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Characteristics of abrasive slurry jet micro-machining: A comparison with abrasive air jet micro-machining

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ABSTRACT

Abrasive slurry jet micro-machining (ASJM) uses a well-defined jet of abrasive slurry to erode features in a solid target. Compared with abrasive water jet machining (AWJM), the present ASJM system operates at pressures that are roughly two orders of magnitude lower and uses a premixed slurry of relatively low concentration. The objective of the present study was to gain a better understanding of the mechanics of erosion in ASJM by comparing its performance in the micro-machining of holes and channels in borosilicate glass with that of abrasive air jet micro-machining (AJM), a process that is simpler and relatively well understood. A new ASJM system was developed and used to machine blind holes and smooth channels of relatively uniform depth that did not suffer from the significant waviness previously reported in the literature. The effect of particle velocity, particle concentration, jet traverse speed and jet impact angle were examined. A direct comparison of ASJM and AJM results was possible since novel measurements of the crushing strength of the aluminum oxide abrasive particles used in both experiments proved to be unaffected by water. Brittle erosion was shown to be the dominant material removal mechanism in both ASJM and AJM in spite of the significant flow-induced decrease in the local impact angles of many of the particles in ASJM. A new model of the rapid particle deceleration near the target surface helped explain the much smaller erosion rates of ASJM compared with those in AJM. The modeling of the erosion process during the micro-machining of channels showed that the effect of the local impact angle at the leading edge of the advancing jet was much more significant in ASJM than in AJM, primarily due to the narrower focus of the jet impact zone in ASJM. The differences in the water and air flow fields and associated particle trajectories were used to explain the steeper side walls and flatter bottoms of the holes and channels machined with unmasked ASJM compared to those with masked AJM. The respective structures of the water and air jets also explained the much sharper definition of the edges of these features using ASJM compared with maskless AJM. The results of the study show that ASJM can be used to accurately micro-machine channels and holes with a width of 350–500 μm and an aspect ratio of 0.5–1.3 without the use of masks.

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1. Introduction

Traditional micro-machining techniques such as micro-milling, chemical wet etching, electrical discharge machining (EDM) and laser micro-machining require relatively expensive equipment, can be time-consuming, and can suffer from a number of other limitations. For example, chemical wet etching requires hazardous chemicals such as hydrogen fluoride (HF) as described by Huang et al. (2011). Micro-milling tool failure is difficult to predict, and tool deflection and radial errors in the tool tip trajectory (run-out) affect the accuracy of the desired features as illustrated by Iordan and Burlacu (2010) and Cheng et al. (2011). Iordan and Burlacu (2010) and Cheng et al. (2011) have also found that micro-milling creates machined chips that have submicron-level dimensions, making their removal difficult. Micro-machining with EDM suffers from electrode wear which makes it difficult to reproduce sharp corners and fillets on the workpiece. As shown by Kucukturk and Cogun (2010), EDM can also produce large temperature variations, increasing the magnitude of compressive and tensile stresses, ultimately leading to crack formation in the workpiece. Ogura and Yoshida (2003) found that micro-machining with a laser causes local melting and a heat-affected zone, as well as material pile-up adjacent to the cut that can obstruct subsequent bonding and device assembly.

Belloy et al. (2000) used abrasive jet micro-machining (AJM) to fabricate components for micro-electro-mechanical systems

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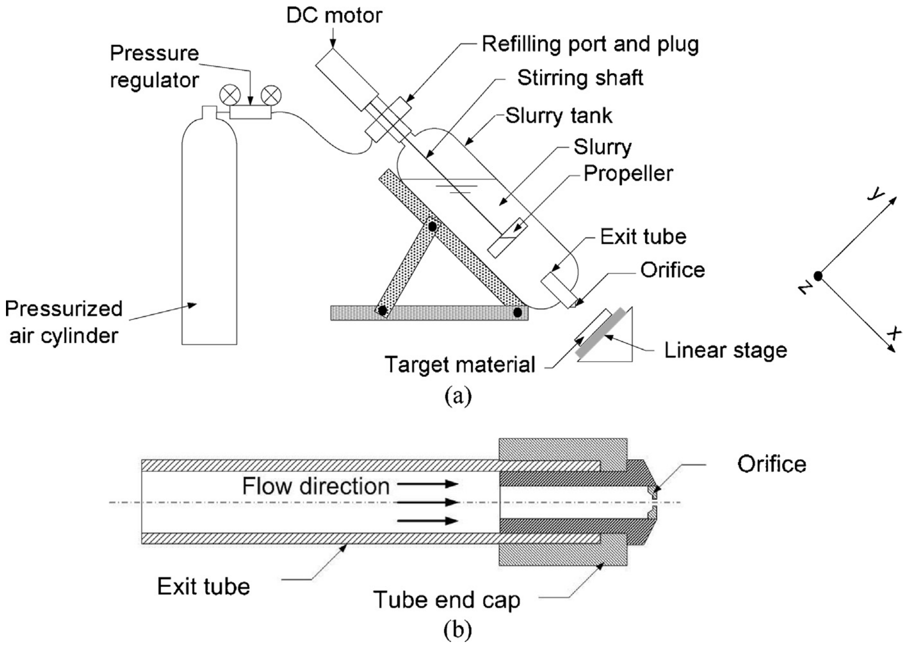

