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Experimental Investigation of ECDM for Fabricating Micro Structures of Quartz

Khac-Ha Nguyen[1], **Pyeong An Lee**[1], and **Bo Hyun Kim**[1,#]

1 Department of Mechanical Engineering, Soongsil University, 369 Sangdo-ro, Dongjak-gu, Seoul, South Korea, 156-743
Corresponding Author / E-mail: bhkim@ssu.ac.kr, TEL: +82-2-820-0653, FAX: +82-2-887-7259

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Recently, the utilization of electrochemical discharge machining (ECDM) has proved to have potential for enhancing the machining efficiency and accuracy of micro-drilling and milling for glass. However, there is a lack of information about the machining conditions for milling in quartz materials, which have different characteristics than glass. In ECDM, gas film and sparks are generated on a tool when voltage is applied between the tool and a counter electrode. Workpiece materials are removed mainly by the heat of the sparks. The spark generation is affected by both the voltage and electrolyte conditions. This study investigated the ECDM characteristics according to machining parameters, such as electrolyte level, electrolyte concentration, pulse voltage, offset pulse voltage, pulse on-time, pulse off-time, and tool feedrate. Surface roughness and sharpness of the rims and edges were observed under different machining conditions. Based on the investigation of the machining conditions, micro structures, including micro grooves and columns, were machined on quartz material.

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1. Introduction

Quartz and glass are very popular materials used in micro-electromechanical systems (MEMS), micro-fluidic or lab-on-chip devices, because they have special characteristics which metals cannot satisfy, such as transparency, higher corrosion resistance, higher temperature resistance, and higher hardness than metals.[1] The piezoelectric properties are also useful for controlling the frequency of oscillators, and for producing very selective filters.

In recent decades, many non-traditional machining processes have been studied for the micro-machining of brittle material, such as an abrasive water jet, laser beam machining, ultrasonic machining, etc., which can be applied to non-conducting materials. However, these methods have inherent problems, such as poor surface quality, and large heat affected zones (HAZ).[2] To overcome these limitations, the micro electrochemical discharge machining (ECDM) process has been studied for fabricating non-conducting and brittle materials.[3] Many researchers have reported the machining conditions for the ECDM milling and drilling process in glass material.[4-7]

Since workpiece's melting is the main material removal mechanism in ECDM, melting temperature of a workpiece (or softening point for glass) is very important in the process. Table 1 shows the properties for quartz and glass. The softening point of quartz is 2 times higher than that of glass (Pyrex). However, the machining conditions for the ECDM milling process of quartz, which has different characteristics from glass, still needs to be explored, especially when using tool diameters smaller than 100 μm.

In the ECDM process, electrolyte level or the tool immersion depth affects discharging frequency and machining efficiency.[6] Doan et al. chose the electrolyte level from 100 to 150 μm with Ø 30 μm electrode,[2] while Abou Ziki et al. chose an electrolyte level of 1 mm with Ø 400 μm electrode,[8] and Yang et al. chose an electrolyte level of 2 mm with Ø 150 μm electrode.[9] However, no reports have been made on the effects of the electrolyte level in the ECDM process.

Previous research reported that when the tool speed is high, force is generated by the contact between the tool and workpiece in ECDM milling of soda-lime and Pyrex glass.[2,5] The surface quality is affected by the strength of the force, so the force is a very important factor when choosing a suitable tool feedrate. This study shows the correlation between tool feedrate and this force.

Jain et al. used large plate electrodes and different conditions of polarity for the cutting of quartz plates, and observed high tool wear with reverse polarity.[10] Reverse polarity conditions or low offset voltage can cause severe tool wear, which should be avoided in micro

Table 1 Physical property of quartz and glass

	Pyrex glass	Quartz
Composition (SiO_2 %)	< 81 %	> 99.99 %
Density(g/cm^2)	2.23	2.21
Hardness (Knoop, kg/mm^2)	418	820
softening point (°C)	820	1670

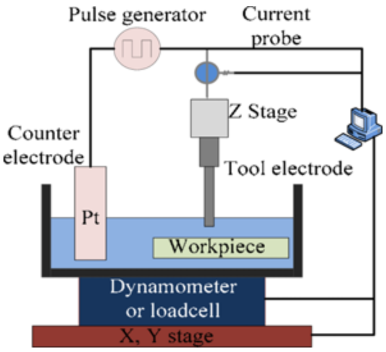

Fig. 1 Experimental system for the micro ECDM

ECDM using a micro tool electrode. Zheng et al. found a suitable offset voltage, according to stable current signal results and stable discharge performance in ECDM drilling of Pyrex glass.[11] However, no reports have been made about the effect of offset voltage in ECDM milling, which is different from ECDM drilling, so it is necessary to find the effect of offset voltage in the ECDM milling process.

This study was undertaken in consideration of both the machining accuracy and efficiency to find appropriate machining conditions for micro ECDM milling, including appropriate electrolyte level, electrolyte concentration, pulse voltage, pulse on-time, pulse off-time, and tool feedrate.

