High-rate J-Testing of toughened nylon 6/6: application of the load separation criterion

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ABSTRACT

J_R curve of toughened nylon 6/6 at high loading rates is determined by means of the load separation criterion. The results are compared with those measured using the multi-specimen testing procedures proposed by ESIS Technical Committee 4 (Polymers, Adhesives and Composites).

1. INTRODUCTION

During the fracture process of a cracked body of a given material, geometry and constraint, Sharobeam and Landes [1] proposed that the load can be separated, in the plastic region, 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 uncracked ligament length and the width of the body, u_{pl} the plastic displacement, G(b/W) and $H(u_{pl}/W)$ the geometry and deformation functions 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 η_{pl} [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 the constant $C_1 = 1/G(b_j/W)$, whereas the term η_{pl} may be calculated from:

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

where C_2 is a constant [2].
It was investigated if the load separation principle could be extended to growing crack experiments [3,4]. 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

$$S_{sb} = \left.\frac{P_s}{P_b}\right|_{u_{pl}} \cdot \frac{W_b^2}{W_s^2} \tag{7}$$

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 sufficient 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 [5]. According to the normalization method two tests must be performed: one test is carried out on a blunt 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 [4]:

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

where P_N is the normalized load. According to the modification introduced by Cassanelli [4] 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 ($u_{pl,min}$). Assuming that during the whole crack tip blunting process ($u_{pl,min} < u_{pl} < u_{pl,lim}$) there is no significant crack growth 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 the "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 [6]:

$$J = \frac{\eta \cdot U}{B_N \cdot (W - a_0)} \tag{10}$$

where U is the area under the load *vs* displacement record, η is a calibration factor depending on geometry and B_N is the net thickness of sidegrooved specimens.

In this work the load separation criterion is used to determine J_R curve of toughened nylon 6/6 at high loading rates. By means of tests on stationary cracks the geometry function (of the specimen in the testing configuration) is determined and compared with that suggested by Rice for bend specimens [7]. Growing crack experiments are carried out for the evaluation of J_R curve. The results are compared with those measured using the multi-specimen testing procedures proposed by ESIS [8] 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 injection moulded bars, with dimensions 80x10x4 mm, by Radici Novacips SpA (Villa d'Ogna (BG), I), is a toughened nylon 6/6 containing 25% wt. rubber, conditioned in air for two months. The impact tests are performed using an instrumented impact pendulum by Ceast SpA (Torino, I) on SE(B) specimens with 40 mm span and at room temperature. For J-testing based on load separation method the tests are performed at 0.6 m/sec. 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, are 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/sec, whereas using the "striker stop" method the impact tests are performed at 0.6 m/sec.

The value of the yield stress of the material at 0.6 m/sec, σ_y (0.6 m/sec) = 48.8 MPa, is extrapolated from data measured in uniaxial tensile tests carried out by an Instron machine model 8501 on dumb-bell specimens at different crosshead speeds.

3. RESULTS AND DISCUSSION

Impact tests carried out on specimens equipped with blunt notches of different length are used to determine η_{pl} and the geometry function G(b/W). The load *vs* displacement traces are shown in figure 1.

