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Simulation of erosive smoothing in the abrasive jet micro-machining of glass

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ABSTRACT

Abrasive jet micro-machining (AJM) is a promising technique to machine micro-features in brittle and ductile materials. However, the roughness of micro-channels machined using AJM is generally greater than that from other methods of micro-machining such as wet etching. Previous investigators have suggested that the surface roughness resulting from AJM can be reduced by post-blasting with abrasive particles at a relatively low kinetic energy. This approach was investigated in the present work by measuring the roughness reduction of a reference unmasked channel in borosilicate glass as a function of post-blasting particle size, velocity, dose, and impact angle. Post-blasting the reference channels reduced the roughness by up to 60%. It was observed that post-blasting at shallower angles was more efficient, probably due to the increased amount of edge chipping as opposed to cratering, which contributed to the enhanced removal of profile peaks, leaving a smoother surface. Moreover, post-blasting with smaller particles ultimately resulted in smoother surfaces, but at the penalty of requiring a relatively large particle dose, and consequently a significantly increased channel depth, before reaching the steady-state roughness. Hence, finishing with smaller particles until reaching the steady-state roughness may not be practical when a shallow channel is desired. A previously developed numerical model was modified and used to simulate the post-blasting process leading to the creation of smooth channels as a function of particle size, velocity, dose, impact angle, and target material properties. The model simulated both crater formation (due to growth of lateral cracks) and the chipping of facet edges. Comparisons with centerline roughness measurements for channels in borosilicate glass showed that the model can predict the transient roughness reduction with post-blasting particle dose with a 7% average error.

1. Introduction

Abrasive jet micro-machining (AJM) utilizes an abrasive particle jet to mechanically etch micron-sized features into various materials for micro-systems fabrication. A possible disadvantage of AJM in micro-fluidic applications is the relatively high resulting surface roughness that can affect fluid flow phenomena. Ghobeity et al. (2012) compared the separation efficiency of glass channels machined using AJM and wet etching and found that the separation efficiency in AJM channels ($R_a \sim 0.4$–$0.6\,\mu$m) was significantly lower (0.2–0.25 times) than that in wet-etched channels ($R_a \sim 2$–5 nm). Similarly, Solignac et al. (2001) observed that the electro-osmotic mobility in AJM channels in soda-lime glass is less than 50% of that in HF-etched channels. Moreover, Ladouceur (1997) has shown that roughness is a constraining factor in opto-electronics devices where it scatters light and attenuates power. Therefore, methods to reduce roughness resulting from AJM operations are highly desirable.

The mechanics of cracking in brittle materials due to Vickers indentation was investigated by Marshall et al. (1982) who derived equations to predict the length and depth of lateral cracks as a function of the material properties and indentation force. Utilizing fracture mechanics models of Vickers indentations (Marshall et al., 1982), Slikkerveer et al. (1998) estimated the erosion rate and steady-state 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 length and a depth equal to that of the plastic zone radius and by assuming that there was no overlap among impact sites. It was concluded that the only important parameter affecting the roughness was the kinetic energy of the impinging particles associated with the velocity

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Table 1
Mechanical properties of the borosilicate glass targets.

Elastic modulus (GPa)	Fracture toughness (MPa $\sqrt{m}$)	Vickers hardness (GPa)	Density (g/cm^3)	Poisson's ratio
63	0.76	5.2	2.2	0.2

component normal to the target. The present authors investigated the accuracy of this model by measuring the dimensions of individual impact sites resulting from the AJM of borosilicate glass by using aluminum oxide particles of various sizes (Jafar et al., 2013a). It was found that lateral crack initiation was better approximated as originating from the indentation depth rather than the bottom of the plastic zone, as was assumed in the model of Slikkerveer et al. (1998). Roughness measurements for various impact angles also showed that R_a increased with tangential velocity component; i.e. R_a was not a function of only the kinetic energy due to the normal velocity. This observation was not explored further in Jafar et al. (2013a) where the analytical model was compared only with steady-state roughness measurements made at 90° impact angle.

