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On the essential work of fracture method: Energy partitioning of the fracture process in iPP films

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Summary
The fracture properties of an iPP are investigated by the EWF method. A separation between crack initiation and propagation fracture parameters is done by splitting the total energy of the load-displacement curves in two. The influence of the DDENT specimen height and the test rate on these different parameters is studied, obtaining that varying the height has no influence in the range 40 to 80mm, but changing the crosshead speed (2 to 100mm/min) has an effect on the fracture parameters. It is interesting to note that the "Initiation Specific Essential Work" (w_e^I) seems not to be sensible to the stress-state transition.

Introduction
Many works are being published (1-10) on the Essential Work of Fracture (EWF) method applied to polymers with the aim of determining their fracture properties (toughness). However, despite this method is being increasingly used because of its simplicity, some aspects of the validity of this technique remain controversial, and we think that they should be discussed more deeply. The aim of this work is to better understand the meaning of the parameters involved in the EWF method.
The theory of EWF was initially developed by Broberg (11), and applied to ductile metals by May and Cotterell (12,13) and later to polymers with a testing protocol that was proposed by the ESIS in 1993 (14). Basically, the theory is based in the consideration that, when a notched specimen is loaded in tension, the total work (W_f) involved in fracture is dissipated in two distinct zones, called the inner (or process) and the outer (or plastic) zones (Fig.1). Broberg postulated that W_f could be divided into two terms: the Essential and the Non-Essential Work of Fracture (W_e and W_p respectively). The first item is related to the instability of the crack tip -where the real fracture process occurs- and it is proportional to the ligament section (lt), while the second one is associated with the plastic work, and considered proportional to the plastic zone volume ($ßl^2t$):

$$W_f = W_e + W_p = w_e lt + w_p ß l^2 t \qquad (1)$$

where w_e is the Specific Essential Work of Fracture (per surface unit), w_p is the Non-Essential Specific Work of Fracture (per volume unit), l is the ligament length and ß a

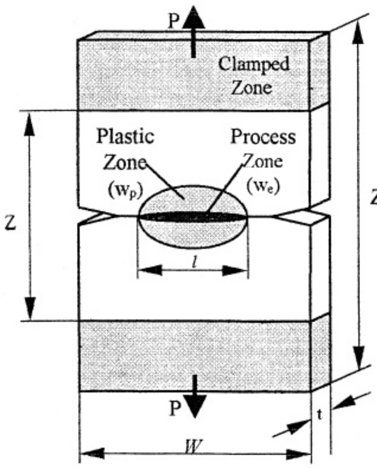


Fig.1. DDENT specimen with the two energy dissipation zones.

shape-factor of the plastic zone. Dividing this equation by the ligament section, we have:

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

Plotting w_f vs. l and fitting to a linear regression, the Y-axis intercept and the slope are w_e and $ßw_p$ respectively, as Eq.2 sets. Theoretically, only w_e is geometry independent and therefore can be a material parameter, and it seems to be equivalent to the J-integral critical value, J_{1c} (1). Following the ESIS protocol of EWF (14), two restrictions must be satisfied for the validity of the EWF theory. Firstly, the minimum ligament length must ensure that plane-stress conditions prevail during the test. It is suggested by the ESIS that this occurs when l is greater than three to five times the thickness, despite this is discussed by different authors (1,3,9). The verification of the l/t ratio for which the transition of plane-stress to mixed-mode conditions occurs may be verified by plotting the maximum net stress (σ_{net}) obtained during the test (maximum load divided by lt) of the Deeply Double Edge Notched Tension (DDENT) specimens against their initial ligament length. Following the Hill's predictions (15), the pure plane-stress solicitation of a DDENT specimen gives a σ_{net} value of $1.15\sigma_y$, which raises to $2.97\sigma_y$ in pure plane-strain conditions. The second restriction sets that the maximum l value must keep the specimen out from edge effects, and must also ensure that the ligament is fully yielded before the crack propagation. For these purposes, the ligament length must satisfy:

$$l < \min(W/3, 2r_p) \tag{3}$$

where W is the specimen's width and $2r_p$ is the plastic zone size generated by the crack tip ($2r_p = (\pi/8)(Ew_e/\sigma_y^2)$ for a line plastic zone).