2. Experimental System

The experimental system for ECDM is shown in Fig. 1. A tool electrode and a counter electrode (platinum) were immerged in electrolytes during the ECDM process. The tool material was a tungsten carbide alloy (WC-Co), fabricated by the micro electrical discharge machining (EDM). The tool diameter was 80~85 μm and the feedrate of the tool was 1~200 μm/s. The electrolyte used in these experiments was a solution of potassium hydroxide (KOH). The concentration of electrolyte was from 10 wt% to 40 wt%. Voltage pulses were applied between the tool and the counter electrode. The workpiece was a 14 mm × 14 mm quartz plate with a thickness of 1.2 mm. The X-Y-Z stages could be controlled by using step motors and linear scale encoders. Under the working tank, a dynamometer (9256 C2, Kistler) was installed for monitoring the force between the tool and workpiece, as well as for detecting the workpiece position during the machining process.

During the ECDM process, the current signal was measured and gathered by using a current probe, connected to an oscilloscope. Fig. 2 shows the current signal according to the voltage supply, for an 80 μm tool diameter and 20 wt% KOH. The figure shows the current (I) passing through the tool electrode at a given voltage (V). During the ECDM process, the voltage-current characteristic depends on 2 main factors: electrolyte concentration, and tool size or geometry. It is necessary to analyze the V-I graph to understand more clearly about the ECDM characteristics.[12,13] In the graph, "C" was the critical voltage (18 V). When the voltage rises above the c voltage ("D" in the graph), the tool surface is fully covered with hydrogen gas film, which is necessary for stable spark generation.[12,13]

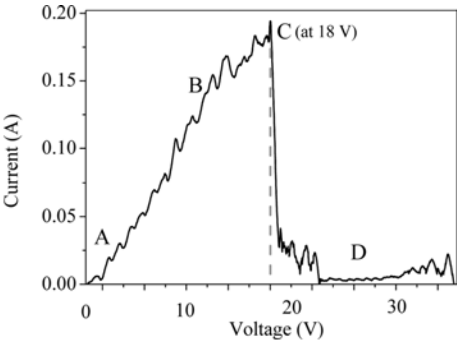

Fig. 2 Voltage-current relationship for an ECDM cell with a tool of 80 μm in diameter, and 20 wt% KOH electrolyte

3. Machining Characteristics

3.1 Effect of electrolyte level

In ECDM, the tool electrode is immersed in the electrolyte. Electrolyte level refers to the immersion depth of the tool from the electrolyte surface. The electrolyte level affects generation of hydrogen gas film during ECDM. As the immersed tool surface increases, it becomes more difficult for the gas film to cover whole tool surface, which means unstable hydrogen gas film is generated.[6] The unstable gas film decreases the machining efficiency.[6] Fig. 3 shows the current waveforms achieved according to the different electrolyte levels of 200 μm, 500 μm, and 1000 μm. As can be seen, when the electrolyte level was 1000 μm, the current shape was not uniform and the current durations were different. In the electrolyte level of 200 and 500 μm, the current shapes were relatively uniform and stable. Fig. 4(a) and 4(b) show micro holes which were machined with initial electrolyte levels of 200 μm and 1000 μm. Fig. 4(c) shows the tool feed in the hole machining. Since the lower electrolyte level is helpful for stable gas generation on the tool surface, the machining time were reduced in the electrolyte level of 200 μm. Since the electrolyte evaporates due to the high temperatures around the tool electrode, it is not easy to minimize electrolyte level. In this study, the initial electrolyte level was set to 200 μm, and additional electrolyte was supplied if it was depleted.

3.2 Effect of electrolyte concentration

To investigate the effects of electrolyte concentration, micro grooves were fabricated using KOH solutions with different concentrations from 10 wt% to 40 wt%. As shown in Fig. 5(a), marks appeared at the bottom of the groove which was machined using 10 wt% KOH. When the concentration of the electrolyte is too low, the generation of hydrogen films (or layer) on the tool electrode becomes unstable, and

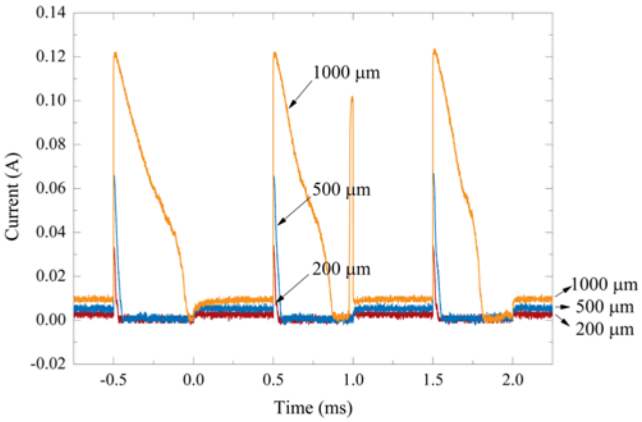

Fig. 3 Current waveforms according to different electrolyte levels (30 V pulse on-time voltage, 0.5 ms/ 0.5 ms pulse on/off-time, 20 wt% KOH)

