The Effects of Dilute Polymer Solutions on the Shape, Size, and Roughness of Abrasive Slurry Jet Micro-machined Channels and Holes in Brittle and Ductile Materials

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Mechanical and Industrial Engineering
University of Toronto

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Abstract

The present study investigated the effect of dilute polymer solutions on the size, shape, and roughness of channels and holes, machined in metal and glass using a novel abrasive slurry-jet micro-machining (ASJM) apparatus. The apparatus consisted of a slurry pump and a pulsation damper connected to an open reservoir tank to generate a 140-μm turbulent jet containing 1 wt% 10-μm Al₂O₃ particles.

With the addition of 50 wppm of 8-M (million) molecular weight polyethylene oxide (PEO), the widths of the channels and diameters of holes machined in glass decreased by an average amount of 25%. These changes were accompanied by approximately a 20% decrease in depth and more "V"-shaped profiles compared with the "U"-shape of the reference channels and holes machined without additives. The present results demonstrate that a small amount of a high-molecular-weight polymer can significantly decrease the size of machined channels and holes for a given jet diameter.
Acknowledgments

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Chapter 1
Introduction

1.1 Overview

1.1.1 Abrasive Slurry Jet Micro-machining

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. As an economical, nontraditional machining process, it offers advantages such as the absence of a heat-affected zone, low machining forces on the work piece, and no tool wear. The small divergence of the jet has made ASJM well-suited for machining relatively small holes and channels.

In previous research by Miller (2004) on high-pressure ASJM, slurry content has typically been 20 wt% and driving pressures have been roughly 70 MPa in order to machine materials such as metals, glass, ceramics, polymers and composites. Pang et al. (2010) 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. (2012) 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 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.
1.1.2 Polymeric Additives

The earliest study of aqueous jets containing polymer additives appeared in the 1960s for firefighting applications by Summers (1995, p 472). Hoyt et al. 1974 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 according to Elbing et al. (2011). 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.

In a dilute polymer solution at rest, the long chains are loosely and randomly coiled because of Brownian motion. At a sufficiently high deformation rate, in either shear or extension, hydrodynamic forces cause the polymer chains to be stretched out and oriented in the flow direction. The extended chains are under tension and thus increase the normal stress in the flow direction. Because of this additional stress, the polymer solution behaves as a viscoelastic material, resisting extension like a solid as well as resisting shear like a fluid, as described by Bird et al. (1987, p. 637). Larson (1999, p. 132) explained how this viscoelastic behaviour increases with molecular weight and concentration).

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. (2008) found that 1000-5000 wppm solutions of high molecular weight polyacrylamide enhanced the stability and increased the breakup length of an abrasive waterjet. Ashrafi (2011) found that the addition of a large amount of cornstarch (10 to 22 wt%) produced a narrower cutting kerf with steeper sidewalls, but did not explain the result. In another study with similar cornstarch solutions and machining conditions, Omrani et al. (2013) also found a reduction in kerf taper, and hypothesized that it was due to changes in the fluid viscosity. The possible role of non-Newtonian elasticity was not investigated.

As for ASJM, only a few studies have attempted to identify the role of polymer additives on the machining. Luo et al. (2010) 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 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. In other studies, polymers have been used in ASJM channels and holes, which are reviewed in Chapters 2 and 3 respectively.

1.2 Thesis Outline and Objectives

Chapter 2 examines the effect of polymer solutions in the dilute range (20 to 400 wppm) on machined channel width, cross-sectional shape, and roughness, and the observed changes in terms of the relative contributions of liquid viscosity and elasticity are explained. This work has been submitted as a journal paper.

Chapter 3 deals with the capabilities of low-pressure ASJM to machine holes in ductile and brittle materials with a focus on the resulting shape, erosion rate, depth and diameter. The experiments examined the effect of adding a high molecular weight polymer to the abrasive slurry. The work also investigated the potential of sacrificial polymeric or glass surface layers to reduce hole opening diameters. This work has also been submitted for publication in a refereed journal.

Chapter 4 summarizes the conclusions of the research and discusses possible future research directions.

1.3 ASJM Apparatus

A novel ASJM apparatus was constructed utilizing an abrasive slurry pump and pulsation damper connected to an open reservoir tank (Figure 1-1). The positive displacement pump (LCA/M9/11-DC, LEWA Inc., Leonberg, Germany) had an adjustable stroke length (0-15mm) 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 and 2.34 ± 0.1% mL/s at pressures of 4 and 7 MPa respectively, 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 ± 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% Al₂O₃ abrasive particles having a nominal diameter of 10 μm (Comco Inc., CA, USA) were prepared in the 18-litre 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 (1995). Homogeneity was confirmed visually and from jet concentration measurements, which are described below.

A sapphire waterjet orifice with a diameter of 180 μm (KMT Waterjet, KS, USA, Figure 1-2) was connected to stainless steel tubing (Figure 1-1). 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, i.e. the

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Figure 1-1 Schematic of the ASJM components (not to scale).
jet diameter was measured optically and found to be 140 µm over the 30-mm standoff distance (jet centerline distance between orifice and target). This value compares well with the theoretical value of 0.64 for a sharp orifice given by Falkovich (2011, p 10). The jets formed at 4 and 7 MPa had velocities of about 110 and 152 m/s respectively, computed using Bernoulli’s equation. These velocities correspond to a Reynolds numbers of 15,120 and 21,280 respectively; thus the jet was turbulent, both being well above the critical Reynolds number of 10,000 for a water jet in air, as described by Dimotakis (2000). Moreover, the maximum Mach number was about 0.1, indicating that fluid compressibility was negligible. The standoff distances, which were 20 and 30 mm, were both below the theoretical breakup length, computed to be 36 mm using the equation provided by Taylor (1962):

\[ x_b = \frac{d_0 B \left( \frac{\rho_l}{\rho_g} \right)^{\frac{1}{2}}}{f(T)} \]

