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Surface roughness and erosion rate of abrasive jet micro-machined channels: Experiments and analytical model

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ABSTRACT

Abrasive jet micro-machining (AJM) uses a high velocity particle jet to erode features in target substrates for a variety of applications, including micro-electro-mechanical and micro-fluidic device fabrication. 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 micro-scale adhesion contact in MEMS and light scattering in optoelectronics devices.

This paper presents experimental data on the effect of particle size, velocity, and angle of attack on the roughness of unmasked channels machined in borosilicate glass using AJM. Single impact experiments were conducted to quantify the damage due to the individual alumina particles. Based on these observations, the assumed location of lateral crack initiation in a relatively simple analytical model from the literature was modified, and used to predict the roughness and erosion rate. The previous model, which calculated an areal roughness, was also modified to yield a 2D linear value of R_a so that it could be compared with linear profilometer scans. This modified model predicted the steady-state roughness and erosion rate of unmasked channels with average errors of 36% and 73%, respectively.

1. Introduction

Abrasive jet micro-machining (AJM) uses an air jet to accelerate solid erodent particles toward the target surface at velocities reaching 300 m/s [1,2]. AJM has been used to make micro-electro-mechanical devices such as inertial sensors [3], electronic devices [4], and micro-fluidic components for capillary electrophoresis chips [5,6] and biochemical separations [3]. The roughness of micro-channels made using AJM can affect fluid flow phenomena in micro-fluidic applications. For example, it has been observed that the rougher the channel, the lower the separation efficiency [2,4] and electro-osmotic mobility [5], and the higher the solute dispersion [7]. Surface roughness also plays a major role in micro-scale adhesion contact in MEMS [8], and is a constraining factor on optoelectronics devices where roughness scatters and attenuates light [9]. Therefore, models to predict the roughness of the evolving features machined using AJM would be very useful.

While the erosion of brittle materials has been extensively studied in the literature [10,11] and several wear models have been developed [12], there are relatively few studies that model the resulting surface roughness. Marshall et al. [13] examined lateral crack formation (i.e. subsurface cracks approximately parallel to the surface) in a number of brittle materials due to the Vickers indentation, and derived equations to predict the length and depth of the cracks as a function of the target material properties and the indentation force. Slikkerveer et al. [1] used those findings to estimate the erosion rate and roughness of channels in a borosilicate glass. They assumed that each particle impact removed a spherical cap of material with a radius and depth equal to that of the predicted lateral crack. This simple model overestimated the erosion rate by a factor of four, while the roughness was predicted to the correct order of magnitude. The results implied that the surface roughness was only a function of the particle kinetic energy due to the velocity component perpendicular to the surface, and was independent of particle size. This is consistent with the observations of Buijs and Pasmans [14] who reported that the roughness of channels machined in soda lime glass increased with increasing velocity of 30 μm alumina particles blasted at perpendicular incidence (i.e., incident 90° to the

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surface). Similarly, Wensink et al. [15] observed that the roughness of channels in Pyrex™ glass and silicon also increased with the kinetic energy of alumina particles (9 and 29 μm) blasted at 90°. However, it is not possible to make direct comparisons of the roughness in these studies because the cut-off wavelength (low-pass filter) was not given in each case.

This paper presents experimental data concerning the effect of particle size, velocity, and angle of attack on the roughness and erosion rate of unmasked channels in borosilicate glass. The damage from single impacting particles was quantified, and used to improve the analytical model of roughness and erosion rate presented in Ref. [1] to better match experimental results.

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 which was held stationary at a nozzle-to-surface centerline stand-off distance of 10 mm. The target material was 3 mm thick Borofloat® 33 borosilicate glass (Schott Inc., NY, US) cut into 100 mm × 50 mm plates. The mechanical properties of the glass as reported by the manufacturer are: elastic modulus: 63 GPa, fracture toughness: $0.76\ \mathrm{MPa}\sqrt{\mathrm{m}}$, density: $2.2\ \mathrm{g/cm^3}$. The average Vickers hardness of the glass (10 indentations, 0.2 kg load) was measured to be 5.2 GPa. Straight, unmasked channels were made by attaching the glass specimen to a computer-controlled stage and scanning it below the stationary nozzle at a scan speed, V_s, of 2 mm/s at different impact angles, θ (Fig. 1).

