

CREATION OF FUNCTIONALLY GRADED GLASS CHANNELS BY ELECTROCHEMICAL DISCHARGE MACHINING PROCESS: A FEASIBILITY STUDY

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ABSTRACT

Functionally graded surfaces – surfaces with properties that are engineered to have spatial variations – have numerous applications such as micropumps, auto-mixers, and flow control for lab-on-chip devices. Manufacturing of functionally graded surfaces is an increasingly important topic of research. This study investigates the feasibility of creating a functionally graded surface during channeling of borosilicate glass by the electrochemical discharge machining (ECDM) process. The ability to create surface roughness gradients in microchannels during the machining process was demonstrated by modifying the input voltage, tool feed rate, and tool rotation speed. Microchannels with graded surface roughness having Ra values ranging from 0.35 to 4.07 μm were successfully machined on borosilicate glass by ECDM. Surface profiles were obtained via a stylus profilometer, and roughness values were calculated after detrending and applying a Gaussian filter. To demonstrate the process versatility, micro channels with increasing and decreasing Ra values were machined, one increasing from 1.43 μm to 4.07 μm , another decreasing from 3.29 μm to 1.10 μm . To demonstrate the process repeatability, a micro channel with similar surface roughness on both ends and a lower Ra value in the center was created. In this channel, the Ra value at the start is 0.35 μm , reducing to 0.24 μm , then rising again to 0.38 μm in the final section.

Keywords: Electrochemical discharge machining, ECDM, microchannels, functionally graded surface

1. INTRODUCTION

Functionally graded materials (FGM) are materials whose composition or properties are designed to vary from one area to another. Examples of FGM can be found in thermal barrier coatings on turbine blades [1], some density-graded solar cells [2], bio-active coatings for medical purposes [3,4], and many others. However, there are cases where it is desirable to grade

only the surface properties of a feature, such as for mixing in microchannels [5]. Lab-on-chip technologies increasingly have a need for simple ways to control fluid flow through increasingly smaller channels.

The effect of surface geometry on fluid flow, particularly in microchannels, has been well documented in literature [6-12]. It was reported that the effect of surface roughness on the pressure drop increases significantly at the micro scale [7]. One study reported the use of a surface roughness gradient as part of a micropump design [10] and another demonstrated the effective use of structured rough surfaces to guide droplet movement [11]. These studies primarily utilized deterministic features such as regularly spaced pillars to create a defined surface roughness. However, one study investigated the effects of random surface roughness resulting from micromilling on blood flow through microchannels, and found that there was a significant drop in the apparent viscosity of blood and water in the milled surfaces [12]. As concluded in these works and others, surface geometry plays a large role in the behavior of fluids in microchannels.

The microchannels in this study are created in borosilicate glass. Glass is a highly desirable material, especially in the biomedical field, for its optical properties, chemical inertness, and heat resistance [13-15]. However, it is relatively difficult to machine, particularly at the microscale [15,16]. Electrochemical discharge machining (ECDM) provides a nontraditional way to machine nonconducting materials such as glass at the micro scale. ECDM is a process in which a DC voltage is applied across two electrodes submerged in an electrolyte. The machining tool acts as the cathode, and the anode is a larger electrode. Due to electrolysis, gas bubbles begin to form around the tool, eventually coalescing to create a gas film. Once a critical voltage is reached, sparks occur at the tool, leading to material removal of the nearby workpiece via melting, vaporization, and chemical action due to the localized rapid heating of electrolyte [17-19]. A schematic of this process is shown in Figure 1.

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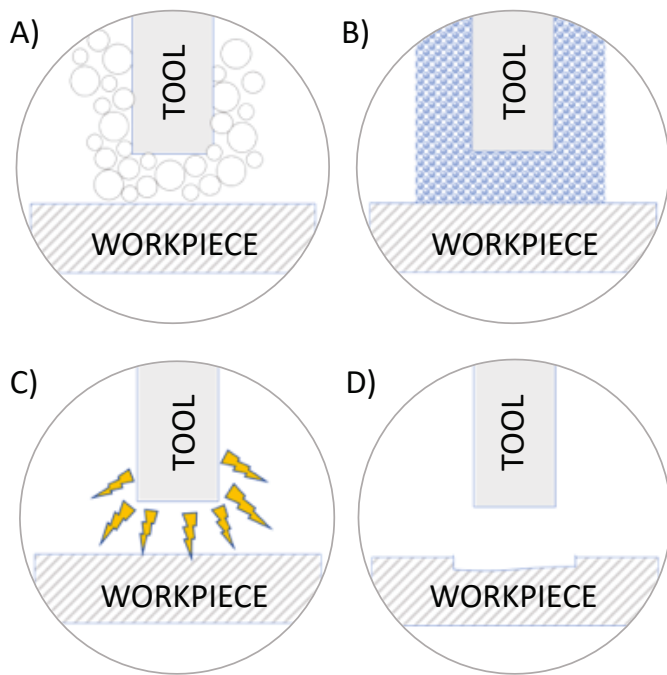


