Feasibility of 3D Surface Machining on Pyrex Glass by Electrochemical Discharge Machining (ECDM)

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Abstract

Pyrex glasses are becoming very important in micro-electro-mechanical systems (MEMSs) and many modern industries due to their anodic bonding properties, transparency and corrosion resistance. However, the inert nature of glass possesses challenges for machining these materials with high accuracy and efficiency, especially in micromachining process. Recently, electrochemical discharge machining (ECDM) has demonstrated to be a potential process for microstructuring of Pyrex glass. However, the key to widening ECDM application lies in how to obtain both high reproducibility and machining accuracy. Generally, in ECDM process, the spark phenomenon is closely related with the machining quality and reproducibility. In this paper, a pulse voltage configuration is induced to improve the spark stability so as to increase the machining reproducibility. The results indicate that optimum combinations of both pulse voltage and electrode rotational rate can realize a better machining accuracy. Finally, the complex 3D microstructures are made to demonstrate the great potential of ECDM process.

Key words: Electrochemical Discharge Machining, ECDM, Pulse Voltage, Pyrex glass, Microstructuring.

1. INTRODUCTION

The micro fabrication of Pyrex glass is one of the key processes in micro-electro-mechanical-system (MEMS) and other modern industries because of its particular properties such as transparency, chemical resistance, biocompatibility and easily bonding with silicon wafers. However, it is difficult to fabricate complex structures with a high aspect ratio by using mechanical micromachining methods due to the hard and brittle properties of glass. Recently, electrochemical discharge machining (ECDM) has been developed to overcome such material machining requirements. The process can be described as follows. The glass, tool electrode (cathode) and auxiliary electrode (anode) are immersed in an electrolyte solution (typically sodium hydroxide or potassium hydroxide). A DC power source is applied between the tool electrode and auxiliary electrode. When the applied voltage is higher than the critical voltage, the electrolysis bubbles coalesce into a gas film to isolate the tool from the electrolyte. Discharges are generated between the tool and the surrounding electrolyte. The heat generated by those discharges and chemical etching contribute to the eroding of the to be machined workpiece if it is positioned in the near vicinity of the tool (typically smaller than 25μm for glass). This phenomenon of material removal is known as the ECDM process.

Hole drilling was the first application of ECDM. In order to microdrill glass more precisely, many physical and chemical mechanisms of this process have been studied. In addition to application in the microhole drilling, fabrication of some 2D and even 3D structures has also been attempted. The first 3D micro-structuring experiment of glass was performed using different types of actuators. In order to obtain a precise machining performance, many studies have been reported on the effects of the working distance and machining voltage, on the influences of machining performance by changing material compositions. In above-mentioned literatures, however, ECDM usually uses a rectified DC voltage as the applied voltage. In such a situation, the over-cut phenomenon seems unavoidable because the thermal energy of discharge is continuous. Figure 1 shows the typical result of a machined microgroove at a DC voltage. It is clearly seen that serious distortion of the groove geometry occurs.

![Figure 1 A machined microgroove in a Pyrex glass with a cylindrical tool of 200μm diameter. The applied voltage was a DC voltage of 40V. The tool was controlled 50μm under the glass surface and to be a constant rate of 100 μm min⁻¹ with a tool rotational rate of 200 rpm.](image-url)
Therefore, a key promise for widening ECDM micromilling applications lies in how to improve the machining quality. This study attempts to overcome this drawback in the ECDM milling process by introducing a pulse voltage in association with different machining parameters. Influences of discharge performance using pulse voltage were estimated by measuring the discharge current waveform. The effects of machining parameters on the ECDM micromilling process, including the tool rotational rate and tool travel rate, are discussed in detail. The results show that the 3D microstructure of Pyrex glass with high aspect ratio can be machined with high accuracy.

2. EXPERIMENTAL DESIGN

2.1 Experimental Setup

In this study, both WEDG and ECDM systems were integrated on the micro-EDM worktable. In WEDG system, it can effectively fabricate microtool in different diameter and shape by controlling the relatively motion between both the wire and tool. On the ECDM experimental apparatus consists of a gravity-feed device. A schematic diagram of the ECDM compound system is shown in Fig. 2.