2.2. Particle characterization

Aluminum oxide particles of various nominal diameters (25 μm, 50 μm, 100 μm, and 150 μm) were used as blast media. The powders were sampled according to ASTM C702-98 [16] in order to minimize sampling bias. The distributions of the particle equivalent circular diameters, $d=2\sqrt{A/\pi}$ were determined based on measurements of the particle areas, A, obtained using an automated optical analysis system (Clemex Vision PE, Clemex Technologies Inc., QC, Canada). Particles with $d<5\ \mu\mathrm{m}$ were ignored, and the size distributions of the 25 and 50 μm alumina particles were fitted with a log-normal distribution [17]:

$$f_1(d)=\frac{1}{d\sigma\sqrt{2\pi}}\,e^{\left(-[\ln(d)-\mu]^2/2\sigma^2\right)} \tag{1}$$

where μ and σ are the log-normal location and scale parameters, respectively (Table 1). The following Weibull distribution was used to fit the size distribution of the 100 and 150 μm particles [18]:

$$f_2(d)=\frac{\kappa}{\lambda}\left(\frac{d}{\lambda}\right)^{\kappa-1}e^{-(d/\lambda)^{\kappa}} \tag{2}$$

where κ and λ are the Weibull shape and scale parameters, respectively (Table 1). These size distributions compared well with those provided by the manufacturer using laser diffraction measurements of airborne particles, with less than 10% difference in the average mean diameter for the four particle sizes.

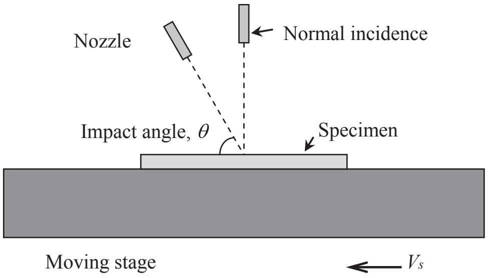

Fig. 1. Schematic of AJM blasting configuration.

Table 1
Measured particle size distribution parameters of aluminum oxide particles.

Nominal particle size from manufacturer (μm)	Diameter range (μm)	Mean diameter (μm)	Log-normal distribution parameters		Weibull distribution parameters	
			μ	σ	λ (μm)	κ
25	8–53	22	2.27	0.41	–	–
50	9–85	41	3.67	0.33	–	–
100	13–245	138	–	–	153.7	3.2
150	15–252	182	–	–	197.8	5.1

Table 2
Measured velocity of aluminum oxide particles for the entire jet at 10 mm from the nozzle exit. Velocity range corresponds to 95% of population.

Condition	Particle size (μm)	Pressure (kPa)	Velocity range (m/s)	Mean velocity (m/s)
#1	25	200	130–202	162
#2	50	100	56–107	80
#3	50	200	88–169	118
#4	50	300	90–191	137
#5	100	100	45–86	57
#6	100	200	66–148	90
#7	100	300	80–158	109
#8	150	200	62–97	78
#9	150	300	72–131	95

The blasting was performed at pressures between 100 and 300 kPa, and the associated particle velocity distributions within the jet at 10 mm from the nozzle exit were measured using high resolution imaging with laser-pulsed backlight illumination (shadowgraphy) [17]. Table 2 lists the measured particle velocities for all the considered machining conditions.

The abrasive mass flow rates were between 3 and 15 g/min (depending on the particle size), as measured by weighing the mass of abrasive particles blasted for 2 min into a closed container having a filter at the end to permit the air to escape. The particle collision model of [19] showed that these particle fluxes were sufficiently low to make the effect of inter-particle collisions negligible.

2.3. Target damage due to single impacts

Buijs and Pasmans [14] related surface roughness to the target damage caused by individual particle impacts. Following this approach, single impact sites were generated by exposing the borosilicate glass to the jet of aluminum oxide particles for 0.1 s using an electronically controlled shutter activated by a solenoid. Particles with sizes of 50 μm, 100 μm and 150 μm were blasted at 100 kPa and the impact sites on the target were measured using an optical profilometer (Model ST400, Nanovea Inc., Irvine, CA) with a depth resolution of 10 nm.

2.4. Roughness and erosion measurement

When the aluminum oxide particles were blasted with $V_s=2$ mm/s, the steady-state roughness was reached in a single pass of the nozzle, so that a transient period was not recorded. Therefore, all further presented roughness data is at steady-state. The roughness was measured along the centerline of the machined