Study of a hybrid polishing process for microhole polishing in quartz

Cheng-Kuang Yang¹, Jung-Chou Hung², Chih-Ping Cheng³, Wan-Ti Lin¹ and Biing-Hwa Yan²²
¹Department of Mechanical Engineering, National Central University, Chung-Li 320, Taiwan
²Technical Development and Test Service Section, Regional R&D Services Department, Metal Industries Research and Development Centre, Tai-Chung 407, Taiwan
³Mechanical and Systems Research Laboratories, Industrial Technology Research Institute, Shin-Chu 310, Taiwan

# Corresponding Author / E-mail: bhyen@cc.ncu.edu.tw, TEL: +886-3-4267353, FAX: +886-3-4254501

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This paper discusses an investigation of a hybrid polishing processes for micro tooling of tungsten carbide and polishing microholes in quartz. A micro tool with a diameter of 100μm is formed by wire electrical discharge grinding (WEDG). The micro-tool is used to machine microholes in quartz by micro ultrasonic vibration machining (MUSM). Microholes 300μm in depth are fabricated after 12min of MUSM. However, debris is difficult to exclude from the machining zone and abrasive particles impact the microhole leading to the microhole wall being filled with micro-chips and micro-cracks during MUSM. To improve the machining characteristics of quartz, especially surface roughness, we experimentally investigate a hybrid polishing processes combining electrophoretic deposition (EPD) and ultrasonic polishing. The process is designed to obtain micro accurate holes in the quartz. The results confirm that the hybrid polishing processes performs well. It is found that the wall surface roughness of the microholes improves from Rmax 0.08μm from Rmax0.48μm.

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1. Introduction

The micro electro-mechanical system (MEMS) has been applied in a variety of applications, such as micro-accelerometers, micro-actuators, medical devices and optical devices. In the MEMSs, quartz is typically used due to its beneficial properties. The basic micro-machining structures used to fabricate complex microstructures are micro holes. However, it is difficult to fabricate microholes with diameters of roughly 100μm using conventional methods. Micro ultrasonic vibration machining (MUSM) is an unconventional method that can be used to machine hard and brittle materials such as quartz. Sun et al. [1] combined wire electric discharge grinding (WEDG) and MUSM to machine microholes in glass. Egashira et al. [2] applied MUSM to drill a microhole with diameter of 5μm and depth of 10μm in quartz. Thoe et al. [3] successfully drilled microholes in non-conductive ceramic coated nickel alloy using USM and electric discharge machining (EDM) combined. Lee et al. [4] utilized a diamond tool to fabricate V grooves with a depth of 100μm and width of 400-500μm. Egashira et al. [5] applied USM to drill the microholes with diameter of 10μm and depth of 20μm. Machining was performed via the ductile regime at a cut depth of 0.05μm. In MUSM, high-frequency vibrations cause abrasive particles to impact a workpiece. Therefore, microhole wall becomes filled with micro-chips and micro-cracks. However, these studies have not been proposed on how to reduce surface roughness of microhole wall.

Electrophoretic deposition (EPD) is a coating technology with advanced ceramic materials. Many studies have utilized EPD as a polish method. Takahata et al. [6] deposited Al₂O₃ onto electrode with a diameter of 100μm and used this electrode to polish the microstructure of SUS303 stainless steel in the micro-EDM process. Tani et al. [7] used SiO₂ particles to polish silicon wafers by EPD. Haga et al. [8] applied the SiO₂ particles in NaOH to produce electrophoretic mobility. The SiO₂ particles were deposited onto a cup-shaped electrode used to polish ZrO₂. Yamamoto et al. [9] used SiO₂ particles under axial loading to polish silicon wafers. Tsui et al. [10] used EPD to fabricate a polishing wheel for finish the surface of SUS316 stainless steel.

Base on the above literature, EPD can be utilized for polishing such materials as SUS303 stainless steel, SUS306 stainless steel, and silicon wafers. Besides, the loose structure of deposited layer in EPD can finish microhole smoothly without produced new cracks on microhole wall, especially for the hard and brittle materials like quartz. Nevertheless, the stability of deposited layer during EPD affects polishing uniformity due to its poor adsorb ability. To manufacture a polishing tool for finish the microhole wall, the characteristics of EPD parameters have to investigate first. Otherwise, in order to indeed reduce the surface roughness of microhole wall after MUSM, the polishing process combining EPD and ultrasonic were investigated in this study.