where \( d_0 \) is the orifice diameter, \( B \) is a constant equal to 2.02, \( \rho_l \) and \( \rho_g \) represent the liquid and gas densities respectively, and \( T \) is Taylor's parameter \( T = \rho_l / \rho_g \left( \text{Re}_L / \text{We}_L \right)^2 \), in which \( \text{Re}_L \) is the Reynolds number of the jet based on the jet diameter \( L=140 \, \mu m \), and \( \text{We}_L \) is the Weber number (a dimensionless ratio of the fluid inertia relative to its surface tension) calculated to be 22,430, also using the jet diameter. The function \( f(T) \) has been numerically approximated by Dan et al. (1997) as \( f(T) = \sqrt{3}/6 \left[ 1 - \exp(-10T) \right] \).
To minimize the settling of particles in the stainless tubing upstream of the orifice, a tube diameter of 3.2 mm was selected to maintain a particle Reynolds number, $Re_p$, of at least 300. Even so, settling occurred in the tubing and reduced the concentration from 1.00 wt% in the reservoir to 0.79 wt% in the jet, the latter measured by weighing samples collected in a beaker during one-minute periods. The collected samples were passed through a filter paper of known mass, and the wet particles and paper were dried in an oven at 150 °C to obtain the mass of the particles. Ten samples were collected this way and were regularly spaced over a period of 60 min. Because the particle concentration varied less than 3%, the slurry concentration in a jet was considered to be constant over the operating periods which lasted up to one hour.

![Orifice geometry (dimensions are in μm).](image)
1.4 References


Chapter 2
The Effects of Dilute Polymer Solutions on the Shape, Roughness and Width of Abrasive Slurry Jet Micro-machined Channels

2.1 Introduction

Section 1.1 summarized the past studies relating to the field of ASJM and polymeric additives. In summary, it was found that machining with concentrated high-molecular-weight polymer solutions at high pressures reduced widths of cuts, and reduced the jet divergence in low-pressure ASJM polishing. The objective of this Chapter is to examine the effect of polymer solutions in the dilute range (20 to 400 wppm) on machined channel width, cross-sectional shape, and roughness, and to explain the observed changes in terms of the relative contributions of liquid viscosity and elasticity.

2.2 Experiments

2.2.1 Channel Machining

Channels were machined in 100×50×3 mm borosilicate glass plates (Borofloat 33®, Schott Inc., NY, USA) by mounting the plates on a computer-controlled linear stage (Zaber Technologies Inc., Vancouver, BC, Canada), capable of vertical motion at speeds up to 7 mm/s (Figure 1-1). The slurry jet was aligned to be perpendicular to a plate, which was scanned at 0.05 mm/s at a standoff distance of 20 mm (the jet centerline distance between the orifice and plate). These operating parameters were selected to provide channels with depth-to-width ratios similar to those in other ASJM studies without additives such as those conducted by Miller (2004), Pang et al. (2010), and Nouraei et al. (2012). As mentioned in Section 1.3, the slurry flow rate was 1.67 ± 0.1% mL/s for all tests, so that the dose of abrasive delivered to the surface (mass of abrasive per unit area) was constant.

The cross-sectional profiles and the roughness of the machined channels were measured using an optical profilometer (ST400, Nanovea Inc., CA, USA), which had a depth resolution of 0.1
µm. Depth measurements were acquired laterally every 5 µm, and roughness data were obtained every 0.1 µm along the channel centreline.

2.2.2 Slurry Preparation

Nine aqueous test fluids were prepared, the details of which are given in Table 2-1, and all had an abrasive concentration of 1 wt%. Glycerin was added to one and polyethylene oxide (PEO), of several molecular weights and concentrations, was dissolved in seven of them.

The viscosity of each fluid was measured to ±0.2 % accuracy using a Cannon-Fenske capillary tube viscometer, following the procedure of ASTM D4889-04 (ASTM 2011). As seen in Figure 2-1, the viscosity increased linearly with the polymer concentration.

<table>
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<tr>
<th>Table 2-1 Properties of the aqueous test fluids.</th>
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Figure 2-1 Viscosity of the PEO solutions versus concentration at 21°C.

The abrasive particles were taken from the supplier’s 1-L bottle using the ASTM quartering technique (ASTM C702-98, 2002) to ensure that the size distribution was uniform after shipping and handling. Samples were weighed on an electronic scale (AP110, OHAUS Corp., Pine Brooke, NJ, USA), accurate to 0.1 mg.

Three widely-different molecular weights of PEO were obtained, namely 0.1 M, 1.0 M and 8.0 M (viscosity-averaged molecular weights, Sigma-Aldrich, St. Louis, MO, USA). To prepare a solution, the desired amount of a particular molecular weight was first dispersed in 20 mL of ethanol to avoid polymer aggregation, and then this mixture was added to 6 L of slurry in the reservoir tank and slowly stirred to minimize polymer degradation.
2.3 Results and Discussion

2.3.1 Reference Channel

A reference channel was machined with fluid number 1, the slurry without additives, and the channel is shown in Figure 2-2. For all test fluids, channel dimensions were found to be uniform along the length of a channel and between channels. More specifically, 3% was the maximum variation in depth and width in three scans taken 5 mm apart along a single channel, and in three additional channels.

Figure 2-2 (a) SEM image of the reference channel, and (b) its cross-sectional profile, measured using an optical profilometer.

Figure 2-2(b) shows that the reference channel had a U-shape with a relatively flat bottom, similar to the shapes observed in Nouraei et al. (2012). The channel was 92 μm deep and 280 μm wide. The profile was measured every 5 μm and the width was taken to be the point where the slope of the linear fit to 5 consecutive profile points reached a slope of 10% from the horizontal.
2.3.2 Effects of Viscosity

The addition of PEO increased the viscosity and induced non-Newtonian behaviour. The addition of glycerin, however, (fluid 2), increased only the viscosity because glycerin molecules are too small to generate non-Newtonian behaviour, as described by Larson (1999, p. 107). Figure 2-3 compares the cross-sectional profiles of channels with and without glycerin; i.e. a comparison of fluids 1 and 2 under otherwise identical conditions. The plot shows that the 10% increase in viscosity caused by the glycerin decreased the channel depth by 19%, but had virtually no effect on the width.

