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Experiments on fracture trajectories in ceramic samples with voids

D. Misseroni

DICAM – University of Trento, I-38123 Trento, Italy

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ABSTRACT

Experimental validation is provided for a linear elastic model describing the trajectory of a crack which propagates under Mode-I conditions in a ceramic sample, as influenced by non-interacting voids. A wide range of experiments were performed by quasi-static loading standard notched unglazed ceramic samples under pure Mode-I loading conditions. It is found that the predicted crack trajectories are in close agreement with the experimental results, so that the model is fully validated and therefore permits correct simulations of crack paths in brittle materials containing small voids.

1. Introduction

Ceramic products find a wide range of applications in many contexts: they are used for traditional items, such as plates and tiles, and for high tech components, such as rocket exhaust cones and coatings for windshield glass in airplanes. Moreover, ceramic materials can be formed to provide extraordinary combinations of mechanical, electrical, thermal and chemical properties for enhanced system engineering. Still, the major limiting factor for these materials is the high brittleness, so that failure through crack propagation limits the material usability and can also yield catastrophic consequences. Theories that predict the geometrical shape of crack trajectories during propagation are important since fracture tortuosity is linked to toughness enhancement, but are rare and often difficult to interpret and use in an industrial environment, so that analytical models to describe fracture mechanisms in ceramics are highly valuable and useful for the design.

Experiments on fracture mechanics show that the crack trajectory is deeply influenced by the presence of defects (such as voids or inclusions) at both micro and macro scales. A crack that is propagating in a brittle material deflects from a straight line when it approaches an imperfection and, roughly speaking, is 'attracted' by a void and 'repelled' by a rigid inclusion. However, the prediction of the crack trajectory is a complex mechanical problem. Models for the prediction of crack deflection in brittle-matrix composites were developed by Lacroix et al. [1] and by Wang and Shing [2], the latter considering crack propagation in piezoelectric ceramics. A discussion about the influence of the orientation of the defects with respect to the crack line may be useful to define the most efficient configuration for obtaining the largest deviation of the crack trajectory. In particular, Tsukrov and Kachanov [3] and Radi [4] studied the interaction between two holes remotely loaded and noticed that the interaction effects and the energy release rate is maximal not in the ideally symmetric arrangements but in the configurations where the symmetry is perturbed.

The fracture trajectory in two-dimensional elastic solids was examined by Sumi et al. [5] and computational models were developed by Xu et al. [6,7] to study the crack growth in heterogeneous solids. Formulations for a curved crack based on a perturbation procedure in which weight functions were not employed, were presented by Hori and Vaikuntan [8].

Movchan and co-workers [9–13] have developed an analytical, two-dimensional model (valid for both plane stress or plane strain) for the determination of the crack trajectory in a linear elastic, but brittle, material. The model considers a semi-infinite crack growing in an infinite elastic-brittle medium and its interaction with small defects in the form of voids or inclusions. The defects are characterized by dipole tensors and the crack path is predicted in terms of elementary functions or by the integration of quantities involving weight functions. The main advantage of this asymptotic model is its simplicity, so that the formula describing the shape of the deflected crack trajectory can easily be used for a variety of fracture configurations and can be implemented as a design tool in many industrial processes.

An attempt to validate the asymptotic model for the prediction of the crack trajectory in ceramics was made by Bigoni et al. [14]

E-mail address: diego.misseroni@unitn.it

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and Valentini et al. [15,16], but their results were far from exhaustive and only indirect (the three-dimensionality of the stress state induced by a Vickers indenter was not coherent with the hypotheses on the basis of the model). More recently, Misseroni et al. [17] presented sound experimental results providing a nice validation of the crack trajectory model, but all obtained on PMMA notched plates, so that results on ceramics have never presented until now.

The aim of the present article is to complement the previous results on PMMA with a study fully dedicated to ceramic materials. In particular, experiments are presented on notched unglazed ceramic tiles, specifically produced for the tests and in which circular and elliptic voids have been manufactured. The experiments validate the reliability of the asymptotic model to predict crack deflections induced by voids for ceramic materials, so that it can be concluded that the approach can be employed in the industrial designs of ceramics.

2. The asymptotic model for Mode-I crack propagation

The asymptotic model for the description of crack-trajectory is summarized in this section (further details can be found in [10,12,15]). A semi-infinite crack is considered growing in an infinite, brittle, isotropic, and linearly elastic body, subject to pure Mode-I loading ($K_I > K_{IC}$), and interacting with a finite number of defects. These, in the form for instance of voids or inclusions, are assumed to be 'sufficiently distant' from the straight trajectory that would be followed by the crack in the absence of disturbances. Only the case of *plane stress* and *voids* of elliptical voids is now presented and the elastic properties of the material are defined by the Lamé constants λ and μ. In the case where more than one defect is present, a non-interaction assumption is introduced, so that the solutions for different defects can be simply superimposed.