2. Experimental design

2.1 Experimental setup

The main experimental equipment consists of a micro-EDM system and ultrasonic vibration unit as shown in Fig. 1. The micro-EDM system has several components : (a) the EDM machine ; (b)
a WEDG mechanism; and (c) a four-axis control system. The WEDG mechanism is fixed onto an EDM worktable. The four-axis control system is fixed onto the EDM machine head, which can be moved left or right and forward or backward via a linear guide using motors X and Y, respectively. The microelectrode is clamped onto a vertical chuck, that is rotated by a motor C, and moved up and down by the EDM main spin motor Z. The motion resolutions of motors X, Y and Z are 1 μm, 1 μm and 5 μm, respectively.

The ultrasonic vibration unit comprises an ultrasonic vibration mechanism, electrophoretic deposition apparatus and motorized stage. The frequency of the ultrasonic vibration mechanism is 30KHz. The motion resolutions of the motorized stage can be increased in the Z direction at resolutions of 0.1-1 μm.

2.2 Materials

Tungsten carbide and quartz were chosen for the electrode and workpiece materials. The properties of tungsten carbide and quartz are listed in Table 1 and Table 2, respectively. The slurry used in the EPD process, included de-ionized (DI) water, NaOH and SiC particles. The surface charges of the particles made up the principal driving force for EPD, and were adjusted by NaOH. 0.25 μm, 0.5 μm and 1.2 μm SiC particles were used as abrasive particles. The auxiliary electrode was made of SUS304 stainless steel.

Table 1 Main constituents and properties of a tungsten carbide electrode

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition</td>
<td>WC (89.4%), Co (10%), TiC/TaC (0.6%)</td>
</tr>
<tr>
<td>WC particle size (μm)</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Specific gravity (g cm⁻³)</td>
<td>14.50</td>
</tr>
<tr>
<td>Hardness (HRA)</td>
<td>92</td>
</tr>
<tr>
<td>Flexural strength (Mpa)</td>
<td>4000</td>
</tr>
<tr>
<td>Compressive strength (Mpa)</td>
<td>6400</td>
</tr>
<tr>
<td>Thermal conductivity (cal/cm-s-℃)</td>
<td>0.26</td>
</tr>
<tr>
<td>Linear expansion coefficient (℃⁻¹)</td>
<td>4.7×10⁻⁶</td>
</tr>
</tbody>
</table>

Table 2 The main chemical composition and properties of quartz

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical compositions (%)</td>
<td>SiO₂ ≥ 99.995</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.21</td>
</tr>
<tr>
<td>Hardness (Mohs, N/mm²)</td>
<td>5.5-6.5</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>50</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>5.11×10⁻⁷ (at 100℃)</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-℃)</td>
<td>1.38 (at 20℃)</td>
</tr>
</tbody>
</table>

2.3 Machining procedures

The experimental process was divided into four procedures. First, a tungsten carbide rod was machined to the required size (diameter of 100 μm) and shaped by WEDG. The electrode tip need to apply the stress concentration effect on the workpiece during MUSM was formed by this process. Figure 2 shows a micrograph of a microelectrode.

Secondly, the microelectrode was utilized to machine microholes via MUSM. Figure 3 shows a micrograph of a microhole. To avoid reduced accuracy of the prefabricated microelectrode due to relocation, an identical microelectrode was used for machining and polishing.

The constant and variable EPD parameters are presented in Table 3. The stability of the deposited layer is determined by investigating the characteristics EPD parameters. A mechanical stirrer was used for constant stir continuously during machining to prevent SiC particles from settling to the bottom of tank. After SiC particles
were deposited onto the microelectrode, the microelectrode was used to polish the microholes.

In the fourth step, a micro-polishing tool was fabricated by EPD for finishing the microholes. Table 4 shows the polishing parameters. To avoid being unable to overcome cutting resistance in the deposited layer, the SiC particles were continually deposited onto the microelectrode for polishing.

After the entire machining process was complicated, scanning electron microscopy (SEM) was utilized to examine the microholes. The surface roughness of the microhole wall was measured by atomic force microscopy (AFM).