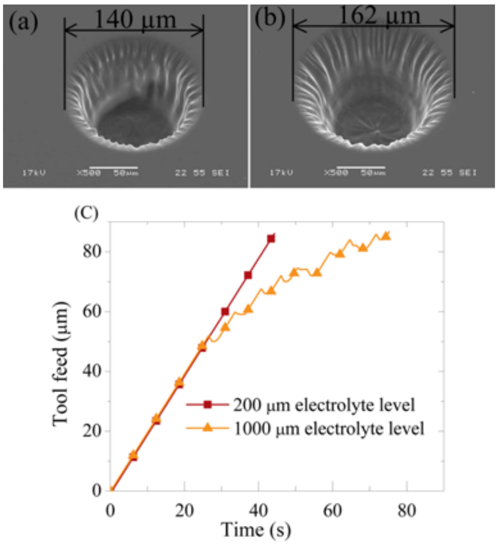

Fig. 4 Micro holes machined with different electrolyte levels (a) 200 μm (b) 1000 μm (c) tool feed in hole machining. (30 V pulse voltage, 0.5 ms/0.5 ms pulse on/off-time, 17 offset voltage, 20 wt% KOH, 82 µm tool diameter, 80 μm machined depth)

the thermal energy is not sufficient to remove the quartz material. The marks seen in the bottom of the groove were due to the mechanical contact between the tool and workpiece during the process. When the electrolyte concentration is too high, however, the thermal energy also becomes too high. As a result, the width of the groove increases and unsteady edges and rims appear, as can be seen in the Fig. 5(c) and 5(d). Fig. 5(b) shows a groove with good surface quality, and sharp edges and rims, machined by using 20 wt% KOH. Considering the above results, KOH electrolyte at a concentration of 20 wt% was chosen for fabricating the quartz material by micro ECDM milling.

3.3 Effect of pulse conditions

In ECDM, voltage is applied between the tool and counter electrode to generate electrochemical sparks on the tool surface. The voltage condition directly affects the intensity and stability of the sparks. Compared to DC voltage, the use of pulse voltage concentrates the thermal energy to the machining area. It can increase machining resolution and reduce the heat affected zone.[14] In this section, the effect of the pulse conditions on the machining characteristics was investigated. Fig. 6 shows the definition of pulse parameters.

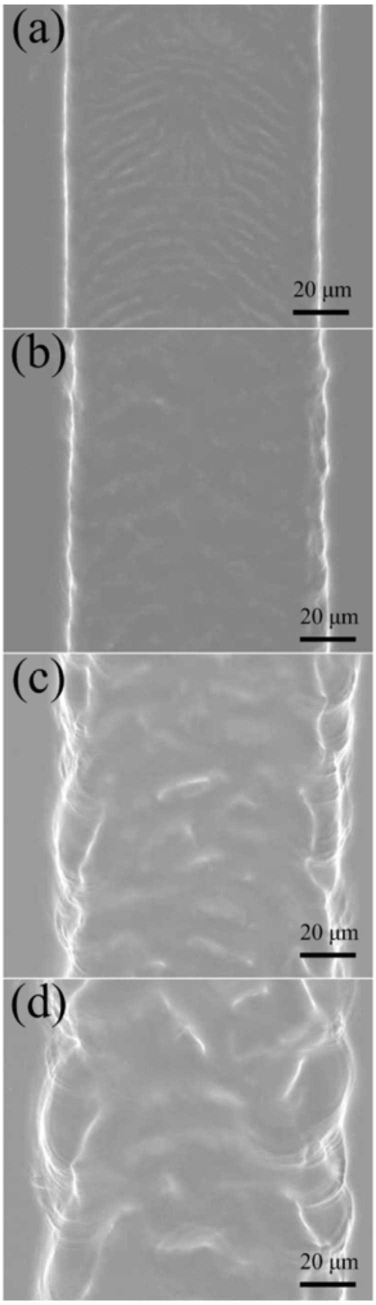

Fig. 5 Micro grooves machined with KOH concentrations of (a) 10 wt%, (b) 20 wt%, (c) 30 wt%, and (d) 40 wt%. (30 V pulse voltage, 0.5 ms/ 0.5 ms pulse on/off-time)

3.3.1 Pulse voltage

To improve the surface quality, it is necessary to find the effects of the pulse voltage on ECDM. Obviously, the thermal energy will be not enough to remove the quartz material if the voltage is too low, but the groove can easily be fabricated by high voltage.[15,16] However, the groove edges and rims are not steady when the voltage increases. Fig.

