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Impact erosion by high velocity micro-particles on a quartz crystal

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ABSTRACT

A computational model using the discrete element method is presented to investigate the high velocity micro-particle impact process on a quartz crystal. The kinetic energy transfer from the impact particles to the target material is discussed. It shows that within the conditions considered 60–88% of the impact energy is consumed for crack formation and propagation, and the initiation of micro-cracks by an impact is mainly attributed to the shear stresses, while tensile stresses create more lateral and median cracks in the subsurface of the target than shear stresses. It also shows that a smaller impact angle with a lower particle velocity within the range considered in this study yields less subsurface damage to the target and also lower material erosion.

1. Introduction

Extensive experimental studies on the brittle material behaviour subjected to both static and dynamic contact loading have been reported to understand the erosion mechanisms [1–6]. It has been found that the erosion mechanisms of brittle materials by a solid particle impact are somewhat similar to that under a quasistatic indentation test [1]. When a brittle solid is subjected to a point load by, say, a sharp rigid indenter, an intense stress field is generated. These intense stresses (shear and hydrostatic compression) are relieved by local plastic flow or densification around the tip of the indenter. When the load on the indenter increases to a critical value, the stresses around the contact zone initiate micro-cracks, which can include lateral cracks parallel to the target surface and radial/median cracks into the substrate. The lateral cracks then propagate and terminate at the target free surface, resulting in actual material erosion or material removal, while the radial cracks running into the substrate degrade the strength of the substrate. By comparing with static indentations, the contact time by a high velocity micro-particle impact is so short that it is difficult to observe the detailed dynamic impact and hence the erosion process. It is therefore essential to adopt alternative approaches in order to understand the interaction between the impacting particles and the target.

Finite element (FE) method has been used to model the impact process by particles on both ductile and brittle materials [7–10]. Li et al. [7] developed an FE model to investigate the material response subject to ultrahigh velocity micro-particle impact on steels. Three material failure modes (failures induced by inertia, elongation and adiabatic shear banding) were identified for a particle impact, which are more comprehensive than the well-known cutting and deformation wear modes and provide a deeper understanding of the ductile impact erosion mechanisms. A multiple impact study was also conducted by Li et al. [8] in which Monte Carlo method was employed to generate the stochastic flow of impact particles. It has been found that the inertia-induced fracture is the primary material erosion mechanism for normal impacts, while it is the thermal-instability-driven failure that contributes to the higher material erosion rate at oblique impacts. For brittle material, Flocker and Dharani [9] studied the development of cracks on a glass during impacts by assigning a crack propagation path, while Behr et al. [10] investigated the dynamic strains on a laminated glass by the impact of low velocity steel balls. In these studies, it was assumed that the material was perfectly elastic, so that the damage pattern is difficult to observe. Continuum damage mechanics (CDM) coupled with FE model was also proposed. Sun et al. [11,12] used a CDM model to examine the mechanical response of a thin glass plate subjected to the impact of a large ball at relatively low velocities. Although the mesh in their FE model was rather coarse, some damaged elements were revealed in both sides of the thin plate. Ismail et al. [13,14] also used a CDM-based FE model to predict the nucleation and crack propagation direction in a glass subjected to static indentation, and the impact damage on the glass. Predicted results were found to be in a good agreement with those experimentally obtained. However, CDM-based FE models are unable to predict the propagation and coalescence of individual cracks; as a result, the final fractured region cannot be accurately predicted. Further, CDM-based FE models are incapable of dealing