A chamber of 90×70×50 mm³ in size was made of acrylic and was fixed on the guide block. The glass was placed on an acrylic base holder, which was fixed in the chamber. The glass was fed to reach and then kept on the desired level by the gravity feeding device. The machining head with the fixed tool can be positioned relatively to the glass by the XYZ stage. A digital indicator was used for the check of touches of the tool and the glass. The chamber was filled with electrolyte to the desired level, which was about 2 mm above the top surface of the glass. A programmable power supply (0-80 V, 10 A) was employed to provide the machining voltage between the tool and auxiliary electrode. To prevent tool deformations during machining, tungsten carbide was used as the tool material. The auxiliary electrode was made of graphite and was larger than the cathode tool. The Pyrex glass of 500 μm thickness is composed mainly of SiO₂ (83%), B₂O₃ (10%) and Al₂O₃ (3%). Waveforms of the voltage and current response were measured by a LeCroy 422, 200 MHz two channel digital storage oscilloscope.

2.2 Machining Procedures

A tungsten carbide rod of 500 μm diameter was fabricated to the required 200 μm diameter by WEDG process and then used as the tool. During the ECDM process, the applied pulse voltage (40V) was provided by a programmable power supply. The electrolyte in the ECDM was 5 M KOH at room temperature. To investigate the machining performance of the ECDM milling, groove machining experiments were conducted using the same travel path (3 mm) and working depth (50 μm). In order to evaluate the machining performance, the top width of groove and machining depth were chosen as parameters (fig. 3). The values of the groove width and machining depth are the mean values of ten experiments for each case. The real shape and surface status of the milled microgroove shown in the following were observed by the SEM system.

3. RESULTS AND DISCUSSION

3.1 Effect of Offset Pulse Voltage on Discharge Performance

The machining accuracy can be improved because the discharge machining occurred only during the pulse-on time (T_on) of the applied pulse voltage and the machining region cools during the pulse-off time (T_off). However, the machining repeatability becomes intolerable as the T_off rises beyond threshold value. In order to investigate the influence of T_off on the discharge performance, a fixed T_on with different T_off were used in this section. A pulse-on time of 2ms was chosen in this study. Various values of T_off, ranging from 1 ms to 8 ms, were used to change the cooling
effect so as to investigate its influences on the discharge performance. The experiments were carried out with machining parameters shown in Table 1.

Table 1 Experimental conditions for the ECDM process.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>5 M KOH</td>
</tr>
<tr>
<td>Tool</td>
<td>WC φ200 μm</td>
</tr>
<tr>
<td>Tool rotational rate</td>
<td>200 rpm</td>
</tr>
<tr>
<td>Machining voltage</td>
<td>pulse voltage 40 V</td>
</tr>
<tr>
<td>Pulse-on time (T_{on})</td>
<td>2ms</td>
</tr>
<tr>
<td>Pulse-off time (T_{off})</td>
<td>1, 2, 4, 8</td>
</tr>
</tbody>
</table>

Figure 4 shows waveforms of current response at different values of T_{off}. It is clearly seen that the discharge performance becomes instable with T_{off} increases. The previous studies demonstrated that the discharge performance was controlled by the stability of gas film\(^{14}\). Due to the T_{off} duration allows the gas film structure to be re-constructed makes sustainability of a dense gas film difficult and the discharge generation unstable. Besides, in the figure 4(c) and 4(d), it is also noteworthy to discuss the detailed discharge performance in the T_{on} duration. In the previously literature\(^{15}\), it was demonstrated that the effective value of the discharge current for machining activity is about 0.2A – 0.4A. There are many peaks of current which correspond to electrolysis current while not discharge as shown in figure 4(c) and 4(d). Based on the above findings, it can be concluded that the suitable T_{off} value for concurrence of both stable discharge performance and cooling effect is 2 ms.

3.2 Effect of the Tool Rotational Rate

In the ECDM drilling procedure, the rotation of the machining tool is also one of the important factors that influence machining quality\(^9\), \(^16\). To examine the effect of different rotational rates on the machining quality in the ECDM micromilling process, experiments were conducted with the rotational rate of the tool varying from 200 to 2000 rpm. The experiments were carried out with machining parameters shown in Table 2. It is obvious from figure 5 that the groove width decreases as the rotational rate increases. The possible reason is that the gas film thickness becomes thinner and more homogeneous with increasing tool rotation. It is also noticed from figure 5 that the tool rotational rate did not have a conspicuous influence on the working depth.

Figure 6 shows the groove machined with a tool rotational rate of 1500 rpm and 40V pulse voltage (T_{on}:T_{off} = 2ms:2ms). It is clearly indicates a better geometry quality. In addition, the flatness and surface roughness on the bottom of the groove (fig. 6(b)) are much better in comparison with that of figure 1.

Although the rotational rate of tool is not directly related to the machining depth, increasing the rotational rate of tool can effectively decrease the roughness of the machining surface.