Table 3 Experimental conditions for the EPD

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>5 · 10 · 15 · 20 · 25 · 30</td>
</tr>
<tr>
<td>SiC concentration (wt%)</td>
<td>5 · 10 · 15 · 20 · 25 · 30</td>
</tr>
<tr>
<td>Deposition time (min)</td>
<td>1 · 3 · 5 · 10 · 20 · 30</td>
</tr>
<tr>
<td>pH</td>
<td>7 · 8 · 9 · 10 · 11 · 12</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
<td>1000 · 2000 · 3000</td>
</tr>
<tr>
<td>SiC Particle size (μm)</td>
<td>0.25 · 0.5 · 1.2</td>
</tr>
<tr>
<td>Solution</td>
<td>DI water</td>
</tr>
<tr>
<td>Dispersant</td>
<td>NaOH</td>
</tr>
</tbody>
</table>

Table 4 Experimental conditions for the polishing process

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polishing time (min)</td>
<td>10 · 20 · 30</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
<td>1000 · 1500 · 2000 · 2500</td>
</tr>
<tr>
<td>SiC particle size (μm)</td>
<td>0.25 · 0.5 · 1.2</td>
</tr>
<tr>
<td>Ultrasonic amplitude (μm)</td>
<td>2 · 3.6 · 5.4 · 6.3</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1 Effects of EPD parameters

3.1.1 Effects of Voltage and SiC concentration on deposited layer thickness

The mobility of SiC particles depends on the electric field, which is adjusted by the voltage. Figure 4 presents the effects of voltage and SiC concentration on the thickness of deposited layer. Experimental results show that thickness of deposited layer increased as the voltage and the SiC concentration increased. According to [11], SiC particles moved rapidly under a higher voltage. The main purpose of this study was to polish the microholes. The layer of SiC particles deposited onto the electrode by EPD does not need to be excessively thick, because the microhole diameter is only 140μm. Thus, voltage and SiC concentration were chosen for the experiments were 5V and 10(wt%), respectively.

3.1.2 Effects of pH on deposited layer thickness and Zeta potential

The pH of the slurry was adjusted using NaOH. The surface charge of SiC particles was related to the different pH values, which in turn affected the deposited layer thickness. Figure 5 shows the effect of pH on deposited layer thickness and Zeta potential. The experimental results indicate that the thickness of the deposited layer increased as the pH increased from 7 to 11. However, the deposited layer thickness showed a sharp reduction when the pH reached 12. To identify the influence of a pH of 12 on layer thickness, the surface charge of SiC particles at different pHs were discussed in terms of the Zeta potential. Figure 5 also shows the effect of the Zeta potential on pH. It can be seen that the Zeta potential was a critical factor for the surface charge of SiC particles. In EPD, the intensity of the surface charge was modified by adjusting the pH, which affected the thickness of deposited layer from particles suspended in the slurry. It should be noted that SiC particles repel each other when the pH reaches 12. At this high pH there are many conductive ions between the SiC particles surfaces and the liquid medium [12], which caused the decrease in the Zeta potential at a pH of 12. Therefore, the experimental results confirm that the thickness of the deposited layer was positively correlated with the Zeta potential.

3.1.3 Effects of Rotational speed and deposition time on deposited layer thickness

During polishing, high rotational speed and long polishing time were the significant parameters that reduced surface roughness. The rotational speed and deposition time needed to prevent the deposited...
layer from becoming ablated by the microelectrode during polishing are discussed.

Figure 6 shows the effects of deposition time and rotational speed on the thickness of deposited layer. The thickness increased as deposition time increased. However, centrifugal force caused the thickness to decrease at high rotational speed. When the deposition time increased from 1min to 30min and the rotational speed was 3000rpm, the thickness of deposited layer was 840 μm. Experimental results clearly demonstrate the deposited layer can be used to polishing.

Figure 7 shows the effects of SiC particle size on the deposited layer thickness. The thickness increased as SiC particle size decreased. During EPD, the particle size affects suspension performance due to gravity. The greater mobility of smaller particle under the influence of an electric field makes it easier for them to overcome gravity. Fig. 8 illustrates the appearance of the SiC deposited layer onto electrode with different particle sizes.

3.2 Effects of polishing parameters

3.2.1 Effects of polishing time on surface roughness and side gap

The principal driving force for EPD is the surface charge on SiC particles. However, poor adsorbability causes the SiC particles to ablate easily from the microelectrode. Therefore, during EPD particles were deposited continually onto the electrode to maintain usability of the deposited layer. The side gap between the electrode (diameter of 100μm) and microhole (diameter of 140μm) was 20μm. The loose structure of the deposited layer exactly to fill the side gap and finishing was smooth without producing new cracks in the microhole wall.