This second restriction brought Karger-Kocsis *et al.* (5-7) to affirm that the material that they were studying, an amorphous copolyester, was the ideal polymer for the approval of the EWF concept since it underwent full ligament yielding prior to the onset of the crack growth. As our material, an isotactic PP, had a similar behaviour (although iPP is semicrystalline), we have tried to extend their observations to our study, and deepen in some other aspects. About the upper limit, it has been recently shown that both values given by eq. 3 are too conservative. (7).

Experimental

Material

The material used in this study was an isotactic polypropylene homopolymer (iPP) film grade (Escorene 4563F1) from Exxon, with an MFI of 9.0 dg/min (230°C, 2.16kg). A preliminary DSC analysis (Mettler 2000, at 10°C/min) gave a melting point of 165.2°C and a crystallinity of 41% considering a value of ΔH_m^0=207.1J/g (16). The material was received as non-oriented films of thickness t=100µm.

Test procedure

Tensile tests were carried out on ASTM-D638 standard dumbbell specimens (type IV), to evaluate the Young's modulus (E) as well as the stress and the strain at maximum load (σ_y, ε_y). In order to carry out the fracture tests, the sheets were cut to obtain DDENT specimens (Fig. 1). The width of the specimens was W=60mm. The height (Z) and the test speed (v) were taken as variables: Z varied between 20 and 150, whereas v was 2, 20 and 100mm·min^{-1}. For each set, at least 20 specimens were tested, with ligament lengths varying from 2 to 20mm with the distribution recommended by the ESIS (11). The ligament length was measured before the test using a travelling microscope.

Results and discussion

Fracture tests

Figure 2 shows a typical load-displacement trace obtained with the DDENT specimens tests. A total similarity between the curves of different ligament length specimens was obtained, thus fulfilling a basic requirement of the theory. The ligament area behaviour was monitored during the tests with the aid of a microscope equipped with a video-camera: when the elastic range (a) finishes, two line plastic zones are generated on the crack tips (showing stress-whitening). After the maximum load (b), they meet each other, indicating that the entire ligament is yielded. Subsequent necking starts on the crack tips, producing a marked load drop until the whole ligament is necked (c). This necking occurs rapidly and, at this moment, the crack starts to grow across the necked zone (d) until final fracture occurs (e).

Usually, all the energy dissipated during the test (the area under the curve) is taken globally as W_f, divided by the section (lt) and represented against l. However, observing the specimens during the tests, and relating the fracture process with the curve shape, one can therefore think that more information can be obtained by partitioning the total work in spite of taking all the energy globally. Fig.2 shows how this division has been made: until point (c) (W_I-Inititation), irreversible initiation processes of yielding, located necking and crack-tip blunting are involved. From this point on (W_{II}-Propagation), two phenomena occur: the crack propagation and an extended necking in the outer zone. The reasons why we have split the curve in (c) are basically two: firstly, it corresponds to a clear transition of the process (the onset of crack propagation); secondly, it is a clearly distinguishable point on the curve, what makes the data treatment easier. Another remark that must be

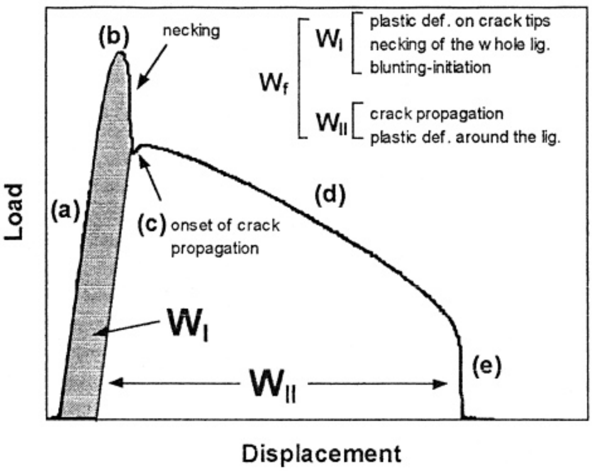


Fig.2. Typical load–displacement curve obtained with a DDENT specimen, indicating the total work partition that has been done and the processes that each item involves: (a) elastic deformation, (b) maximum load, ligament yielding is completed and localised necking starts, (c) localised ligament necking is finished, propagation starts, (d) stable propagation and generalised necking, (e) rupture.

