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Effect of entrained air in abrasive water jet micro-machining: Reduction of channel width and waviness using slurry entrainment

Naser Haghbin [a], Farbod Ahmadzadeh [a], Jan K. Spelt [a,b], 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, 05 King's College Road, Toronto, ON, Canada M5S 3G8

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ABSTRACT

The erosion produced by abrasive water jets is a result of the complex interaction of the three-phase jet (water-air-abrasive) and the target. The objective of the present work was to isolate the effect of the entrained air in abrasive water jet micro-machining (AWJM) by comparing milled surfaces made by AWJM with those produced by high-pressure slurry jet micro-machining (HASJM) while maintaining a constant particle velocity. An existing model developed for abrasive particle velocities in AWJM was modified and used to predict the particle velocity in HASJM, and then verified using a double disc apparatus (DDA). The model allowed prediction of the conditions required to achieve average particle velocities of ~255 m/s using the two systems with the same 38 μm garnet particles. Under this condition of equal particle velocity, there was a very large reduction in the centerline waviness, W_a, of micro-channels made in SS316L and Al60661-T6 using HASJM; typically 3.4 times smaller waviness than found in channels made with AWJM using the same dose of particles. This was found to be mainly due to the much larger variation in abrasive flow rate in AWJM brought about by the air/particle entrainment system, rather than any fundamental change in erosion mechanism due to the impact of the non-homogeneous three phase air/particle/water in AWJM. The centerline roughness, R_a, was approximately the same in both processes at a traverse velocity of V_t=4572 mm/min and a nozzle angle of 90°. For both processes, W_a and R_a increased with an increase in pressure and abrasive particle dose, and decreased with an increase in nozzle angle. For micro-channels of a given depth, the widths of those made with HASJM were 26% narrower than those produced with AWJM, mainly due to the wider jet that resulted from the entrained air in AWJM, again at the same particle velocity. The erosion rate in HASJM was found to be about 27% lower mainly because of a smaller width of micro-channels in HASJM.

1. Introduction

Abrasive water jet micro-machining (AWJM) and abrasive slurry jet micro-machining (ASJM) are water-jet based technologies for micro-machining a variety of materials such as metals, glass, ceramics, polymers, and composite materials. It is often important to minimize surface roughness and waviness in controlled-depth milling using these processes in order to prevent the need for further finishing operations [1].

The air that is entrained by an abrasive water jet can have three effects: a) it creates a nonhomogeneous three-phase jet in which the abrasive particles are carried and strike the target in a bubbly flow, b) it can lead to variations in the abrasive flow rate, and c) it causes an increase in the jet diameter [2,3].

The first effect causes a nonhomogeneous three-phase flow due to existence of air bubbles in the jet. For example, Chahine et al. [4] found that in a multi-phase flow, air bubbles can apply repulsive forces to small particles so that particles concentrate in the liquid phase. Firouzi et al. [5] demonstrated that, in a mixture of particles, air bubbles, and water, there is a high probability of particle-bubble collisions that affect particle motion. It is therefore expected that a non-uniform distribution of particles will occur in the abrasive water jets used for AWJM, which could lead to an increase in the surface waviness and roughness. The bubbly flow at the target could also lead to water drop erosion. For example, water droplets striking a solid surface can also generate a high 'water hammer' pressure, leading to plastic deformation as explained by Huang et al. [6]. Oka et al. [7] found erosion damage on an aluminum alloy by water droplet impingement depends on water pressure and the nozzle standoff distance. Chillman et al. [8] observed that the injection of air into a plain water jet accelerates drop impingement erosion on an aluminum alloy surface due to the creation of water droplets at relatively lower standoff

* Corresponding author at: Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3. Tel.: +1 416 979 5000; fax: +1 416 979 5265.
E-mail address: mpapini@ryerson.ca (M. Papini).

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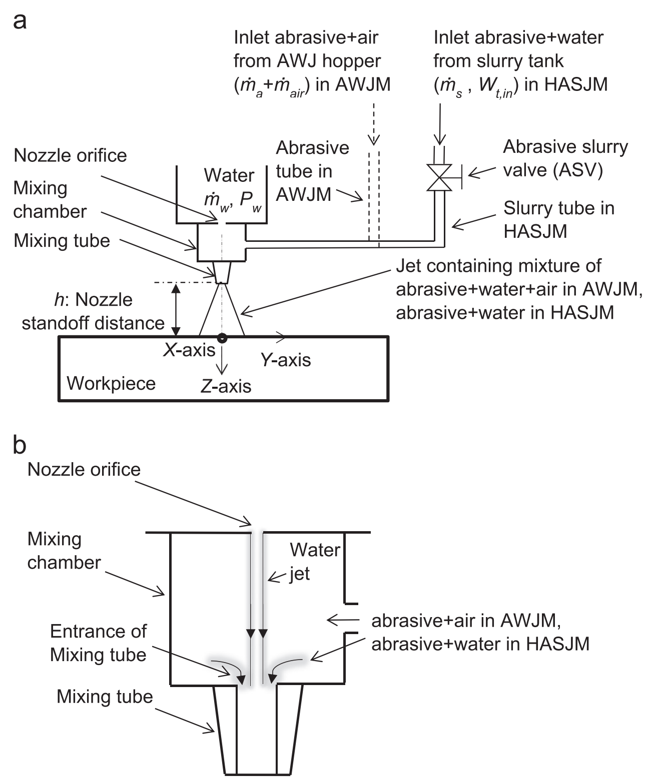

Fig. 1. (a) Schematic of the nozzle in the AWJM and HASJM systems. *X*-axis is along the channel length. (b) Schematic of high-pressure water jet from the orifice entering the mixing tube and entraining abrasive in either air (AWJM) or water (HASJM). Not to scale.

distances. However, Haghbin et al. [2] reported that the core region of submerged and unsubmerged water air jets did not break up into water droplets for standoff distances between 2 and 5 mm. The effect of the bubbly flow was found to be negligible in the present work.

