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Dynamic crack propagation in a heterogeneous ceramic microstructure, insights from a cohesive model

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Abstract—A 2D plane-strain dynamically propagating crack under tensile loading is simulated with cohesive elements. Information of the main crack is extracted from a diffuse crack network with the use of graph properties. Micro-transgranular fracture properties are calibrated by comparing the crack path transgranular fracture percentage of numerical simulations with experimental data. Results show that although weaker grain boundaries cause more deflections in the crack path and consequently increase the crack length and roughness, the overall toughness is decreased due to reduction of transgranular fracture. The main crack failure mode transition at grain boundaries is compared to static (Hutchinson and Suo, 1992) and dynamic (Xu et al., 2003) classical analytical predictions. It is observed that in many cases, before the arrival of a transgranular fracture at a grain boundary, a micro-daughter crack starts to propagate on the interface. The crack tip extension through this daughter crack/mother crack mechanism complicates the interpretation of the main crack speed in dynamic regime. Yet, the dynamic analysis brings a more accurate prediction of the crack path in microstructures compared to the static one when the data are segregated according to this mechanism.

Keywords: Dynamic crack propagation; Intergranular and transgranular cracking; Roughness; Parallel cohesive elements; Graph theory

1. Introduction

Evaluating the tortuousness of a crack path in a heterogeneous microstructure is a key component for predicting toughness. In ceramics, cracks dissipate energy while propagating along grain boundaries (intergranular) or inside grains (transgranular). Therefore, deflection/penetration mechanisms at grain boundaries should be investigated in order to estimate the total energy dissipation. Numerous research has been dedicated to study the deflection/penetration criterion in the static regime [14,16,12]. However, there are only a few studies on the equivalent dynamic problem, i.e. when the kinetic energy cannot be neglected due to a high crack velocity. A notable example is the work of Xu et al. [28] in which several deflection and penetration cases were studied experimentally for a single infinite interface. Subsequently, an analytical dynamic criterion, which was extended from a static criterion [16], was developed. Beside the interface angle and fracture properties, which are the governing parameters for the static regime, the crack velocity was integrated in the dynamic analytical estimate. Crack path predictions were consistent with experiments in case of velocities less than ≃40% of the Rayleigh wave speed [28]. Dooley et al. [7] verified these experimental observations numerically by using an extrinsic cohesive element approach [5]. The obtained simulated crack speeds after deflection were similar to the ones measured experimentally. All mentioned studies were conducted for dynamic cracks that reached a well-defined infinite interface. In [20] Li and Zhou estimated the probability of dynamic crack deflections at interfaces of particle-reinforced brittle composites based on the static crack criterion. This estimation was modified by considering correction factors to account for microstructural attributes such as finite reinforcement size, and phase volume fractions. In an experimental study on aluminum nitride microstructures, Hu et al. [15] used the dynamic criterion of Xu et al. [28] to interpret qualitatively a crack type transition from intergranular to transgranular under a high strain rate. Yet, the quantitative verification of a dynamic deflection/penetration criterion for a dynamic crack propagating in a microstructure and confronting several finite interfaces (grain boundaries) remains unexplored. This verification requires to simulate *long* dynamic cracks in *large*[1] micro-

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[1] Long and large are written in italic as they are relative terms. By long and large we imply that one must access statistically significant data.

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structures, which leads to challenging numerical simulations. Moreover, extracting crack path information from diffuse dynamic crack networks requires robust numerical post-processing tools.

In the present study, cracks are simulated in silicon nitride microstructures by using cohesive zone modeling [8,3,29,5]. An efficient parallel extrinsic cohesive element approach was implemented in the open-source finite-element library Akantu [1], which allows for an unprecedented level of refinement. We use algorithms derived from graph theory for the post-processing of crack patterns, extraction of their geometrical and mechanical properties. The simulations of large microstructures and the extraction of the main cracks permit the estimation of micro-transgranular fracture properties and the analysis of the crack roughness.

In the following, Section 2 recalls briefly the main components of the analytical models for static [16] and dynamic fracture [28] mode selections. The numerical approach is presented in Section 3. This section contains the numerical time integration scheme, cohesive zone modeling, and the application of graph theory for extracting the main crack. The estimated material parameters are reported in this section as well. Section 4 presents the numerical simulations set-up and numerical results. The procedure for the calibration of transgranular fracture properties and the analysis of the crack roughness and energy dissipation will be discussed. The section continues with the detailed comparison of numerical simulation results with analytical (static and dynamic) criteria. Concluding remarks are reported in the last section.