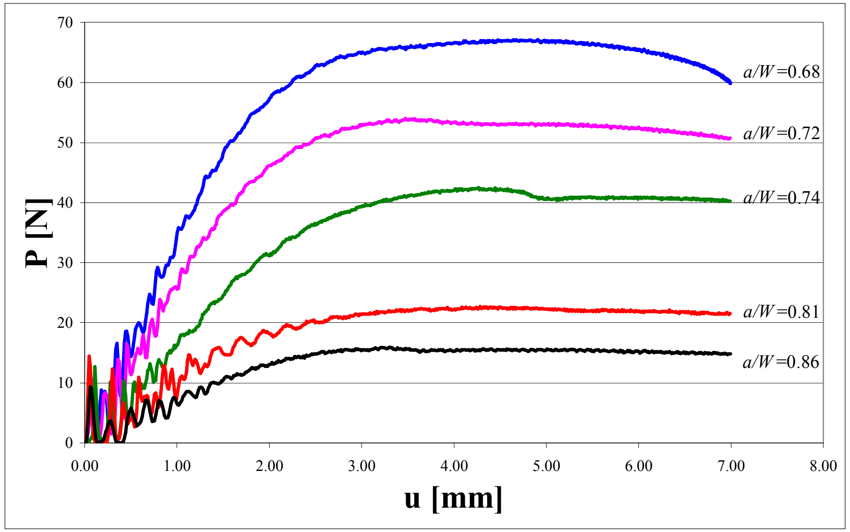

Fig.1: Load vs displacement traces of blunt notched specimens

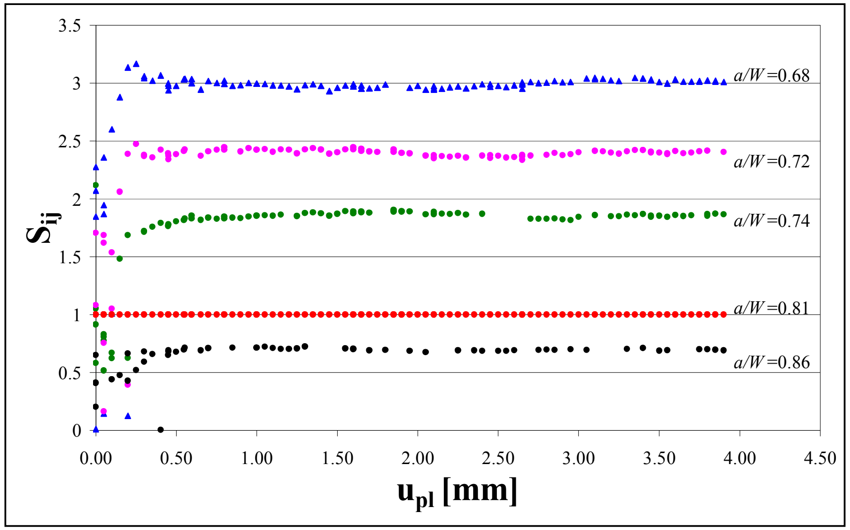

Fig.2: The separation parameter vs plastic displacement of blunt notched specimens

According to equation (3) the separation parameter S_{ij} is determined for each specimen, assuming as a reference the curve measured for a/W=0.81. The results are shown in figure 2.

The separation parameters maintain a constant value all over the plastic region except for a limited zone at the early region of plastic behaviour. Beyond the above mentioned region at low plastic displacements, the constancy of S_{ij} implies that the load can be represented in the separable form. Figure 3 shows the separation parameter S_{ij} *vs* b_i/W for different plastic displacements. The data reduce into one curve demonstrating that the geometry function is not dependent on the plastic displacement. Using equation (4) η_{pl} = 1.81 is determined.

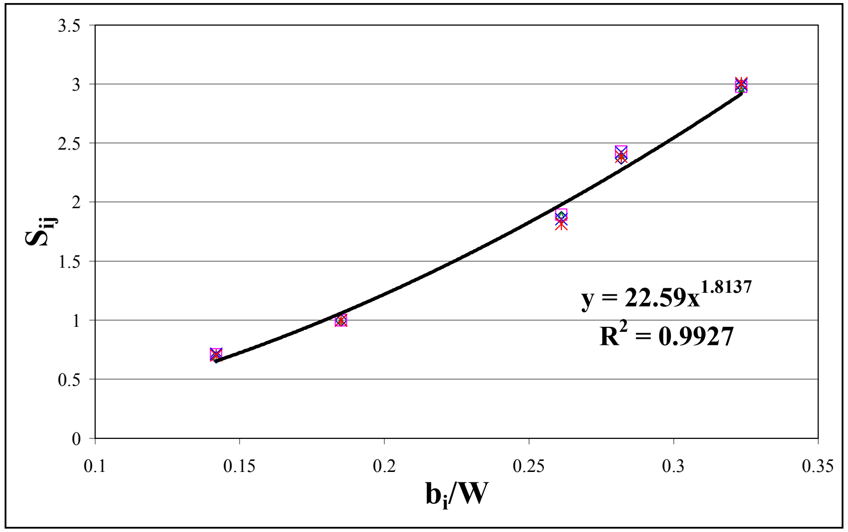

Fig.3: The separation parameter vs b_i/W for blunt notched specimens

This value can be considered close enough to the value of 2 derived by Rice [7] and widely adopted in literature for SE(B) specimens. The geometry function $G(b/W)=(b/W)^{1.81}$ is thus obtained.

To construct J_R curve according to the normalization method, two impact tests – on both a sharp notched specimen and a blunt notched specimen – are performed. Table 1 shows a summary of the crack lengths measured for the sharp and blunt notched specimens.

Tab.1: Crack length measurement for the sharp and blunt notched specimens.

specimen	***initial a/W***	***final a/W***
sharp notched	*0.58*	*0.62*
blunt notched	*0.81*	

The fracture propagation produced by impact on the sharp notched specimen is controlled by means of a hammer stop block system. The measured curves are shown in figure 4.