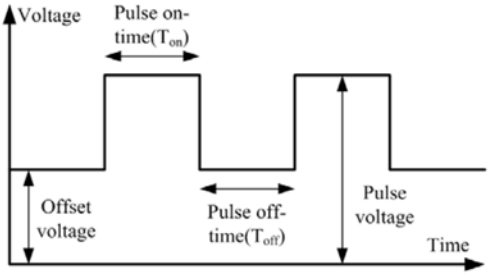

Fig. 6 Definition of pulse parameters

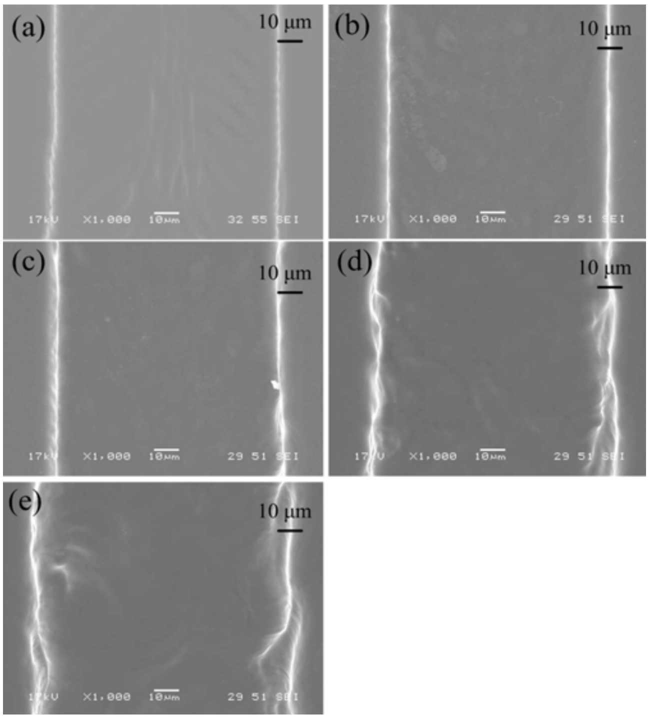

Fig. 7 Micro grooves machined with pulse voltages of (a) 23 V, (b) 27 V, (c) 30 V, (d) 33 V, and (e) 36 V (10 V offset voltage, 0.5 ms/ 0.5 ms pulse on/off-time, 78 μm tool diameter, 1500 rpm tool rotational speed, 10 μm depth of layer)

7 shows representative samples of grooves machined using 23~36 V pulse voltage. Fig. 8 shows the surface roughness and the depth of the grooves. To measure the groove depth and surface roughness, a noncontact three-dimensional surface profiler (NanoView-E1000, Nano System Inc.) was used. The surface roughness was measured 5 times at different areas along the toolpath.

Fig. 7(a) shows the micro groove machined at 23 V. Some marks appeared on the bottom of the groove because of contact between the tool and workpiece when the pulse voltage was too low. The Fig. 7(b) and 7(c) show the micro groove machined at 27 V and 30 V, providing good surface quality, and straight edges and rims. Their surface rougnesses (Ra) are 0.123 μm and 0.094 μm respectively as shown in Fig. 6(a). In Fig. 7(d) and 7(e), unsteady edges and rims of the groove can be observed when using 33 V and 36 V pulse voltage. The surface roughness also increased remarkably at 36 V (Ra 0.7 μm) and 33 V (Ra 0.34 μm) pulse voltages, compared to 27 V and 30 V. It is due to the high thermal energy at high voltage. When low pulse voltage is applied, there is mechanical contact between the tool and workpiece during the process. Therefore, the surface roughness will be increased when using the low pulse voltage 23 V (1.15 μm). Additionally, the surface roughness deviation also rises when the pulse voltage is too high or too low (23 V, 36 V).

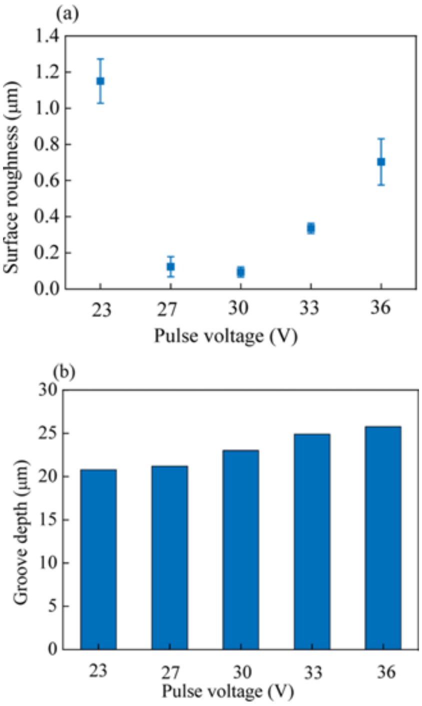

Fig. 8 Effect of pulse voltage on (a) the groove surface roughness and (b) groove depth

Fig. 8(b) shows the effect of pulse voltage on groove depth in more detail. It can be seen clearly that the groove depth increases as the pulse voltage increases.

3.3.2 Offset voltage

To localize the discharge energy to the machining area, pulse voltage is preferable for ECDM. During the pulse off-time, discharge energy (or high temperature) dissipates, and electrolyte is flushed. Therefore, the machining resolution can be minimized. To eliminate the occurrence of discharge for the duration of the pulse-off time, the offset voltage should be lower than the critical voltage. Fig. 9 shows the grooves which were machined with different offset voltages. Fig. 10(a) shows the surface roughness of grooves. In Fig. 9(a)~9(c), good quality of the bottom surface and edges were observed at small offset voltages (5, 10, 15 V). Their surface roughnesses are about 0.1 μm as shown in Fig. 10(a).

