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Abrasive waterjet micro-machining of channels in metals: Model to predict high aspect-ratio channel profiles for submerged and unsubmerged machining

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ABSTRACT

Recent advances in the development of miniaturized nozzles have made possible the use of abrasive waterjets to perform controlled-depth micro-milling. Haghbin et al. (2015) discussed the effects of the surrounding fluid in the micro-machining of shallow channels in 316L stainless steel and 6061-T6 aluminum using a prototype nozzle having an orifice diameter of 127 μm and a 254 μm mixing tube diameter. This paper uses those results to develop a new surface evolution model that predicts the size and shape of relatively deep micro-channels resulting from unsubmerged and submerged abrasive water jet micro-machining (AWJM). For both unsubmerged and submerged AWJM, and for both materials, the erosive efficacy distribution changed suddenly after the initial formation of the channel. The initially wide distribution was due to backflow of the abrasive slurry along the channel walls, which did not occur once the channel was formed and most of the flow was directed along the channel length. A novel approach in which two different erosive efficacy expressions are sequentially used in a surface evolution equation is presented and shown to accurately predict the evolving surface topography for micro-channels up to aspect ratios of 3.

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1. Introduction

Micro-channels with a wide range of low to high aspect ratios (i.e. depth/width) have many applications in micro-electromechanical systems (MEMS) and micro fluidics systems, such as those in lab-on-chip devices (Bhagat et al., 2008), microchip electronic cooling systems (Thakre et al., 2014), biomedical micro-devices (Chang et al., 2000), biochemistry (Ohno et al., 2008), and electrophoretic applications (Kawai et al., 2010). Abrasive water jet micro-machining (AWJM) is an attractive technology for producing micro-channels because of its ability to machine a wide range of ductile and brittle materials with no heat affected zone, minimal residual stress, and relatively little edge damage.

To obtain a micro-channel of a given required aspect ratio with a low waviness and roughness, the AWJM process must be precisely controlled. This is most easily accomplished using multiple passes at a relatively high scan speed. Researchers such as Agus et al. (2002), have also found that using this multi-pass strategy is an efficient solution because it decreases surface waviness, and reduces total costs associated with the purchase of spare parts, energy, and abrasive. Furthermore, Wang and Guo (2002) found that, for the same machining time, multi-pass AWJ milling in ceramics at a high traverse speed can result in a higher material removal and lower surface roughness than single-pass machining with a slow traverse speed. Shipway et al. (2005) also showed that using a high traverse velocity and multi-pass machining in titanium results in a lower roughness and waviness of channels than a single pass at a low traverse velocity. The present work thus focuses on the development of a model to predict the depth and shape of micro-channels made using multiple nozzle passes.

The first relatively simple mathematical models of AWJ machining could predict only the depth of cut made by relatively large nozzles, rather than the actual channel shape as it is milled and becomes deeper. For example, for water-only jets, Crow (1973) derived an equation for depth as a function of water velocity and the properties of the target (rock), and Rehbinder (1980) developed a model to predict the water pressure required to reach a required depth in the cutting of rock. Hlavác and Vašek (1994) proposed an energy approach to express the depth of a deep cut made by a water-only jet in rock in terms of the initial jet velocity, traverse

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velocity, cutting time, and the strength of the rock. In AWJ machining, Hashish (1984) presented a model to predict the depth of cut in ductile materials as a function of the different abrasive waterjet parameters (i.e. water pressure, abrasive flow rate, traverse velocity, and jet diameter).

A key step for controlled-depth abrasive water jet (AWJ) milling is to develop a model to predict the size and shape of the channel cross-sectional profile (Kong et al., 2012). Alberdi et al. (2010) modeled the kerf shape of a straight channel in aluminum 7075-T651 as a Gaussian bell function using the maximum channel depth, maximum width, and the width at half of the maximum depth as parameters. Freist et al. (1989) defined the kerf shape for AWJ milling in ceramics using a cosine function. Laurinat et al. (1993) described channel kerf profiles in different materials using modified cosine functions, and related their model to the standoff distance and the traverse feed rate. They divided the kerf profile in two zones, and developed analytical models for the total depth of cut in the case of ductile materials. Wang (2006) presented an empirical model using a dimensional analysis technique to determine the depth of cut in alumina ceramic, but the model did not predict the shape and width of channels. Ojmertz and Amini (1994) used statistical methods such as interpolation and regression analysis to model the shapes of channels in a milling process, but these types of empirical approaches require many experiments, varying a large number of parameters, and must be repeated for each target material/abrasive powder combination. Artificial intelligence approaches, such as the genetic algorithms applied by Carrascal and Alberdi (2010), also require a great deal of data spanning the range of the many machining parameters in order to predict the kerf profile in AWJ machining. Simulation approaches to predict the shape of AWJ milled footprints, such as the finite element methods presented by Anwar et al. (2012) or the unit event approach used by Lebar and Junkar (2004) require long computational times and many simplifying hypotheses.