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Nomenclature

a	crack length (m)
α_p	particle impact angle (degs)
A	area of the parallel bond cross-section (m^2)
B	solid specimen width in single-edge notch bending test (m)
d_p	average particle size in diameter (μm)
E_c	Young's modulus of the particle elements (GPa)
E_{con}	consumed energy in impact process (J)
E_0	kinetic energy before impact (J)
E_1	kinetic energy after impact (J)
$\overline{E}_c$	Young's modulus of the parallel bond (GPa)
F	loading force in single-edge notch bending test (N)
$\overline{F}_i^n$	normal direction force (N)
F^n	scalar value of $\overline{F}_i^n$ (N)
$\overline{F}_i^s$	shear direction force (N)
$\overline{F}^s$	scalar value of $\overline{F}_i^s$ (N)
$\overline{M}_i^n$	normal direction moments (N m)
$\overline{M}^h$	scalar value of $\overline{M}_i^n$ (N m)
$\overline{M}_i^s$	shear direction moments (N m)
$\overline{M}^s$	scalar value of$\overline{M}^s$ (N m)
I	moment of inertia of parallel bond cross-section (N m)
J	polar moment of inertia of parallel bond cross-section (N m)
R_{min}	minimum particle element size in radius (μm)
R_{max}	maximum particle element size in radius (μm)
$\overline{R}$	parallel bond radius (m)
v_p	particle impact velocity (m/s)
W	solid specimen height in single-edge notch bending test (m)
k_n/k_s	ratio of normal to shear stiffness of the particle elements
$\overline{k}_n/\overline{k}_s$	ratio of normal to shear stiffness of the parallel bond
ρ	density of the particle elements (kg/m^3)
μ	particle friction factor
$\overline{\lambda}$	radius multiplier of the parallel bond
σ_{max}	maximum tensile stress (MPa)
$\overline{\sigma}_n$	tensile strength of the parallel bond (MPa)
$\overline{\sigma}_c$	shear strength of the parallel bond (MPa)
τ_{max}	maximum shear stress (MPa)

with a large number of cracks and interactions among broken elements when they come into contact, so that it is hard to model the propagation of many micro-cracks in brittle materials by treating the target material as continuum in an FE model.

By contrast, discrete element method (DEM) appears to be a promising approach to overcome these issues. This method, which was proposed by Cundall and Strack [15] for the analysis of rock mechanics, treats the target material as a solid specimen with arbitrarily sized spherical elements bonded together. The break of the bonds among the elements can represent the crack formation and propagation in the specimen to study the erosion process [16]. Fundamentally, DEM solves Newton's equations of motion to resolve particle motion and uses a contact law to resolve inter-particle contact forces by what is called the contact model, and this model is usually employed to simulate motion and collisions of individual particles, especially in granular flows and powder mechanics. Moreover, DEM can also simulate the behaviour of material by assembling many small elements through bonding at their contacts by what is called the bonded-particle model (BPM) [17], which is widely employed to investigate the mechanical machining on brittle materials due to its advantage in representing the initiation and propagation of cracks. Su and Akcin [18] and Rojek et al. [19] used BPM to simulate the tool-rock interaction in rock cutting, while Tan et al. [20,21] used this approach to investigate the crack length and depth in the scratching of alumina ceramics. Recently, BPM was used to simulate the laser-assisted machining process for silicon nitride ceramics and to study the material removal process [16]. Thus, it is encouraging to use this method in modelling the erosion process for brittle materials under high velocity micro-particle impacts.

In this study, a discrete element (DE) model is developed to represent the impact process by a high velocity micro-particle on a brittle specimen, namely a quartz crystal. The developed model is then verified numerically and experimentally. The model is finally used to study the material response to a high velocity micro-particle impact to explore the impact process, the erosion process and mechanisms, the energy consumption during an impact, and the subsurface damage induced by the impact.

2. Discrete element model

2.1. Target solid specimen model

In order to model the material response to the impact of a micro-particle using DEM, it is essential to create a solid specimen whose mechanical properties are the same as those of the real target material. For this purpose, the BPM is used, in which the solid specimen is divided into a selected number of spherical elements that are bonded together at their contact points as shown in Fig. 1(a). The BPM is implemented in a three-dimensional (3D) software program, PFC3D, using a parallel-bond model which can transmit both forces and moments between particle elements and is often used to simulate solid specimens of brittle materials [16,20,21].

A parallel bond can be envisioned as a finite-sized disk of elastic massless material around the contact and centered at the

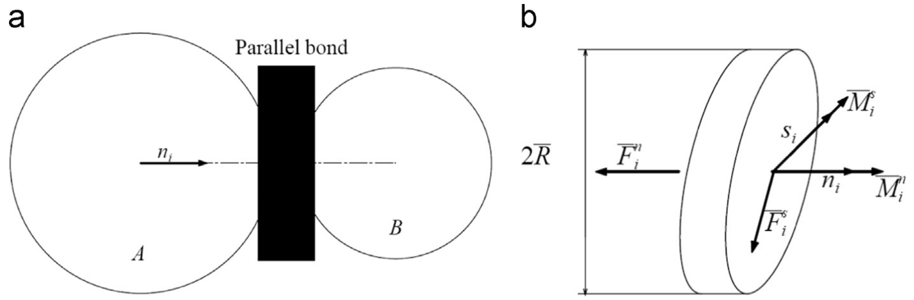

Fig. 1. Parallel-bond model: (a) parallel-bond idealization, (b) forces and moments carried in the bond material.