However, high offset voltage of over 17 V resulted in rapidly increased surface roughness and formation of crack marks at the groove edges (Fig. 9(d) and 10(a)). The critical voltage was around 18 V, as shown in Fig. 2. When the offset voltage is as high as the critical voltage, the discharge energy, or thermal energy, is not localized. As a result, the groove width and the surface roughness increase. Furthermore, the surface roughness deviation also increased with an increase in offset voltage, because of the occurrence of unstable discharge at high offset voltages. This shows that pulse voltage is preferable to DC voltage for

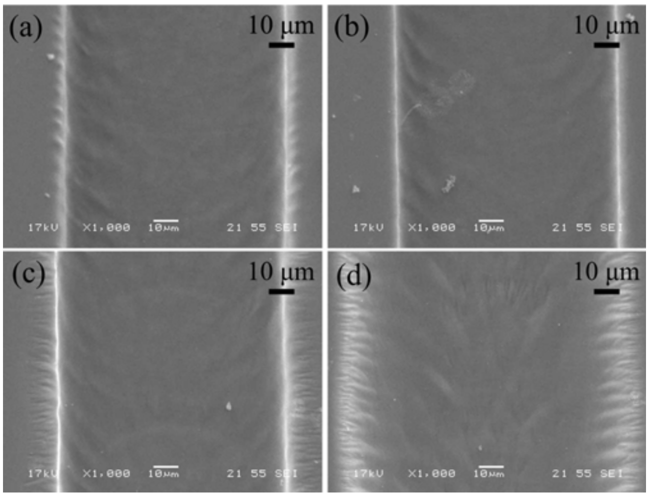

Fig. 9 Grooves machined with offset voltages of (a) 5 V, (b) 10 V, (c) 15 V, and (d) 20 V (30 V pulse on-time voltage, 0.5 ms/ 0.5 ms pulse on/off-time, 20 wt% KOH, 10 μm machined layer depth, 20 μm groove depth, 200 μm electrolyte level, quartz material)

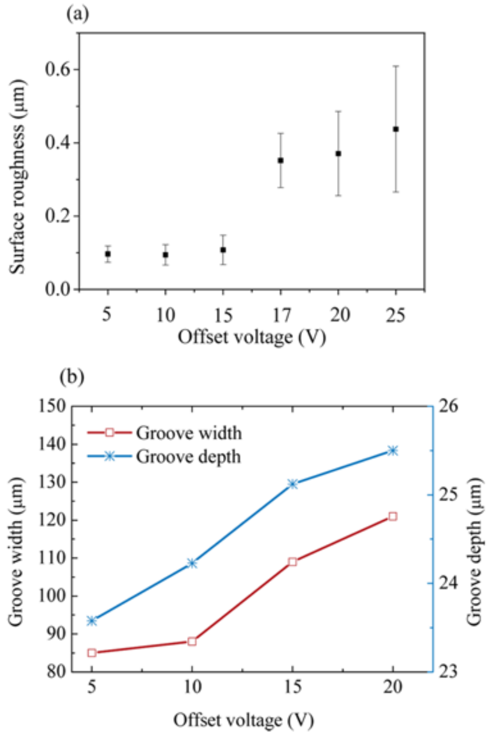

Fig. 10 (a) Surface roughness and (b) groove width and depth, according to offset voltage

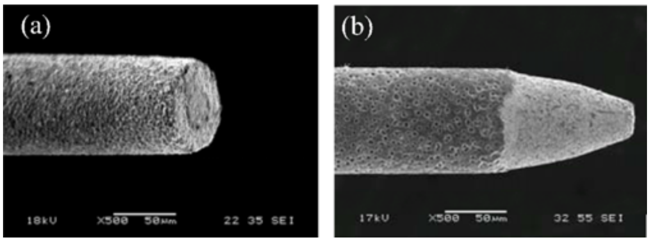

Fig. 11 Micro tool (a) before and (b) after erosion when using an offset voltage of 0 V

