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# Study of precision micro-holes in borosilicate glass using micro EDM combined with micro ultrasonic vibration machining

B.H. Yan [a,*], A.C. Wang [a], C.Y. Huang [a], F.Y. Huang [a]

[a] *Department of Mechanical Engineering, National Central University, Chung-Li, Taiwan 32054, ROC*

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**Abstract**

Because of its excellent anodic bonding property and surface integrity, borosilicate glass is usually used as the substrate for micro-electro mechanical systems (MEMS). For building the communication interface, micro-holes need to be drilled on this substrate. However, a micro-hole with diameter below 200 μm is difficult to manufacture using traditional machining processes. To solve this problem, a machining method that combines micro electrical-discharge machining (MEDM) and micro ultrasonic vibration machining (MUSM) is proposed herein for producing precise micro-holes with high aspect ratios in borosilicate glass. In the investigations described in this paper, a circular micro-tool was produced using the MEDM process. This tool was then used to drill a hole in glass using the MUSM process. The experiments showed that using appropriate machining parameters; the diameter variations between the entrances and exits (DVEE) could reach a value of about 2 μm in micro-holes with diameters of about 150 μm and depths of 500 μm. DVEE could be improved if an appropriate slurry concentration; ultrasonic amplitude or rotational speed was utilized. In the roundness investigations, the machining tool rotation speed had a close relationship to the degree of micro-hole roundness. Micro-holes with a roundness value of about 2 μm (the max. radius minus the min. radius) could be obtained if the appropriate rotational speed was employed. 

*Keywords:* Borosilicate glass; Micro electrical-discharge machining; Micro ultrasonic vibration machining; Micro-hole; micro-tool; High aspect ratio

## 1. Introduction

In packaging MEMS-related devices, such as micro valves and micro flow sensors etc., borosilicate glass is usually used as the substrate for bonding with silicon wafers. To build up the electrical through channel and connect the internal system between the silicon wafer and environment, micro-holes are drilled in the glass surface before they are bonded. Drilling these micro-holes is difficult with traditional machining processes. There are several methods used to manufacture micro-holes, MEDM [1,3,5,8,9,11], excimer laser drilling [6], LIGA [2,10], electrochemical discharge machining (ECDM) [12] and MUSM [4,7] etc. Because of the different working mechanisms, the results produced by these methods are distinct.

For example, in MEDM, a micro-hole with a diameter of 160 μm and depth of 380 μm could be drilled within 2 min [5]. MEDM can be used to manufacture only conductive material and the recast layer on a machined surface, containing craters and micro cracks will cause poor surface and size accuracy. Laser micro machining technology can be used to fabricate a hole under diameter of 4 μm [6]. However, laser beam machining causes deterioration and micro-cracks on the machined surface. The LIGA technique has been found suitable for producing three-dimensional microstructures with micro-holes in metal, polymers and ceramics [2,10]. However, the LIGA method affects the configuration precision in micro-hole machining with high aspect ratios because of light diffraction (such as X-ray). ECDM can improve the material removal rate (MRR) and surface roughness to 1.5 mm/min and 0.08 μm, respectively [12], but as with chemical etching, the walls of the micro-holes will be over etched due to the ECDM process. MUSM has been proved successful in hard and brittle material. Masuzawa et al. demonstrated that micro-holes as small as 5 μm

* Corresponding author. Tel.: +886-3-4267353; fax: +886-3-4254501.
*E-mail address:* bhyen@cc.ncu.edu.tw (B.H. Yan).

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(depth 10 μm) and 3-D micro machines could be created by combining wire electrical discharge grinding (WEDG), MEDM and MUSM [4,7]. Because MUSM relies on the micro mechanical forces to remove material, for micro-hole machining with high aspect ratios, small changes in the mechanical forces can have a significant consequence on manufacturing stability and precision. Furthermore, the mechanical forces dominated the MUSM parameters. In depth studies have not been conducted on how these parameters affect the manufacturing stability and accuracy.

A machining method combining MEDM and MUSM has been designed to finish micro-holes with high aspect ratios. During the entire machining process, the micro-tool was remained in the same fixture, so tool eccentricity problems were avoided. For avoiding the micro-tool oscillating or breaking during the manufacturing process, the ultrasonic apparatus was set up the side to vibrate workpiece. This arrangement significantly enhanced the micro-holes machining precision.

