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Abrasive slurry jet micro-machining of holes in brittle and ductile materials

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ABSTRACT

This paper investigated the effects of elasticity and viscosity, induced by a dilute high-molecular-weight polymer solution, on the shape, depth, and diameter of micro-holes drilled in borosilicate glass and in plates of 6061-T6 aluminum alloy, 110 copper, and 316 stainless steel using low-pressure abrasive slurry jet micro-machining (ASJM). Holes were machined using aqueous jets with 1 wt% 10 μm Al_2O_3 particles. The 180 μm sapphire orifice produced a 140 μm diameter jet at pressures of 4 and 7 MPa. When the jet contained 50 wppm of dissolved 8 million molecular weight polyethylene oxide (PEO), the blind holes in glass were approximately 20% narrower and 30% shallower than holes drilled without the polymer, using the same abrasive concentration and pressure. The addition of PEO led to hole cross-sectional profiles that had a sharper edge at the glass surface and were more V-shaped compared with the U-shape of the holes produced without PEO. Hole symmetry in glass was maintained over depths ranging from about 80–900 μm by ensuring that the jets were aligned perpendicularly to within 0.2°. The changes in shape and size were brought about by normal stresses generated by the polymer. Jets containing this dissolved polymer were observed to oscillate laterally and non-periodically, with an amplitude reaching a value of 20 μm. For the first time, symmetric ASJM through-holes were drilled in a 3-mm-thick borosilicate glass plate without chipping around the exit edge.

The depth of symmetric blind holes in metals was restricted to approximately 150 μm for jets with and without PEO. At greater depths, the holes became highly asymmetric, eroding in a specific direction to create a sub-surface slot. The asymmetry appeared to be caused by the extreme sensitivity of ductile materials to jet alignment. This sensitivity also caused the holes in metals to be less circular when PEO was included, apparently caused by the random jet oscillations induced by the polymer. Under identical conditions, hole depths increased in the order: borosilicate glass > 6061-T6 aluminum > 110 copper > 316 stainless steel. The edges of the holes in glass could be made sharper by machining through a sacrificial layer of glass or epoxy.

1. Introduction

Applications of low-pressure abrasive slurry jets, or micro abrasive suspension jets as they are also sometimes called, have been evolving for over a decade. One important application is in the abrasive slurry jet micro-machining (ASJM) of glass. As a machining process, it is economical and offers advantages such as the absence of a heat-affected zone, low forces on the work piece, no tool wear or vibration, and the ability to machine virtually any material. The small divergence of the jet makes ASJM well suited for precision machining.

Miller (2004) developed a high-pressure ASJM system, using a slurry content of approximately 20 wt%, 8 μm diameter garnet abrasives, pressures of roughly 70 MPa, and 40–60 μm diameter orifices. The system was used to cut a variety of materials, including metals, polymers, glass, and composites, with thicknesses ranging from 50 to 3000 μm. The depth to width ratios of the cuts were much greater than those typical of laser cutting. Nguyen et al. (2009) drilled holes in glass using a low-pressure (3 MPa) and a high concentration (8.2 wt%) slurry, and, in a companion paper,

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Wang et al. (2009a) studied the effects of pressure and machining duration on erosion in holes in glass. In both papers, the hole cross-sections were found to be W-shaped, related to the dominance of ductile erosion when the abrasive particles had relatively low kinetic energy. Nouraei et al. (2014) found that higher kinetic energies led to U-shaped holes with flatter bottoms and steeper sidewalls. Wang et al. (2009b) examined the profiles of holes machined in glass and found them to be asymmetric because of orifice vibration and misalignment. A typical cross-sectional profile shape was divided into various zones, and the shape of each zone was explained in terms of the direction of the slurry flow relative to the walls of the hole. Aqueous jets containing long-chain polymer additives, but not abrasives, have been studied for several decades. Hoyt et al. (1974) discovered that polymers delayed droplet formation and therefore enhanced jet stability by damping free surface disturbances. Another application of polymeric additives is friction reduction in turbulent pipe flow. For example, Elbing et al. (2011) found that trace concentrations of order 10 wppm (weight parts per million) reduced wall friction by about 75%. These advantages resulted from induced elasticity in the fluid. In general, the polymer chains are stretched from their initially-coiled equilibrium state when subjected to a sufficiently high deformation rate. This action generates normal stresses which increase the resistance to extensional deformation; i.e. the fluid behaves partially as an elastic solid, as described by Larson (1999, p. 123).

Hashish (1991) compared the cutting of aluminum using high-pressure abrasive waterjet machining (AWJM at 345 MPa), in which abrasive particles and air are entrained in a high-velocity jet, and high-pressure abrasive slurry-jet cutting. In both sets of experiments, the water contained 3 wt% 18-million (18-M) molecular weight polyacrylamide (PAM). The slurries were assumed to be Newtonian; therefore, the effects of fluid elasticity induced by the added polymers, as described by Larson (1999, p. 123), were not considered. He found that ASJM produced twice the cutting depth as AWJM using the same abrasive flow rate and pressure. Nguyen et al. (2008) found that concentrated solutions (1000–5000 wppm) of 1-M PAM enhanced the stability and increased the coherent length of an abrasive waterjet. Ashrafi (2011) found that the addition of a large amount of cornstarch (10–22 wt%) in AWJM produced cuts having narrower kerfs with steeper sidewalls, In another study with cornstarch, Omrani et al. (2013) also found a reduction in kerf taper, and hypothesized that it was due to changes in the fluid viscosity. The role of fluid elasticity generated by the polymer was not considered.