![Graph showing cross-sectional profiles of channels](image)

**Figure 2-3 Cross-sectional profiles of channels machined with the water/glycerin mixture (fluid 2) and with water alone (fluid 1); the latter is the reference profile in the preceding figure.**

It is hypothesized that the 19% reduction in depth was caused by two viscous effects. First, as a particle approached the target, its larger drag made it decelerate more as it approached the plate in the stagnation zone, in accordance with the work of Clark (1992); i.e. the increased viscosity reduced the particle’s impact energy and hence its ability to erode. Secondly, the 10% increase in viscosity increased the momentum equilibration number, as defined by Humphrey (1990), by 10%, reflecting a slightly greater tendency for particles to follow the streamlines and thereby decreasing the local impact angle at the bottom of the channel, as illustrated in Figure 2-4 by trajectories (a) and (b). Since the erosion of brittle materials depends strongly on the velocity component perpendicular to the surface, as described by Slikkerveer et al. (1998) and in the work of Ballout et al. (1996), the net effect was to reduce erosion and therefore the channel
depth. In principle, this second effect should also have changed the channel width, but the effect appears to be negligible for a 10% increase in viscosity.

![Streamlines and expected particle trajectories and impact angles in the stagnation zone for (a) a reference fluid and (b) for a fluid with a higher viscosity.](image)

**Figure 2-4** Streamlines and expected particle trajectories and impact angles in the stagnation zone for (a) a reference fluid and (b) for a fluid with a higher viscosity.

### 2.3.3 Effects of PEO

To investigate the effects of this elasticity or additional stress, channels were machined using the seven different PEO solutions of Table 2-1.

#### 2.3.3.1 PEO and Agglomeration

Türkman (1991) describes the use of polymeric additives in industrial wastewater treatment to coagulate particles and promote their settling. Hence it was necessary to determine whether agglomeration affected the present experiment. Laser shadowgraphy was used to measure the size distribution and settling velocities of the aluminum oxide particles, in water and in the 50 wppm solution of 8-M PEO (fluid 4). The latter fluid, as Table 2-1 shows, was 10% more viscous than water. The velocities and size distributions were measured in a 50x100x3 mm glass vessel using a double-pulsed Nd:YAG laser (neodymium: yttrium aluminum garnet), which produced up to 0.3 J/pulse at a repetition rate of 1 kHz and which passed through a diffuser (1108417, Lavision GMbH, Goettingen, Germany). The laser was placed opposite a high-speed...
CCD camera (Imager Pro PlusX, Lavision GmbH, Goettingen, Germany) with a zoom lens. More details of this system and the shadowgraphic technique can be found in Dehnadfar et al. (2011). Based on 1,500 measurements made in each liquid, it was found that the particle size distributions were the same, indicating that the polymer did not cause agglomeration. The settling velocity did decrease, though, but the value was consistent with the 10% increase in the drag force predicted by Stokes' law.

Figure 2-5(a) presents the channel profiles for the 25 and 50 wppm 8-M PEO solutions (fluids 3 and 4), along with the profile of the reference channel (fluid 1) under identical experimental conditions. The 25 and 50 wppm solutions decreased the channel width by 10% and 21%, respectively, and the depth by 20% and 46%. As shown in the figure, the PEO profiles had more of a "V"-shape than the "U"-shape for the water-only slurry; that is, with polymer there was no flat-bottom section (cf. Figure 2-2). Figure 2-5(b) shows that the width decreased linearly with polymer concentration in this range.
Figure 2-5 (a) Cross-sectional profiles of channels machined with slurries of water, 25 and 50 wppm solutions of 8-M PEO (fluids 1, 3, 4). (b) The decrease of channel width with concentration.

The increased resolution for the two PEO solutions in Figure 2-5 is attributed to polymeric normal stresses – i.e., stresses due to liquid elasticity – because Section 2.3.2 showed that a 10% increase in viscosity did not change the width. The depth decrease of 46% relative to the water-only case, was the sum of the effects of viscosity and normal stresses. A 19% reduction was caused by the increased viscosity, as shown by Figure 2-3 for the glycerin/water mixture. Because the 50 wppm solution had the same shear viscosity as the glycerin liquid (Table 2-1), the additional 27% decrease in depth with this fluid must have been caused by normal stresses.

Such stresses can reduce the energy of a particle close to the target as the fluid velocity approaches zero. Figure 2-6 shows stagnation-point regions where normal stresses are
generated, at the front of a particle and at the impact point on the target. The induced stresses create an additional resistance to motion, thereby further decelerating the particle.

![Diagram of particle motion]

**Figure 2-6 Stagnation point regions where normal stresses create an extra drag on a particle approaching the target.**

The decreased channel width produced with the polymer solutions could have been the result of changes in the jet velocity distribution. However, this possibility is unlikely because Goren and Norbury (1967) found that the velocity profile in turbulent jets of aqueous PEO solutions did not change significantly. It is therefore more likely that fluid elasticity reduced the jet footprint in the stagnation region by focusing the streamlines and decreasing the spread of the flow. The stagnation region of a Newtonian jet impinging on a flat surface has hyperbolic-like streamlines (Figure 2-4) and a uniform extensional strain rate throughout, as described in Schlichting (2004, p. 110). In this flow field, the stretch of a polymer chain depends on its residence time, which increases with proximity to the stagnation point. Consequently, elastic effects increase in streamlines that are progressively nearer to the stagnation point. This behaviour has been confirmed by Muller et al. (1990) who used optical birefringence to show that the degree of chain extension in a dilute high-molecular-weight polymer solution was maximum near the stagnation point. Given that polymer chains resist flow extension in proportion to the amount by which they are stretched, streamlines leaving the stagnation point spread less, causing the
impacting particles to strike closer to the centreline. That is, the jet is more focused (Figure 2-7), decreasing the channel width and causing profiles with more curvature.

