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Numerical and experimental study on ultrasonic vibration-assisted micro-channelling of glasses using an abrasive slurry jet

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ABSTRACT

The ultrasonic-vibration assisted micro-channelling process on glasses by an abrasive slurry jet (ASJ) is presented and discussed both numerically and experimentally. A numerical investigation using the dynamic meshing technique in Computational Fluid Dynamics (CFD) is carried out first to model the ASJ flow and explore the effect of ultrasonic vibration on the stagnation zone, particle impact velocity and impact angle, and viscous flow induced erosion process. It has been found that the static pressure in the stagnation zone, particle impact velocity and impact angle are varied periodically with an assistance of the ultrasonic vibration on the workpiece which in turn could affect the material removal process in ASJ micro-channelling of glasses. It is also found from simulation that the ultrasonic vibration is beneficial to the viscous flow induced erosion during the low pressure ASJ micro-machining process. Then, a set of ultrasonic vibration-assisted micro-channelling experiments are conducted on glasses using an ASJ to evaluate its effect on the major micro-channelling performance. It is found that ultrasonic vibration-assisted ASJ micro-channelling increases the material removal rate, channel depth and top channel width, while decreases the channel wall inclination angle, as compared to the traditional ASJ micro-channelling process at the same experimental condition. However, the surface quality on the bottom of the channel seems to be not significantly affected by the ultrasonic vibration. These findings from the experiment are in a reasonably good agreement with the corresponding simulated results.

1. Introduction

Micro-devices are fundamental elements of high-density and high-integrity systems, such as micro-electro-mechanical system (MEMS) and micro-reactors. Micro-machining is normally required for the fabrication of the micro-features on these devices [1]. The quality of the machined micro-structures, such as micro-channels and micro-holes, plays an essential role in the reliability and performance of these devices in practice. Due to the small sizes, complex details and high demands for surface quality, traditional machining techniques, like turning, milling and drilling, are unable to meet the demands of these micro-machining tasks [2]. Current non-traditional machining techniques also exhibit limitations in micro-machining these small structures. For instance, laser machining often results in a severe heat affected zone around cutting features [3], electrical discharge machining applies for only electrically conductive materials and is associated with low surface quality which may involve thermal damages from the process as well [4], and chemical etching is associated with a low erosion rate in addition to its environment influence [5]. The increasing trend towards miniaturisation increases the demand for micro-machining technologies which can efficiently and accurately produce complicated micro-features on a variety of exotic materials.

As a non-traditional machining technology, abrasive waterjet (AWJ) machining technology has been proven to be able to efficiently machine a wide range of materials, especially difficult-to-machine materials, without or with minimum thermal or mechanical damages induced by the process [6,7]. A reduction in scale of this technology, such as using a smaller nozzle, lower water pressure, and smaller fine abrasive particles seems to be an attractive avenue to be explored for meeting the pressing needs of industry in the fabrication of micro-features. Wang et al. [8] have employed the abrasive slurry jet (ASJ) machining system to drill micro-holes on glasses to understand the associated material removal mechanisms. It has shown that a lower pressure ASJ is a viable micro-machining technology for brittle materials, and the viscous flow induced erosion when a jet impacts a material surface plays a dominant role in the creation of the W-shaped micro-hole features which is also found by Cao and Cheung [9] in study of the

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material removal mechanisms during the fluid jet polishing process. Pang et al. [10,11] used an ASJ to machine micro-channels on glasses in order to understand micro-channel formation mechanisms, and develop predictive models to effectively control and optimise the machining process. It has been shown from this study that the bottom surface of micro-channel suffers from severe waviness, which is believed to be caused by the jet deflection during the nozzle traverse motion and water pressure fluctuation. A similar study of the ASJ machining of micro-holes and micro-channels on glasses was conducted by Kowsari et al. [12] and Nouraei et al. [13], respectively. It was able to produce micro-channels with low waviness on the bottom surface, since a pulsation damper was used to eliminate the substantial vibration and stabilise the pump pressure. The mathematical model for predicting the profile of the machined micro-channel was also developed by them using a surface evolution method similar to [14]. In a word, the low pressure and fine abrasive particles were used in these ASJ micro-machining experiments for reducing the surface damage, and hence the processing efficiency was relatively lower than that with high pressure and large abrasive particles.

Ultrasonic vibration-assisted micro-machining technology is extensively applied in grinding, cutting and polishing of hard-brittle materials in order to enhance the processing efficiency and quality. It has been found by Shen et al. [15] that the ultrasonic vibration during grinding procedure causes a reduction in the machining force and only results in the micro-fracture on ceramics that can improve grinding efficiency and provide better surface integrity. Zhou et al. [16] found that with the ultrasonic vibration-assisted cutting, the critical depth of cut was larger than that in traditional diamond cutting of glass which indicated that the ultrasonic vibration was beneficial to the ductile regime machining. Recently, an ultrasonic vibration-assisted AWJ polishing method was employed by Lv et al. [17] to improve the polishing efficiency and enhance the surface quality on lapped aluminium nitride substrates. Therefore, it is encouraging to use ASJ with the aid of ultrasonic vibration to improve the micro-machining efficiency while guaranteeing the surface quality as well. Little research has been conducted to investigate the effect of ultrasonic vibration on the characteristics of the AWJ flow, especially, the low pressure ASJ flow. A stagnation zone and water-film would form on the target surface due to the low pressure ASJ impingement which would affect the distribution and trajectory of the abrasive particles when they hit on the target surface, thus, an investigation into the effect of the ultrasonic vibration on the these characteristics is significant to the development of ASJ micro-machining technology.

