APPLICABILITY OF THE LOAD SEPARATION CRITERION AND THE NORMALIZATION METHOD TO HIGH-RATE J-TESTING OF DUCTILE POLYMERS

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ABSTRACT

The load separation criterion, which assumes that during the fracture process of a cracked body the load can be represented as the product of two separate functions, a geometry function and a material deformation function, was previously studied in stationary crack tests and then extended to growing crack experiments on both metallic and polymeric materials. On the basis of the load separation criterion a single specimen method, labelled normalization method, was developed for determining J_R curve of ductile materials. According to this method, firstly used in testing metallic materials and then extended to polymers, J_{Ic} is estimated by performing only two tests and, through the experimental determination of the material key curve, J_R curve is drawn. This paper examines the applicability of the load separation criterion and the normalization method in determining J_R curve of a toughened polyamide 6/6 at high loading rates (1 m/s). The analysis of procedure problems associated to this high experimental rate is performed. The results obtained using the normalization method are then compared with those measured via multi-specimen testing procedures proposed by ESIS Technical Committee 4. The results show that, unlike low loading rate tests, the presence of the oscillations in the load *vs* displacement traces, due to the inertial effects produced during the impact, complicate considerably the elaboration of the data, with particular reference to the identification of the separable blunting region. The comparison of J_{Ic} values obtained according to the different procedures examined indicates that the values of $J_{Ic}=J_{0.2}$ (taken at 0.2 mm crack growth) are in good agreement, whereas consistent differences among the values of J_{Ic}=J-blunting (taken at the blunting line) are observed.

1 INTRODUCTION

During the fracture process of a cracked body of a given material, geometry, and constraint, Sharobeam and Landes [1] proposed that in the plastic region the load can be separated according to the following expression:

$$P = G\left(\frac{b}{W}\right) \cdot H\left(\frac{u_{pl}}{W}\right) \tag{1}$$

where P is the load, b and W the ligament length and the width of the body respectively, u_{pl} the plastic displacement, G(b/W) and $H(u_{pl}/W)$ the geometry and deformation function respectively. The plastic displacement is defined as:

$$u_{pl} = u - P \cdot C(b/W) \tag{2}$$

where u is the displacement and C(b/W) is the elastic compliance of the specimen. Sharobeam and Landes highlighted that, in stationary crack experiments, for two measurements on specimens of crack length a_i and a_j, the separation parameter S_{ij} defined as

$$S_{ij} = \left.\frac{P(a_i)}{P(a_j)}\right|_{u_{pl}} \tag{3}$$

has a constant value over the whole domain of the plastic displacement. From the separable form of the load the parameter η_{pl}, which enters in the expression of J (see eqn (10)) [1], can be evaluated using the following expression:

$$\eta_{pl} = \frac{b}{W} \cdot \frac{dG(b/W)}{d(b/W)} \cdot \frac{1}{G(b/W)} \tag{4}$$

The geometry function can be constructed from the experimental determination of the separation parameters for different measurements as follows:

$$S_{ij} = C_1 \cdot G(b_i/W) \text{, for constant } b_j/W \tag{5}$$

where $C_1 = 1/G(b_j/W)$, whereas the term η_{pl} may be calculated from:

$$G(b_i/W) = C_2 \cdot (b_i/W)^{\eta_{pl}} \tag{6}$$

being C_2 a constant.

Sharobeam et al. [2] and Bernal et al. [3] investigated if the load separation principle could be extended to growing crack experiments. It was observed that the load separation assumption was valid during crack propagation up to more than 40% of the initial uncracked ligament length. It was also evidenced that, defining a new separation parameter as

$$S_{sb} = \left. \frac{P_s}{P_b} \right|_{u_{pl}} \tag{7}$$

where the subscript s and b denote sharp and blunt notched specimens respectively, from S_{sb} *vs* b_s/W plots it is possible to determine the geometry function as a power law. The data can be reasonably fitted by the same power law function obtained from stationary crack experiments. The plot of S_{sb} *vs* u_{pl} shows three distinct zones: an unseparable region at the beginning of the plastic behaviour ($u_{pl} < u_{pl,min}$) – the separable behaviour exists when the plastic pattern has been completely developed –, a region where the separation parameter remains constant ($u_{pl,min} < u_{pl} < u_{pl,lim}$) and a last region where the separation parameter starts to decay when fracture begins to propagate ($u_{pl} > u_{pl,lim}$). The two former regions correspond to the "blunting region" of the sharp notched specimen and the test can be treated as a stationary growing test. The application of the load separation principle is valid in the two latter regions up to a sufficiently high plastic displacement level.

