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The effects of dilute polymer solution elasticity and viscosity on abrasive slurry jet micro-machining of glass

K. Kowsari [a], D.F. James [a,*], M. Papini [b,a,**], J.K. Spelt [a,b,***]

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

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ABSTRACT

The present study investigated the effect of dilute polymer solutions on the width, shape, and centerline roughness of micro-channels machined using a specially-designed abrasive slurry-jet micro-machining (ASJM) apparatus. A positive displacement slurry pump and a pulsation damper were connected to an open reservoir mixing tank to generate a turbulent jet containing 1 wt% 10 μm Al_2O_3 particles flowing through a 180 μm sapphire orifice at 4 MPa.

The behavior of non-Newtonian fluids containing long-chain polymers is affected by both their viscosity and their resistance to extensional deformation (i.e. their “elasticity”). The effects of viscosity and elasticity on erosion were separated by conducting experiments using aqueous solutions of equal viscosity, but differing elasticity. It was observed that jets began to oscillate laterally if the polymer concentration became too high.

The width of the machined channels decreased 21% with the addition of 50 wppm of 8 M PEO, the highest concentration possible with a stable jet. This change was accompanied by a decrease in the channel depth of 46% and an increase in the centerline roughness of 29%. These changes were due to normal stresses generated in the PEO solutions (an elasticity effect), and were not attributable to viscosity. It was also seen with this and other polymer solutions, that the channel cross-sections were more V-shaped compared with the U-shape of the reference channel machined using the glycerin solution. The same changes in shape, channel width, and centerline roughness were observed at a lower concentration of the same PEO (i.e. 25 wppm), but to a lesser degree. Similar changes were also evident with more concentrated 1-M PEO solutions (i.e. 25–400 wppm), but again to a lesser extent. However, even a very concentrated 2.5×10^4 wppm solution containing 0.1 M PEO had no effect, indicating the predominant role of polymer molecular weight in determining the magnitude of fluid elasticity and its influence on particle motion in the erosive slurry. The present results demonstrate that even a small amount of a high-molecular-weight polymer can significantly decrease the width of machined micro-channels for a given jet diameter.

1. Introduction

Applications of low-pressure abrasive slurry-jet micro-machining (ASJM) have been evolving for over a decade. The suspension of a dry abrasive powder in a water jet permitted fine machining of virtually any material with a high-surface quality and without thermal damage. Because divergence of the jet is small, ASJM is well-suited for the milling of micro-channels, where increasing the resolution has been the focus of most research in the area.

In previous research on high-pressure ASJM, slurry content has typically been 20 wt% and driving pressures have been roughly 70 MPa [1]. However, Pang et al. [2] used pressures in the 10 MPa range and evaluated dimensions and surface morphology of micro-channels in glass. By varying operating parameters, they concluded that low-pressure ASJM is a viable process in manufacturing micro-electromechanical devices. Nouraei et al. [3] compared maskless low-pressure ASJM with masked abrasive air-jet micro-machining (AJM) by using the two processes to make holes and channels in borosilicate glass. They investigated the effects of ASJM pressure, particle concentration, jet speed, and jet impact angle, and found that the side walls of channels and holes

* Corresponding author at: Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario, M5S 3G8, Canada. Tel.: +1 416 978 3049; fax: +1 416 978 7753.
** Corresponding author at: Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, M5B 2K3, Canada. Tel.: +1 416 979 5000x7655; fax: +1 416 979 5265.
*** Corresponding author at: Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario, M5S 3G8, Canada. Tel.: +1 416 978 5435; fax: +1 416 978 7753.
E-mail addresses: david.james@utoronto.ca (D.F. James), mpapini@ryerson.ca (M. Papini), spelt@mie.utoronto.ca (J.K. Spelt).

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were steeper and the bottoms were flatter with ASJM than with AJM. Furthermore, maskless ASJM yielded smaller feature widths for a given jet diameter and produced sharper edges than could be obtained with maskless AJM. This improved performance with maskless machining represents a potentially significant financial advantage of ASJM over AJM.

To explore further improvement in the smallest feature width that can be machined using a given jet diameter, the present work investigated the effects of dissolving a small amount of a high-molecular-weight polymer in the slurry. The earliest study of aqueous jets containing polymer additives appeared in the 1960s for firefighting applications [4]. Hoyt et al. [5] discovered that polymers improved jet stability by damping surface disturbances and thereby reducing or eliminating droplet formation. Another hydrodynamic effect of polymeric additives is friction reduction in pipe flows. The presence of a high-molecular-weight polymer, even at concentrations of order 10 wppm (weight parts per million), can reduce wall friction by as much as 75% in a turbulent pipe flow [6]. Both of these benefits arise from induced viscoelasticity in the fluid. In general, long-chain polymeric additives increase the resistance to elongational deformation, the effect increasing with molecular mass and concentration. When subjected to a sufficiently high strain rate, the polymer chains are stretched from their initially-coiled equilibrium state and generate normal stresses, causing the fluid to resist deformation; i.e. the liquid exhibits elasticity, a property of some non-Newtonian fluids [7]. Polymer additives have been tried in high-pressure abrasive water jet machining (AWJM), in which abrasive powder is entrained in a high-velocity water jet. Nguyen et al. [8] found that 1000–5000 wppm solutions of high molecular weight polyacrylamide enhanced the stability and increased the coherent length of the jet before breakup. Ashrafi [9] found that the addition of a large amount of cornstarch (10–22 wt%) produced a narrower cutting kerf with steeper sidewalls, but did not explain the result.