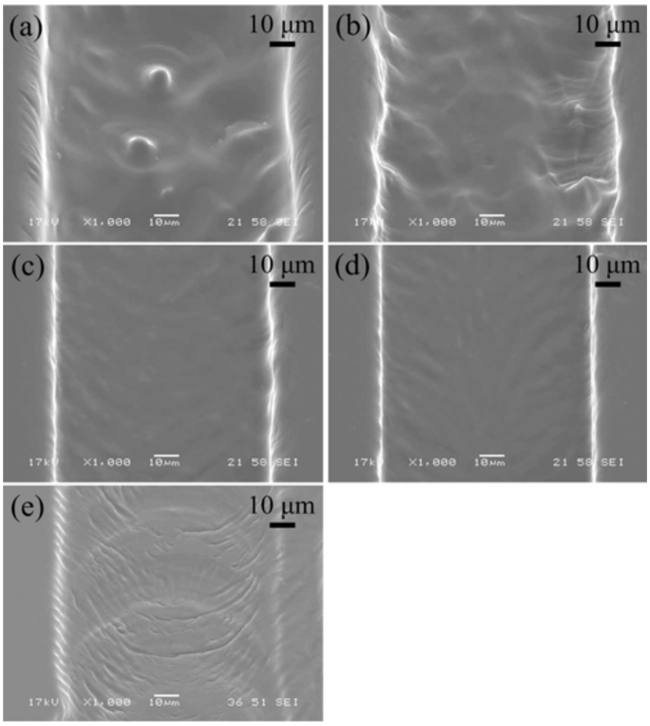

Fig. 12 Grooves machined with voltage pulse off-times of (a) 0.055 ms, (b) 0.167 ms, (c) 0.5 ms, (d) 1.5 ms, and (e) 4.5 ms (30 V pulse voltage, 10 V offset voltage, 0.5 ms pulse on-time)

better surface quality and machining resolution. Fig. 10(b) shows that the groove width and depth increased as the offset voltage increased.

Fig. 11 shows the micro tool before and after machining a micro groove at an offset voltage of 0 V. Even at 0 V, the tool can be eroded because electron is supplied from the tool electrode to the counter electrode. During the pulse off-time, in this study, a negative current flow was observed at the offset voltage of 0 V. The current flow stopped when the offset voltage was 2.3 V. Based on the above findings, it can be concluded that the suitable offset voltage for improving the surface quality as well as eliminating the marks at the groove edges should be around 5 V to 10 V for fabricating grooves in quartz material.

3.3.3 Pulse off-time

To investigate the effect of the pulse off-time, micro grooves were machined using different pulse off-times between 0.055 ms and 4.5 ms, keeping the pulse on-time fixed at 0.5 ms. Fig. 12 shows the micro grooves machined at the different pulse off-times. As the pulse off-time gets short, the pulse voltage becomes more like DC voltage. When the pulse off-time is too short (0.055 ms and 0.167 ms), the surface becomes rough as shown in Fig. 12(a) and 12(b). As the pulse off-time increases the surface quality improves while the rims and edges of the grooves become clear and sharp as shown in Fig. 12(c) and 12(d). This is because the pulse off-time is helpful to localize the heat and improve the machining resolution. When the pulse off-time is too long, however, the heat energy produced will not be enough to remove the material

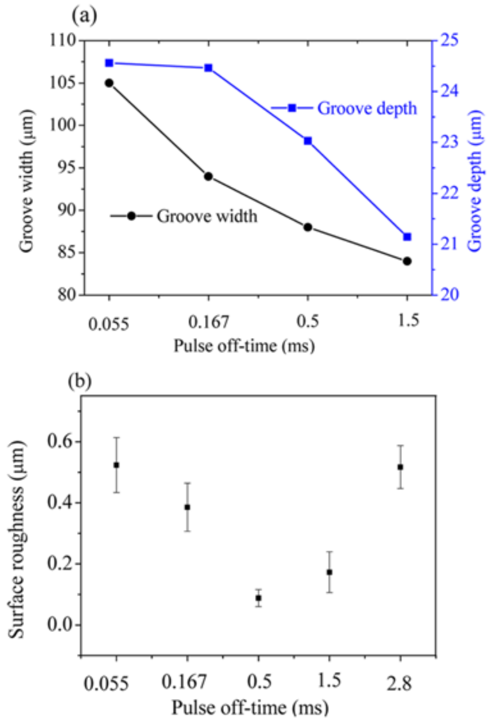

Fig. 13 Effect of pulse off-time on (a) groove width and depth, and (b) groove surface roughness

comparing to the tool feedrate. As shown in Fig. 12(e), the tool contacts with the workpiece and cracks are made on the groove surface when the time is too long.

Fig. 13(a) shows the variance of the groove width and depth according to the pulse off-time. The groove width increased as the pulse off-time decreased, as the total discharge time is longer over the same total operation time. In addition, the micro groove depth decreases as the pulse off-time increases. Fig. 13(b) shows the effects of the pulse off-time on the groove surface roughness. As can be seen in the figure, the surface roughness is high when the pulse off-time is too high or too low. Additionally, the surface roughness deviation increased when the pulse off-time was longer or shorter than 0.5 ms. While machining with a short pulse off-time, the surface quality deteriorates due to high thermal energy, while mechanical cracks make the surface worse for long pulse off-times.

3.3.4 Pulse on-time

Fig. 14 shows the micro grooves machined at different pulse on-times from 0.167 ms to 4.5 ms, keeping the pulse off-time fixed at 0.5 ms. It can clearly be seen that the micro groove edges and rims became unsteady at long pulse on-times, due to the high thermal energy released during the long machining process.[16] However, many cracks can be observed at the bottom of the grooves when using a low pulse on-time of 0.167 ms. This is caused by contact between the tool and workpiece during the machining process when only a short discharge time is applied. In contrast, Fig. 14(b) shows a good surface quality and straight rims and edges when using the pulse on-time of 0.5 ms.