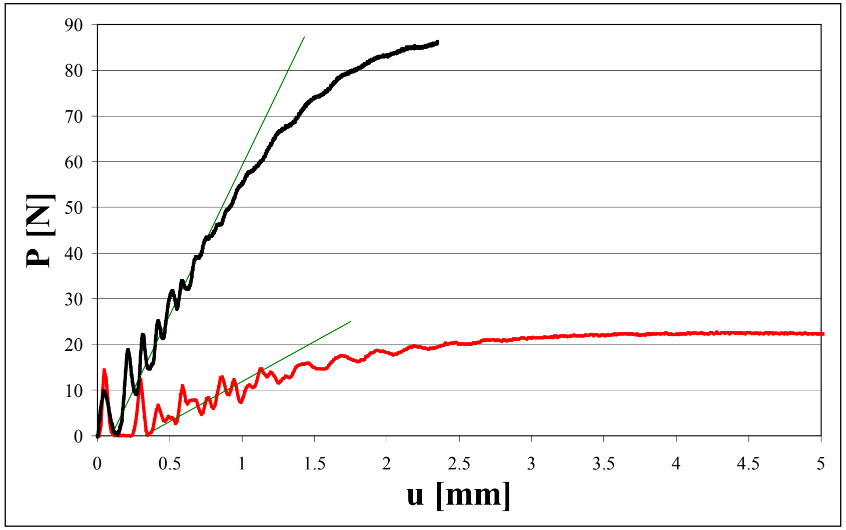

Fig. 4: Load vs displacement curves measured for blunt (red) and sharp (black) notched specimens

The evident oscillations of the signals, due to the inertial phenomena produced during the early stage of the impact, do not allow the correct determination of the separation parameter of the sharp notched specimen at low values of plastic displacements. The curve load *vs* plastic displacement of the blunt notched specimen is thus replaced by a best fit curve up to a plastic displacement sufficiently high to permit the correct determination of the separation parameter of the sharp notched specimen up to its final point. The separation parameter S_{sb} is evaluated for the sharp notched specimen by dividing the measured load by the load of the stationary test, recalculated using the fitting equation, at different values of constant plastic displacement according to equation (7). Figure 5 shows the separation parameter *vs* the plastic displacement.

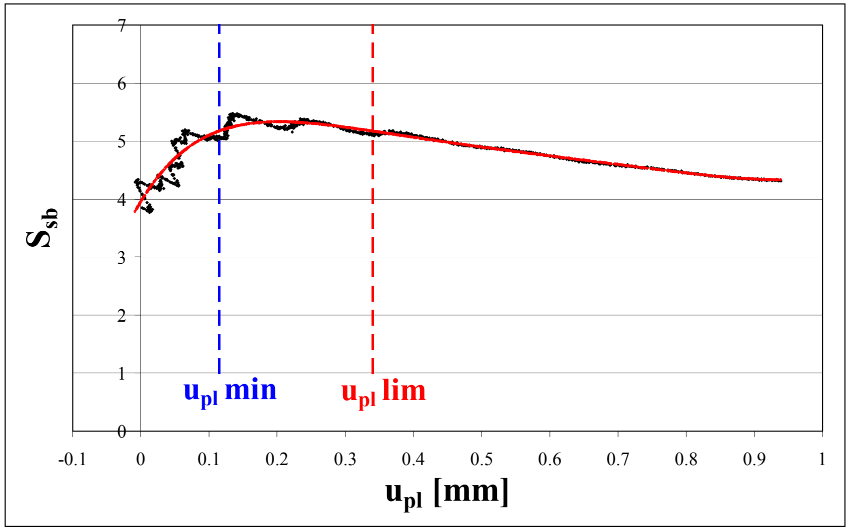

Fig. 5: The separation parameter S_{sb} vs plastic displacement for the sharp notched specimen

According to Landes et al. [3,9], the plot S_{sb} *vs* plastic displacement is constituted by three distinct zones: the unseparable region up to

$u_{pl,min}$, the separable region in which the separation parameter maintains its constancy up to $u_{pl,lim}$ and the last zone where the separation parameter decays in coincidence of crack growth initiation. In figure 5 the separable region is identified by assuming a variation of the separation parameter from its maximum lower than 10%. At $u_{pl,lim}$, considered as the limit of the crack blunting region, the value of J_{Ic} is determined: J_{Ic}=8.06 kJ/m^2. Within the separable blunting region, the points (P'_N, u'_{pl}) - see equation (9) - together with the corresponding final point are fitted by a power law expression that provides the "material key curve" (figure 6).