done is that the energy splitting has been done parallel to the elastic range curve slope with the purpose of leaving out the elastic energy that is initially stored, which is not actually dissipated since it is theoretically released later as energy available for the fracture processes. This kind of splitting was suggested by Karger-Kocsis *et al.* (6,7), although they made the division vertically under the maximum load, thus deciding in favour of a separation between yielding (w_y) and necking (w_n).

Despite it was suggested that the amorphous polymers that present localised shear banding as their deformation mechanism are the ideal polymers to apply the EWF (5), the iPP studied (which is semicrystalline, and shows diffuse shear yielding during the tensile tests) had a similar fracture behaviour (and thus similar load-displacement traces shape) as the materials described above. From the curves obtained with specimens of different *l* for each set, we calculated W_f, W_I and W_{II} (obviously $W_f = W_I + W_{II}$), and, dividing by *l*t their specific values were obtained, respectively: w_f, w_I and w_{II}. These specific values were plotted against *l* in order to determine the best linear fit of the data in plane-stress, and also in mixed-mode conditions. Thus, for each set three regression lines in plane-stress and three in mixed-mode were obtained, and each one gave us an essential (w_e, Y-intercept) and a non-essential specific work (βw_p, slope) item. 'I' and 'II' superscripts have been used to denote the parameters obtained from w_I-*l* and w_{II}-*l* plots respectively. Additionally, mixed-mode data have a supplementary 'm' symbol. According to references (1,6,13), the extrapolation of the mixed-mode data to zero ligament length may give a plane-strain specific essential work of fracture, called $w_{I,e}$ according to the classical nomenclature.

Influence of the specimen height (Z)

It was observed that when Z increases, the shape of the load-displacement curves is "shifted " to the right, producing a clear decrease in the slope of the elastic range and an increase in the final displacement, although the total energy seems not to be substantially modified.

Despite the range of Z studied was from 20 to 150mm, it was shown in a recent work (9) that, for the iPP studied, only in the range from 40 to around 100mm the specimens were free from edge effects (Z<40mm) or undulation problems (Z>100mm).

One finds some difficulties in choosing a *I* value for the plane-stress to mixed-mode transition. It has been shown in many recent works that the minimum threshold of *l*>(3-5)t underestimates the value in with plastic films (1,3,4,9,10), and the Hill's criterion must be adopted. In spite of choosing the *l* value at which σ_{net} becomes higher than $1.15\sigma_y$, we decided in taking the value at which σ_{net} increases rapidly with decreasing *l*, as suggested

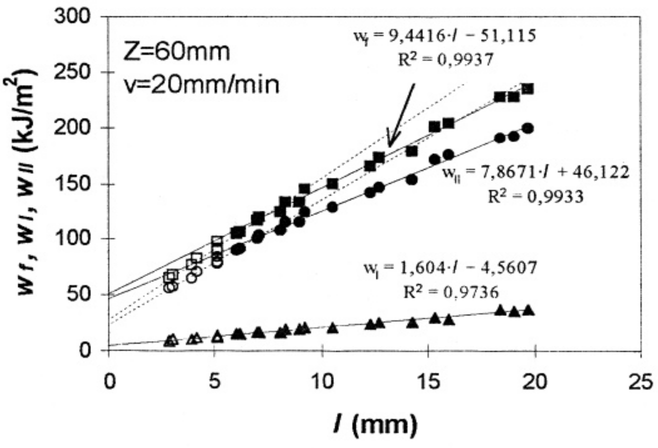


Fig. 3. w_f, w_I *and* w_{II} *against ligament length, with the best linear fits (* ■:w_f-*l*; ▲: w_I-*l*; ●: w_{II}-*l*; *full symbols and continuous lines for plane-stress data, and open symbols and dashed lines for mixed-mode data). Z=60 mm and v=20mm·min^{-1}.*