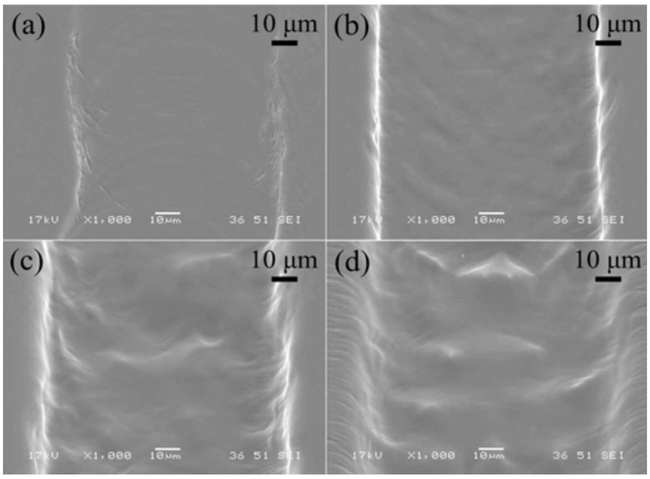

Fig. 14 Grooves machined with voltage pulse on-times of (a) 0.167 ms, (b) 0.5 ms, (c) 1.5 ms, and (d) 4.5 ms (30 V pulse voltage, 10 V offset voltage, 0.5 ms pulse off-time)

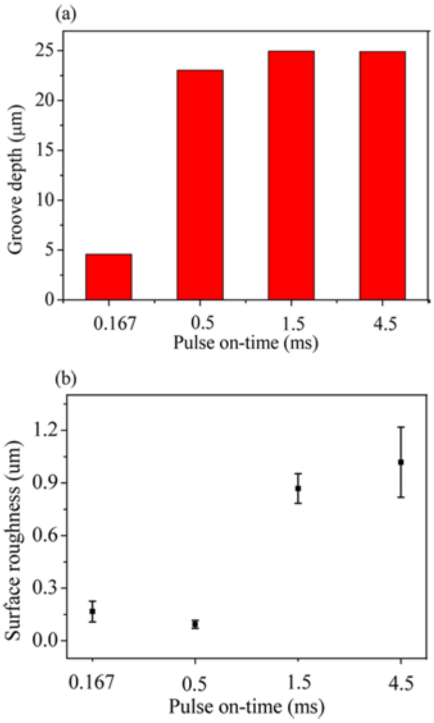

Fig. 15 Effects of pulse on-time on (a) groove depth and (b) surface roughness

Fig. 15 shows the effects of pulse on-time on the groove depth and surface roughness in more detail. As the pulse on-time increased from 0.5 ms, the groove surface roughness and depth also increased. The groove depth machined at the pulse on-time of 0.167 ms was very small, because the micro tool was bent and broken by the high contacting force between the tool and workpiece. Overall, the surface roughness deviation increased when the pulse on-time was longer or shorter than 0.5 ms.

3.4 Effect of tool feedrate

The tool feedrate affects groove surface roughness, machining time, and groove edge sharpness. The micro tool might contact with the workpiece and be broken if the tool feedrate is higher than the material

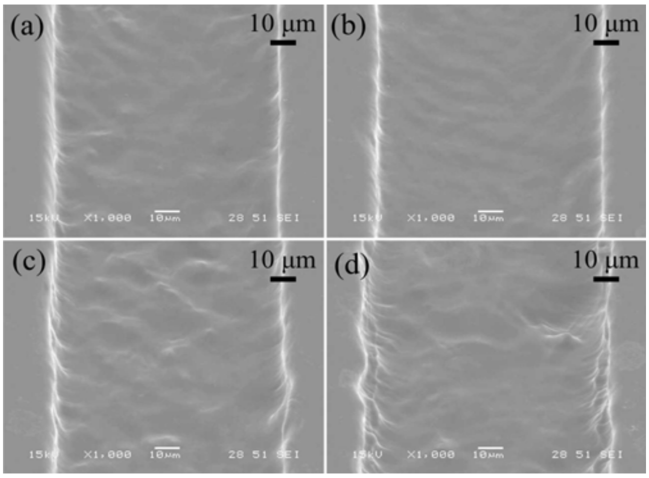

Fig. 16 Grooves machined with a feedrate of (a) 1 µm/s, (b) 2 µm/s, (c) 10 µm/s, and (d) 60 µm/s. (30 V pulse voltage, 10 V offset voltage, 0.5 ms/0.5 ms pulse on/off-time)