Figure 9 presents the results for the effects of polishing time on surface roughness and the side gap. The surface roughness decreased as polishing time increased, and the side gap increased slowly with polishing time. After polishing for 30min, surface roughness was reduced to Rmax 0.39μm, and the side gap of the microhole had expanded by only 2μm.

3.2.2 Effects of rotational speed on surface roughness and side gap

Generally, surface roughness decreases as rotational speed increases during polishing. This is because a high rotational speed produces more polishing behavior. As the result, the surface roughness decreased as the rotational speed increased from 1000rpm to 2500rpm. The side gap also increased with rotational speed as shown in Fig. 10. Although the surface roughness was reduced to 0.345μm at 2500rpm, the improvement in surface roughness was unapparent as rotational speed increased. To gradually reduce surface roughness and the side gap, 0.25μm and 0.5μm SiC particles were used in this experiment instead of 1.2μm SiC particles.
3.2.3 Effects of SiC particle size on surface roughness and side gap

Quartz is both hard and brittle. New axial and radial fractures can be caused by SiC particles during polishing. To prevent such fractures and reduce surface roughness of the microhole wall, small SiC particles were used. Figure 11 illustrates the effects of SiC particle size on surface roughness and the side gap. Surface roughness decreased as the SiC particle size decreased. It was found that the small 0.25 μm SiC particles certainly not only improved the quality of the surface roughness but also reduced the side gap.

3.2.4 Effects of ultrasonic amplitude on surface roughness and side gap

Ultrasonic vibration can improve polishing efficiency. This is because the application of high frequency vertical vibrations to the workpiece provides another polishing procedure for finishing. In this study we adjusted the amplitude of the ultrasonic vibration so as to improve surface roughness; the frequency was fixed at 30KHz. Figure 12 presents the results showing the effect of amplitude on surface roughness. Surface roughness decreased as amplitude increased. An amplitude of 6.3 μm produced longer polishing distances than a amplitude of 2 μm leading to a gain in polishing efficiency. Furthermore, the side gap also increased slightly as amplitude increased. The ultrasonic vibration causes the SiC particles to slip along both the axial and radial directions to further smooth the microhole wall. The result show that the finest surface roughness was obtained with ultrasonic assisted EPD.

3.3 Micrographs of microholes in quartz

Figure 13 shows micrograph of the microhole in quartz. The microhole drilled via MUSM was filled with micro-cracks (Fig. 13(a)). Therefore, EPD was used to deposit SiC particles onto the microelectrode for polishing (Fig. 13(b)). Furthermore, ultrasonic provided high-frequency vibrations and was combined with EPD (Fig. 13(c)).

Fig. 10 Effects of rotational speed on surface roughness and side gap.

Fig. 11 Effects of SiC particle size on surface roughness and side gap.

Fig. 12 Effects of ultrasonic amplitude on surface roughness and side gap.

Fig. 13 Micrographs and AFM measurement of the microhole in quartz

It is clear from Fig. 13(c) that the appearance of microhole wall was indeed improved compared with Fig. 13(a) and Fig. 13(b). The surface was smooth with almost no micro-cracks when ultrasonic was applied. The surface roughness of microhole wall was measured by AFM also shown in figure 13.

4. Conclusions

In this study we applied a hybrid polishing process, combining EPD and ultrasonic vibration to reduce the surface roughness in quartz microholes wall after MUSM. The following conclusions are based on the experimental results.

1. The suitable parameters for EPD are a voltage of 5V, a pH of 9 and SiC concentration of 10wt%. This can stabilize the SiC deposited layer at a rotational speed of 3000rpm and deposition time of 30min.
2. The reason for the sudden reduction in the thickness of deposited layer when the pH of 12 is that the SiC particles repel each other at this high pH due to numerous conductive ions. This phenomenon can also be confirmed via the Zeta potential.
3. The surface roughness of the microhole wall was reduced...
from $R_{\text{max}}$ 0.48$\mu$m to $R_{\text{max}}$ 0.08$\mu$m after a polishing time of 30min, a rotational speed of 2500rpm, an SiC particle size of 0.25$\mu$m and an ultrasonic amplitude of 6.3$\mu$m. Additionally, the side gap of the microholes increased by only 1.5$\mu$m for these same parameters.

REFERENCES