Table I. EWF parameters obtained varying Z, at v=20mm·min^{-1}, and varying v, with Z=60mm (units: w_e [kJ/m^2], βw_p [MJ/m^3], Z [mm], v [mm·min^{-1}]).The regression coefficient (R) and the 95% confidence limits (between parentheses) are shown.

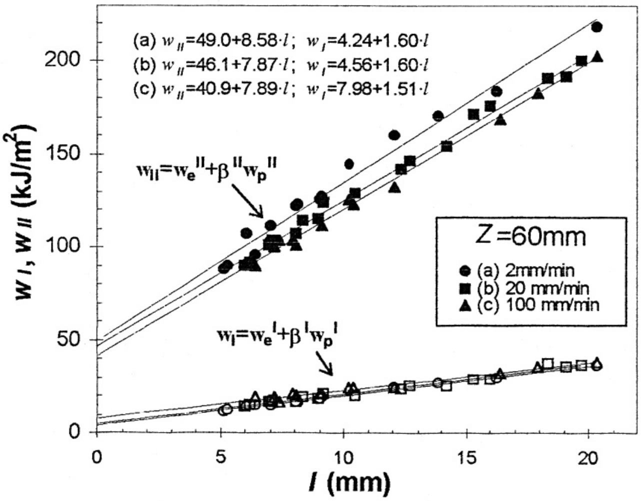
Plane-stress									
Z	w_e	βw_p	**R**	w_e^I	$\beta^I w_p^I$	**R**	w_e^{II}	$\beta^{II} w_p^{II}$	**R**
40	**48.7** (3.4)	**9.77** (0.29)	0.995	**4.57** (1.41)	**1.73** (0.13)	0.972	**44.5** (2.8)	**7.98** (0.25)	0.994
60	**51.1** (2.4)	**9.44** (0.19)	0.997	**4.56** (0.86)	**1.60** (0.07)	0.987	**46.1** (2.1)	**7.87** (0.17)	0.997
80	**47.6** (3.9)	**9.63** (0.32)	0.994	**4.22** (0.85)	**1.67** (0.07)	0.993	**43.5** (3.3)	**7.96** (0.28)	0.993
120	**51.7** (2.6)	**9.28** (0.22)	0.997	**6.07** (0.24)	**1.74** (0.02)	0.999	**47.0** (1.8)	**7.34** (0.16)	0.998
v	w_e	βw_p	**R**	W_e^I	$\beta^I w_p^I$	**R**	w_e^{II}	$\beta^{II} w_p^{II}$	**R**
2	**53.4** (3.9)	**10.16** (0.37)	0.991	**4.24** (0.61)	**1.60** (0.06)	0.992	**49.0** (3.6)	**8.58** (0.34)	0.990
20	**51.1** (2.4)	**9.44** (0.19)	0.997	**4.56** (0.86)	**1.60** (0.07)	0.987	**46.1** (2.1)	**7.87** (0.17)	0.997
100	**48.9** (2.4)	**9.40** (0.20)	0.998	**7.98** (0.97)	**1.51** (0.08)	0.986	**40.9** (2.1)	**7.89** (0.18)	0.997
Mixed-mode									
Z	$w_{e,m}$	$\beta w_{p,m}$	**R**	$w_{e,m}^I$	$\beta^I w_{p,m}^I$	**R**	$w_{e,m}^{II}$	$\beta^{II} w_{p,m}^{II}$	**R**
40	**22.7** (4.5)	**14.63** (1.15)	0.998	**3.97** (0.92)	**1.70** (0.23)	0.965	**18.7** (3.7)	**12.93** (0.93)	0.989
60	**28.6** (4.3)	**12.61** (1.01)	0.984	**4.85** (0.83)	**1.53** (0.19)	0.962	**23.4** (3.3)	**11.20** (0.77)	0.988
80	**27.0** (4.3)	**12.57** (1.03)	0.987	**7.24** (2.17)	**1.08** (0.51)	0.722	**19.8** (3.0)	**11.49** (0.71)	0.992
120	**23.9** (2.8)	**13.30** (0.67)	0.995	**4.61** (0.66)	**1.87** (0.16)	0.986	**19.3** (2.3)	**11.43** (0.54)	0.995
v	$w_{e,m}$	$\beta w_{p,m}$	**R**	$w_{e,m}^I$	$\beta^I w_{p,m}^I$	**R**	$w_{e,m}^{II}$	$\beta^{II} w_{p,m}^{II}$	**R**
2	**20.5** (7.7)	**15.71** (2.04)	0.983	**3.56** (3.09)	**1.56** (0.81)	0.805	**17.0** (5.1)	**14.15** (1.34)	0.991
20	**28.6** (4.3)	**12.61** (1.01)	0.984	**4.85** (0.83)	**1.53** (0.19)	0.962	**23.4** (3.3)	**11.20** (0.77)	0.988
100	**21.7** (4.1)	**13.47** (0.98)	0.989	**6.44** (1.30)	**1.76** (0.31)	0.942	**15.3** (3.2)	**11.71** (0.77)	0.991

