FULL PMMA KINETIC LAW OF FRACTURE: FROM QUASI-STATIC TO DYNAMIC REGIME

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Abstract

This study uses digital image correlation for the extraction of the stress intensity factor of PMMA in quasi-static and dynamic regime. The area quantification induced by the cracking of PMMA is a major focus of this work. Created surface resulting from crack propagation was measured over the entire length of test pieces. At approximately 0.6 c_R, the amount of fracture surface created is higher than twice the projected fracture surface on the average fracture plane, close to the “mirror” zone. Kinetic laws representing K_{ID} and G_{ID} according to the crack speed are thus compared with those from the literature by considering dynamical effects induced by rapid crack propagation. The dynamic fracture energy must be considered as a function of created surface since the microcrack branching velocity has been reached.

1. Introduction

Polymethyl methacrylate (PMMA) is one of important engineering materials and has been widely used in various fields and sectors, such as architecture, transportation, electronics and health. Due to its brittleness and its transparency at room temperature, PMMA has been used for a long time as a model material to understand the fracture mechanisms induced by cracking in brittle elastic linear material.

The toughness and the fracture energy are the well-known material parameters of the LEFM considered for a predictive behavior model. Few studies have examined the complete achievement of the full PMMA kinetic law of fracture, from quasi-static to dynamic regime. In the same way, very few studies deduce these laws from displacement field measurements realized by digital image correlation (DIC). It is the case of this study which established, the evolution of the stress intensity factor (SIF) according to the PMMA crack speed using a fast camera allowing the acquisition of 1280*800 resolution images at 60 000 frame/s. Surface quantification induced by PMMA fracture was also highlighted in this study and correlated to the cracking mechanisms. The different parts (from quasi-static to dynamic) of the kinetic law of fracture are finally discussed as a function of local mechanisms and fracture surface area.

2. Results

Based on a stability criterion, involving the mechanical stiffness notion, a numerical analysis based on the Virtual Crack Closure Technique (VCCT) was implemented with the finite element software Abaqus. In doing so, fracture tests in the opening mode (mode I) were carried out. The aim of the numerical study was to show the influence of various parameters such as the part geometry (Compact Tension CT, Disk-shaped Compact Tension DCT and Tapered Compact Tension TCT), the notch length, the notch width and the piece scale factor on the crack growth stability. Results showed the strong influence of the notch width on the mechanical system stability. The larger the scale factor and notch length, the more stabilized the system. It would also appear that TCT geometry is more suitable to the crack growth stabilization. From experimental stabilized fracture tests, the resistance curve of PMMA was obtained for the different « compact tension » type geometry. A material toughness of 1.25 MPa.m$^{0.5}$ and a material fracture energy of 0.5 kJ/m^2 were measured for a crack speed from 0.1 to 3.0 mm/min. Those values were also obtained by DIC with the use of Ufreckles calculation code (developed by J. Réthoré [1]).

To obtain the PMMA kinetic law of fracture in dynamic regime, a Strip Band Specimen (SBS) type geometry, known in the literature to generate few inertia effects was used for the fracture tests. By varying the notch width of the specimen, from 0.9 to 3.6 mm, different available energy release rates are obtained. Crack tip velocities between 0.20 and 0.65 c_R are thus obtained (Rayleigh wave speed $c_R = 930$ m/s). The fracture surfaces show a well-known macrobranching phenomenon for a crack speed $v = 0.60\ c_R$.

Microbranches appear along the crack front for v = 0.40 c_R [2], [3], [4] and the first conical mark appears for v = 0.20 c_R. As expected, the density of conical marks varies linearly with the crack speed. Surface roughness and surface area induced by crack propagation were quantified by 3D optical microscopy and correlated to local fracture mechanisms. A surface area greater than twice that commonly used in calculation (crack length by sample width), without taking into account the subsurface, is obtained upstream of the mirror zone considering a crack speed of 0.60 c_R. Same results are obtained by J.-B. Kopp *et al.* [5] on the fracture behavior of Rubber Toughened (RT-PMMA) in dynamic regime. The research also proposes a study of the magnification influence on the measured areas. Some examples of the surface roughness induced by cracking are represented in Fig. 1.