![Diagram](image)

**Figure 2-7 Comparison of particle impact angle in a polymeric solution (θ) and water (ϕ).**

When the slurry had a concentration of 75 wppm of the same PEO (solution 5), the channel width increased by 5%, contrary to the trend of Figure 2-5(b). The increase was caused by a jet instability that resulted in a 40-μm amplitude oscillation, producing an effective jet diameter of 220 μm. Rothstein and McKinley (1999) found that instabilities in non-Newtonian jets are can result from randomly fluctuating vortices formed upstream of a sharp orifice. Avoiding the instability limited the concentration range for each polymer molecular weight.

The experiments were extended to include an additional scanning pass. Figure 2-8 shows that a second pass with the same 50 wppm of 8-M PEO solution (fluid 4) had no effect on the width, but increased the channel depth by 35%, resulting in a total depth close to that of the reference channel. Therefore, the reduction in depth brought about with PEO solutions can be compensated for by additional machining passes without affecting the decreased width.
Another machining characteristic of interest was surface roughness. In the present experiment, channel roughness was measured along the centreline for 5 mm using an optical profilometer, and the data were analyzed according to the ISO 4288 (1996) standard. The roughness, designated $R_a$, varied by 7% variation over two 5-mm lengths, which were 1 mm apart along a single channel, and over three single scans of separately machined channels. The $R_a$ values using water and the glycerin/water mixture (fluids 1 and 2) were both approximately 0.5 $\mu$m, while the roughness from a single pass with the 50 wppm 8-M PEO solution was 0.7 $\mu$m. A t-test analysis showed that the difference between these values was statistically significant with a confidence interval of 95%. Micrographs of the two surfaces are presented in Figure 2-9, which shows that the surface texture of the channel machined with the PEO solution was significantly coarser than that of the channel machined with water alone.
Figure 2-9 SEM images of surfaces in the central regions of channels, indicated by the rectangle in (a), machined using: (b) water only (fluid 1) and (c) water with 50 wppm of 8-M PEO (fluid 4).

Since roughness increases with the normal impact component as discussed, for example, by Slikkerveer et al. (1998), the difference is believed to be caused by the focusing effect discussed earlier and shown in Figure 2-7. Since glycerin had a negligible focusing effect, it did not increase the roughness.

2.3.3.2 Tests with the 1-M PEO

Fluid elasticity increases with molecular weight, because longer chains generate more tension and thus produce larger normal stresses, as described by Bird et al. (1987, p. 637). With shorter chains, lower effects are expected, and these effects were assessed in the present work by using 1-M PEO. Concentrations with this polymer were varied up to 400 wppm, at which point the jet became unstable. As shown by Figure 2-10, (i) a 25 wppm solution (fluid 6) had no significant effect on the channel width, but decreased the channel depth, relative to the reference channel, by 32%; (ii) a 200-wppm solution (fluid 7) reduced the width by 13% and the depth by 39%; and (iii) when the concentration was 400 wppm (fluid 8), the jet was unstable and its larger effective diameter due to the lateral jet oscillation caused the width to increase by 7%. 
Figure 2-10 Cross-sectional profiles of channels machined with water and with three concentrations of 1-M PEO (fluids 1, 6, 7, and 8).

These data with 1-M PEO solutions confirm that, with a stable jet, the polymer caused both the channel depth and width to decrease, as was found with the 8-M solutions.

Figure 2-11 compares the change in the channel width obtained with the two highest molecular-weight polymers, over their range of concentrations. The plot shows that the channels made with the 1-M PEO were much wider than those machined with the 8-M PEO. This result suggests that normal stresses were larger with the 8-M PEO slurries even though polymer concentrations were much lower. Therefore, the polymer focusing effect depends more strongly on molecular weight than concentration, a finding consistent with other flows containing polymer additives, such as in the work of James and McLaren (1975).
2.3.3.3 Test with 0.1-M PEO

To further probe the effect of molecular weight, channels were machined with a slurry containing the lowest-molecular-weight PEO, the 0.1-M sample (fluid 9). This short-chain polymer increased the shear viscosity significantly, as Table 2-1 indicates, and thus the channel depth was reduced considerably, as Figure 2-12 shows. But, even at a concentration of 2.5 wt% (25,000 wppm), the channel width was unchanged, re-confirming that polymeric effects depend more strongly on molecular weight than concentration. Because the width was not affected, the shallow depth appears to have been caused solely by the fluid’s higher viscosity, namely, 9 mPa.s versus 1.1 mPa.s for the other PEO solutions (Table 2-1).
2.4 Conclusions

In contrast to the channel width decrease observed in the AWJ work of Ashrafi (2011) using concentrated short-chain polymer solutions and high pressure, the present results demonstrate that dilute high-molecular-weight solutions in low-pressure ASJM can significantly increase the resolution of machined micro-channels.

2.5 References


Chapter 3
The Effects of Dilute Polymer Solutions on the Shape, Depth, and Diameter of Abrasive Slurry Jet Micro-machined Holes in Brittle and Ductile Materials

3.1 Introduction

In addition the works described in the literature review of Section 1.1, a number of studies have focused on ASJM hole drilling. Nguyen et al. (2009) drilled holes in glass using a low-pressure (3 MPa) and a high concentration (8.2 wt%) slurry, and, in a companion paper, Wang et al. (2009a) studied the effects of pressure and machining duration on erosion in holes in glass. In both papers, the holes were found to be "W"-shaped, related to the dominance of a ductile erosion caused by low abrasive kinetic energy. Nouraei et al. (2013) found that higher kinetic energy led to "U"-shaped holes with flatter bottoms and steeper sidewalls. Wang et al. (2009b) examined the profiles of holes machined in glass and found them to be asymmetric because of orifice vibration and misalignment. A typical cross-sectional profile shape was divided into various zones, and the shape of each zone was explained in terms of the direction of the slurry flow relative to the walls of the hole.

