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Surface evolution models for abrasive slurry jet micro-machining of channels and holes in glass

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ABSTRACT

Abrasive slurry jet micro-machining (ASJM) uses a jet of abrasive slurry to erode features with relatively high resolution without the need for a patterned mask. The present study investigated the ability of a surface evolution model to predict the profiles of micro-channels and holes machined in borosilicate glass with a newly developed ASJM system. The system could produce micro-channels with depth and width variations along their length of less than 3%, and a channel-to-channel repeatability within 5%. The fundamental erosion rate of the borosilicate glass was measured as a function of impact angle using a slurry of water mixed with a low concentration of 10 and 25 μm nominal diameter aluminum oxide particles. This erosion rate-impact angle relationship was used in an existing model developed previously for the abrasive air jet micro-machining of brittle materials. The results demonstrated that, despite the differences in abrasive flow patterns between air and slurry based systems, the surface evolution model accurately predicted the profiles of micro-channels with a maximum error of 7% for aspect ratios (depth/width) of up to 5. The predicted profiles of holes were also in reasonable agreement with a maximum error of 14% for aspect ratios close to 1.

1. Introduction

Abrasive slurry jet micro-machining (ASJM) utilizes pressurized water to accelerate suspended abrasive particles such as garnet or aluminum oxide (Al_2O_3). Material removal occurs by mechanical erosion with little of the heating that can alter material properties [1]. Slurry jets have relatively high resolution machining capabilities [2], allowing for the fabrication of features such as micro-holes and channels without the use of patterned masks. Furthermore, the ready control of the erosion rate through the operating parameters such as slurry jet flow rate or pressure, concentration, impact angle and traverse speed simplifies the geometrical control of micro-machined features, such as, for example, channels of varying depth or width.

A high pressure (70 MPa) abrasive slurry jet (ASJ) system for cutting metals, glass, ceramics, polymers and composite materials was developed by Miller [3]. The system consisted of a pair of plunger water pumps powered by compressed air connected to an abrasive storage vessel filled with abrasive suspensions. The abrasive mixture was added to the pressurized water from the pumping unit before the slurry exited the orifice. It was found that the particle mass flux was not constant in the apparatus due to the development of a layer of unmixed particles at the bottom of the storage vessel. Pang et al. [4] developed a similar ASJ apparatus for low pressure (2–14 MPa) micro-machining applications using an air-driven water pump, an abrasive slurry tank and a shaker to control the abrasive concentration. The micro-channels machined with this apparatus were found to be wavy due to mechanical vibration.

Nouraei et al. [5] developed a low pressure (1–4 MPa) ASJ prototype utilizing compressed air to drive the slurry and a slurry tank with a mixing propeller. However, due to the small size (i.e. 500 mL) of the pressurized cylinder used as the slurry tank, the total continuous machining time was less than 5 min. Moreover, the spring-loaded seals in the setup were not rated for pressures higher than 5 MPa, and as a result, micro-machining at higher kinetic energies was not feasible. The ASJ system used in the present work overcomes the shortcomings of these previous devices.

Pang et al. [6] modeled the erosion rate, opening width and wall slope of ASJ machined channels in glass using dimensional analysis and multi-variable regression of experimental data. While this approach is practically very useful, it relies on data obtained from a relatively large set of experimental trials. For the further development of ASJM technology, it is desirable to develop models

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capable of predicting the shape and size of micro-machined features without recourse to extensive testing. Surface evolution models have been developed primarily to predict the shapes of masked features fabricated by abrasive air jets in brittle materials such as glass by ten Thije Boonkkamp and Jansen [7], and Slikkerveer and in't Veld [8]. Ghobeity et al. [9,10] improved the accuracy of these evolution models by using a “first-pass profile”, and later, an analytical model [11] to characterize the erosive efficacy across the mask opening when performing abrasive air jet micro-machining (AJM). The surface evolution models were later modified by Getu et al. [12,13] to predict the profile of masked and unmasked AJM features in ductile materials.

Axinte and coworkers [14,15] used the waterjet footprint, similar to the first-pass profile described above, and a surface evolution model in order to model abrasive high-pressure abrasive waterjet milling (AWJM) processes. The cross-sectional profile of the jet footprint was predicted for a wide range of scan speeds. The velocity exponent, *k*, which relates the etching rate to the impact velocity, was obtained from the shallow single pass profile of the jet foot print rather than from fundamental measurements of erosion rate. Correction coefficients accounting for changes in etch rate with depth were implemented in order to predict the jet foot print up to aspect ratios (channel centerline depth/width) of 1.1. Such correction coefficients are not necessary in the case of ASJM, since the standoff distance does not affect the depth and width of such micro-machined features [5].