The method for the evaluation of J_R curve of a material, theoretically based upon the load separation principle, is labelled normalization method [3]. According to the normalization method two tests must be performed: one test is carried out on a blunt notched specimen while the other on a sharp notched specimen. The deformation function can be constructed by normalizing the load measured in the test carried out on the sharp notched specimen by the geometry function:

$$P_N = \frac{P}{W^2 \cdot G(b/W)} = H(u_{pl}/W) \tag{8}$$

where P_N is the normalized load. According to the modification introduced by Bernal [3] considering that $u_{pl,min}$ exists since load separation is valid, the following equation can be written:

$$P_N^{'} = P_N - P_{N,\min} = \beta \left(\frac{u_{pl} - u_{pl,\min}}{W} \right)^n = \beta \left(\frac{u_{pl}^{'}}{W} \right)^n \tag{9}$$

where $P_{N,min}$ is the normalized load at the lower limit of load separation validity domain ($u_{pl,min}$). By determining the crack growth during the crack tip blunting process ($u_{pl,min} < u_{pl} < u_{pl,lim}$) via the analytical expression of the blunting line [4] P'_N can be experimentally determined in the separable blunting zone. P'_N can also be calculated for the final point since the final crack length can be physically measured. The deformation function can then be determined by regression of all the P'_N *vs* u'_{pl}/W data points by one curve called material key curve. From the instantaneous values of load and displacement, by means of an iterative technique based on the application of the material key curve, the instantaneous crack length can be calculated and therefore J_R curve drawn. J values are evaluated using the relationship [4]:

$$J=\frac{\eta\cdot U}{B\cdot(W-a)}=\left(\eta_{el}\frac{U_e}{B\cdot(W-a)}+\eta_{pl}\frac{U_p}{B\cdot(W-a)}\right) \tag{10}$$

where U_e and U_p are the elastic and the plastic contribution to the area under the load *vs* displacement record (U), η, η_{el} and η_{pl} are calibration factors depending on geometry, B is the net specimen thickness and a is the initial crack length.

Aim of the present research is the study of the applicability of the load separation criterion and the normalization method in determining J_R curve of polymers at high loading rates. In particular this method is tentatively applied to evaluate J_R curve of toughened polyamide (PA) 6/6 at a loading rate of about 1 m/s. The analysis of procedure problems associated to this high experimental rate is performed. J_R curve constructed via normalization method is compared with those determined using the multi-specimen testing procedures proposed by ESIS [5] for the determination of J-fracture resistance at impact speed. Two different multi-specimen procedures are analysed: “reduced velocity” testing (a series of nominally identical notched specimens is impacted at increasing velocities) and “striker stop” testing (a series of nominally identical notched specimens is impacted at the same velocity but, for each impact test, the movement of the striker is arrested at a pre-determined displacement).

2 EXPERIMENTAL DETAILS

The material, manufactured and supplied in the form of 80x10x4 mm injection moulded bars, by Radici Novacips SpA (Villa d’Ogna (BG), I), is a toughened PA 6/6 (containing 25 wt.% rubber), conditioned in air for three months. The impact tests are performed at room temperature using an instrumented impact pendulum by Ceast SpA (Torino, I) on SE(B) specimens with 40 mm span. For J-testing based on the load separation method the tests are performed at 0.6 m/s. The sharp notched specimens are machined by means of a notching machine by Ceast SpA (Torino, I). The blunt notches are produced as key-hole notches with a tip radius of 1 mm. The final crack length in sharp notched specimens, broken open after cooling in liquid nitrogen, is measured by means of an optical travelling microscope. For J-testing according to the “reduced velocity” method the test speed ranges from 0.2 to 0.43 m/s, whereas using the “striker stop” method the impact tests are performed at 0.6 m/s. The value of the yield stress of the material at 0.6 m/sec, σ_y (0.6 m/s) = 48.8 MPa, is extrapolated from data measured in uniaxial tensile tests carried out at different crosshead speeds by an Instron machine, model 8501, on dumb-bell specimens.

3 RESULTS AND DISCUSSION

To construct J_R curve according to the normalization method two impact tests – on both a sharp notched specimen (initial a/W = 0.58 and final a/W = 0.62) and a blunt notched specimen (a/W = 0.81) – are performed. The fracture propagation produced by impact on the sharp notched specimen is controlled by means of a hammer stop block system. The measured load *vs* displacement curves are shown in figure 1.

The parameter η_{pl} and the geometry function necessary for the experimental determination of the deformation function have been previously determined by performing impact tests, in SE(B) configuration, on specimens containing blunt notches of different lengths [6].