by Wu *et al*. (1). Such a transition can also be situated by observing the decay of the w_f data when *l*<6mm (Fig.3). Following this citerion, the *l* transition value was taken about 5-6mm (this part of the study is omitted in this work as this is also deeply discussed in another work, ref.9). Fig.3 presents the linear fits obtained for one of the sets (Z=60mm, tested at 20mm·min^{-1}). It can be observed, from Table I, that the plane-stress values are similar for all Z, excepting for Z=120mm (probably influenced by specimen undulation), while those of mixed-mode show some more scatter. This dispersion is reasonable as the number of data was much higher in plane-stress than in mixed-mode. However, all the fitting coefficients (R^2) and confidence limits were good, indicating a low degree on the experimental errors. Thus, it can be affirmed that the calculated fracture parameters do not depend upon the specimen length (Z) in the range 40-80mm.

Influence of the test rate (v)

Increasing the test rate had a sensible effect on the shape of the load-displacement traces of DDENT specimens: the maximum load raised up and the total gage displacement decreased. The plot of w_I and w_{II} against *l* for three different test rate sets is shown in Fig.4. To preserve its clarity, the w_f vs. *l* data and all the data in mixed-mode have been omitted, though the fracture values calculated can be found in Table I. From this table, one can see that although the plane-stress global parameters (w_e, ßw_p) are not significantly sensitive to the variations of v (as reported in (3,7)) the splitting reveals higher dependence of stages I and II values on v: while w_e^I increases with v (up to 40%), w_e^{II} decreases with it (up to 11%). This indicates that, as the strain rate increases, the specific essential work of fracture is higher for initiation (w_e^I), and lower for propagation (w_e^{II}). Further investigations should help to elucidate if this can be attributed to v or maybe to a bad splitting of W_f. On the other side, the plastic items seem to decrease slightly when the test rate raises. As it was shown recently that the ß factor decreased with v (7), further

Fig.4. w_I *and* w_{II} *against ligament length for the three test speeds studied. All the data shown are in plane-stress conditions. Z=60mm.*



work must be carried out to evaluate ß, and thus w_p, to analyse the evolution of these parameters with v.

Discussion

It is obvious that when this splitting is done, the sum of the w_e^I and w_e^{II} values gives theoretically w_e, what is found to be verified in plane-stress and in mixed-mode. The same occurs with the plastic item, $ßw_p$. Therefore, from the approximately 50 kJ/m^2 of w_e in plane-stress, about 9% is used during state I (initiation), while the rest is dissipated in stage II (propagation). For $ßw_p$, that is about 9.5 MJ/m^3, 17% correspond to stage I and the rest to stage II. Thus, stage II (crack propagation and generalised necking around the ligament) involves much more work than stage I (yielding and necking of the ligament, and crack-tip blunting). Actually, it would be more accurate to compare the w_p terms instead of $ßw_p$, because there is no reason why $ß^I$ (shape factor of the yielded zone) and $ß^{II}$ (shape factor of the plastic or necked zone) should be equal as the processes involved are different. However, no determination of the plastic zone shape factor was carried out in this study.

