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Masked micro-channel machining in aluminum alloy and borosilicate glass using abrasive water jet micro-machining

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ABSTRACT

Abrasive water jets (AWJs) have recently been used to mill unmasked features as narrow as 600 µm. This paper investigated the use of metal masks in order to decrease this minimum possible feature width in Al6061-T6 and borosilicate glass. Although there was under-etching on the channel sidewalls below the mask edges, it was nevertheless found that masked channels could be machined that were between 2–3 times narrower with 11% lower centerline roughness and 44% lower waviness than those created without masks. It was also found that increases in mask thickness led to increases in the channel centerline depth and width, and decreases in the centerline roughness and waviness. Increases in the abrasive mass flow rate increased the channel width, but decreased the depth. Finally, the normalized instantaneous centerline erosion rates in the masked channels decreased faster with depth than in the unmasked cases. Reasons for these trends were discussed in terms of changes in abrasive slurry flow and in the size of the stagnation zone within the channels brought about by the masks. Overall, the study demonstrates that masked AWJ micro-machining of features as narrow as ~150 µm wide is possible, thus demonstrating the feasibility of the technique for the manufacture of microfluidic and other components.

1. Introduction

The next generation of devices used in micro-electromechanical systems (MEMS) and microfluidic systems will require directional etch capabilities for the micro-fabrication of three-dimensional non-planar components [1]. Traditional isotropic wet etching cannot be easily used to create such geometries, and other anisotropic etching technologies such as the electric discharge method and laser micro-machining are expensive, and can result in a heat affected zone and residual stresses, which can affect the material properties of the target material [2]. Deep reactive-ion etching can be used to fabricate very small and high-aspect features, but it suffers from a very low etch rate [2]. Abrasive water jet (AWJ) technology, on the other hand, can be used to very rapidly mill 3D structures by varying the traverse speed [3], and without creating a significant heat affected zone. This has driven efforts to reduce the minimum machinable feature size of AWJ to bring it into the realm of micro-machining.

A newly developed micro-nozzle with a mixing tube size of 254 µm has made it possible to use AWJs for micro-machining purposes [4], such as creating micro-channels with a width of 600 µm [5], micro-holes with a diameter of 660 µm [6], and micro-cutting of components on the order of a few mm in size [7]. However, Liu et al. [8] have found that further downsizing of micro-nozzles will face considerable challenges associated with abrasive micro-particles agglomeration and nozzle blockage that can result in an inconsistent abrasive feed rate.

A number of techniques exist to reduce feature width, especially in relatively tough materials, using high pressure micro-waterjet technologies. For example, Haghbin et al. [9] found that submerged abrasive waterjet micro-machining (AWJM) of metals in water decreased the channel width by about 18% at a channel depth of 1200 µm (aspect ratio, depth/width, of 2) compared to AWJM in air. This was because the effective jet size significantly reduced due to an increase in the drag of the surrounding water when the jet was submerged. In later studies, Haghbin et al. found that by feeding a premixed slurry (rather than a mixture of particles and air) into the mixing chamber of an AWJ machine, they were able to decrease the channel roughness and waviness by 16%, and 50%, respectively [10], and the channel width by 26% [11]. Efforts have also been made to improve the machined surface quality in cuts made using AWJs by studying the vibration of the nozzle and pulsating the jet. For example, Hreha et al. [12] derived models to predict surface roughness parameters based on vibration parameters and the traverse speed of the AWJ nozzle head. The study showed that

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the traverse speed of cutting head was the biggest factor affecting the surface topography that occurs during the cutting process of materials with E = 200 GPa (Stainless Steel AISI 309) and with 15 mm thickness. In another study [13], it was found that an increase in abrasive mass flow rate (400 g/min) resulted in lower vibration while more vibration was observed at lower abrasive mass flow rate (250 g/min). Finally, Lehocka et al. [14] used a pulsating water jet with frequency of 20.38 kHz on bronze and brass. Their study showed that the depth of cuts and material removal increased when higher pulsating water jet transitions were used. In addition, higher traverse speed resulted in lower roughness of the surface for certain materials such as bronze.

A possible technique for further reduction of channel width in AWJM is to use patterned masks attached to the surface. This technique has successfully been used for a number of years in the compressed air-driven abrasive jet micro-machining (AJM) process. For example, Belloy et al. [15] used AJM to create microfluidic chips and micro sensors in glass using metallic masks. Wensink et al. [16] compared different masks and found electroplated copper to be a highly resistant mask material for AJM, suitable to create < 50 μm features accurately. Pawlowski et al. [17] developed a polymer masking technology which had relatively large erosion resistance, and made various types of structures as small as 20 μm using AJM. Sayah et al. [18] used photolithographic process to fabricate elastomer masks for creating different patterns (e.g. semi-ellipsoidal channels) in glass and piezo materials using AJM. Ghobeity et al. [19] used 3 mm thick tempered steel masks clamped to the substrate 250 μm apart from each other in order to create ~200 μm wide micro-channels in glass at an aspect ratio of 0.25. Nouhi et al. [20] introduced an AJM shadow mask attached to the nozzle which allowed direct writing of ~ 380 μm micro-channels in glass at an aspect ratio of 0.5. Finally, Ally et al. [21] used a 3 mm thick hardened steel mask clamped 250 μm apart in AJM for making micro-channels with a width of 240 μm (aspect ratio ~ 1) in 6061-T6 aluminum alloy, 316 L stainless steel, and Ti-6Al-4 V alloy.