As for ASJM, only a few studies have attempted to identify the role of polymer additives on the machining. Luo et al. [10] analyzed the effects of concentrated (of the order of 10^3 wppm) solutions of several high-molecular-weight polymers on low-pressure polishing of glass. The term 'high', here and elsewhere, refers to molecular weight in the millions. It was found that the additives sharpened the separation between the polished and unpolished regions by reducing the width of the transition zone between them. The authors hypothesized that the polymer chains, extended in the jet direction, minimized momentum exchange with the surrounding air and thus decreased the divergence angle of the jet.

Wang et al. [11] compared ASJM holes machined in glass using relatively concentrated aqueous solutions of high-molecular-weight polyacrylamide (PAM solutions of the order of 10^3 wppm), anionic polyacrylamide (HPAM), and cationic polyacrylamide (PAMA). The deepest hole with the smallest diameter was obtained using 5 M PAM; however, no comparisons were made to a hole machined with water alone.

In summary, then, past studies have found that machining with concentrated, high molecular-weight polymer solutions, at pressures of 14 MPa and above, reduced channel widths and hole diameters. The objective of the present study was to examine the effect of polymer solutions in the dilute range (25–400 wppm) on machined channel width, cross-sectional shape, and centerline roughness, and to explain the observed changes in terms of the relative contributions of liquid viscosity and elasticity.

2. Experiments

2.1. ASJM apparatus

An ASJM apparatus was constructed utilizing an abrasive slurry pump and pulsation damper connected to an open reservoir tank (Fig. 1). The positive displacement pump (LCA/M9/11-DC, LEWA Inc., Leonberg, Germany) had an adjustable stroke length (0–15 mm) and frequency range (0–3.5 Hz) which permitted operation over a relatively wide range of flow rates and pressures. Although the pump could deliver a flow rate of 5 mL/s at 8 MPa, in the present experiments the flow rate was maintained at $1.67 \pm 0.1\%$ mL/s at a pressure of 4 MPa, using a variable frequency drive (CFW-10, WEG, Jaraguá do Sul, Brazil). A pre-pressurized pulsation damper (FG 44969/01–9, Flowguard Ltd., Houston, TX, U.S.A.) was installed downstream of the pump to reduce pressure and flow rate pulsations to within $\pm 3\%$. A manual valve was used to relieve the pressure before disassembling the system. To minimize the transfer of vibrations to the jet, the pump and orifice were mounted on separate supports and were connected by a flexible pipe.

Aqueous slurries of 1 wt% Al_2O_3 abrasive particles having a nominal diameter of 10 μm (Comco Inc., CA, USA) were prepared in the 18 L reservoir tank (28 cm diameter, 33 cm deep) using an 8-cm-diameter propeller rotated at 100 rpm. The propeller was positioned 11 cm above the bottom of the tank to optimize mixing as recommended by Dutta and Pangarkar [12]. Homogeneity was confirmed visually and from jet concentration measurements, which are described below.

A sapphire waterjet orifice with a diameter of 180 μm and a length/diameter ratio of 1.67 (KMT Waterjet, KS, USA, Fig. 2) was connected to stainless steel tubing (Fig. 1). The jet diameter was measured using a microscope attached to a digital camera, and the contraction coefficient (the ratio of the jet cross-sectional area to that of the orifice) was found to be 0.60 ± 0.03 for all solutions.

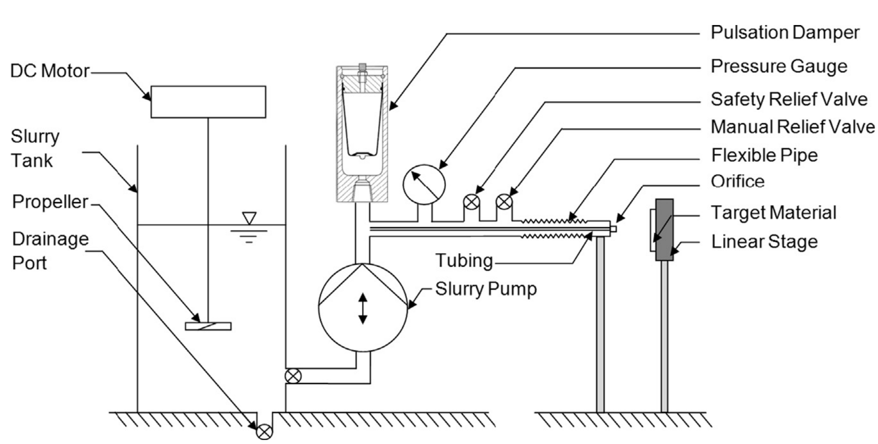

Fig. 1. Schematic of the ASJM components (not to scale).