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Abrasive waterjet micro-machining of channels in metals: Comparison between machining in air and submerged in water

Naser Haghbin [a], Jan K. Spelt [b,a], Marcello Papini [a,b,*]

[a] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3
[b] Department of Mechanical and Industrial Engineering, University of Toronto, 5King's College Road, Toronto, ON, Canada M5S 3G8

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ABSTRACT

Abrasive water jet technology can be used for micro-milling using recently developed miniaturized nozzles. Abrasive water jet (AWJ) machining is often used with both the nozzle tip and workpiece submerged in water to reduce noise and contain debris. This paper compares the performance of submerged and unsubmerged abrasive water jet micro-milling of channels in 316L stainless steel and 6061-T6 aluminum at various nozzle angles and standoff distances. The effect of submergence on the diameter and effective footprint of AWJ erosion footprints was measured and compared. It was found that the centerline erosion rate decreased with channel depth due to the spreading of the jet as the effective standoff distance increased, and because of the growing effect of stagnation as the channel became deeper. The erosive jet spread over a larger effective footprint in air than in water, since particles on the jet periphery were slowed much more quickly in water due to increased drag. As a result, the width of a channel machined in air was wider than that in water. Moreover, it was observed that the instantaneous erosion rate decreased with channel depth, and that this decrease was a function only of the channel cross-sectional geometry, being independent of the type of metal, the jet angle, the standoff distance, and regardless of whether the jet was submerged or in air, in either the forward or backward directions. It is shown that submerged AWJM results in narrower features than those produced while machining in air, without a decrease in centerline etch rate.

1. Introduction

There has been increased recent interest in the use of abrasive waterjets (AWJ) for micro-machining. For example, miniature AWJ nozzles have been used to micro-machine through-cut features as small as 200 μm [1], stainless steel micro-channels for fuel cells [2], stainless steel plates for orthopedic implants to repair bone and skull fractures [3], and miniature mechanical components, such as planetary gears [4]. Liu et al. [5] used AWJ to machine micro-features in composites and thin metals, and Liu and Schubert [4] outlined some of the difficulties involved in preventing clogging by fine abrasives as they flow from the mixing tube to the micro-nozzle. A key motivation for this interest in AWJ micro-machining is the ability to machine a wide range of materials with no heat-affected zone, minimal residual stress and relatively little edge damage [6]. There has also been considerable attention paid to the use of AWJ machines to perform controlled depth milling of larger scale features having widths greater than 1.3 mm. For example, Hashish [7,8] performed preliminary milling experiments on aluminum, titanium, glass and graphite composites with an AWJ machine, concluding that it is one of the most energy efficient methods for material removal, and has a great potential in milling applications. Axinte et al. [9] machined multi-pass channels in glass and developed models to predict their developing cross-sectional shapes. Kong et al. [10] machined straight, single-pass channels in titanium, while Billingham et al. [11] milled overlapped, single-pass channels in titanium. Shipway et al. [12] investigated the role of waterjet pressure, jet impingement angle, traverse speed, and abrasive size on waviness and roughness of milled channels in titanium.

A vast published literature shows the effect of standoff distances on width, depth and AWJ velocity for cutting applications; however, very few of them discuss these effects in milling applications. Regarding milling, Laurinat et al. [13] showed that the top kerf width of channels is proportional to the standoff distance. Alberdi et al. [14] found that the standoff distance is the most important factor for the kerf width. Srinvasu et al. [15] reported an increased width at a shallower jet impingement angle, i.e. nozzle angle less than 90°, which is due to the increase in

* Corresponding author at: Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3. Fax: +1 416 979 5265.
E-mail address: mpapini@ryerson.ca (M. Papini).

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width of jet footprint. Moreover, they found that the kerf width deceased with the increase in jet feed rate, although the difference was insignificant. For cutting, Kovacevic [16] showed that an increase in the standoff distance decreased the depth of cut almost linearly. Chen et al. [17] explained that this is because the jet power reaching the workpiece decreases when standoff increases, and therefore the lower part of the kerf cannot be machined as efficiently. Momber and Kovacevic [18] noted that, compared to other cutting parameters, changes in the standoff distance do not significantly influence the velocity of the abrasive particles. Clark and Burmeister [19] also discussed the stagnation effect as the formation of a film on the impacted zone that decreases the particle velocity and the ability to erode. Matsumura et al. [20] explained that this stagnation effect is controlled by the channel sidewall angles, which changes the slurry flow direction and reduces the AWJ velocity. Lv et al. [21] used a CFD model to simulate slurry velocity in the impact zone.

All of previous studies of AWJ cutting and milling have been conducted with the nozzle and target in air rather than submerged. However, AWJ machining is frequently performed with a submerged nozzle and workpiece in order to reduce noise, splash and airborne debris. For example, Radavanska et al. [22] suggested using submerged AWJ machining as a safer machining method, with some of the kinetic energy of the jet being consumed in order in order to reduce noise.