The second effect of entrained air in AWJM can contribute to an increase in surface waviness due to the limitations of the particle/air feed systems used in AWJM. For example, abrasive flow can be affected by particle agglomeration resulting from high humidity or the generation of electrostatic forces, and by particle segregation as reported by Tang and Puri [9], and its effect on flowability [10]. Pak and Bechringer [11] reported that providing a uniform air flow rate in the particle/air feeder was key to having a consistent particle flow rate in nozzles used in AWJM. Bertho et al. [12] found that the instantaneous abrasive flow rate in a two-phase mixture of air and particles fluctuated at the output of the abrasive tube (Fig. 1) due to the compressibility of the entrained air. Some solutions have been proposed for delivering a uniform particle flow in a particle/air system. For instance, Tardos and Lu [9] suggested using vibratory feeders, but these systems could not provide a constant flow rate for relatively small particles (e.g. cement with a diameter of 143 μm) due to powder bridging, compaction, and agglomeration. Some air abrasive blasting systems utilize a particle feeding system that creates an upward air flow, which is passed through the powder bed, generating a cloud of suspended particles (e.g. aluminum oxide of 25 μm), which then settles into a collection funnel connected to the nozzle, as described by Ghobeity et al. [13]. Such systems provide a more uniform air flow through the particles resulting in a more consistent particle flow than traditional vibrating hoppers. Yang et al. [14] suggested that Van der Waals attractive forces between micro-particles that lead to poor flowability can be reduced by applying a hydrophobic coating. Nevertheless, Haghbin et al. [2] found that significant mass flow rate fluctuations persisted with coated abrasive particles in AWJM using small (254 μm mixing tube diameter) nozzles due to inconsistent particle flow though the abrasive tube leading to the nozzle mixing tube. In the present work, such fluctuations were found to significantly affect the waviness of the channels made using AWJM.

The third effect of entrained air, the increase in the jet diameter, is due to the formation of a diffuse, unsteady transition zone between the jet core and the surrounding air as described by Momber and Kovacevic [15]. Yanaida and Ohashi [16] and Huang et al. [6] found that a plain water jet breaks up after a certain standoff distance due to entrainment of surrounding air. Chillman et al. [8] concluded that the presence of entrained air in a water jet accelerates the break up into a droplet flow, compared to a plain water jet. Osman et al. [17] found that the water and air flow in the nozzle separate as a core jet of water surrounded by an annular air flow. Haghbin et al. [2] found that the AWJ emerging from a micro-nozzle had a core zone surrounded by a droplet zone. Later, Haghbin et al. [3] showed that the jet divergence angle in HASJM (1.5°) was smaller than that in AWJM (6.9°). In the present work, the effect of this difference in divergence on the channel width was quantified for the same channel depth and abrasive particle velocity.

Particle kinetic energy has a large effect on the depth, waviness and roughness of micro-channels milled using abrasive jet processes [18]. Predicting or even measuring the particle velocity in such multi-phase flows can, however, be challenging. Narayanan et al. [19] developed an analytical model for abrasive particle velocities in AWJM systems considering the entrained air as a compressible fluid. Li et al. [20] used the momentum and continuity principles to predict particle velocity in a two-phase (i.e. air and abrasive) jet. Nouraei et al. [21] adapted this model to predict the particle velocity in a low-pressure abrasive slurry-jet micro-machining system that used a two-phase flow consisting of water and particles. The present HASJM system differs from that of Nouraei et al. [21] in that the abrasive slurry is injected into the high-pressure mixing tube of a water-jet machine, resulting in much greater particle velocities.

Measuring particle velocities in abrasive water jets using laser Doppler velocimetry [22], or particle image velocimetry [23] has proven to be unreliable due to difficulties in distinguishing abrasive particles in a mixture of abrasive, water and air. Later, Balz and Heiniger [24] found that particle velocity and size distributions could be measured within an abrasive water jet using PIV and the laser induced fluorescence of dyed abrasive particles. Balz et al. [25] also showed that ultra-fast X-ray particle velocimetry is a feasible method to measure particle velocities and spatial positions of individual abrasive particles in a three-phase jet consisting of abrasive, water, and air. Using magnetic particles in inductive methods [26] raises questions about whether the results are applicable to other abrasive particles. The impact force method [27] can only provide the net impact velocity of the three-phase mixture. Ruff and Ives [28] introduced a double-disc apparatus (DDA) for measuring the average particle velocity in the free jet in abrasive air-jet micro-machining (AJM). This technique was applied to an abrasive water jet system by Liu et al. [29]; however, the measurements were not independently verified and were made using much larger nozzles than used in a micro-machining process.

In contrast to AWJM, no air enters HASJM systems, because the abrasive and water are first premixed in a separate container before being accelerated. The premixed slurry is then either pumped through the orifice [30], or entrained into the mixing tube of an AWJ nozzle and mixed with the high-speed water jet passing through the orifice [31]. The advantage of entraining the slurry is that less orifice damage occurs, since only water, rather than the