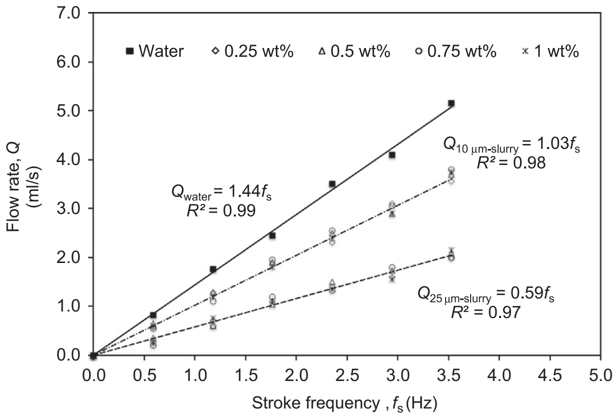

Fig. 2. Flow rates of water, 10 and 25 μm nominal diameter Al_2O_3 slurries of various concentrations as a function of pump stroke frequency. Each point is the average of 5 measurements, amongst which the variability was less than 8% of the mean.

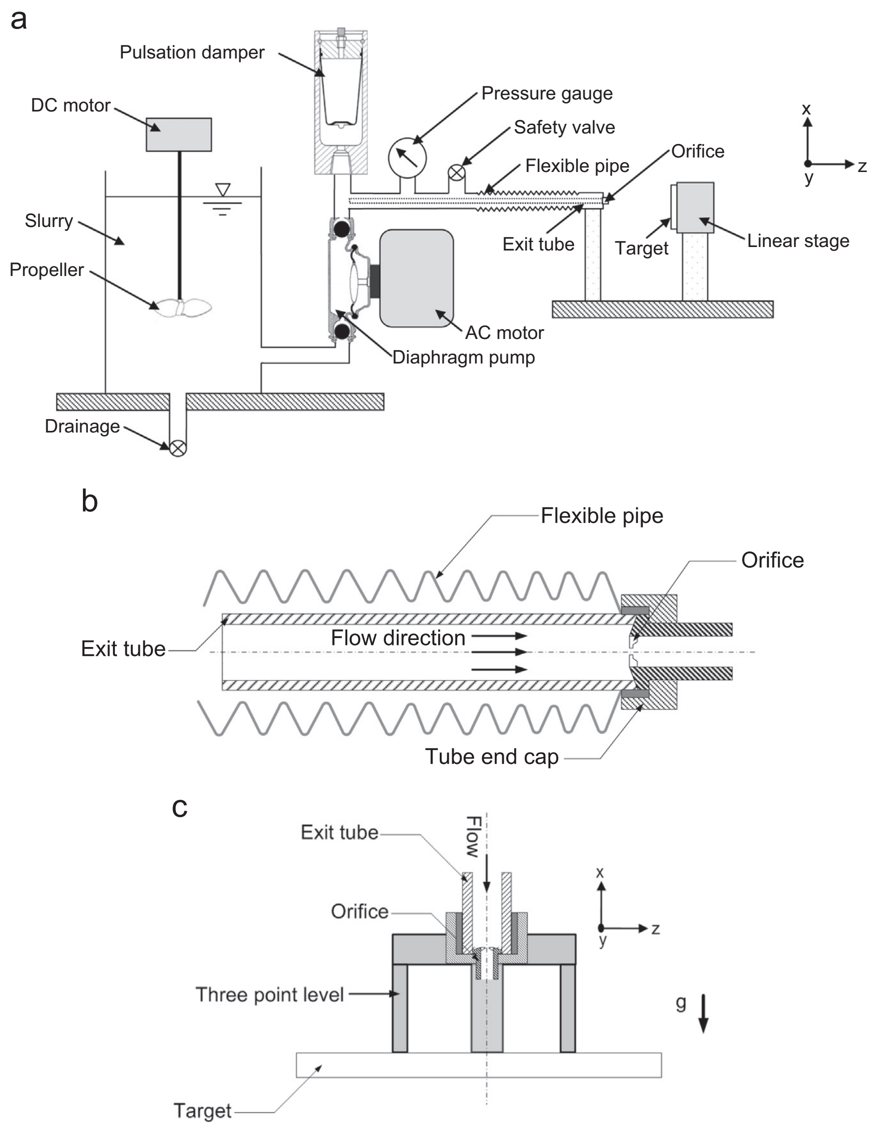

Fig. 1. (a) Schematic of the abrasive slurry jet apparatus, (b) orientation of orifice installation, and (c) orientation of orifice in micro-hole machining experiments (not to scale) [18].