FIGURE 1: Schematic of ECDM mechanism. (A) Electrolysis forms gas bubbles around the tool. (B) Bubbles coalesce to form an isolating gas film. (C) Spark discharge occurs. (D) Workpiece material is removed.

Some studies have looked at the surface morphologies resulting from different process parameters such as tool feed rate, electrolyte concentration, applied voltage, etc. [20,21]. The objective of this study is to demonstrate that the surface roughness resulting from machining microchannels via ECDM can be explicitly controlled to create functionally graded channels during the machining process. It is known that channel wall roughness is linked with hydrophobicity and greatly affects flow rate at the microscale [8,22], thus the flow properties can be controlled to an extent without the use of external forces. This has potential applications for a number of microfluidic purposes such as lab-on-chip devices and auto-mixers.

2. MATERIALS AND METHODS

The 3-axis micro-ECDM setup is detailed in Figures 2 and 3. The tool—a 0.5 mm tungsten carbide rod—was mounted in a spindle attached to a micro-stepper motor acting as the Z-axis. The borosilicate glass workpiece was fixtured in an acrylic tank whose X-Y position was controlled by two more micro-stepper motors. To provide a pulsed voltage, the DC power supply was connected to a pulse width modulator (PWM). The frequency and duty cycle were set to 300 Hz and 50%, respectively [23]. The anode was a Ti-6Al-4V plate, and the tool-workpiece gap was set to a nominal 45 μm . The tank was then filled with 0.5 molar sodium hydroxide such that the length of tool immersed in the electrolyte was 2 mm [23,24].

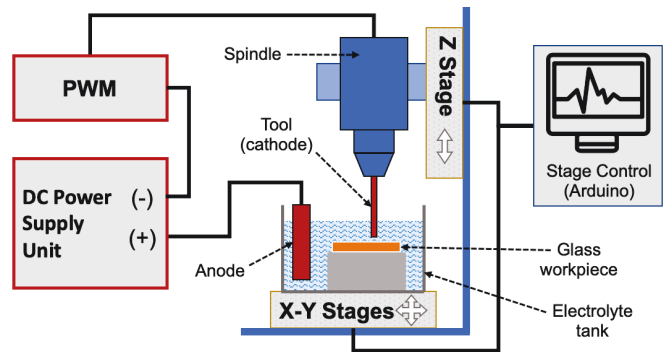


FIGURE 2: Schematic of micro ECDM setup.

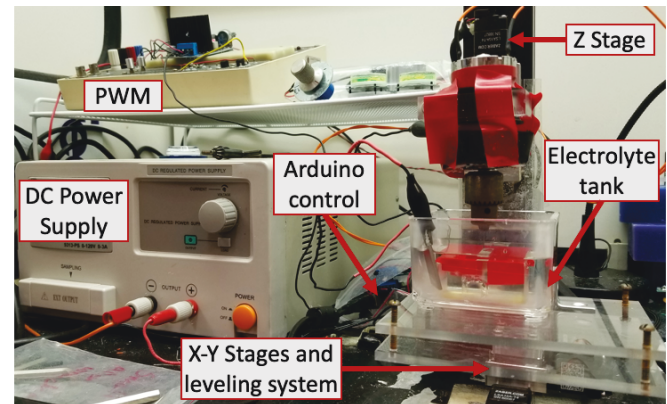


FIGURE 3: Experimental ECDM setup.

