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Quantitative fractography of mixed mode fracture in glass and ceramics

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Abstract

Many ceramic structural applications involve a combination of tensile (mode I) and shear (mode II) loading conditions. Quantitative fractography was performed on monolithic and *R*-curve materials. Soda-lime-silica glass was selected as the monolithic material. A mica glass ceramic was selected to represent *R*-curve materials. Mixed-mode fracture surfaces in both materials were characterized by an absence of the mist region. For the mica glass ceramic, crack-to-mirror size ratios were found to be a function of the crack length and mode mixity. Hackle markings on mixed-mode fracture surfaces appear as lances and differ from those observed on surfaces failed in pure Mode I. Atomic force microscopy showed that the features in different regions on the mixed-mode fracture surfaces are similar and differ only by scale. The practical implications of these observations are that forensic analyses can be used without a priori knowledge of the loading conditions.

Keywords: Fractography; Mixed mode fracture; Failure analysis; Atomic force microscopy; Hackle

1. Introduction

There are many applications in which the loading configuration is such that both tensile and shear stresses are involved in the fracture event, i.e., mixed mode conditions. Some examples are hybrid bearings on aircraft engines, impact fracture, edge chipping and rock fracture, to name a few.[1–5] It is important for forensic analysis to understand the influence of mixed mode condition on the fracture features that occur during these events so that we can obtain maximum amount of information. In order to understand the formation of fracture features during mixed mode loading conditions we examined two types of materials fractured in mixed-mode conditions: an amorphous monolithic material, soda-lime-silica glass, and a mica glass ceramic that exhibited *R*-curve behavior. Soda lime silica glass was chosen primarily to eliminate microstructural effects and the mica glass ceramic was selected to represent an *R*-curve material. We used two test geometries: flexure beams and diametral compression specimens. Thus, we examined both small and large cracks. We used indentation to produce controlled small and large crack sizes for both the test geometries. The purpose of this work is to study fractography of mixed-mode fracture from surface cracks on soda lime silica glass and a mica glass ceramic at room temperature. The fracture surfaces and the associated measurements in mixed-mode loading are compared to those in pure mode I. We found that there are significant differences in the appearance of fracture surface in mixed mode as compared to mode I loading. The practical implications of these findings are discussed.

2. Materials and methods

The study of mixed mode failure in glass bars and disks is well documented in the literature.[6–9] Only a summary of the pertinent data will be described here in terms of the crack-to-mirror size ratio and the difference in crack and loading geometry. Studies have been reported for indented cracks of flexure bars as well as on diametral compression (Brazilian) disk tests.[6–11] In addition, chevron notch specimens have been reported on the diametral compression specimens.[9,12] The data are in several references and will be discussed in Section 4.

The mica glass ceramic (MGC) chosen had a composition of 46% SiO_2, 17% MgO, 16% Al_2O_3, 10% K_2O, 7% B_2O_3 and 4% F[13] and has elongated mica crystals dispersed in a borosilicate glass matrix.[14,15] Previous studies have shown the

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presence of crack growth resistance (*R*-curve) behavior in the MGC up to a critical value of crack size (150 μm).[16] Vickers indentations were introduced on MGC bars of dimensions 40 mm × 4 mm × 3 mm using 0.05, 0.1, 0.2, 0.3, 0.5, 1 and 2 kg indent loads to create a range of crack sizes. Larger crack sizes were created by introducing multiple indents, such that the crack from one indent links up with the crack from the neighboring indent. Different precrack sizes were introduced primarily to study the influence of crack growth resistance behavior on the crack to mirror size ratio and the stress intensity at microbranching. The indentations were introduced at different angles, θ (90°, 80°, 70°, 55° and 45°) with respect to the tensile stress direction. $\theta = 90°$ represents pure mode I loading where the crack is oriented perpendicular to the tensile stress axis and $\theta < 90°$ represents the mixed-mode loading conditions. The as-indented mica glass ceramic bars were fractured in three point flexure on a span of 25 mm at a loading rate of 150 N/min at room temperature.

The mirror radius (r), semi-elliptical crack length ($2b$) and the semi-elliptical crack depth (a) were measured, either using optical microscopy or scanning electron microscopy; all specimens failed from the indentation site. The indented cracks can be approximated as semi-circular surface cracks and an equivalent semi-circular crack length can be calculated,[17,18] which will be referred to as the critical crack size (c).

$$c = \sqrt{ab} \tag{1}$$

The use of "c" instead of "a", the semi-minor axis, with the elliptical integral of the second kind to account for geometric changes, allows for the equivalent area of the semi-elliptical crack to be represented by a semi-circular crack with a known geometric factor.[18] For a semi-circular crack that is small relative to the thickness,[18,19] $Y = 1.26$.