Submerged machining has also been discussed by a few researchers with respect to abrasive slurry jet machining. For example, Shimizu [23] found that a submerged stationary slurry jet with a pressure of 20 MPa at standoff distances between 20 and 40 mm caused cavitation erosion on the workpiece after 2 h of machining. Madadnia et al. [24] found a similar cavitation effect on an aluminum sample at standoff distance 50 mm after 180 s of machining with a stationary submerged water jet having a diameter of 254 μm at a pressure of 240 MPa submerged in a slurry solution. However, submerged milling using an abrasive water jet, and the effect of the surrounding water on the erosion rate, depth, and width of channels appears not to have been considered in the literature. Since the drag on the particles due to the surrounding fluid is significantly different when machining in air and water, the effect on the topography of the resulting micro-machined features needs to be considered.

This paper presents a comparison of submerged and unsubmerged abrasive water jet micro-milling (AWJM) of micro-channels in 6061 aluminum alloy and 316L stainless steel using a novel prototype miniature nozzle with a 254 μm mixing tube. Experiments were conducted to examine the relative effects of nozzle standoff, channel depth and jet impingement angle on the erosion rate and shapes of channel cross-sections.

2. Experiments

2.1. Experimental setup

An OMAX 2626 Jet Machining Center (OMAX Corp., Kent, WA, USA) was used with a prototype nozzle having orifice and mixing tube diameters of 127 μm and 254 μm, respectively. Channels were micro-milled at pressures between 131 MPa and 268 MPa with the nozzle and target submerged in water (Fig. 1) and in air. A treated 320-mesh garnet, with an average size of 38 μm (Fig. 2) was used in all experiments Table 1 presents the machining test conditions. The aluminum alloy 6061-T6 and stainless steel 316L target samples were 3 mm thick and were cut into $16 \times 5\ \text{cm}^2$ pieces. These were clamped to a stationary base that was placed underneath the nozzle at standoff distances between 2 and 4 mm (Fig. 1).

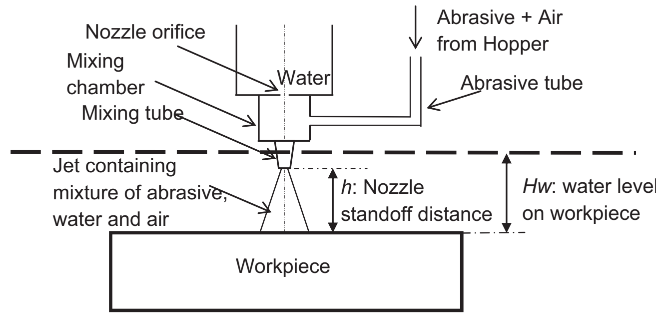

Fig. 1. Schematic of submerged abrasive water jet. Not to scale.

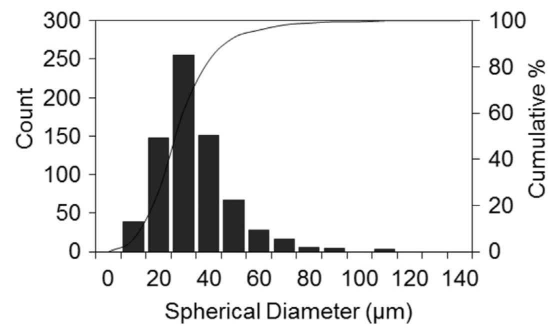

Fig. 2. Particle size distribution of garnet abrasive. Curve gives cumulative percent.

Table 1
Machining parameters.

Standoff distance (mm), h	2, 2.5, 3, 3.5, 4
Submerged depth (mm), H_W	20
Abrasive mass flow rate (g/s), $\dot{m}_a$	0.6–1.1
Garnet nominal diameter (μm)	38, 75
Water pressure (MPa), P	138
Traverse speed (mm/min), V_t	1000, 4572
Nozzle angle (deg), Θ	90°, 60°, 45°, 30°, 15°
Number of passes, n	1, 2, 4, 10, 20, 30, 40, 50
Orifice diameter/mixing tube diameters (μm), d_O/d_M	127/254
Workpiece materials	SS 316L, Al 6061-T6, Glass

The nozzle movement was computer controlled with a positioning accuracy of ±76 μm over 30 cm and a maximum scan speed of 4572 mm/min. Table 1 gives the range of AWJ parameters used in the experiments. The resulting micro-channel profile shapes were measured using a non-contact optical profilometer (model ST 400, Nanovea, Irvine, CA, USA) having a lateral and vertical resolution of 0.1 μm. A scanning electron microscope was used for further characterizing the channels.

2.2. Jet size

The jet diameter was used to characterize its spreading behaviour at different standoff distances. It is difficult to define a jet diameter for a water jet since the entrained air bubbles [18] create a diffuse, unsteady transition zone between the jet core and the surrounding media, water or air, as shown in Fig. 3. In the past, the jet edge has been defined as the location where the impact of individual water droplets was measured [25,26], or the location where the impact force of the jet drops to 5% of its maximum impact force [27].

In the present work, the effective jet diameter at a given standoff distance was defined as the entrance width of the slot cut by the jet in a rigid, 3 mm thick polyurethane modeling foam (Renshape, Huntsman Advanced Materials). Because of its very