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On the erosion process on quartz crystals by the impact of multiple high-velocity micro-particles

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ABSTRACT

A computational model using the discrete element method is presented to investigate the impact process of multiple micro-particles on a quartz crystal. It is shown that the impacts initiate median and lateral cracks that degrade the strength of the substrate material and facilitate material removal in subsequent impacts. Elemental materials are removed through breaking their contacts with all adjacent elements by crack propagation and intersection. A larger overlapping impact condition between two impacts is more efficient for material removal in the second impact, but a total overlap does not yield the maximum material removal. The number of micro-cracks and the thickness of the cracked layer left on the eroded specimen are also studied in relation to the impact conditions.

1. Introduction

The material removal in abrasive jet machining, including abrasive waterjet (AWJ) and abrasive air-jet (AAJ), is mainly realized by impact erosion. For different materials and impact conditions, an impact may cause brittle mode erosion and ductile mode erosion, although both modes may coexist in an erosion process [1,2]. In abrasive jet machining, the erosion process is often described as to have cutting wear and deformation wear, where the former is more about remove material in chips and the latter is through crack formation and propagation [1,3]. In a recent study on high velocity micro-particle impacts on ductile steels [4,5], the erosion process has been further defined in three failure modes based on the underlying mechanisms of material removal, i.e. inertia-induced tension failure, elongation-induced tension failure and adiabatic shear banding (ASB)-induced failure. For brittle materials, it has been found from experimental studies [6–9] that the erosion induced by particle impacts is through the propagation and intersection of cracks formed by the impacts. It may be noted that these studies rely primarily on the observation of the eroded surfaces to derive the erosion process since the duration of the impact event is too short to experimentally study the impact process. Therefore, alternative approaches are required to study the dynamic behaviour when abrasive particles impact a target and the associated erosion of the target material.

Numerical simulation provides an effective approach to understanding the dynamic behaviour when the impacting particles contact with the target material. Considerable studies using the finite element (FE) method have been reported on the simulation of the erosion process by a single particle impact [4,10–12]. Since the erosion process may involve the impact of multiple particles, such as in abrasive jet machining, studies on the multiple impact process have also been conducted using FE models [5,13–15]. It is noted that most of these studies focused on ductile materials, where plastic deformation and thermal diffusion dominate the material removal process. Few studies on simulating the impact erosion by multiple high-velocity particles on brittle materials have been reported [12]. This is mainly due to the fact that the FE method based on the continuum damage theory experiences difficulties in dealing with numerous cracks and interactions among broken elements when they come into contact, such that it is hard to model the propagation of many micro-cracks in brittle materials, and hence the discrete nature of cracks is lost in the computation.

The bonded-particle model (BPM), in which spherical elements with arbitrarily sized distribution bonded together to model the target material with certain properties, is extensively used in simulating the rock mechanics according to the discrete element method (DEM) [16,17]. In this way, these bonds can be broken by the external force and moment acting on the contacts among the spherical elements that can numerically represent the initiation,

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Nomenclature

d_{jx}	major axis of the ellipse (μm)
d_{jz}	minor axis of the ellipse (μm)
d_p	average particle diameter (μm)
D	nozzle inner diameter (mm)
l	distance between two successive impacting particles in a plane parallel to the target surface (μm)
L	nozzle travel distance (μm)
L_1	actual machining length (μm)
L_j'	length of the jet plume in the simulation model (mm)
m_a	abrasive mass flow rate (mg/s)
m_L	mass of impacting particles during nozzle travelling over a distance, L
m_p	average mass of a single abrasive particle (kg)
m_{pl}	mass of impacting particles in per unit length of erosion (kg/m)
n_{pt}	number of impacting particles during nozzle travelling over a distance, L
P_a	air pressure (MPa)
r_p	particle radius (μm)
S	standoff distance (mm)
T_t	total time taken by all the impacting particles to hit the target surface during nozzle travelling over a distance, L, in the simulation model (s)
u	nozzle traverse speed (m/s)
u'	traverse speed for particles in the simulation model
v_{ap}	average particle velocity from nozzle exit along the jet axial direction (m/s)
v_p	particle impact velocity (m/s)
α_j	nozzle (or jet) impact angle (°)
α_p	particle impact angle (°)
φ	impact distance ratio
θ_A	jet expansion angle of a pure air jet flow (°)
θ_p	jet expansion angle of a particle flow (°)
θ_R	average resultant particle impact angle in simulation model (°)
ρ_p	particle density (kg/m^3)
σ_{max}	maximum tensile stress (MPa)
τ_{max}	maximum shear stress (MPa)