The fracture surfaces were examined and the distance from the center of the crack to the mirror boundary, defined as the mirror radius, r_1, was measured.

3. Technical background

Fractography is an important tool used to identify fracture origins and identify features in the fracture process. Fractography studies have shown that fracture surfaces of materials that fail in a brittle manner from surface cracks are characterized by a sequence of three distinct fracture features surrounding the critical crack which initiated fracture. For Mode I fracture, the critical crack is surrounded by a relatively flat and smooth region called the mirror region, which is followed by a slightly tortuous region called the mist region, which is then bounded by a highly tortuous region consisting of large radial ridges called the hackle region. Macroscopic crack branching occurs after the hackle region, cf. Figs. 1 and 2. Depending on the material discipline, i.e., metals, polymers, etc., the name for these regions change, but the characteristics of the phenomenon is same. Distance of the various boundaries from the crack origin was empirically related to the applied stress at fracture[20–24]:

$$\sigma_f (r_j)^{1/2} = M_j; \quad j = 1, 2, 3 \tag{2}$$

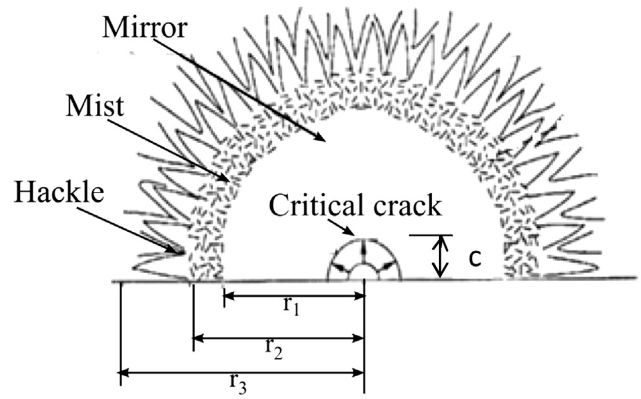

Fig. 1. Schematic of fracture surface features observed for fracture in Mode I loading. The semi-circular crack size is c. r_1 is the mirror–mist boundary, r_2 is the mist–hackle boundary and r_3 is the radius of the macroscopic crack branching boundary.

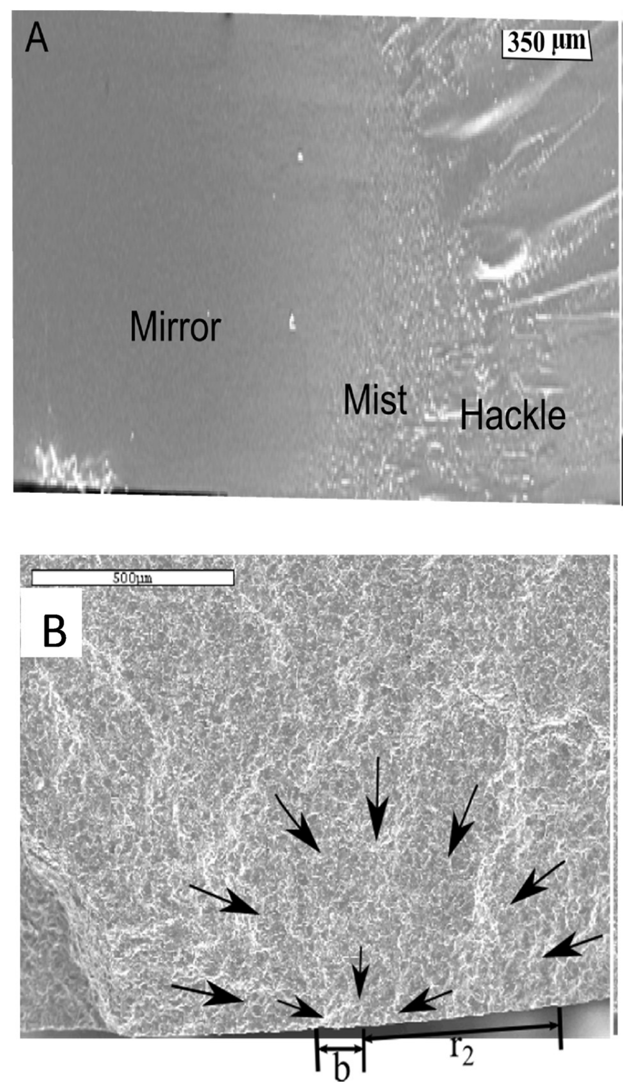

Fig. 2. SEM Images of fracture surface of materials fracture in Mode I. (A) Soda lime silica glass and (B) mica glass ceramic. b is the radius of the semi-circular crack. r_2 is the distance from center of crack origin to the hackle boundary. Inner arrows indicate crack boundary and outer arrows indicate hackle boundaries.