The use of polymeric additives in ASJM holes is limited. Wang et al. (2009c) investigated machining using a variety of polymers, namely polyacrylamide PAM, anionic polyacrylamide (HPAM), and cationic polyacrylamide (PAMA), along with a variety of abrasives, specifically 22-μm-diameter garnet, boron carbide, and white and brown corundum. They found that the slurry containing 6,000 wppm 5-M PAM and white corundum particles yielded the most symmetrical holes with the largest material removal rate. No comparisons were made to holes machined without additives.

In summary, previous studies in ASJM were limited to asymmetrical holes in glass and did not identify clearly the role of polymers and the mechanisms by which they change the erosion. In this chapter, the effect of adding a high molecular weight polymer to the abrasive slurry (fluid 4), i.e. dissolving 50 wppm of 8-M PEO is examined in glass and various metals through comparison with reference holes machined without additives. The polymer concentration was selected based on the results of Chapter 2, which produced the minimum ASJM channel width.
The work also investigates the potential of sacrificial polymeric or glass surface layers to reduce hole opening diameters.

## 3.2 Experiments

### 3.2.1 Hole Machining

The process parameters were selected to provide holes with shapes and diameter-to-depth ratios similar to those in other ASJM studies conducted without additives, such as the study by Nouraei et al. (2013). Holes were machined in borosilicate glass plates at an orifice-to-target standoff distance of 30 mm. The duration of machining was controlled using a shutter to intercept the jet. Five holes were machined separately under identical conditions with the water-only slurry, and the maximum variation in their depths was less than 3%. Three different aqueous slurries were prepared, all having a 1 wt% concentration of 10-μm alumina abrasive particles. One slurry contained only water and abrasive, another also contained 5.2 wt% glycerin, and in the third 50 wppm of 8-M PEO was dissolved. The glycerin concentration was selected to yield a viscosity equal to that of the PEO solution, specifically 10% higher than that of water. The PEO solution was prepared using the method described in Section 1.3.2.

During initial tests, it was found that accurate alignment of the jet normal to the target plane was crucial to obtain symmetric holes; e.g. a misalignment of even 0.5° produced a relatively large asymmetry (Figure 3-1(a)). To reduce misalignment, a three-point-guide (Figure 3-2) was used to connect the orifice plate and target surface, and were measured to be parallel to less than 0.1° using an electronic level (Digital Level Model Number 35-222, Micro-Mark, Berkeley Heights, NJ, USA). The resulting machined holes were found to be symmetric, as shown in Figure 3-1(b).
Figure 3-1 Holes machined using an aqueous slurry jet with (a) a 0.5° misalignment, and (b) alignment correction with an accuracy of 0.1°.

Figure 3-2 Nozzle guide to maintain constant standoff and alignment with the target.
3.2.1.1 Elasticity-Induced Jet Oscillation

In Chapter 2, it was noted that the addition of PEO, but not the glycerin, caused the jet to oscillate. This behaviour was investigated further for the PEO solution by capturing microscope images having a field of view of $3 \times 2 \text{mm}^2$ for 10 seconds at a frequency of 29 Hz, and then extracting the position of the jet from each frame. The jet diameter was found to be consistent at 140 $\mu$m, but its lateral position oscillated with a varying amplitude up to 20 $\mu$m, producing an effective jet diameter of 180 $\mu$m. Without the PEO, the jet had the same diameter (140 $\mu$m), but did not oscillate. The frequency spectrum in Figure 3-3 shows that there was no dominant frequency in the jet oscillation. This is consistent with the work of Rothstein and McKinley (1999), who found that oscillations in non-Newtonian jets can result from randomly fluctuating vortices formed upstream of a sudden contraction, such as that of the orifice in Figure 1-2.

![Figure 3-3](image-url)

Figure 3-3 Fourier transform plot of the amplitude of the lateral jet oscillations see with a solution containing 50 wppm of 8-M PEO.
3.3 Results and Discussion

3.3.1 Reference Holes without Additives

Figure 3-4 shows an example of a hole machined in glass using the aqueous slurry without PEO or glycerin, at a flow rate of 1.67 mL/s for 8 minutes.

![Figure 3-4 Microscope images of a hole machined using the water-only jet (a) hole opening in the plane of the target surface, and (b) cross-sectional profile.](image)

The side walls of the hole merged with the target surface through a curved region that ended in a frosted zone on the surface. Cross-sectional profiles of the holes were viewed through an adjacent optically-clear edge in the glass plate, using a microscope having a field of view of 2000×1500 μm² and quantitatively characterized using an image analysis system (Clemex Vision PE, Clemex Technologies Inc., QC, Canada) and digital software (ImageJ software—http://rsb.info.nih.gov/ij/). Figure 3-5 illustrates how the profiles machined with the water-only slurry at 1.67 mL/s developed with exposure duration, and shows that the opening width
increased more relative to the jet diameter than did the width of the sidewalls. This is shown in Figure 3-6 which compares the hole depth (Figure 3-6(a)), frosting diameter (Figure 3-6(b)), and average diameter (Figure 3-6(c)), defined as the cross-sectional area of the hole divided by its depth, all three normalized by the jet diameter. It is seen that the hole depth increased less-than-linearly with exposure duration, consistent with the findings of Nouraei et al. (2013). It is hypothesized that the decline in depth enlargement was due the decreasing flow and particle velocity as the depth of liquid in the hole increased. Figures 3-6(b) and 3-6(c) reveal that the relative increase in the frosting diameter, of the lightly abraded surface, with exposure time was much more than that of the average diameter.
Figure 3-5 Profiles of holes machined in glass under identical conditions with the water-only slurry at 1.67 mL/s.
Figure 3-6 Plots of (a) depth, (b) frosting diameter, and (c) average-diameter normalized by the jet diameter versus exposure time in holes machined in glass with the water-only slurry at 1.67 mL/s.