In work more closely related to the conditions of low-pressure ASJM than of high-pressure AWJM, Luo et al. (2010) compared low-pressure abrasive slurry jet polishing of glass with and without 4000 wppm (0.4 wt%) of a high-molecular-weight polymer, and found that the polymer sharpened the transition zone separating polished and unpolished regions, because of reduced divergence of the streamlines of the polymeric jet about the stagnation zone. In a companion study, Liao et al. (2009) investigated the effects of additives such as sodium hexametaphosphate (NaP), 4-M polyethyleneglycol, 20-M polyacrilic acid, 12-M PAM, and antimony trinitride on the low-pressure abrasive slurry-jet polishing of glass. They found that a combination of NaP and PAM resulted in the lowest surface roughness and postulated that this effect was due to the lower viscosity of this solution relative to others considered in the study, but did not consider fluid elasticity.

Wang et al. (2009c) investigated machining using a variety of polymers such as PAM, anionic polyacrylamide (HPAM), and cationic polyacrylamide (PAMA), and several abrasives (22 μm garnet, boron carbide, and white and brown corundum). They found that the slurry containing 6000 wppm 5-M PAM and white corundum particles yielded the most symmetrical holes with the largest material removal rate. No comparisons were made to holes machined without additives.

Most recently, Kowsari et al. (2014) studied the effects of dilute concentrations of polyethylene oxide (PEO, 25–400 wppm), on the shape, roughness, and width of low-pressure ASJM channels machined in glass. It was found that, for a constant jet velocity, diameter and dose of abrasive, the channel width decreased by 21% with the addition of 50 wppm of 8-M (PEO). This change was caused by normal stresses generated by the polymer, which focussed the erosion to a smaller blast zone.

The objective of the present study was to extend the above research on the effects of long-chain polymers in ASJM to the drilling of holes in ductile and brittle materials, with a focus on the

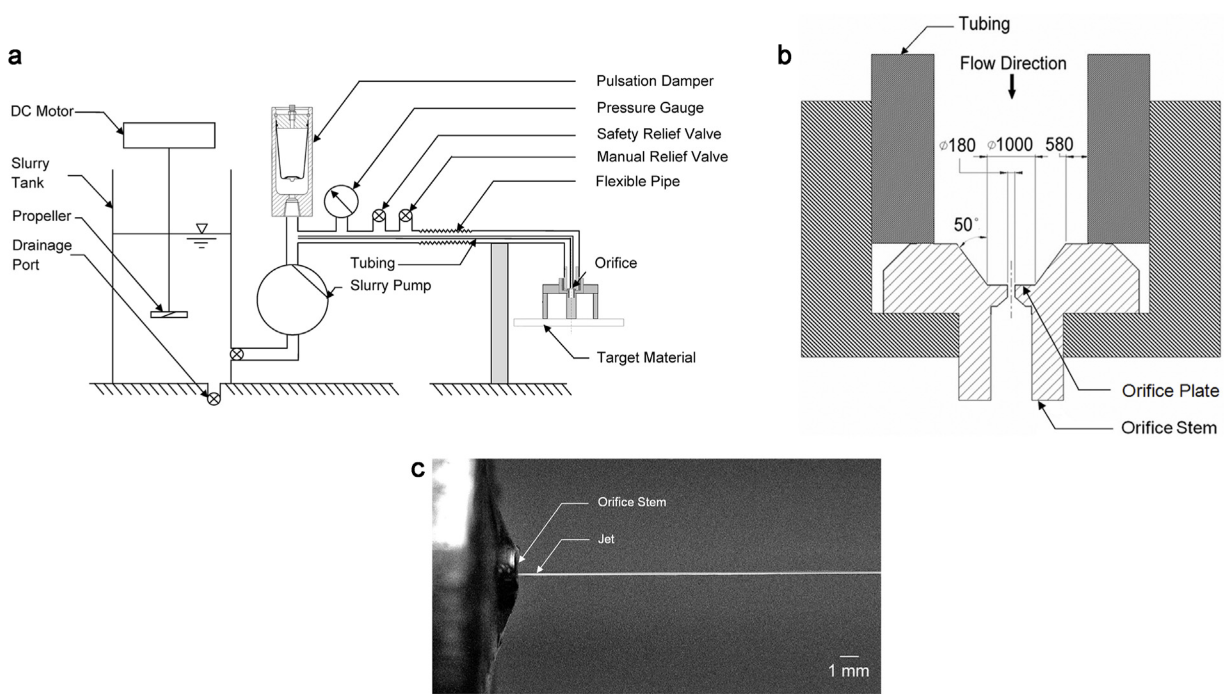

Fig. 1. (a) Schematic of the ASJM components (not to scale). (b) Orifice geometry (dimensions are in μm).