One can ask himself why we may obtain a linear dependence of *l* of both w_I and w_{II}. Following the Broberg's theory (11), making the supposition that the dependence is linear (at least in plane-stress) should imply that w_e^I and w_e^{II} represent the specific work dissipated only in the inner zone, and w_p^I and w_p^{II} in the outer zone. The analysis of the energetic contributions of stage II is quite simple: w_e^{II} can be associated to the crack propagation and w_p^{II} to the necking process. But more difficulties are found when the same analysis is done on stage I: taking in account that w_I is the specific work dissipated during yielding, localised necking and blunting of the ligament, which energy dissipation processes can be associated to the inner and the outer zones? We think that three different suppositions can be done: 1) that all the work is related to the inner zone; 2) that yielding is related to w_p^I and necking to w_e^I; 3) that the model takes all the considerations globally and cannot be applied to w^I like is done to w_f.

Answering to the questions discussed above, not all the energetic contributions of stage I can be associated to the inner zone, since the slope of the w^I-*l* regression lines is not negligible, so the first supposition can be discarded. After the results, we cannot decide

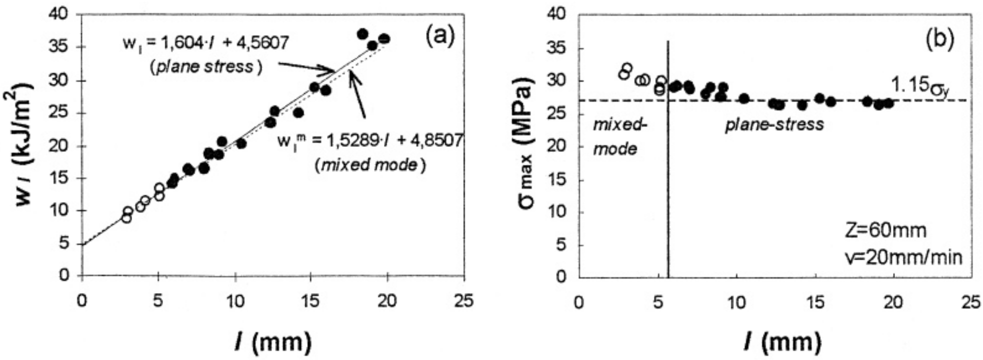


Fig.5 (a) w_I vs. l for the set Z=60mm, v=20mm·min^{-1} (full symbols and continuous line in plane-stress, open symbols and dashed line in mixed-mode). (b) Net stress against l for the same set following the analysis of Hill (15).

between the second and third supposition, because the regression line is so straight that the Broberg's linear model seems to be applicable, but we are not sure that a so simple work contribution division is close to the reality. To avoid the problem we have decided to take from now on all the phenomena (yielding, localised necking and blunting) as a whole as 'initiation'.

The influence of the transition from plane-stress to mixed-mode on the w_I-l and w_{II}-l diagrams must be analysed, too: when the ligament is reduced, the wf data fall out of the plane-stress regression line for a l value of about 6mm (■ symbols in Fig.3), indicating that mixed-mode conditions prevail in the range l<6mm. This is also observed with the w_{II}-l plot (• symbols in Fig.3). On the other hand, the w_I data seem not to be subjected to such a transition, as can be seen clearly in Fig.5(a), thus suggesting that the energy dissipation processes occurring during stage I are independent of the stress state of the ligament. This is a surprising result, since the analysis based on the Hill's considerations (15) takes the maximum load (which is found to be in the stage I) as the criterion that indicates the stress state of the ligament, as shown in Fig.5(b), where it can be seen that the maximum net stress grows rapidly when mixed-mode conditions prevail (this observation is reinforced by the decay of the w_f values in Fig. 3 for l<6mm). These considerations lead us to think that, although the stress-state could modify the maximum load, it may not change the energy dissipated in this stage, what can be of most interest since w_e^I (and $ß^I w_p^I$) may characterise the material in any stress state.