propagation and intersection of the micro-cracks inside the target specimen, and hence investigating the material removal mechanisms for brittle materials. Ye and Kang [18] used BPM to simulate the intergranular and transgranular fracture behaviour of granite under different pre-stressed machining in order to observe the damages and cracks of the surface/subsurface. A three-dimensional discrete element (DE) model was presented by Zang and Wang [19] to investigate the impact fracture behaviour of single glass and laminated glass planes, respectively, and the cracks, impact forces and kinetic energy conversion during the impact process could be obtained from the simulation results. In order to study the dynamic behaviour when abrasive particles impact a target surface and explore the initiation, propagation and interaction of cracks induced by the impacts, and hence the material removal process, DEM seems to be an effective alternative method to address these issues.

In an earlier study [20], DEM was used to model and simulate the impact erosion by a single micro-particle at a high velocity on a quartz crystal. In this paper, the model is extended to study the multiple micro-particle impacts. The extended model is then

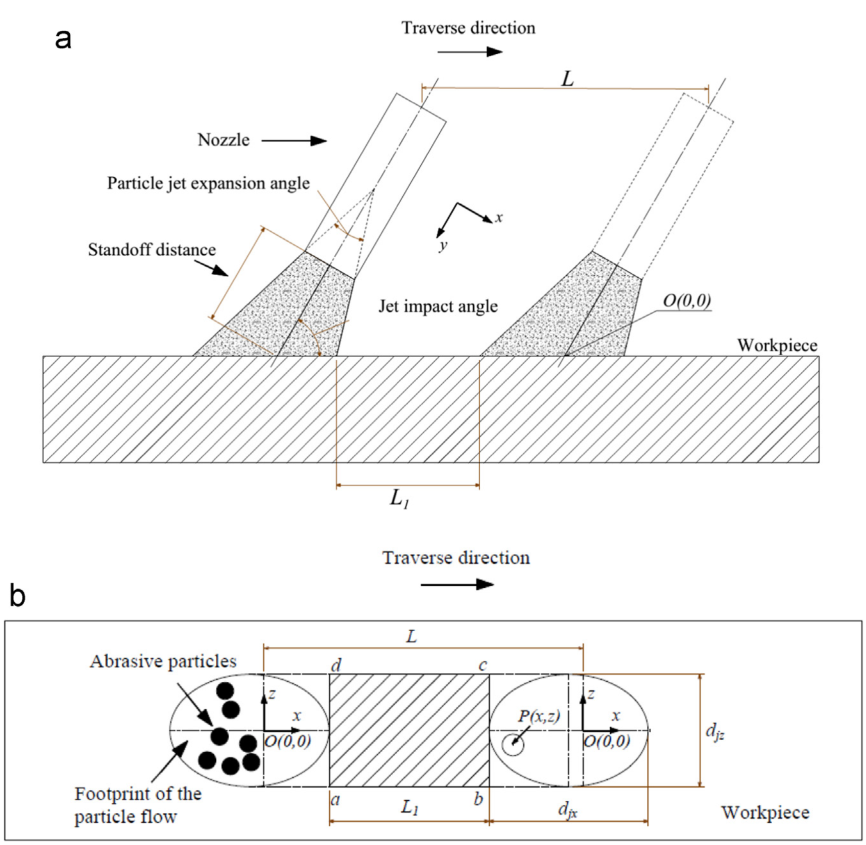

Fig. 1. Schematic representation of a micro-channelling process by an abrasive jet: (a) relevant parameters, and (b) footprints of a particle flow.