Experiments consisted of varying voltage, feed rate, and tool rotation speed at set intervals to create distinct sections within a machined channel, denoted as “Section A”, “Section B”, etc. Each parameter set was used to machine for a distance of 3 mm so the analysis of the final surface would not be affected by end conditions of the channel or transition zones between sections. For example, a channel that is graded using two tool rotation speeds (measured in rotations per minute, or RPM) began machining with the first RPM setting and after 3 mm of machining had been completed, the system was switched to the second RPM setting without stopping or interrupting the machining process.

2.1 Data Analysis

The surfaces in this study are characterized by obtaining a profile with a profilometer, then surface roughness was quantified by the arithmetical mean deviation (R_a). The surface profile of each machined channel was obtained using a Mitutoyo SJ-410 stylus profilometer. Using MATLAB, the profile was first detrended to compensate for tilt in the system before applying a Gaussian filter [25]. In order to eliminate waviness caused by the eccentricity of the stage, the cut-off value was set to 0.3048 mm—the known eccentricity of the stage’s lead screw. The resulting profile was taken as the mean line, and the roughness profile was calculated as the resultant high-pass component. Some samples were also imaged using a scanning electron microscope (SEM) after sputtering with gold.

3. RESULTS AND DISCUSSION

Two-section channels were machined, demonstrating the ability to significantly change the surface roughness during machining. Figure 4 shows a channel in which the surface roughness significantly decreases from the first section to the second. This channel was machined with constant applied voltage of 75 V and tool rotation of 1200 RPM while the tool feed rate was varied. The first section was machined at a feed rate of 2.0 $\mu\text{m/s}$, which was increased to 6.0 $\mu\text{m/s}$ after a set time to create the second section. The calculated R_a values are 1.93 and 1.05 μm , respectively. The green highlighted portions of the profile show the data used to calculate the roughness parameters. The SEM images highlight the differences in the surfaces of the two sections, with Section A showing more asperities, possibly caused by the increased number of sparks per area due to the slower feed rate [26].

Figure 5 shows another channel where the R_a value drastically increases between sections. The applied voltage and tool feed rate were held constant at 75 V and 6.0 $\mu\text{m/s}$, respectively. Machining began with a tool rotation speed of 1200 RPM, which was then turned off for Section B. The resulting R_a

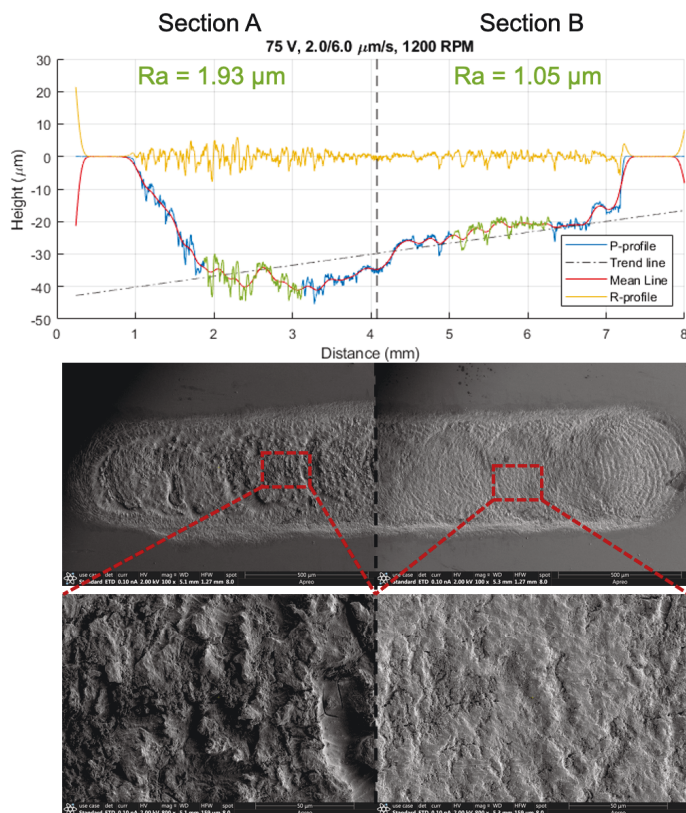


FIGURE 4: Top: Surface and roughness profiles and SEM images of two-section functionally graded channel with decreasing surface roughness. Machining parameters were input voltage of 75 V and tool rotation speed of 1200 RPM. The feed rate began at 2.0 $\mu\text{m/s}$, then changed to 6.0 $\mu\text{m/s}$ after 3 mm were machined. Bottom: SEM images of surfaces.

