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Numerical simulation of surface roughness and erosion rate of abrasive jet micro-machined channels

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ABSTRACT

Abrasive jet micro-machining (AJM) utilizes the impact of particles in high-speed air jets to erode ductile or brittle target surfaces and produce micro-scale features such as channels and holes, as well as planar areas of controlled depth. The roughness of micro-channels for micro-fluidic applications made using AJM can affect fluid flow phenomena such as separation efficiency, electro-osmotic mobility and solute dispersion. Moreover, surface roughness plays a major role in microscale adhesion contact in MEMS and light scattering in optoelectronics devices. A numerical model was developed to simulate the brittle erosion process leading to the creation of unmasked channels as a function of particle size, velocity, dose, impact angle and target material properties. For the first time, erosion was simulated using models of two damage mechanisms: crater removal due to the formation and growth of lateral cracks, and edge chipping. Accuracy was further enhanced by simulating the actual relationship between particle size, velocity and radial location within the jet using distributions measured with high-speed laser shadowgraphy. Comparisons with experimental data showed that the model can predict the average roughness of the centerline of channels machined on borosilcate glass with 9% average error over a wide range of particle kinetic energies. The simulation also allowed for the first time the prediction of surface profile waviness and the transient roughness leading to a steady-state. The numerical model predicted the glass erosion rate with an average error of 29% for a broad range of AJM process conditions. The results indicated that the main erosion mechanism in the AJM of borosilicate glass was chip removal by lateral cracking. Edge chipping normally occurred when the impact angle was small and a particle impact occurred on an eroded surface near the apex of a peak, resulting in the removal of a relatively small portion of the peak. Thus, edge chipping contributed to profile smoothing and less so to erosion.

1. Introduction

Abrasive jet micromachining (AJM) has been used to make micro-electro-mechanical devices such as inertial sensors [1], electronic devices [2], and micro-fluidic components for capillary electrophoresis chips [3,4] and biochemical separations [1]. The roughness of micro-channels made using AJM can affect fluid flow phenomena in microfluidic applications. For example, it has been observed that the rougher the channel, the lower the separation efficiency [2,5] and electro-osmotic mobility [3], and the higher the solute dispersion [6]. Surface roughness also plays a major role in micro-scale adhesion contact in MEMS [7], and is a constraining factor on optoelectronics devices where roughness scatters and attenuates light [8]. Therefore, models to predict the roughness of the evolving features machined using AJM would be very useful.

Ghobeity et al. [9] developed an analytical model based on an earlier study [10] to predict the cross-sectional shape and depth of masked and unmasked channels machined with AJM using the erosive power distribution of the jet. Their model predicted the depth of masked channels with a maximum error of 8% up to an aspect ratio of 1. Ciampini and Papini [11] developed a cellular automaton simulation for the prediction of the size and shape of masked features produced with AJM of brittle targets. The model simulated multiple particle to surface and particle to mask collisions by tracking the trajectories of individual erosive particles, and showed good agreement with experimental results. Neither of these models simulated the surface roughness of channels.

The mechanics of cracking in brittle materials due to Vickers indentation was investigated by Marshall et al. [12] who derived equations to predict the length and depth of lateral cracks extending parallel to the surface as a function of the material properties and indentation force. Slikkerveer et al. [13] used these

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Nomenclature

a	indented zone size
A	particle area
b	plastic zone size
c, C, d_0	edge chip dimensions, Fig. 2
c_L	lateral crack length
d	particle diameter
d_{nom}	nominal particle diameter
d_s	nozzle to target stand-off distance
E	target elastic modulus
F	chipping force
h	indentation distance from an edge
H	target hardness
K_c	fracture toughness of target
$\dot{M}$	particle mass flow rate
P	impact force
P_0	force threshold to form lateral cracks
r	distance from jet center
R	particle radius
R_a	arithmetic average roughness
U	particle kinetic energy
v	particle velocity
$\overline{V}_*$	normalized average velocity
α	edge angle
β_w	abrasive jet focus coefficient
θ	impact angle
κ, λ	Weibull distribution parameters
μ, σ	log-normal distribution parameters
ρ_p	particle density
φ	impact force inclination
ψ	included angle of indenter