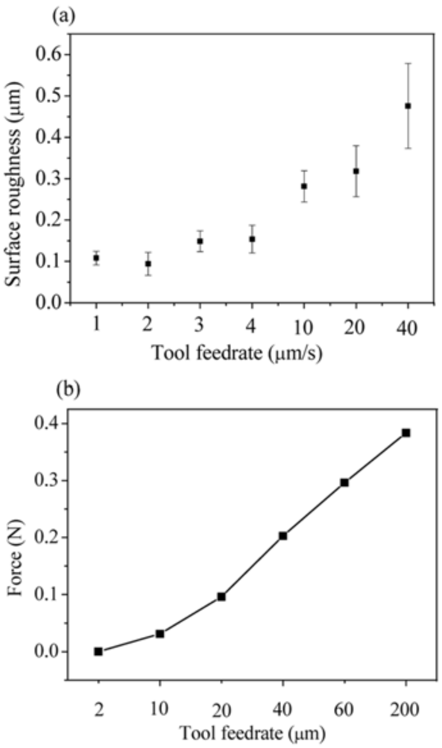

Fig. 17 Effects of tool feedrate on (a) groove surface roughness, and (b) force between the tool and workpiece

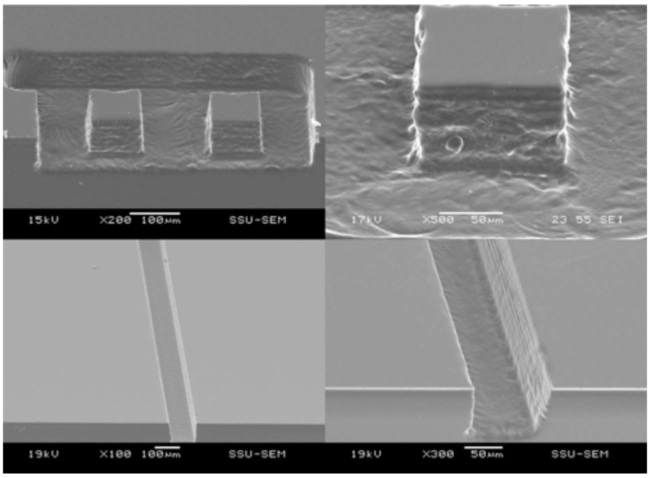

Fig. 18 Micro column and grooves machined on quartz (30 V pulse voltage, 10 V offset voltage, 0.5 ms pulse on-time, 0.5 ms pulse off-time)

Table 2 Machining conditions for the finishing cut

Electrolyte level	200 µm
Electrolyte	20 wt % KOH
Pulse voltage	30 V
Offset voltage	10 V
Pulse on-time	0.5 ms
Pulse off-time	0.5 ms
Tool feedrate	2 µm/s

removal rate.[17] For investigating the effect of tool feedrate on the machining performance during the ECDM milling process, experiments were conducted with a tool feedrate ranging from 1 µm/s to 200 µm/s. During the machining process, the force between the tool and workpiece was measured, and the correlation between the tool feedrate and force was analyzed. Fig. 16 shows the micro grooves machined at 1 µm/s, (b) 2 µm/s, (c) 10 µm/s, and (d) 60 µm/s. It can be seen clearly in the figures that uneven edges and rims appeared as the tool feedrate increased. Fig. 17(a) shows that the surface roughness and deviation increased as the tool feedrate increased. It can be explained that a high tool feedrate results in low discharge energy released in the area where the tool passes through. Therefore, the force between the tool and workpiece is increased along with the feedrate. The force between the tool and workpiece according to the tool feedrate was presented in the Fig. 17(b).

4. Fabrication of 3D Micro Structures of Quartz

Fig. 18 shows the micro columns and a groove machined in quartz. 3D micro structures were fabricated in 2 steps: a rough cutting step, and a finishing step. In the rough step, a high pulse voltage (35 V) and tool feedrate (100 µm/s) were used. At high pulse voltages, a high thermal energy is released during the discharging process, allowing a high material removal rate and tool feedrate to be achieved. However, the surface quality after the rough cutting step is very bad, and it is necessary to improve the accuracy in the finishing. The machining conditions were chosen for finishing based on the above experimental results, and are presented in Table 2.

5. Conclusions

The investigation presented in this paper demonstrated the effects of different machining conditions on the machining resolution and surface roughness of micro grooves fabricated on quartz by ECDM. According to the results achieved, the following conclusions can be made.

1. The use of low electrolyte levels increases the thermal energy during the ECDM process, because low electrolyte levels result in low resistivity between the electrodes and high discharge current value. The electrolyte level was used and maintained at 200 μm for machining the micro groove in quartz material.
2. Electrolyte concentration, which affects directly the generation of hydrogen films, is a factor used to improve the ECDM machining resolution.
3. The ECDM characteristics according to the offset pulse voltage configuration, such as pulse voltage, offset voltage, pulse on-time, and pulse off-time, were investigated. The use of an offset pulse voltage improves the machining resolution and avoids the tool erosion phenomenon.
4. The dynamometer was used to measure the force between the tool and workpiece, allowing investigation of the correlation between tool feedrate and force. When the tool feedrate increases beyond the material remove rate, the force between the tool and workpiece increases because of reduced discharge energy. A high tool feedrate cannot be used to fabricate grooves with good surface quality, but it is useful to reduce the machining time of 3D structures in the rough cutting step.

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