A mathematical model to predict relatively shallow AWJ milled surface profiles or 'footprints' using a relatively large nozzle (mixing tube diameter of 1 mm, with an average garnet particle size of 180–300 μm), was developed by Axinte et al. (2010) for brittle materials with the jet incident perpendicular to the surface, i.e., at a 90° jet impact angle. This model for brittle materials was subsequently applied to single straight paths in a titanium alloy, normally considered to be a ductile material, for moving jets with arbitrary angle (Kong et al., 2012), and for overlapped single and multiple straight paths in titanium (Billingham et al., 2013). This footprint approach is similar to that pioneered by Ghobeity et al. (2008) that utilized a shallow first pass profile in order to determine the erosive efficacy of the blasting system in the prediction of the surface evolution of features machined in glass using abrasive air jet micro-machining (AJM). This AJM methodology has also been extended so that it could be used for ductile materials such as polymethylmethacrylate (PMMA) at both normal and oblique angles of attack (Getu et al., 2007, 2008), and to metals (Ally et al., 2012). Nouraei et al. (2014) also successfully applied the AJM model for brittle materials to the abrasive slurry jet micro-machining of borosilicate glass.

While useful for planning the milling of relatively wide and shallow features, the footprint models developed thus far for AWJ using relatively large nozzles (1 mm) are not appropriate for the presently considered multi-pass micro-machining of high aspect-ratio channels. As machined features become deeper, the local impact angle on the steep sidewalls changes. Oka et al. (1997) and many others have shown that for ductile materials, the erosion rate depends strongly on the impact angle. Since the current AWJ footprint models do not consider this dependency, they are appropriate only for shallow and wide features, and have therefore been tested only up to an aspect ratio (ratio of feature depth to width) of 0.4. The earlier AJM surface evolution models, on the other hand, do consider this dependence on the local impact angle, as well as other complications associated with the prediction of very high aspect-ratio features (up to 2.5), such as the use of curvature-dependent smoothing (Ghobeity et al., 2007) near rapid changes in sidewall slope.

Haghbin et al. (2015) presented erosion rates and cross-sectional profiles of micro-channels in SS316L and Al6061-T6 made using a novel prototype miniaturized nozzle with a 254 μm mixing tube operating in air and when submerged under water. They showed that submerged AWJM, which is used to reduce dust and noise, produces narrower channels than those made in air without a reduction in the centerline etch rate. In contrast to micro-channels machined using air driven AJM, the instantaneous centerline erosion rate and volumetric erosion rates decreased with channel depth due to jet spreading with increased effective standoff distance and the jet stagnation zone at the bottom of the channel within the footprint of the jet. The decrease in erosion rate due to the stagnation zone was only a function of channel geometry, and was independent of the standoff distance, jet angle, jet direction (forward or backward machining) and whether the jet was submerged or in air. These effects were captured conveniently by defining a centerline instantaneous erosion rate that was normalized by the erosion rate of a shallow channel at the same effective standoff distance, E_{inst}. This normalized instantaneous centerline erosion rate decreased with increasing centerline depth, d, according to a single master power-law curve that reflected the increase in the stagnation zone size. In addition to being independent of the nozzle-to-surface standoff distance via the normalization, E_{inst} was independent of target material (glass or metal) and the surrounding fluid (air or water).

The present paper demonstrates that the erosive efficacy distribution also changes with channel depth, reflecting changes in the local particle impact angles within a deepening machined channel. Previous AWJM models have not considered these changes and are, therefore, limited to relatively shallow channels. The new model can predict the shapes of channels machined in water and in air on 6061-T6 aluminum alloy and 316L stainless steel targets up to aspect ratios of 3.2. Since these targets span a wide range of material properties such as hardness and density that are known to strongly affect the erosion rate, the model is expected to be generally applicable to a wide variety of metals and other ductile materials.

2. Experiments

2.1. Micro-machining of high aspect ratio channels

The experimental setup and the AWJ parameters and procedure are described in detail in Haghbin et al. (2015). Briefly, an OMAX 2626 Jet Machining Centre (OMAX Corp., Kent, Washington, USA) fitted with a prototype nozzle having an orifice diameter, d_O, of 127 μm and a 254 μm mixing tube (i.e. focusing or collimating tube) diameter, d_M, with a 28 mm mixing tube length, L_M, was used to machine straight micro-channels up to an aspect ratio of 3.2 in aluminum 6061-T6 and stainless steel 316L target samples. The prototype nozzle was a 5/10 MAXJET 5, which had the same nozzle body as the 7/15 Mini MAXJET 5 (OMAX part no. 305764-07) as discussed by Liu and Sagawa (2014) (i.e. only the mixing tube and orifice were changed). The water flow rate at a machining pressure of 138 MPa was 0.213 L/min. Fig. 1 presents the size distribution and an image of the treated 320-mesh garnet (Barton International, Glens Falls, NY, USA) with an average equivalent spherical diameter of 38 μm used in all experiments. The abrasive mass flow rate, $\dot{m}_a$, was varied between 0.6 and 1.1 g/s.

The straight micro-channels were machined using multiple nozzle passes (up to $n = 50$) at a traverse velocity of $V_t = 1000$ mm/min

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