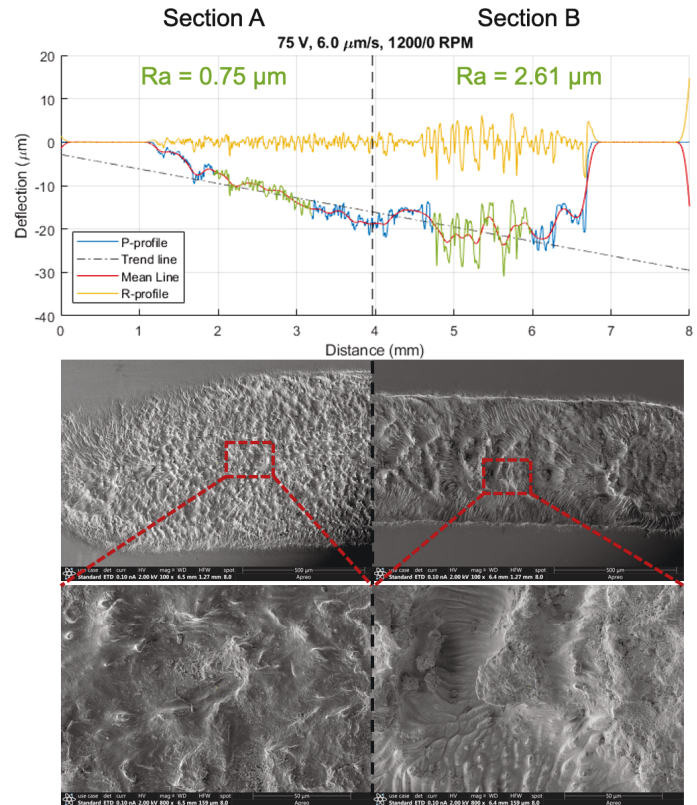


FIGURE 5: Top: Surface and roughness profiles and SEM images of two-section functionally graded channel with increasing surface roughness. Machining parameters were input voltage of 75 V, tool feed rate of 6.0 $\mu\text{m/s}$, and tool rotation speed of 1200 RPM. After 3mm, the tool rotation was turned off to create the second section. Bottom: SEM images of surfaces.

values were 0.75 and 2.61 μm , respectively. The SEM images show glass re-melt in Section B not seen in Section A, likely the result of the lack of tool rotation.

Tool rotation is known to improve the circulation of the electrolyte and to help clear out debris from material removal, and it avoids discharge energy being focused in one area [27]. This explains the high instance of glass remelt areas found in Section B, but not Section A. It has been reported that increasing the tool rotational speed effectively decreased surface roughness, as the gas film thickness becomes thinner and more homogenous with increasing tool rotation [28].

Expanding on the results of the two-section channels, Figure 6 shows a three-section channel with a more gradual decrease in surface roughness. This gradient was created by increasing tool rotation as machining progressed from 0 to 1200 to 3000 RPM while applied voltage and feed rate were held constant at 80 V and 10.0 $\mu\text{m/s}$, respectively, again demonstrating the effects of tool rotation on surface roughness.

In contrast, by instead increasing the machining voltage in increments of 5 V (70, 75, then 80 V) while feed rate was held at 10.0 $\mu\text{m/s}$ and rotation was set to 3000 RPM, another channel was made with gradually increasing roughness (Figure 7). The higher voltage results in an increase in the rate of gas bubble

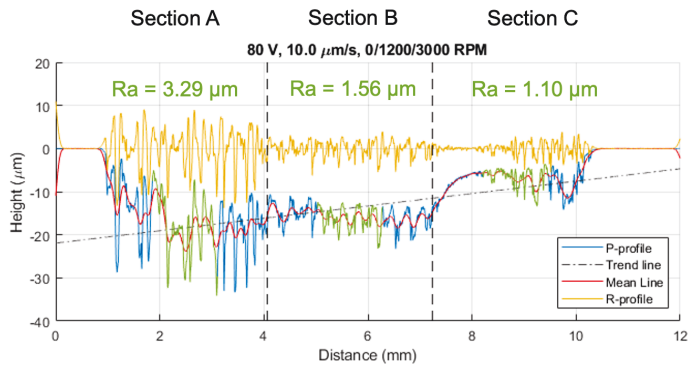


FIGURE 6: Surface and roughness profiles of 3-section channel machined at 80 V, feed rate of 10 $\mu\text{m/s}$, with tool rotation speeds varying from 0 RPM in Section A to 1200 RPM in Section B to 3000 RPM in Section C.

formation, leading to more spark generation [29]. This means that at higher applied voltage, there is higher discharge energy, leading to a higher material removal rate (MRR). At the same feed rate as in Sections A and B, the higher MRR caused increased surface roughness.