Fig. 1. (a) Schematic of the abrasive slurry jet apparatus (Nouraei et al., 2011), and (b) orientation of orifice installation (not to scale).

(MEMS) such as inertial sensors. Schlautmann et al. (2001) and Guijt et al. (2001) used AJM to produce micro-fluidic components for capillary electrophoresis chips. One of the disadvantages of AJM is that the compressed air jet used to propel the erodent particles against the target material diverges significantly after the nozzle exit, lowering the resolution of the process considerably. Zhang et al. (2005) suggested that AJM must be used in conjunction with patterned erosion resistant masks in order to define the micro-feature edges. Wensink et al. (2002) found another potential weakness of AJM, which is the relatively high surface roughness of the micro-machined features and made some progress in improving the surface quality.

Abrasive slurry jet micro-machining (ASJM) is similar to AJM except that pressurized water instead of air is used to accelerate the suspended abrasive particles such as garnet or aluminum oxide (Al_2O_3). As reported by Liu (2010) in both AJM and ASJM, material removal occurs by erosion with little heating that can alter material properties. Wodoslawsky (2011) found that for the same jet dimension and flow speed, slurry jets have a much lower divergence angle than air jets, allowing for the micro-machining of smaller features without the use of patterned masks.

High pressure ASJM was investigated by Miller (2004), who used a slurry at a pressure of 70 MPa to cut micro-slots into metals, glass, ceramics, polymers and composite materials. Nguyen et al. (2009) and J. Wang et al. (2009) studied the mechanisms of micro-hole formation in glass with ASJM. Based on the crack free surfaces of machined holes, it was concluded that ductile erosion mechanisms dominated. Also, it was shown that increasing the pressure and erosion time increased the hole depth, with an insignificant effect on the hole diameter. The holes were characterized by a “W” shaped cross-section, which was explained in terms of the variation in particle trajectories near the target. It was illustrated that as the slurry jet flow expands along the target surface, three zones develop, each with a different erosion rate. A direct impact zone results from the initial impact of the slurry jet on the target. An adjacent wavy zone is due to the subsequent slurry flow along the target surface spreading out from the impact zone. And an accumulation zone develops as the slurry flow momentum decreases and particles accumulate at the bottom of the machined holes in a turbulent mixture. C.Y. Wang et al. (2009) studied the effect of operating parameters such as slurry pressure, jet exposure time, standoff distance and particle concentration on the machining of micro-holes in glass. It was observed that the material removal rate was approximately proportional to the applied pressure, jet exposure time and particle concentration. The hole depth and material removal rate decreased with increasing standoff distance. Pang et al. (2010, 2012) modeled the erosion rate, opening width and wall slope of machined channels in glass using dimensional analysis and multi-variable regression of experimental data. They found that the machined channels suffered from severe waviness due to the mechanical vibration of the equipment.

The present study examined the micro-machining of holes and channels in borosilicate glass with a new ASJM system, and compared the machined features with those produced by abrasive air jet micro-machining (AJM). This enabled an improved understanding of the mechanics of micro-slurry jet erosion and its relation to the fluid flow of the impinging jet.

2. Experiments

2.1. ASJM setup

Hashish (1991) and Miller (2004) suggested that the ASJM process parameters that control the quality of machined features fall into three categories: (i) hydraulic parameters such as the water jet pressure and nozzle geometry; (ii) machining parameters including principally the traverse speed, standoff distance and global impact angle; and (iii) the abrasive material, its flow rate, and the particle shape and size.

Fig. 1(a) shows a schematic of the low-pressure ASJM system that was developed for the present study. Air from a pressurized cylinder was used to propel the premixed slurry from a 500 mL tank (Swagelok, Mississauga, ON, Canada) through a sapphire orifice toward the target material. A 100 mm long stainless steel exit tube with 4 mm I.D. was positioned within the slurry tank so that it butted against the orifice, in order to maintain a slurry flow rate adequate to prevent particle sedimentation and clogging of the orifice. The specimens were mounted on a computer-controlled linear stage (KT-LSM100A, Zaber Technologies Inc., Vancouver, BC,

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