By subtracting the elastic displacement from the total displacement (according to eqn (2)), the load *vs* plastic displacement curves for both the specimens are constructed. It has been evidenced [7] that, in impact, the first peak of the load *vs* displacement trace is not related to the specimen bending compliance and, in the present research, it is not taken into consideration for the calculation of the current compliance of both sharp and blunt notched specimens.

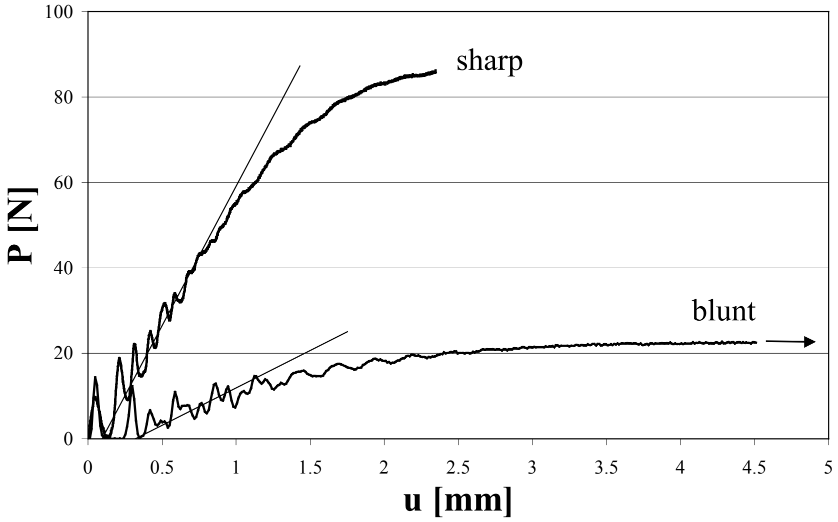

Figure 1: Load *vs* displacement traces for blunt and sharp notched specimens

As observed in stationary crack tests [6], in impact the oscillations of the signal do not permit the correct determination of the separation parameter at low values of plastic displacement. Therefore a smooth mean curve is traced by means of a computer-aided curve fitting procedure through the experimental load *vs* plastic displacement curve of both blunt and sharp notched specimen. For the sharp notched specimen the separation parameter is evaluated according to eqn (7) normalizing the load by the load of the stationary test (blunt notch) at different values of constant plastic displacement (see figure 2) using: i. measured values for the sharp notched specimen and fitted values for the blunt notched specimen; ii. fitted values for both sharp and blunt notched specimen. In the first case the separation parameter is labelled S_{sb}^{*}, in the second case S_{sb}^{**}. As it can be observed in figure 2, the definition of the separable blunting region is not immediate. Then the separable blunting region is tentatively identified as the interval Δu_{pl} – whose extremes are $u_{pl,min}$ and $u_{pl,lim}$ – where the variation of S_{sb}^{**} from its maximum (ΔS_{sb}^{**}) keeps lower than a specific amount. The effect of different intervals Δu_{pl}, corresponding to different ΔS_{sb}^{**}, on J_{Ic} and J_R curve is explored. On the basis of a preliminary research of the plateau limits beyond which no constancy of the separation parameter can be admitted, the explored range of ΔS_{sb}^{**} is included between 4 and 20% (the different extents of the separable blunting region are shown in figure 2).

At $u_{pl,lim}$, considered as the upper limit of the crack blunting region, the value of J_{Ic} is determined. Within the separable blunting region the points (P'_N, u'_{pl}) – determined using the load *vs* plastic displacement fitting equation – together with the corresponding final point are fitted by a power law expression (see eqn (9)) that provides the material key curve. In the region of fracture propagation, from $u_{pl,lim}$ up to the final point, the instantaneous crack length values are obtained and J_R curve constructed and fitted by a power law expression. Figure 3 shows J_R curves determined using different extents of the separable blunting zone.

The results show that J_R curve is scarcely affected by the choice of the extent of the separable blunting region, at least in correspondence of ΔS_{sb}^{**} included between 8 and 20 %. This indicates that J_R curve is not sensitive to the extent of the region used for its construction provided this zone is included within the true separable blunting region.