The shape of the cross-sectional profile, shown in Figure 3-4(b), can be divided into three zones, similar to those found by Wang et al. (2009), the shapes of which can be described by the flow and erosion mechanism. Figures 3-6(b) and 3-6(c) demonstrated that both the average diameter, which was sensitive to the amount removed in zones A and B, while the frosting diameter, which was governed by the degree of erosion in zone C also increased with exposure time but at different rates. Regarding the rate difference, it is hypothesized that zone A (Figure 3-7(a)) evolved due to erosion by the high impact angles, $\alpha$, of the deflecting flow as shown in Figure 3-7(b). The relatively lower material removal in zone B is explained by two effects: (i) the shallower impact angles, $\theta$ (Figure 3-7(b)), of the return slurry travelling toward the surface, since erosion is maximum at 90° in glass as described by Gustavsson (2002), and (ii) the
reduced particle kinetic energy after the initial impact in zone A. The curvature of zone C was primarily created by the erosion by the peripheral streamlines near the surface of the jet, which added a highly erosive flow component to the return slurry due to its high-velocity and perpendicular incidence, $\phi$, as shown in Figure 3-7(b). Therefore the frosting diameter was developed by a flow having a higher erosive energy than the average diameter, consistent with the larger growth rate of the frosting diameter relative to the average diameter, shown in Figures 3-6(b) and 3-6(c). Figure 3-6(b) also shows that the curvature of zone C evolved with exposure time rather than completely forming immediately prior to the initial jet impact as described by Wang et al. (2009).
Figure 3-7 (a) Hypothesized streamlines of the flow field during the machining process. (b) Magnified regions of the boxes in (a) to illustrate the flow components’ velocities and impact angles relative to the surface and particle impact angle, $\alpha$, near the stagnation point.

In Chapter 2, where channels and not holes were machined, the results were much less sensitive to the alignment of the slurry jet, for an orifice misalignment of approximately 0.5° produced no asymmetry. In that case, the slurry was relatively free to flow away from the primary impact zone, and so secondary erosion of the channel walls was small. In contrast, the flow within a
hole was highly confined, so that secondary erosion of the hole walls became much more significant and susceptible to small changes in the direction of the incident jet.

3.3.1.1 Through-holes

The exposure time was extended to pierce through a 3-mm-thick borosilicate glass, requiring 90 minutes of machining at a flow rate of 1.67 mL/s, and the profile is presented in Figure 3-8(a). As shown in Figure 3-8(b), the exit of the pierced hole was circular. In contrast, Hashish (1988) observed chipping at the exit edges of holes, which he attributed to sub-surface stress waves created by the impact of high-pressure AWJM jets. The 180 μm diameter of the exit hole was larger than the jet diameter, 140 μm without PEO, probably because of flow near the stagnation point, as illustrated in Figure 3-7(a). It was also observed that the initial breakthrough was followed by about three seconds of transient widening of the exit before the jet could pass through the target without interference. As illustrated by Figure 3-8, the cross-section of the entrance hole continued to broaden and lengthen with time as the radius of curvature grew.
Figure 3-8 (a) Comparison of profiles of a hole machined in glass with the water-only slurry for 8 minutes and a through-hole after 90 minutes, at a flow rate of 1.67 mL/s. (b) Microscope image of the exit of the through-hole.
3.3.2 Comparison of Holes in Glass and Metal, and Polymer Plates

Figure 3-9(a) superimposes the profiles of shallow holes machined in glass, 316 stainless steel, 110 copper, and 6061-T6 aluminum alloy. As shown, there are significant differences in the shapes and sizes of the four holes even though they were all machined at a flow rate of 2.34 mL/s for 10 seconds. Of particular interest is the much sharper definition of the hole edge with the metals, compared with the larger radius of curvature with the glass. This increased definition of the jet erosive zone was also reflected by the absence of frosting on the metal surfaces, an example of which is shown in Figure 3-9(b). As described in Section 3.3.1, a high impact angle (ϕ) is dominant near the opening of holes. Since the erosion of brittle materials such as glass is a maximum at a perpendicular incidence, these materials have highly eroded hole entries. Ductile materials, however, have lower erosion rates at high impact angles, as explained by Gustavsson (2002), which resulted in much less erosion in zone C. In contrast to the holes in glass in Section 3.3.1, the shallow impact angle (θ) of the low-velocity return slurry (Figure 8(b)) was dominant in the entry region of the metal holes. This effect is consistent with the findings of Liu (2007), who compared high-pressure AWJM holes drilled in glass and aluminum and found considerable wear in the vicinity of the entrance in holes machined in glass, but not in aluminum.
Figure 3-9 (a) Profiles of holes machined in brittle and ductile materials under identical conditions, using the aqueous slurry at a flow rate of 2.34 mL/s; (b) microscope images of the hole openings machined under identical conditions in (i) 6061 aluminum, (ii) 110 copper, (iii) 316 stainless steel, and (iv) borosilicate glass.

When holes were machined in the borosilicate glass, deep symmetrical holes were possible because the process was stable. With metals, though, the process became unstable and grooves
were formed. This instability was investigated further using transparent polymethylmethacrylate (PMMA), which eroded in the same ductile manner as the metals. Figure 3-10, obtained under the same conditions as those in Figure 3-9, shows that the hole was asymmetrical, in (a) and that a groove developed, in (b) The erosion rate increased upon the onset of groove formation at a depth of approximately 250 μm, because the return slurry began to flow away from the incoming jet via the groove; whereas in holes without grooves, the return slurry dissipated the jet's impact energy because of interference. As a result, the PMMA hole had the highest erosion rate among the metal holes.

![Diagram](a)
The origin of the asymmetry which led to the formation of the grooves was investigated by comparing a hole drilled into a plate fixed at a reference angular position about the jet centreline with another hole machined into the plate after it was rotated by 90° relative to the reference angular position. Comparisons confirmed that the direction of the grooves was consistent with that of orifice misalignment. As described in Section 3.2.1, when the orifice angle was within 0.1° of 90° to the surface, there were no irregularities in the holes machined in glass, which were presented in Section 3.3.1. Drilling in ductile materials is apparently much more sensitive to jet alignment. It is hypothesized that this sensitivity was due to the erosion rate being a maximum at an impact angle of approximately 30° in metals and 90° in glass, as described by Gustavsson (2002). Streamline curvature near the stagnation point reduced the impact angle of particles as illustrated in Figure 3-7, causing an increased erosion rate on the walls of the metal holes. Any perturbation of the jet flow toward one side of the hole would increase the erosion rate on that side, thereby decreasing the local impact angle and further accelerating the erosion at that location. Once a groove started, its erosion was accelerated by the progressively decreasing impact angle and, as mentioned above, the decreasing resistance to incoming slurry.
flow as the slot develops. In contrast, the glass was more tolerant of small misalignments since the erosion rate on the sides of holes was relatively small at shallow impact angles.