The present authors (Jafar et al., 2013b) also developed a numerical model of the erosion process that was used to predict the steady-state roughness and erosion rate of unmasked channels resulting from AJM on borosilicate glass as a function of particle size, velocity, dose, and impact angle. It was assumed that two brittle damage mechanisms contributed to erosion: (1) crater removal due to the initiation and growth of lateral cracks and (2) edge chipping due to the propagation of cracks through a facet in the direction of the impact. The model predicted the steady-state roughness and the erosion rate of unmasked channels machined in borosilicate glass with average errors of 9% and 29% respectively, when compared with experimental data over a wide range of machining conditions. Moreover, the model predicted profile shape parameters such as waviness, skewness, and kurtosis with less than 15% error compared with experimental data. The results showed that, although the number of edge chipping events (the second erosion mechanism) increased with decreasing angle of attack, the main damage mechanism was crater removal, even at shallow angles.

The roughness of a typical borosilicate glass channel machined with AJM depends strongly on the particle kinetic energy, varying from 0.1 μm to 9 μm using alumina particles with average sizes from 5 μm to 200 μm, respectively (Slikkerveer et al., 1998). The smoothing of glass surfaces after AJM has not been investigated extensively in literature. Wensink et al. (2002) achieved a 100% reduction in the roughness of two reference channels machined in borosilicate glass using either 9 μm or 29 μm alumina by annealing the eroded glass at a temperature just below its softening point. In contrast, a post-blast wet etching of the reference channels with hydrofluoric acid produced a rougher surface, probably because of the opening of cracks generated by the AJM. Post-blasting the reference channels with 3 μm alumina decreased the roughness of both reference channels by about 25% while the depth of the channels increased approximately 10 μm. Mineta et al. (2009) examined the reduction of roughness due to post-blasting using a wet abrasive on a borosilicate glass (Pyrex^{TM}) substrate. Both the original and the post-blasted channels were machined using an aqueous abrasive slurry of 4 μm alumina, however the later were machined with a lower pressure so that a ductile-mode erosion was dominant, resulting in a roughness reduction of about 50%.

The present work investigated the role of post-blasting particle size, velocity, dose, and impact angle on roughness reduction of unmasked channels machined in borosilicate glass using AJM. A numerical model, which was previously developed to predict the steady-state roughness resulting from the AJM of an initially un-eroded surface (Jafar et al., 2013b), was used to predict both the transient and steady-state roughnesses resulting from post-blasting smoothing operations.

2. Experiments

2.1. Apparatus and target material

The experiments were conducted using an AccuFlo abrasive blaster from Comco Inc. (Burbank, CA, USA) with a blasting nozzle having an inner diameter of 1.5 mm that was held stationary at a nozzle-to-surface stand-off distance of 10 mm (centerline distance between the nozzle exit and the target). The target material was 3 mm thick Borofloat® 33 borosilicate glass (Schott Inc., NY, USA) with the mechanical properties given in Table 1. To create unmasked channels, the glass specimen was clamped to a computer-controlled stage and moved across the blast zone of a stationary nozzle at a scan speed, V_s, of 0.25–20 mm/s using various angles of nozzle inclination, measured with respect to the target surface, θ. Varying the scan speed provided a convenient way of changing the particle dose.

The surface roughnesses were reported as the average of three repeat measurements along a 5 mm length of the centerline of the machined channels using an optical profilometer (Nanovea Inc., Irvine, CA) with a 0.2 μm step size and a cut-off length of 800 μm. A more detailed discussion of the roughness measurements can be found in Jafar et al. (2013a).

To provide a baseline channel roughness from which various post-blasting scenarios could be evaluated, unmasked reference channels were machined at normal incidence (i.e. $\theta = 90^\circ$), using 150 μm alumina particles at a scan speed of 4 mm/s and a pressure of 200 kPa. The average depth of three machined reference channels measured with the optical profilometer was 165 μm, with a standard deviation of 7.6 μm, while the average width was approximately 3 mm. The steady-state roughness of these same reference channels was $R_a = 5.0$ μm, with a standard deviation for three channels of 0.27 μm. The reference channels were then post-blasted with alumina particles of various sizes (50, 100 and 150 μm) at pressures of 100 and 200 kPa, and impact angles of 30°, 60° and 90°. The standard deviations over three measurements of the centerline roughness and centerline depth (or erosion rate) of the post-blasted channels were less than 10% of the mean values. Table 2 summarizes the AJM process parameters used in the machining of the reference and the post-blasted channels.

Table 2
Process parameters used to machine the reference and the post-blasted channels.

Channel	Particle size (μm)	Pressure (kPa)	Impact angle (°)	Scanning speed (mm/s)	Stand-off distance (mm)
Reference	150	200	90	4	10
Post-blasted	50, 100, 150	100, 200	30, 60, 90	0.25–20	10