results to estimate the erosion rate and roughness of channels in borosilicate glass by assuming that each particle impact removed a spherical cap of material with a radius equal to that of the predicted lateral crack and a depth equal to that of the plastic zone, and by assuming that there was no overlap among impact sites. This simple model overestimated the erosion rate by a factor of four, while the roughness was predicted to the correct order of magnitude. Both the erosion rate and the roughness were functions of the kinetic energy of the particles. Verspui et al. [14] implemented this model in a Monte Carlo simulation of the erosion of a glass due to the impact of 30 μm alumina particles at 200 m/s. Their model gave a good prediction of the steady-state erosion rate for this single condition with an error below 30%; however, the steady-state roughness was overestimated by a factor of 10.

Jafar et al. [15] conducted single impact experiments to quantify the damage on borosilicate glass due to the impact of individual alumina particles and observed that the location of lateral crack initiation could be better estimated as the indentation size rather the plastic zone size. Implementing this change in the analytical model of [13] significantly improved the predictions of the steady-roughness and erosion rate of channels machined using AJM on borosilicate glass. Although the analytical model provided convenient and relatively accurate predictions, it did not simulate the actual erosion process, and hence could not predict profile parameters such as waviness, skewness and kurtosis that are related to the shapes and distributions of the asperities. Similarly, since the analytical model addressed only the steady-state roughness and erosion rate, it could not simulate the transient development of roughness and topography from an initial state to a steady-state condition. Finally, the analytical model assumed that lateral cracking was the sole erosion mechanism in a brittle material, and the possibility of edge chipping of the facets of an eroded surface was not considered. This paper describes a numerical model that simulates the erosion process and predicts the centerline roughness and erosion rate of unmasked channels machined in borosilicate glass using AJM. The model incorporates the effects of particle size, velocity, angle of attack, and particle dose, and permits the simulation of the erosion in the transient period prior to the onset of a steady-state surface topography. In addition to lateral cracking, the contribution of the edge chipping of asperities was considered for the first time as a damage mechanism in the erosion process. Comparisons were made with experimental measurements of roughness and erosion rate as a function of the erodent dose and processing conditions.

2. Target damage due to particle impacts

Although the damage to a flat surface of a brittle material due to sharp indentation has been extensively studied in literature, after a number of impacts the surface can no longer be considered flat and particle impacts on asperity edges may lead to edge chipping rather than the formation of the lateral or median/radial cracks described in [12,16]. Therefore, as mentioned previously, two damage mechanisms were considered in the present simulation: (1) material removal due to crack formation, and (2) edge chipping.

2.1. Crater removal

When a sharp particle strikes a substrate, compressive stresses cause a plastic zone to form beneath the indentation zone. Assuming that all the kinetic energy of the impinging particle is dissipated in plastic deformation, the impact force, P, at the maximum indentation depth generated by a particle of radius R and velocity v impacting perpendicular to the surface is [17]

$$P = [2\pi\sqrt{2H}\tan(\psi)\rho_p]^{2/3} v^{4/3} R^2 \tag{1}$$

where H is the target hardness, ρ_p is the particle density, and ψ is the included angle of the indenting edge of the particle. The load threshold to form lateral cracks was estimated as [12]

$$P_0 = \frac{1200\, E\, K_c^4 \tan^{2/3}(\psi)}{0.75^2 H^4} \tag{2}$$

where E denotes the target elastic modulus and K_c is the fracture toughness. If the indentation force, P, is greater than the threshold, P_0, lateral cracks are predicted to initiate from the bottom of the plastic zone at a depth b [12], or from the bottom of the indentation zone at a depth a [18–22], and curve toward the surface as they grow radially outward (Fig. 1a). A chip is removed when the lateral crack reaches the surface. The size of the indented zone, a, the plastic zone size, b, and the lateral crack length, c_L, all depend on the particle kinetic energy, U, and the mechanical properties of the target as given by the following relations [12,13]:

$$a = \left(\frac{3\,U}{2\pi H}\right)^{1/3} \tag{3}$$

$$b \cong 0.63\, a \left(\frac{E}{H}\right)^{1/2} \tag{4}$$