The position of the elliptical void, with the major and minor semi-axes denoted by a and b respectively, is defined through: (i) the coordinates of the center (x_1^0, x_2^0) and (ii) the inclination θ of the major axis with respect to the x_1-axis. Fig. 1 shows a sketch of the problem set-up, with the adopted nomenclature.

The deflection of the crack trajectory $H(l)$ in the vicinity of the elliptical voids can be described by the following closed-form formula

$$H(l) = \frac{(1-\nu^2)R^2}{2x_2^0}\Big[2(1+m^2) - t(2+t-t^2+m^2(1+t) + 2m\cos 2\theta(1+2t)(1-t^2) - 2m\sin 2\theta(2t-1) \times (1+t)\sqrt{1-t^2})\Big], \qquad (1)$$

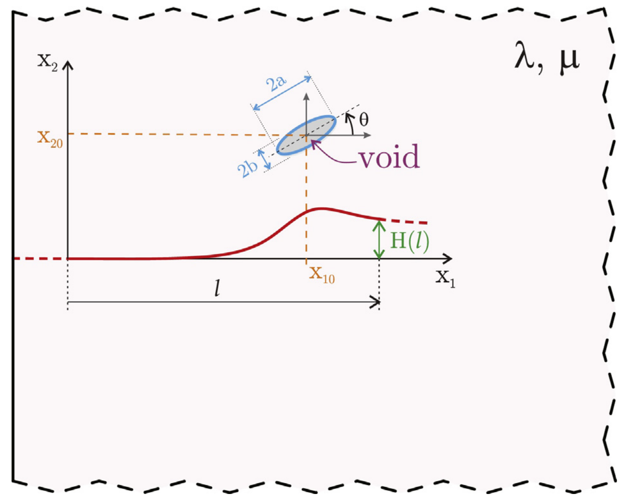

Fig. 1. The geometry of a crack interacting with an elliptical void, which is defined by the major and minor semi-axes (a and b respectively), by the coordinates (x_1^0, x_2^0) of the center, and by the inclination θ.

where l is the crack tip coordinate and

$$R = \frac{a+b}{2} \quad \text{and} \quad m = \frac{a-b}{a+b}.$$

It is important to remark that the expression (1) depends on the Poisson's ratio ν, the angle of inclination θ of the major axis, and the parameters R and m of the elliptical void.

The crack deflection at infinity, say, 'far away' from the small void, can be obtained from Eq. (1) in the limit $l \to \infty$, which for a particular case of an elliptical void becomes

$$H(\infty) = \frac{R^2}{x_2^0}(1+m^2). \qquad (2)$$

and does not depend on the orientation of the void.

3. The experimental validation of the asymptotic model

The experimental validation of the asymptotic model was provided employing the experimental setup reported in Fig. 2. Systematic experiments were performed through quasi-static loading of V-notched ceramic samples under Mode-I conditions.

Notched, unglazed tiles with circular or elliptical defects were specifically manufactured for the experiments (courtesy of SACMI, Italy). Due to their complex shape and the precision needed for the voids it was impossible to use a disk cutter. Instead, all sample were cut using a high pressure water-jet cutter. This system is

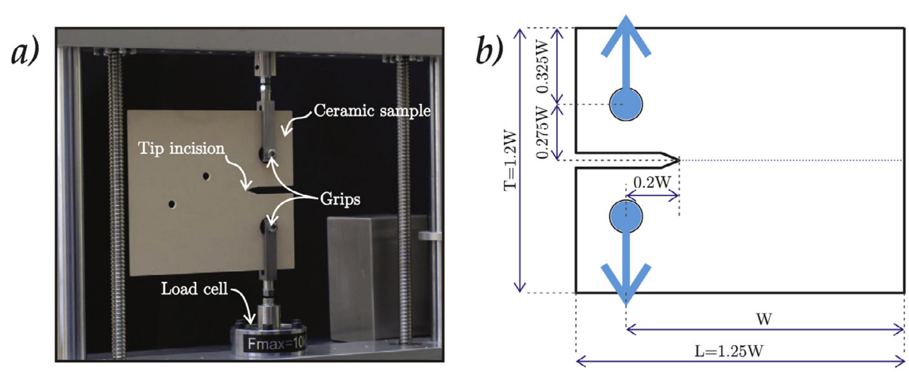

Fig. 2. (a) The experimental setup employed to provide the pure Mode-I loading on the ceramic samples. (b) Sample geometries as prescribed by the standard test method ASTM E647-00.