2. Analytical model for fracture mode selection

There are two possible fracture types for a crack path under mode I tensile loading when it reaches a grain boundary. The first type is interface debonding, usually a mixed-mode crack propagation, which plays a key role in material toughening. The second type, which is a mode-I fracture, happens when the crack penetrates the following grain. A schematic describing the geometry relevant to the dynamic crack deflection/penetration is shown in Fig. 1. An interface (dashed line) bonds two identical homogeneous isotropic elastic solids. A semi-infinite dynamic mode-I crack with velocity v_1 approaches the interface (see Fig. 1a). The kinking angle β is the angle between the arriving crack plane and the interface. Fig. 1b shows that in case of penetration the crack velocity will not be changed due to similarity of materials on both sides of the interface. It is considered that if the crack deflects (see Fig. 1c), it continues with a velocity v_2 as an interfacial crack. Two important static and dynamic regimes need to be considered. We follow the reasoning and notation of Xu et al. [28] for the description of these two regimes in the next subsections.

2.1. Static crack penetration/deflection analysis

The competition between the two modes of crack propagation under remote static loading has been studied by He and Hutchinson in 1989 [14], and Hutchinson and Suo in 1992 [16]. The analysis was restricted to the simple case of an identical isotropic solid on the two sides of the interface. The crack continues its propagation within the crack plane, if the mode-I static crack energy release rate, G_I^s,

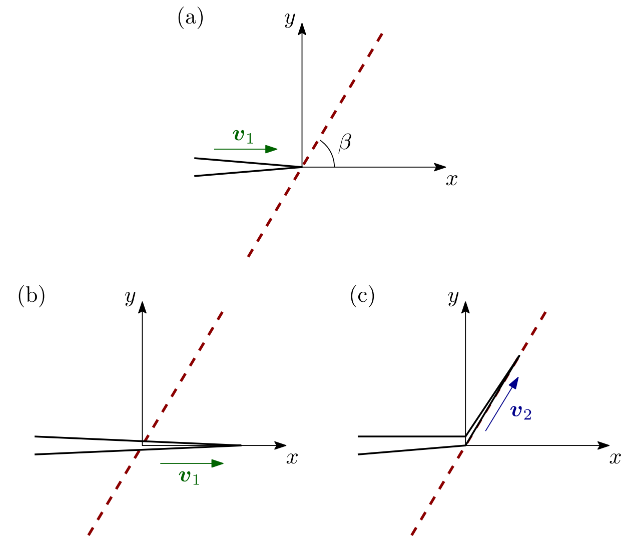

Fig. 1. Schematic of a semi-infinite crack tip arriving at an infinite interface placed at an angle β. (a) incident crack with a velocity $\boldsymbol{v}_1$, (b) penetration with no change of velocity, and (c) deflection with a new velocity $\boldsymbol{v}_2$.

reaches or exceeds the transgranular fracture toughness Γ^{TG}. G_I^s based on the static stress intensity factor, K_I^s, is defined as follows:

$$G_I^s = \frac{1-\nu^2}{E}(K_I^s)^2 \tag{1}$$

where E is the Young's modulus and ν is the Poisson ratio of the material. An equivalent criterion can be defined if the crack deflects its path on the interface. The deflection is continued if the static energy release rate of the kinked crack tip G^{sk} reaches or exceeds the fracture toughness of the interface Γ^{IG}. The interfacial angle β relates the mode-I stress intensity factor before crack deflection K_I^s, with the static mode-I K_I^{sk}, and mode-II K_{II}^{sk} stress intensity factors for a mixed-mode crack after deflection (see Eqs. (2) and (3)) [2,16].

$$K_I^{sk}(\beta) = K_I^s\left(\frac{3}{4}cos\frac{\beta}{2} + \frac{1}{4}cos\frac{3\beta}{2}\right) \tag{2}$$

$$K_{II}^{sk}(\beta) = K_I^s\left(\frac{1}{4}sin\frac{\beta}{2} + \frac{1}{4}sin\frac{3\beta}{2}\right) \tag{3}$$

The static kinked energy release rate is then obtained as:

$$G^{sk}(\beta) = \frac{1-\nu^2}{E}\left[K_I^{sk}(\beta)^2 + K_{II}^{sk}(\beta)^2\right] \tag{4}$$

When the crack reaches a point in which both cases, deflection and penetration are possible (decision point), Hutchinson and Suo [16] argued that the crack deflects if the following condition is satisfied.

$$R_s(\beta) = \frac{G^{sk}(\beta)}{G_I^s} \geqslant \frac{\Gamma^{IG}}{\Gamma^{TG}} = R_m \tag{5}$$

Injecting (1) and (4) in (5) shows that the ratio R_s does not depend on the value of the stress intensity factor or material properties and is only governed by the kinking angle β.