Since AJM systems typically operate at relatively low blasting pressures (~0.4 MPa), they are more suitable for the micro-machining of brittle materials (e.g. glass). AWJ systems typically use water pressures up to 350 MPa, making them also appropriate for the machining of tougher materials such as metals. Metal masks have been used in an AWJ setups utilizing a relatively large nozzles for the precision milling of complex shapes in both ductile and brittle materials. For example, in an early study by Hashish [22], patterns with a width of 15.2 mm and depth 2.5 mm were first cut into a mild steel mask, which was then clamped to the workpiece, and finally, the cut shape was milled into the workpiece while the abrasive jet traversed across the mask. In later studies, Hashish used 6.3 mm thick mild steel masks with an isogrid pattern to mill 25 mm wide features in aluminium [23] and gamma titanium aluminide [24] using AWJ with a 1.19 mm diameter nozzle. Farayibi et al. [25] cut a pattern into a Ti-6Al-4 V/WC composite and used it as a mask in order to mill a pattern into an aluminium plate using AWJ. More recently, Miles et al. [3] demonstrated that AWJ with mild steel masks using a variety of techniques can be used to accurately mill pockets on the order of a few cm in width to depths in excess of 25 mm in both brittle and ductile materials. They showed that progressively eroding shaped masks can be used to produce contoured radii and that the use of progressively larger stepped masks can be used to prevent mask undercutting in the machined features. Finally, they described a process by which a milled channel around the perimeter of masked pockets could be used to obtain near vertical sidewalls on the machined feature.

Use of masks in a variety of abrasive jet machining processes has also been shown to affect fluid flow at the surface. For example, in a study of the ability of abrasive slurry jets to polish surfaces, Matsumura et al. [26] used computational fluid dynamics models to show that the size of the stagnation zone in the region immediately above the target surface changed depending on the slope of the sidewalls of a metal mask, thus mitigating the formation of cracks in glass. Schwartzentruber and Papini [6] used an unpatterned 1 mm steel mask to prevent the large-scale fracture generated by the high stagnation pressure developed during the AWJ micro-piercing of borosilicate glass. For air-driven AJM, Dehnadfar et al. [27] showed that the particle velocities through a mask were significantly lower than those seen in a free jet.

In summary, while masks have been used to pattern micro-features into surfaces using other abrasive jet technologies, they have been seldom used with AWJs. The few studies of masked AWJ that do exist mostly have utilized much larger nozzles and mask openings than those required in micro-machining applications. Moreover, these previous studies did not consider the effects of the mask opening size and thickness on the shape and quality (i.e. centerline waviness and roughness) of the features. This paper investigated the feasibility of using metal masks to micro-machine channels in glass and Al6061-T6 using AWJM. In particular, the effect of mask thickness and opening size on the dimensions and shape of the resulting micro-channels were investigated, and the shapes of channel profiles in masked and unmasked micro-channels were compared and discussed.

2. Experiments

2.1. Experimental setup

The abrasive water jet micro-machining (AWJM) apparatus used in this study is described in detail in Haghbin et al. [9]. Briefly, an OMAX 2626 Jet Machining Center (OMAX Corp., Kent, WA, USA) capable of water pump pressures, P_p, of up to 345 MPa was used with a micro-nozzle having orifice and mixing tube diameters of 127 μm and 254 μm, respectively (Fig. 1a). Although a larger nozzle could have been used in the masked experiments, the larger erosive footprint would have limited the practical minimum distance between adjacent machined micro-channels. Moreover, it would have made direct comparisons between unmasked and masked machining more difficult to interpret. The nozzle movement was computer controlled with a positioning accuracy of ± 76 μm over 30 cm and a maximum traverse speed of 4572 mm/min. A treated 320-mesh garnet, with an average size of 38 μm [5] was used in all experiments. The target samples were 3 mm thick aluminum alloy 6061-T6 and borosilicate glass (Borofloat®, Schott Inc., NY, USA) that were cut into 16 cm long by 5 cm wide 3 pieces. These materials were chosen based on their ability to exhibit typical ductile and brittle erosive behaviors [28], and because of their widespread use in micro-fluidic (Borofloat) [29] and micro-heat exchanger (aluminum alloys) [30] applications.

Using a special jig (Fig. 1c), two 20 mm wide 316 L stainless steel (Fig. 1a) strips of thickness t_m (Table 1) were clamped to the target samples parallel to each other to act as masks for creating straight micro-channels. On each side of the jig, adjustable screws on two bottom sliders were utilized to move the masks towards each other, whilst keeping them parallel to each other. The masks were advanced until they sandwiched a plate of known thickness (i.e. the desired masked opening W_m) placed between them (Fig. 1b and Table 1). Once the masks were positioned at their required position, they were clamped to the jig by tightening the four screws on the top sliders. An additional four clamps were used to prevent mask liftoff when exposed to the relatively high water pressure of 134 MPa. The nozzle was placed at a standoff distance of h (Fig. 1a and Table 1) and the machining was conducted in air. As discussed further in Section 3.5, 316 L stainless steel was found to be appropriate as a mask material due to its much lower erosion rate compared to the Al6061-T6 and glass targets.

2.2. Micro-machining experiments

Similar to the maskless machining in Haghbin et al. [5], straight, stepped channels with lengths of 15 mm and at various depths were machined into the two masked target materials using n = 2, 6, 10, 20,