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Fracture behaviour of notched round bars made of PMMA subjected to torsion at −60 °C

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ABSTRACT

This paper presents seventy new experimental results from PMMA notched specimens tested under torsion at −60 °C. The notch root radius ranges from 0.025 to 7.0 mm. At this temperature the non-linear effects previously observed on specimens of the same material tested at room temperature strongly reduce.

The averaged value of the strain energy density over a control volume is used to assess the critical loads to failure. The radius of the control volume and the critical strain energy density are evaluated a priori by using in combination the mode III critical stress intensity factor from *cracked-like* specimens and the critical stress to failure detected from semicircular notches with a large notch root radius.

1. Introduction

Modelling damage around notches has proven to be very difficult and strongly dependent on the microstructural aspects of each material. Therefore, proposed fracture criteria are based on critical values of some macroscopic stresses [1], critical virtual cracks [2–5], non-local averaged parameters [6], stress intensity factors [7–12], notch rounding approach [13,14], strain energy density (SED) [15–21], J-integral [22,23] and Cohesive Zone Models [24–29].

Under linear elastic conditions when the stress concentrators are cracks, the stress intensity factors, SIFs, provided by the linear elastic fracture mechanics can be applied. Notch stress intensity factors, NSIFs, substitute SIFs in the case of sharp, zero radius, V-notches. As soon as the notch is *blunted*, i.e. the notch root radius R is not zero, the stress singularity disappears. The linear elastic fracture mechanics continues to be valid, but up to a some critical value of R which varies from material to material [30]. The problem becomes more involved if the loading symmetry is lost, i.e. when the notched structural component is subjected to *mixed mode* loading as widely discussed in previous works by other researchers [31–36] and also by the present authors [37–42].

While systematic experimental data on fracture of blunted notched specimens (with notches of different root radii) loaded under mode I and mixed mode loading (I + II) have been recently provided [33,34,37–41], the results from *blunted* notched specimens under torsion loading are relatively scarce since the research activity has mainly considered cracked bars under torsion [43–48].

Some results were reported from ceramic notched components under combined tension and torsion, brittle glass and graphite under pure torsion [49–51]. In those papers the authors underlined that no other data were available in the

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Nomenclature

d	notch depth
E	Young's modulus
E'	generalised Young's modulus
e_3	parameter quantifying the influence of the stress state for the calculation of R_C
G	shear modulus
$K_{t,\text{net}}$	stress concentration factor referred to the net area
K_{IIIc}	mode III critical stress intensity factor from cracked specimens
M_T	torque applied to the specimen
R	notch root radius
r_0	distance between the notch tip and the origin of the coordinate system for SED computations
r	distance between the crack tip and a given point, according to linear elastic fracture mechanics
R_C	radius of the control volume
SED	strain energy density criterion
W_c	theoretical critical energy density
$\overline{W}$	average strain energy density
Greek	
2α	notch opening angle
ϕ	gross diameter of the specimens
τ_c	critical stress under torsion loading
$\tau_{\max}$	maximum shear stress calculated on a notched specimen
$\tau_{\text{nom},n}$	nominal shear stress referred to the net area
ν	Poisson's ratio

literature. In parallel, many researchers have devoted strong efforts to investigate theoretically the stress distributions of sharp and blunt notches under torsion loading and under linear elastic conditions [52–59].

Dealing with the specific case of blunted notches and polymethyl-methacrylate (PMMA) samples, some experimental results under mixed mode (I + III) loading were provided in [60]. V-notched bars with a constant value of the opening angle ($2\alpha = 60°$) and a root radius ranging from 0.2 to 1.2 mm were considered. Some results from semicircular notches with a larger notch root radius (4.0 mm) were also provided in that contribution. In Ref. [60] cracking and fracture of PMMA shown by the notched specimens loaded in torsion were seen to be very complex. In particular, the torque vs. twist angle curves were characterised by an initial linear-elastic stretch followed by an almost horizontal plateau preceding the final fracture. Strong non-linear effects were observed and documented by those authors.

Similar effects have been recently reported by the present authors who have summarised results for different kind of notched specimens made of PMMA (V-shaped, U-shaped and round shaped notches) [61]. That paper gives an account of about 70 fracture tests from notched specimens (with notches of different depth and radii) under torsion loading. In all tests, maximum loads and failure angles have been measured as a function of notch root radius and specimen geometrical configuration. PMMA specimens under torsion loading behave completely differently from those tested under tensile loading; the notched specimens during the torsion tests display a large plastic behaviour and the influence of the effective resistant net area is found to be the predominant parameter instead of the notch shape details (i.e. notch opening angle and tip radius). A non-conventional approach of these data in terms of strain energy density, as an extension of previous contributions [62–64], has been carried out showing a good agreement between experimental results and theoretical fracture assessment but only when the notch root radius is lower than or equal to 5 mm.

With the aim to strongly reduce (or remove at all) the non-linear effects observed at room temperature, some new tests at low temperature have been performed on the same material.

Altogether 70 new results from PMMA specimens tested under torsion at −60 °C are summarised in the present contribution.

The same kind of notches used in [61] have been considered to survey a wide range of stress concentrations. The specimens have been tested at −60 °C to have a behaviour closer to the linear elastic one, as previously made under mode I and mode II loadings [37–41].

The results obtained in [61] showed that at room temperature the SED provides a good prediction of the maximum torques up to a limit value of the notch root radius equal to 5 mm. At low temperature, this restriction is removed, with a failure reasonably governed by the stress concentration effects. The averaged SED criterion provides good maximum torque assessments for all specimens, independent of the notch root radius. The control volume radius and the critical SED values were found to be dependent on the temperature.