3.3.3 Effects of Fluid Elasticity

3.3.3.1 Tests on Glass

Figure 3-11(a) presents the profiles of shallow holes machined with the water-only slurry compared with the two types of solution, at 1.67 mL/s and 5s duration. The 10% increase in viscosity with glycerin solution reduced the depth by 6%, but it did not significantly change the profile shape, the average diameter, nor the size of the frosted zone (Figure 3-11(b)). The decreased hole depth was due to the larger particle drag that because of the increased viscosity which decelerated the particles and hence reduced the erosion at the bottom of the hole, as described by Clark (1992). In addition to this viscosity-induced reduction, the depth of the hole was reduced 17% further by the polymer. The additional resistance to motion was created by induced stresses at the front of a particle, further decelerating the particle and reducing its impact energy.

The added polymer also changed the shape of the hole, from the "U"-shape without polymer to more of a "V"-shape, as illustrated in Figure 3-11(a).
Figure 3-11 (a) Hole profiles, and (b) microscope images of the openings of shallow holes machined under identical conditions with the water-only slurry (left), the glycerin solution (middle) and the PEO solution.

The polymer decreased the depth of the hole. Figure 3-12(a) shows the depth increasing with exposure time for deep holes machined in glass, with and without the PEO. The plot reveals that the polymer reduced the depth by an average amount of 29\%, over an 8-minute period.

Figures 3-12(b) and 3-13(c) are plots of the frosting and average diameters as functions of depth, showing these quantities decreasing by averages of 25\% and 15\% respectively, with water and with a 50 wppm of 8-M PEO. The changes in depth, diameter, and shape are similar to those in machined channels in Chapter 2. As described previously, this extra resistance near
the stagnation zone (Figure 3-7(a)) caused the primary area of jet erosion to be smaller since the streamlines were more focussed.
Figure 3-12 Measurements of depth, (b) the frosting diameter, and (c) the average diameter versus exposure duration in holes machined with and without 50 wppm of 8-M PEO. The dashed lines are only to help guide the eye.

The effects of elasticity were generally smaller with deeper holes. For example, it was found that, whereas PEO reduced the frosting and average diameters by 41% and 13% in the 125-µm deep holes, these reductions were only 15% and 6%, respectively, for 800 µm holes, since the larger extensional rates that occur in shallow holes generated more resistance to motion. The elongational rate decreases as the holes become deeper, because of a decrease in the flow velocity within the cavity, consistent with the decreasing rate of depth evolution with exposure time (Figure 3-12(a)).

3.3.3.2 Tests on Various Metals

The effects of fluid elasticity on holes machined in the metals are presented in Figure 3-13.
Tests revealed that the PEO reduced the depths by approximately 20% compared to the water-only holes. Although the holes machined with the PEO solution had smaller average openings, they were highly irregular. This irregularity was tested for directional consistency using the same procedure as that in Section 3.3.2. The results indicate that, contrary to what was found for aqueous slurry holes in ductile materials, for polymeric slurry holes in metals, asymmetry was not always related to the direction of the jet. The asymmetry likely resulted from oscillations of the jet in random directions when it contained PEO, as discussed in Section 3.2.2. This jet instability lead to transient jet asymmetry which, combined with the sensitivity of the ductile erosion mechanism to changes in the impact angle, would quickly cause the holes to become non-circular.
3.3.4 Machining through a Sacrificial Surface Layer

It was of interest to see if a sacrificial layer on top of the target could be used to decrease the hole opening diameter and reduce or eliminate the frosted zone. Figure 3-7 illustrates the flow within a hole and the edge rounding created by the back flow.

This interest was investigated by covering the target surface with two materials in order to minimize the opening diameter in the target plate as shown in Figure 3-14, which also shows that a reduction in depth, equivalent to the thickness of a layer, can be expected in a hole machined through a coating.

Four sacrificial layers were tested: two thicknesses, a coating of epoxy adhesive (J-B Weld, Sulphur Springs, Texas, USA) with two thicknesses, specifically (i) 500 and (ii) 800 μm; and a 150-μm-thick borosilicate glass cover slip (iii) bonded to the target using a room-temperature process (Jia et al. 2004) and (iv) glued to the target using cyanoacrylate adhesive. Thicknesses were measured using a digital caliper accurate to ±20 μm.

Figure 3-15 compares hole openings with the four layers to an opening without a layer. The micrographs show that the sacrificial layers significantly reduced the diameter of the frosted
zone and hence the effective opening diameter, for example, by 38% in the case of the 500-μm-thick epoxy layer. However, the hole machined with the glued cover slip had irregular edges, as shown by (d) and (e) presumably due to leakage and erosion at the interface between the bonded glass surfaces.

Figure 3-15 Microscope images of the openings of holes machined at 1.67 mL/s for 8 minutes (a) without sacrificial layer, (b) with 500-μm-thick and (c) a 800-μm-thick epoxy coatings, (d) bonded and (e) glued 150-μm-thick borosilicate glass slides.