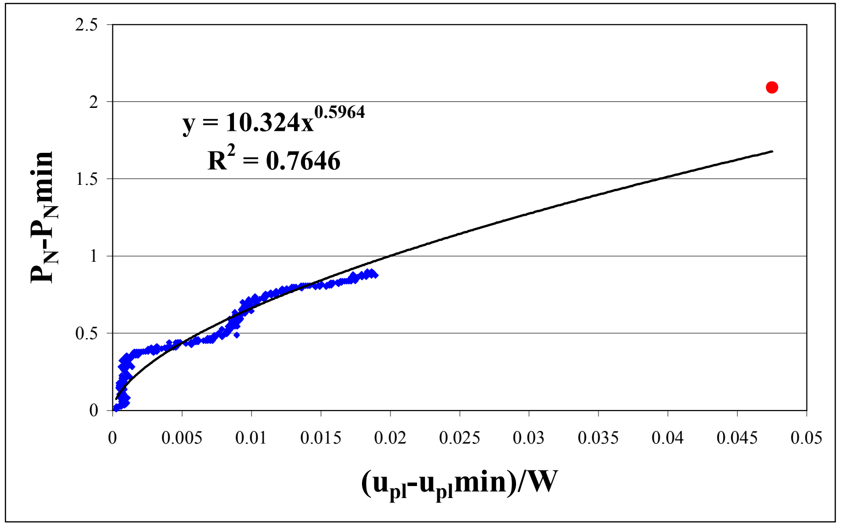

Fig. 6: Construction of the "material key curve"

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 can be constructed and fitted by a power law expression. J_R curve determined by means of the normalization method is then compared with J_R curves constructed by using the multi-specimen testing procedures proposed by ESIS [8]. Figure 7 shows J_R curves determined using the load separation criterion and the multi-specimen testing procedures. Blunting and exclusion lines [6] are also traced.

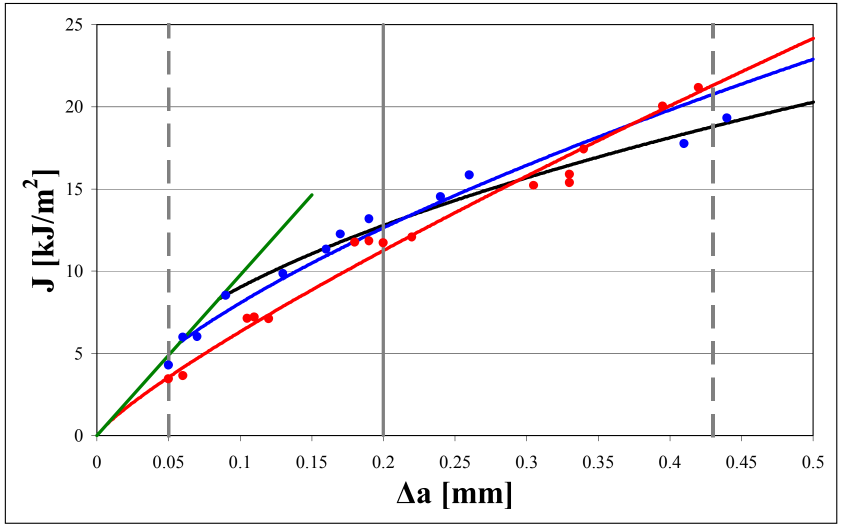

Fig. 7: Comparison among J_R curves determined using the different J-testing procedures (separation criterion - black, "reduced velocity" - blue, "striker stop" - red)

J_R curves (fitted according to power law) and the values of J_{bl} (identified at the intersection of the blunting line with J_R curve) and $J_{0.2}$ (identified as the value of J_R curves at Δa=0.2 mm) determined using the different methodologies are reported in table 2.

Tab.2: Results obtained using the different J-testing procedures.

J-testing method		**J_R curve**	**J_{bl} [kJ/m^2]**	**$J_{0.2}$ [kJ/m^2]**
Load separation criterion		$J=28.74\cdot\Delta a^{0.504}$ $r^2=0.99$	8.32	12.78
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:

i. J-testing methods explored lead to three slightly different J_R curves;
ii. $J_{0.2}$ results are in good agreement with each other;
iii. consistent differences are observed in J_{bl} results.

4. CONCLUDING REMARKS

The normalization method based upon the load separation criterion can be considered as a promising method for the study of the high-rate fracture toughness of ductile polymers. The method is simple. Using only two tests it permits to construct J_R curve in agreement with those measured with multi-specimen approaches that, even if more consolidated, require an extensive experimental activity. A deeper investigation regarding the role played by the inertial effects in the application of the normalization method is in progress.

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