "Yielding Work" method and ◇ the values obtained with the "Initianion Work" method.

Both methods of energy partitioning seem to be applicable when analysing L-d curves of DDENT specimens at least under static loading conditions. The method "Initiation Work" could likely be improved. According to this method, the partition is done at the end of ligament yielding (point (b) in fig. 3-*II*). However, in same cases could be better to use the experimental position of the onset of crack propagation, which may be located between points (a) and (b) based on fig.3. In addition, for high crosshead rates, the data acquisition period can be a relevant limiting factor for its application since small variation in the location of the end of necking process may represent a large variation of the stored elastic energy of the system, as indicated by the dashed lines in fig. 6-*III*.

As the testing rate is increased, most of the energy consumed can be related with the yielding process and less with necking and tearing According to this assumption, the value of $w_{e,y}$ obtained with the "Yielding Work" method should be somehow constant with increasing loading rate and approach the w_e value obtained at impact rates. This value has been recently related to the plane-strain essential work of fracture [11].

Impact Rate

As mentioned before, only the thin specimens showed ductile fracture at impact rate. Therefore, the thick uPVC ribbon could not be evaluated at this testing rate.
When the impact results (Table 2) are compared with those obtained by the energy partition method "Yielding Work" (Table 1) one can notice a quite good agreement between the static $w_{e,y}$ and dynamic w_e values. On the other hand, application of the energy partitioning methods to this high load rate is questionable.
The energy partition method "Initiation Work" cannot be applied as the L-d curves do not clearly show the onset of necking. The "Yielding Work" method is more promising in respect with the specific yielding-related terms but produces a negative value of $w_{e,n}$ that does not make sense. The difference between w_e and $w_{e,y}$ in table 1 already indicates for the effect of some unstable (i.e. less ductile) fracture at dynamic loading. This may reflect in the negative $w_{e,n}$ found.

Table 2. EWF at impact rate (1.2 m/s)-

1,2 m/s		
t=0.25mm	w_e	βw_p
W_f	11.8 ± 2.8	4.8 ± 0.3
$W_{f,y}$	16.7 ± 2.6	3.5 ± 0.3
$W_{f,n}$	-4.9 ± 1.3	1.3 ± 0.2
$W_{f,I}$	0.6 ± 1.6	2.4 ± 0.2
$W_{f,II}$	11.2 ± 1.3	2.5 ± 0.2

Nevertheless, based on the results in table 1 one can pose the question: Can toughness be represented by a single parameter, e.g. $w_{e,y}$? Under a practical point of view, it would be of great help to predict the failure of a specimen under plane-strain stress conditions. However, we must keep in mind that the non essential work of fracture involves quantitatively most of the energy dissipated during ductile fracture. In addition, it seems to be very sensitive to small variations in testing conditions. It provides indirect information of the deformation mechanisms that can be found during failure of the specimen, and the extent in which they are present[17]. Since the evolution of this term can be of great use to characterise the influence of small variations on morphology, orientation, or testing conditions, it is convenient to analyse both terms, essential and non essential work of fracture.

Conclusions

Based on this work devoted to study the effects of specimen thickness, deformation rate and energy partitioning on the work of fracture parameters of unplasticised PVC (uPVC) sheets the following conclusions can be drawn:

- neither the specific essential work of fracture (w_e), nor the plastic work term (βw_p) vary with the thickness in the studied range (t=0.25-0.5mm)
- w_e and βw_p are independent on the deformation rate under static loading conditions (<100 mm/min). w_e and its yielding-related constituent ($w_{e,y}$) strongly decreased due to dynamic loading (1.2 m/s)
- The "Yielding Work" energy partition method provided a value in static loading, $w_{e,y}$, which was in good agreement with the w_e value obtained at dynamic rates. The method "Initiation Work" did not prove to work as well on this material as it did with iPP. A deeper analysis of this method suggests that some modifications can be made to improve and adapt it to other materials.

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