Table 3 Experimental conditions for the process.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>5 M KOH</td>
</tr>
<tr>
<td>Tool</td>
<td>WC φ200 μm</td>
</tr>
<tr>
<td>Tool travel velocity</td>
<td>100 μm/min</td>
</tr>
<tr>
<td>Working depth</td>
<td>50μm</td>
</tr>
<tr>
<td>Groove length</td>
<td>3000 μm</td>
</tr>
<tr>
<td>Machining voltage</td>
<td>pulse voltage 40 V</td>
</tr>
<tr>
<td>(T_{on}:T_{off} = 2ms:2ms)</td>
<td></td>
</tr>
<tr>
<td>Tool rotational rate</td>
<td>200, 500, 1000, 1500, 2000 rpm</td>
</tr>
</tbody>
</table>
3.3 Influence of Travel Rate of the Tool

In this study, the tool travel in the XY plane is controlled by the XY stage during the ECDM micromilling process. By using this mechanism, the micro tool electrode might contact with the workpiece and then be broken as the tool travel rate is higher than the material removal rate. For estimating the upper limit of travel rate during the ECDM milling process, experiments were conducted with the travel rate ranging from 100 to 4000 \( \mu \text{m/min} \). Figure 7 shows the results of the machined groove width and machining depth respectively. As the tool does not stay on the same place, increasing travel rate results in a decrease of the material removal. Hence, it is obvious seen from Fig. 7 that the machining depth and groove width decreases as the travel rate increases.

However, when the machining depth is too smaller, the contaminants (i.e. bubbles, debris) become more difficult to remove from the gap between tool end and bottom face of groove. Thus, it results in decrease of discharge phenomenon at the tool end. As a consequence, the discharge energy is concentrated at the tool sidewall. This might be the possible reason why the groove width increase as the travel rate increases upon 1000 \( \mu \text{m/min} \).

Figure 8 shows the results with the travel rate of 1000, 3000 and 4000 \( \mu \text{m/min} \). As shown in this figure, in contrast to the groove with travel rate 1000 and 3000 \( \mu \text{m/min} \) (fig 8a, fig 8b), figure 8(c) exhibits an irregular groove pattern and worse machining surface. It is also noticed from our experiments that the groove width and the machining depth undergo serious variation when the tool travel rate is above 3000 \( \mu \text{m/min} \). Based on the studies finding, it suggest an upper limit of 3000 \( \mu \text{m/min} \) travel rate.
Figure 8 Micrographs of microgroove machined with a tool rotational rate of 1500 rpm and 40V rectangular pulse voltage ($T_{on}$:$T_{off} = 2\text{ms}:2\text{ms}$) at tool feed velocity of (a)1000 $\mu\text{m}/\text{min}$ (b) 3000 $\mu\text{m}/\text{min}$ (c) 4000 $\mu\text{m}/\text{min}$.

4 THREE-DIMENSIONAL MACHINING

To machine a deeper groove, a sequence of Layer-by-layer machining with a small working depth was used. The groove is machined with a working depth of 50$\mu\text{m}$ for etch layer until the target depth is achieved. The tool travels one stroke for every layer with a travel rate of 1000 $\mu\text{m}/\text{min}$. Figure 8 shows the results of the layer-by-layer machining for various target depths of 100 and 350$\mu\text{m}$ without conspicuous variation in groove shape. The machining examples display that the layer-by-layer method is effective for 3D micromachining. Figure 10 shows various 3D structures machined using the layer-by-layer machining. The machining examples show that the ECDM micromilling process for the 3D microstructuring of Pyrex glass is achievable.

5. CONCLUSIONS

The aim of this study was to realize 3D machining in Pyrex glass. The major conclusions drawn from this study are summarized as follows.

1. In contrast to DC voltage, a pulse voltage can substantially enhance the machining accuracy.
2. The machining accuracy conspicuously enhances as the rotational rate is increased due to the distribution effect in discharge energy induced by the centrifugal force.
3. The serious variation of the groove width is a suitable criterion to assess the limit upper of the tool travel rate.
4. Based on the results, the suitable parameters derived for the ECDM micromilling process are the following: rectangular pulse voltage of 40V ($T_{on}$:$T_{off} = 2\text{ms}:2\text{ms}$), rotational rate of 1500 rpm and travel rate of 1000 $\mu\text{m}/\text{min}$.
4. Complex 3D microstructures of Pyrex glass are achieved by layer-by-layer ECDM micromilling without any mask.

Figure 12 Micrographs of microgroove machined at target depth of (a)100 $\mu\text{m}$ (c) 350 $\mu\text{m}$.

Figure 13 Various examples of 3D microstructure of Pyrex glass.
6. REFERENCES