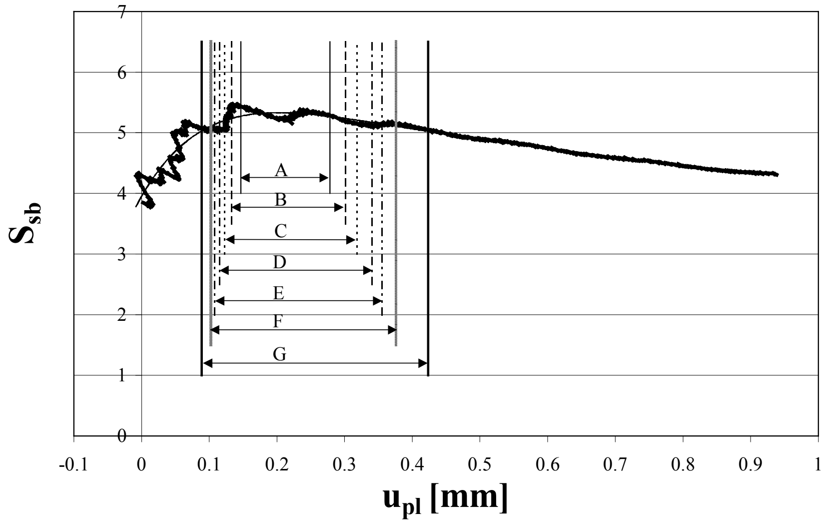

Figure 2: S_{sb}^{*} (▬) and S_{sb}^{**} (—) *vs* plastic displacement for the sharp notched specimen and regions corresponding to different ΔS_{sb}^{**} (see text): (A) 4, (B) 6, (C) 8, (D) 10, (E) 12, (F) 14 and (G) 20%

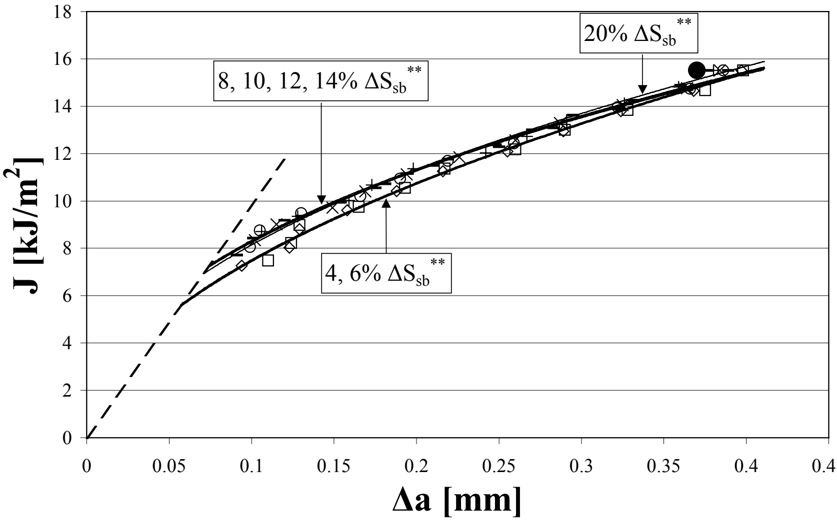

Figure 3: Construction of J_R curve for extents of the separable blunting region corresponding to different ΔS_{sb}^{**} (see text): (◇) 4, (□) 6, (-) 8, (○) 10, (×) 12, (+) 14 and (−) 20%; (●) final point

J_R curve constructed by means of the normalization method assuming the separable blunting region corresponding to $\Delta S_{sb}^{**} = 10\%$ is then compared with J_R curves determined through the application of the multi-specimen testing procedures proposed by ESIS [5]. J_R curves (fitted according to power laws) and the values of J_{bl} (identified as the intersection of the blunting line with J_R curve) and $J_{0.2}$ (identified as the value of J_R curve at $\Delta a = 0.2$ mm), determined using the different methodologies, are reported in table 1.

Table 1: Results obtained using the different J-testing procedures

J-testing method		R-curve	J_{bl} [kJ/m^2]	$J_{0.2}$ [kJ/m^2]
Normalization method		$J=23.11\cdot \Delta a^{0.445}$ ($r^2=0.99$)	7.26	11.28
Multi-specimen procedure	"Reduced velocity"	$J=35.88\cdot \Delta a^{0.649}$ ($r^2=0.96$)	5.66	12.63
	"Striker stop"	$J=43.06\cdot \Delta a^{0.834}$ ($r^2=0.98$)	0.71	11.25

It appears that $J_{0.2}$ results are in good agreement with each other whereas consistent differences are observed in J_{bl} results.

4 CONCLUDING REMARKS

In impact the determination of J_R curve of polymers via the normalization method is made more complicated than at low loading rates because of the inertial phenomena. Load oscillations raise difficulties in the determination of specimen elastic compliance, in the construction of material key curve and in the identification of the separable blunting region. By means of a numerical smoothing process used to remove the inertial oscillations of the data the normalization method is applied and it is evidenced that J_R curve is scarcely influenced by the extent of the separable blunting region used for its determination. The comparison with multi-specimen procedures indicate the normalization method as a promising method for the study of high-rate fracture toughness of polymers.

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