Damage zone interaction due to non-oriented Vickers indentations on brittle materials

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Induced damage in brittle materials due to two interacting Vickers indentations at various orientations was investigated using a three-dimensional finite element model. The model considers ‘tensile cracking and compressive yielding’ behavior of ceramics. Damage evolution due to both the simultaneous and sequential double indentations was studied. The simulation results indicated that the induced damage zone patterns are strongly a function of the relative orientation of the two indenters. The existence of another nearby indentation reduces the crack size on the side closer to the first indentation but increases the overall median damage zone size. These results were validated by sequential Vickers indentation experiments on borosilicate glass. The evolved damage patterns were further rationalized based on Bousinesq and blister field stress fields. Finally, the implication of these results on material removal mechanisms due to simultaneous interaction of several grits in a ceramic grinding process is discussed.

1. Introduction

Vickers indentation experiments have been widely used to model the material removal mechanism and to analyze the interaction between the diamond grits of a grinding wheel and a ceramic workpiece during a grinding process [1–3]. It has been well established that median cracks develop normal to the surface during the loading phase and lateral cracks develop parallel to the surface during the unloading phase of a Vickers indentation cycle [1]. The median cracks are viewed as the residual damage because they remain in the workpiece after grinding and the lateral cracks are considered to be responsible for the material removal. However, the damage evolution and the material removal process during grinding of brittle materials cannot be fully captured by a single indentation test because the induced damage is also strongly influenced by the interaction of the stress fields created simultaneously by several neighboring grits.

To more realistically depict the damage and material removal phenomena in a ceramic grinding process, scratching models [3–6], multi-indentation experiments [7, 8], and multi-scratch experiments [9] were employed in the literature. However, analytical models that take into account the material removal mechanisms and the interaction effects during ceramic grinding are difficult to develop due to the complicated stress fields created by the moving indenter or the interacting indentations and scratches. Thus, the experimental results usually have to be interpreted qualitatively or empirically. Finite element methods are being increasingly used to solve these complex problems and to gain a better insight into the stress distribution and the damage development during the indentation tests. Recently, Zhang and Subhash [10, 11] developed an ‘elastic-plastic-cracking’ (EPC) model that accounts for tensile cracking and compressive yielding of brittle materials and simulated single indentation and double indentation experiments. The model was found to capture the development of median cracks during the loading phase and the development of lateral cracks during the unloading phase of a Vickers indentation cycle [10]. The induced damage zone size was strongly influenced by the separation distance between the two diagonally-aligned indentations [11]. In the current work, the relative orientations of the two indenters were varied systematically to analyze their influence on the induced damage.

The motivation for the current work stems from the experimental observations of Choi and Salem [7] where, “repulsive” and “attractive” modes between the cracks created by two adjacent non-aligned indentations were noted. They found that irrespective of the orientations of the Vickers indenters, the cracks due to the second indentation were repulsed by the cracks due to the nearby first indentation for “asIndented” condition. The induced cracks due to the second indentation tend to be smaller on the side closer to the first indentation than those farther away. But the cracks created by the first and the second indentations were “attractive” when the specimen was annealed after the
first indentation. The resulting interaction modes were attributed to the residual stress field produced by the deformation mismatch between the elastic and plastic zones within the indentation imprint [7]. In a grinding process, the ground workpiece should be in the “as-indented” condition due to multi-loading of the diamond grits. Thus, the annealing effect was not considered in this investigation.

The paper is organized as follows. In Section 2 a brief description of the EPC constitutive model and the finite element discretization of the double indentation model are provided. The numerical results for the sequential and simultaneous indentations in various orientations are presented in Section 3. These results are validated by sequential indentation experiments on glass in Section 4. The resulting damage patterns are further analyzed in Section 5 by utilizing Bousinesq and Yoffe solutions for point loads. Finally, the implications of the results for ceramic grinding are discussed and conclusions are presented.

2. Model description

The elastic-plastic-cracking (EPC) model recently developed by Zhang and Subhash [10] has been successfully utilized to analyze indentation induced cracking in brittle materials. The model was also utilized to develop a ‘brittleness measure’ that characterizes the propensity for cracking in brittle materials. Since the complete details of the model are available elsewhere, only a brief description of the model is presented here for completeness.

Fig. 1 shows the EPC model, which includes a tensile linear elastic response OB followed by cracking and the associated stress release process BC. The point B represents the uniaxial tensile fracture strength of the material where cracking initiates. The line DE denotes a brief description of the model is presented here for completeness.

Upon cracking, stresses and strains are assumed to be material constants. In this paper, \( u_0 \) is assumed to be the maximum crack opening displacement \( u_1 \) and is given by

\[
t_i = \sigma_f f_i \quad (i = 1, 2, 3), \quad \text{where} \quad f_i = (1 - u_i/u_0)^n.
\]

Here \( \sigma_f \) is the uniaxial macroscopic fracture stress, and \( u_0 \) and \( n \) are assumed to be material constants. In this paper, \( u_0 \) is assumed to be the maximum crack opening displacement (COD) (at C in Fig. 1) and is taken to be 5 μm based on the experimental work of Yu and Kobayashi [12] on ceramic matrix composites. The parameter \( n \) controls the shape of the post-cracking (stress release) curve BC and is assumed to be parabolic in nature with \( n = 2 \).

The COD \( u_1 \) at a given stress state is estimated by multiplying the cumulative cracking strain \( e_i \) by a characteristic length \( h \) [13], i.e.,

\[
u_i = h e_i = h \int d \epsilon_i \tag{3}
\]

where, \( h \) is the cube root of the corresponding element volume, and \( d \epsilon_i \) is the incremental strain between two adjacent time steps during the cracking process at any material point. Once COD is calculated for a given crack under a given state of stress, the total damage magnitude at any material point is calculated by defining the effective COD \( u_d \) along the three orthogonal directions as per

\[
u_d = \sqrt{u_1^2 + u_2^2 + u_3^2} \tag{4}
\]

\[Fig. 1 \quad \text{Elastic-plastic-cracking constitutive model for typical brittle materials.}\]