Figure 3-16(a) compares the cross-sectional profiles of the holes, all machined for 8 minutes, through each of the epoxy layers and directly in the glass target plate, and shows that the epoxy coating decreased the radius of the opening curvature, i.e. increased the edge sharpness, but did not eliminate this rounding even when the thickness was increased. During the drilling process, the higher erosion rate of the epoxy relative to that of glass created additional backflow that widened the interface diameter of the layer. This residual erosion in the epoxy hindered the coating's intended ability, which was to restrict the backflow and thus reduce the curvature in the machined hole. When the coating material was changed to glass, the equivalent erosion rates of the layer and target caused the edge was significantly sharpened, as shown in the profiles presented in Figure 3-16(b). However, leakage between the glass cover plate and the target caused the profile of the hole opening to be asymmetric regardless of the bonding method, as indicated in the upper part of the figure.
As expected, the coatings reduced the depths because of the time required to drill through the sacrificial layers. This is illustrated in Figure 3-16(c) by the similar depths of the 6-minute hole in the bare target and the 8-minute hole through the target covered with the 150-μm-thick glass cover plate; i.e. approximately 2 minutes was required to drill through 150 μm of glass.
(b)
Figure 3-16 Profiles of holes machined at a flow rate of 1.67 mL/s for 8 minutes without a sacrificial layer and holes machined for 8 minutes using (a) 500 and 800-mm-thick epoxy coatings, and (b) water-bonded and glued borosilicate slides. (c) Profiles of holes machined at a flow rate of 1.67 mL/s for 6 minutes without a sacrificial layer and a hole machined for 8 minutes using a 150-µm-thick bonded borosilicate cover slip.

3.4 Conclusions

In contrast to the asymmetrical ASJM holes in glass observed in the work of Wang et al. (2009c) and cutting width decrease by using concentrated polymer solutions in high-pressure AWJM of Omrani et al. (2013), the present results demonstrate that asymmetry can be eliminated by orifice alignment and the use of dilute high-molecular-weight solutions or sacrificial layers can significantly decrease the diameter of micro-holes in brittle and ductile materials.
3.5 References


4.1 Summary

A novel abrasive slurry jet micro-machining (ASJM) system was designed and built to investigate the effects of polyethylene oxide (PEO), of varying molecular weight and concentration, on the shape, size, and roughness of micro-channels in glass and micro-holes machined in glass and metals. The effects of viscosity and elasticity were separated by comparing results to those obtained with added glycerin, which changed only the viscosity. When polymer was added, the jet was found to be unstable as it oscillated laterally, and thus its effective diameter increased.

Parameters related to flow, geometry and abrasive were fixed, and a reference channel was machined with water and particles only. For this channel, the width was about twice the jet diameter and the depth to width ratio was about 0.3. The largest decrease in channel width was 21% using the 50 wppm solution of the 8-million molecular weight PEO. With this fluid, the channel depth decreased by 46%, the roughness increased by 29%, and the channel had more of a "V"-shape than the "U"-shape obtained with the reference channel. These results are in contrast to channels machined with a glycerin/water mixture having the same viscosity, for that fluid produced no change in width, only a 19% decrease in depth. Similar changes were seen in holes machined in glass. When 50 wppm of 8-M PEO was dissolved in the slurry, the "U"-shaped profiles of the reference holes became more "V"-shaped. This was accompanied by decreases in the depth, frosting diameter, and average diameter of 29%, 39% and 31% respectively over the depth range. The frosting diameter was also reduced by 38% by machining with an aqueous slurry through a 500-μm-thick epoxy sacrificial layer. The use of polymers in ductile materials resulted in irregular erosion, due to the elasticity-induced jet oscillations combined with the ductile erosion mechanism.

The maximum decrease in width with 1-M PEO channels was 13% at 200 wppm (relative to the water slurry), with a 39% reduction in depth. With the lowest molecular weight PEO, 0.1 M, a concentration of 2.5 wt% did not change the channel width, but decreased the depth by 83%.
An additional pass of a slurry jet containing 8-M PEO was found to increase the channel depth without changing the width or the roughness. This was in contrast in hole machining because both frosting and average diameters were found to increase with depth. When the machining duration was increased until the target was pierced, the diameter of the circular exit was about 22% larger than that of the jet's.

The symmetry of holes machined in ductile materials was limited to depths of approximately 250 µm by groove formation. A comparison of shallow holes machined under identical conditions demonstrated that the material removal rate was higher in glass and than in metal holes, which had significantly sharper openings.

### 4.2 Conclusions

The major conclusions of this thesis are outlined below:

- The jet axis must be perpendicular to the target plane to within 0.1° in order to eliminate asymmetry in holes machined in glass. A higher tolerance is required to machine symmetric holes in ductile materials that are deeper than approximately 250 µm. Deeper holes tend to become asymmetric and develop into grooves. Channels are less sensitive to jet alignment and cross-sectional profile symmetry can be obtained even with a misalignment of 0.5°.

- Channels can be made deeper without affecting the width; in holes however, the frosting and average diameters both increase with depth.

- The material removal rate is highest in shallow holes in glass, followed by 6061-T6 aluminum, 110 copper, and 316 stainless steel.

- Increasing the viscosity decreases the channel depth, but leaves the width unchanged. Similarly, it decreases the hole depth, and does not affect the shape or frosting diameter. In addition to viscosity, elasticity further reduces the depths of holes and channels.
• In glass, dilute polymer solutions can reduce the widths of channels, as well as the extent of frosting around holes and the average diameters of holes. However, they can cause irregularities in holes drilled in ductile materials.

• Similar changes in channel shape, width, and depth occurred in channels machined with either a relatively high concentration of 1-M PEO or a lower concentration of 8-M PEO. However, the changes were larger with the higher molecular weight polymer.

• The use of a sacrificial layer can reduce both the frosting diameter and the radius of curvature of the edges of holes machined in glass.

4.3 Directions for Future Work

Since the elasticity-induced jet oscillations increase the effective jet diameter, further decreases in channel width as well as hole diameter may be possible using orifice designs that preserve the stability of a jet at higher polymer concentrations. This may also improve the roundness of holes drilled in metals using PEO solutions, and may lead to reduced hole diameters.

Machining of smaller channels and holes with a given jet diameter may also be possible using PEO of higher molecular weights. Erosion rate might increase as a consequence of decreased fluid viscosity by means of raising the temperature. Elimination of leakage at the interface of a sacrificial layer and target surface may lead to further reductions in frosting diameters and opening curvatures of holes.