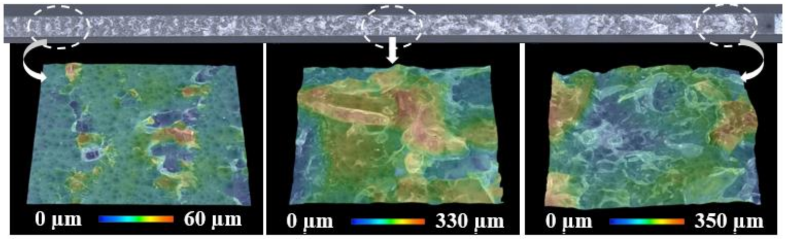
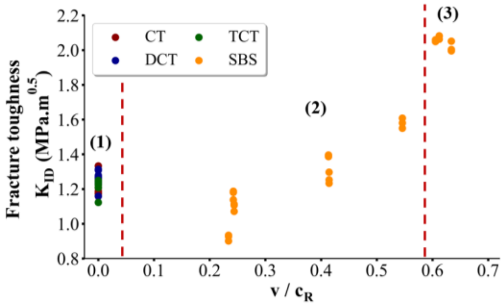


Fig. 1 – Fractures surfaces of SBS specimen (crack speed of 650 m/s). Crack propagates from right to left.

The use of Ufreckles allowed the identification of the crack front and the quantification of the SIF at the crack tip. The extraction of the SIF required a sensitivity study of the size of the extraction domain used. Image correlation shows the homogeneity of the strain field upstream of the crack during material cracking, which illustrates the homogeneity of the applied loading and the control of the boundary conditions. Ufreckles showed that the quasi-permanent regime was reached after a crack length of 4 cm, coinciding with the increase of the area created at the first moments of cracking. In this area, the critical stress intensity factor K_{ID} evolves between 0.9 MPa.m$^{0.5}$ for 0.23 c_R and 2.1 MPa.m$^{0.5}$ for 0.64 c_R (*cf*. Fig. 2).

Dynamic stress intensity factor (K_{ID}), for v = 0.23 c_R, is lower than in quasi-static regime (*cf*. Fig. 2). This decrease is attributed to viscous effects, to a local rise in temperature at the crack tip. Adiabatic thermal effects must be considered for the understanding of the cracking mechanisms of PMMA in dynamic regime [6], [7]. PMMA needs to be view as a visco-elastic material which is not always considered in the literature. Besides, a rather linear evolution of K_{ID} was obtained for $0.23 < v/c_R < 0.60$. The increase of K_{ID} for v > 0.60 c_R seems to be due to not considering the created surface area in calculations. Lastly, the stress factor K_{ID}, obtained by a local approach, is compared to the fracture energy G_{ID}, obtained by a global approach.



(1) Quasi-static, CT/DCT/TCT geometries

(2), (3) Dynamic, SBS geometry

(1) → (2) Instable regime, K_{ID} ↘

(2) Stable, K_{ID} ↗

(3) "Instable", created surface ↗

Fig. 2 – PMMA kinetic law of fracture, from quasi-static to dynamic crack regime

3. Conclusions

The use of VCCT has highlighted the factors influencing the stabilization of crack propagation. Through this study, uniaxial and stabilized monotonous tensile tests on CT, DCT and TCT geometries were performed. The quasi-static fracture toughness and energy are estimated from the R-curves. For a dynamic propagation regime, the use of a SBS geometry, and the Ufreckles computational code allowed the obtention of the PMMA kinetic law of fracture for $0.23 < v/c_R < 0.65$. These measurements as well as image correlation support the highlighted cracking mechanisms of PMMA.

References

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