A question raised by Karger-Kocsis *et al.* (6) was if the similarity that they found between the values of w_e^I and we,m (or $w_{I,e}$ following the classical nomenclature) was fortuitous or not. They argued that, as the thickness increases, plane-strain conditions prevail and thus the necking work diminishes against the yielding contribution. In our case, plane-stress prevails due to the reduced thickness of the iPP studied (100µm) and thus the values of both parameters are clearly different ($w_e^I \approx$ 4.5kJ/m^2, $w_{e,m} \approx$ 25kJ/m^2). Nevertheless, we think that it is difficult that the $w_{e,m}$ so-calculed may represent a true plane strain value, since the Y-intercept will depend on the number of data used for the extrapolation, the proximity of these data from the axis, and the l value at which of the stress transition occurs. Moreover, it must be taken in consideration that the experimental error grows highly when one works with very short ligament length specimens.

Relating to this, hopeful results have been found refeering to w_e^I, and some further work should be done to check if w_e^I is similar to the plane-strain J_{Ic} value for this iPP.

Conclusions

The EWF requirement of full ligament yielding prior to crack propagation was met with a semicrystalline polymer (iPP).

The splitting of the total fracture work between two energetic contributions that involve clearly different processes was successfully applied, and allowed us to determine fracture parameters for initiation and propagation. Thus, initiation and propagation values of $w_e^I \approx 4.5kJ/m^2$, $w_e^{II} \approx 45.5kJ/m^2$ respectively were found, indicating that much of the energy dissipated in the inner zone is used during stage II (propagation). However, it must be kept on mind that this kind of analysis is only possible on materials that show characteristic load-displacement traces presenting a marked load drop after the maximum.

The fact that w_e^I seems not to be subjected to the stress-state transition suggests that it may represent an interesting intrinsic material fracture property, and should be compared to J_{Ic}.

The EWF parameters studied are independent of the specimen length (Z) in the range from 40 to 80mm, and in the range studied only the initiation and propagation parameters depend on the test rate (v), though it is concluded that further work should be carried out on the v influence on the essential and non-essential parameters, and the shape factors of both stage I and II.

References

1. Wu J, Mai YW (1996) Pol. Eng. Sci. 36:2275
2. Maspoch ML, Santana OO, Grando J, Ferrer D, Martinez AB (1997) Polym. Bull. 39:249
3. Hashemi S (1993) J. Mat. Sci. 28:678
4. Hashemi S (1997) Pol. Eng. Sci. 37:912
5. Karger-Kocsis J (1996) Polym. Bull. 37:119
6. Karger-Kocsis J, Czigány T, Moskala EJ (1997) Polymer 38:4587
7. Karger-Kocsis J, Czigány T, Moskala EJ (1998) Polymer 39:3939
8. Mouzakis DE, Stricker F, Mülhaupt R, Karger-Kocsis J (1998) J. Mat. Sci. 33:2551.
9. Maspoch ML, Ferrer D, Gordillo A, Santana OO, Martinez AB (in press) J. Appl. Pol. Sci.
10. Maspoch ML, Hénault V, Ferrer D, Velasco JI, Santana OO (to be published) Polym. Bull.
11. Broberg KB (1975) J. Mech. Phys. Solids 23:215
12. Mai YW, Cotterell B (1986) Int. J. of Fracture 32:105
13. Mai YW, Cotterell B, Horlyck R, Vigna G (1987) Polym. Eng. Sci. 27:804
14. Gray R (1993) Testing Protocol for Essential Work of Fracture, ESIS-TC4 Group.
15. Hill RH (1952) J. Mech. Phys. Solids 4:19
16. Wunderlich B (1990) Thermal Analysis, Academic Press, NY, USA

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