To demonstrate the process repeatability, a micro channel was successfully machined with an “A-B-A” pattern—the surface roughness on the ends of channel is roughly equal, while the center section has a lower Ra value. This channel was made by varying the feed rate, beginning at 4.0 $\mu\text{m/s}$, increasing to 6.0 $\mu\text{m/s}$ for Section B, then ending with 10.0 $\mu\text{m/s}$ in the final section, shown in Figure 8. The applied voltage was a constant 75 V and tool rotation was set at 3000 RPM.

The reason different feed rates were required to achieve similar roughness values for Sections A and C is likely due to the extended machining time. The setup used is a closed system, resulting in the temperature of the electrolyte increasing over time, which is known to increase the conductivity of the electrolyte and to affect the gas film [21,30,31]. It should be noted that both increasing and decreasing surface roughness gradients were achieved, implying that while temperature of the electrolyte is an important factor, it does not dominate these results.

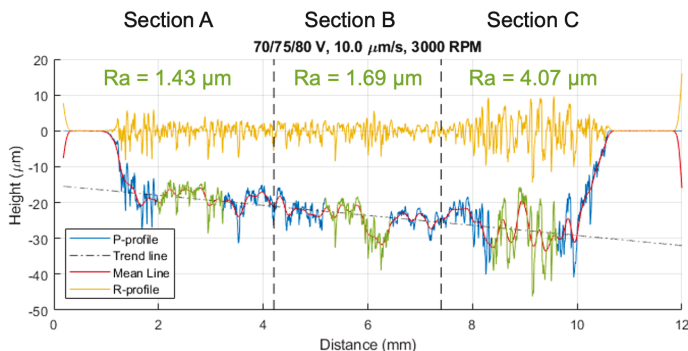


FIGURE 7: Surface and roughness profiles of 3-section channel machined at a feed rate of 10 $\mu\text{m/s}$, tool rotation speed of 3000 RPM and three voltage settings: 70 V, 75 V, then 80 V in Sections A, B, and C, respectively.

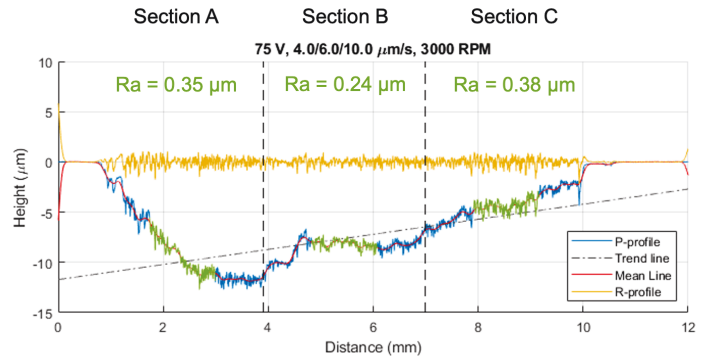


FIGURE 8: Surface profiles of “A-B-A” three-section channel with lower surface roughness in the center, and equal roughness on both ends. The channel was machined at 75 V, 3000 RPM tool rotation, and with 4.0, 6.0, and 10.0 $\mu\text{m/s}$ feed rates for Sections A, B, and C respectively.

4. CONCLUSION

This study has successfully demonstrated the ability to create a functionally graded channel in glass with a single ECDM operation. By adjusting standard machining variables such as voltage, feed rate, and tool rotation speed, we were able to control the resultant surface roughness. This provides a simple way to not only tailor the surface geometry of glass microchannels without necessitating a second process, it also demonstrates that a specified surface roughness gradient can be produced simultaneously to machining.

ACKNOWLEDGEMENTS

Financial support provided by the National Science Foundation under Grant No. CMMI-1833112 is acknowledged.

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