In this study, Computational Fluid Dynamics (CFD) method is first employed to develop a three-phase flow, e.g. water, air and particles, to represent an ASJ using the mixture model and discrete phase model (DPM). Then a dynamic mesh is introduced into the CFD model to simulate the ultrasonic vibration on the workpiece in order to explore its effect on the characteristics of the ASJ, including the stagnation zone, particle impact velocity and impact angle in the initial impact zone, and the viscous flow induced erosion process in the secondary impact zone. Finally, a set of ASJ micro-channelling experiments is conducted to explore the effect of the ultrasonic vibration on the major micro-channelling performance, such as the material removal rate (MRR), channel depth, top channel width, channel wall inclination angle and line roughness on the channel bottom surface.

2. Model formulation

The two-phase mixture model and the standard k–ε turbulence model were used for simulating the multi-phase air-water flow, and the abrasive particles were uniformly injected over the inlet and tracked using the discrete phase model (DPM), so that a three-phase including water, air and particles is considered in this study. In order to consider the effect of the ultrasonic vibration on the characteristics of the ASJ, a dynamic mesh was introduced into the model that enables the workpiece to be moved periodically in simulation. Thus, the major governing equations used to develop the CFD model and the boundary conditions for the simulation are given below.

2.1. Governing equations

The mixture model used in this study assumes that the jet flow consists of two phases, i.e. water and air, where water is treated as the primary phase, and it allows the two phases to be inter-penetrating with each other, thus, the volume fractions of water and air phases can be equal to any value between 0 and 1. The mixture model also enables the two phases to move at different velocities using the concept of slip velocities, and to interact with each other in terms of inter-phase mass, momentum and energy transfer, such that it can realistically simulate the characteristics of the low pressure waterjet flow field. The details of the mixture model have been described in Fluent [18].

The continuity equation of the mixture takes from

$$\frac{\partial}{\partial t}(\rho_m)+\frac{\partial}{\partial x_i}(\rho_m u_{m,i})=0 \tag{1}$$

and the momentum equation for the mixture can be expressed as

$$\frac{\partial}{\partial t}(\rho_m\rho_m u_{m,j})+\frac{\partial}{\partial x_i}(\rho_m u_{m,i}u_{m,j}) = -\frac{\partial P}{\partial x_j}+\frac{\partial}{\partial x_i}\mu_m\left(\frac{\partial u_{m,i}}{\partial x_j}+\frac{\partial u_{m,j}}{\partial x_i}\right) +\rho_m g_i+F_j+\frac{\partial}{\partial x_i}\sum_{k=1}^{n}\alpha_k\rho_k u_{Dk,i}u_{Dk,j} \tag{2}$$

where x_i and x_j are coordinate directions, n is the number of phases, F_j is the body force in the x_j coordinate directions, g_i is the acceleration of gravity in the x_i coordinate directions, α_k is the volume fraction of phases, ρ_k is the density of the phases, ρ_m is the density of the mixture, μ_m is the viscosity of the mixture, $u_{m,i}$ represents the mass-averaged velocities in the x_i coordinate directions, $u_{m,j}$ represents the mass-averaged velocities in the x_j coordinate directions, $u_{Dk,i}$ represents the drift velocities in the x_i coordinate directions, and $u_{Dk,j}$ represents the drift velocities in the x_j coordinate directions.

In practice, the transportation for the ASJ is a fully developed turbulent flow, where the transport equations for the turbulence energy k and dissipation rate ε are solved and shared by the two phases throughout the whole field based on the standard k-ε model. This model is mathematically given by

$$\frac{\partial}{\partial t}(\rho_m k)+\frac{\partial}{\partial x_i}(\rho_m k u_{m,i})=\frac{\partial}{\partial x_i}\left[\left(\mu_m+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k-\rho_m\varepsilon \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_m\varepsilon)+\frac{\partial}{\partial x_i}(\rho_m\varepsilon u_{m,i})=\frac{\partial}{\partial x_i}\left[\left(\mu_m+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho_m\frac{\varepsilon^2}{k} \tag{4}$$

where $\mu_t=\rho_m C_\mu(k^2/\varepsilon)$ is the turbulent viscosity, G_k is the generation of turbulent kinetic energy caused by the mean velocity gradients, σ_k and σ_ε are the turbulent Prandt1 numbers for k and ε, respectively, and C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$ are constants, which can be taken from [19] and given by $C_\mu=0.09$, $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $\sigma_k=1$ and $\sigma_\varepsilon=1.3$.

These general governing equations are converted into Fluent and used for turbulent two-phase mixture flow. After the solution of the two phases has been completed, particle motions and trajectories are handled by the DPM, where Fluent treats particle