## 2. Method

### 2.1. Experimental set-up

The experiment equipment consisted of an EDM machine, a four-axis control system and an ultrasonic machining unit (as shown in Fig. 1). The four-axis control system was fixed onto the EDM worktable. Here the borosilicate glass or copper plate moved along the front

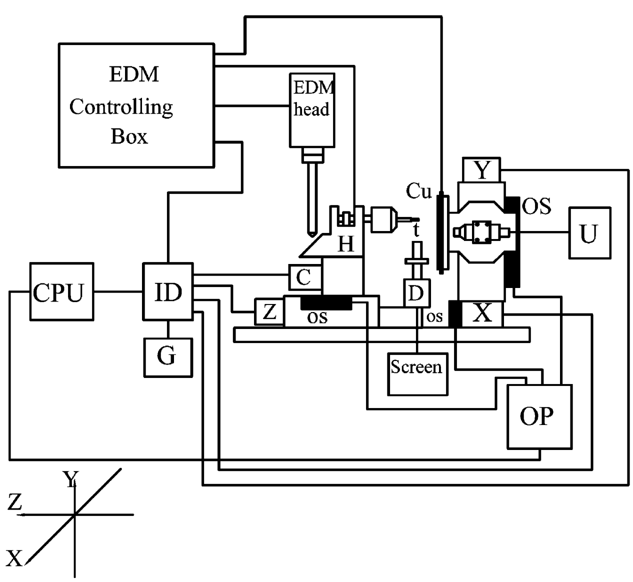



Fig. 1. The configuration of MEDM and MUSM apparatus: U, ultrasonic vibration equipment; OS, optical scale; OP, optical scale counter; X, Y and Z, motors for *x*-, *y*- and *z*-axes movement; Cu (copper plate), EDM electrode; H, rotating chuck holder; t, micro-tool; D, computer controlled display; C, motor for c-axis rotation; ID, interface circuit and motor driver; G, function generator; CPU, computer.

and back direction using motor X and moved up and down using motor Y. The micro tool was clamped into a horizontal chuck rotated by motor C and directed left and right by motor Z. The movement resolutions of motors X, Y and Z were 0.2 μm, 0.2 μm and 0.5 μm, respectively. To enable removing the debris easily from the micro-holes during MUSM, the machining operation was performed horizontally. The ultrasonic machining unit (frequency, 30 kHz) included an electronic generator, a transducer and horn-tool combination equipment. The tool was a cylindrical rod screwed onto the horn tip. A small piece of borosilicate glass was chemically glued onto a small rectangular plate [4] attached to the tool tip (as shown in Fig. 2).

### 2.2. Materials

Borosilicate glass (Pyrex, Corning 7740) is a silica composition with excellent anodic bonding property, surface integrity, thermal properties and acid resistance. This glass has always served as the substrate for micro sensors. Because borosilicate glass is hard and brittle, it is very suitable for micro-hole drilling using the MUSM method. For maintaining precise micro-hole sizes and shapes, the micro-tools must have high wear resistance and rigidity. A circular tungsten carbide rod with a diameter of 0.3 mm was selected as the MEDM and MUSM tool [4]. Micro-hole precision can be improved by using oil as the slurry medium [13–15]. Silicon carbine grains, suspended in kerosene, were chosen as the working slurry whose concentrations were 10%, 20% and 30% in the MUSM process. And the averaged abrasive sizes were 1.2 μm (about 75% particle sizes were from 0.9 to 1.5 μm) and 3 μm (about 75% particle sizes were from 2.6 to 3.4 μm).

### 2.3. Machining procedures

The machining processes were divided into two main parts. First, the tungsten carbide rod was fashioned into a micro-tool using a copper plate as electrode in the MEDM step. This tool was then used with the MUSM procedure to drill a micro-hole in the borosilicate glass. The above procedures are described in detail below:

To EDM the micro-tool, the circular tungsten carbide rod was fixed at horizontal direction and rotated clockwise. At the same time, a copper plate was fastened to a jig and moved vertically up and down automatically. The diameter of the tool was reduced by the moving plate edge (as shown in Fig. 3(a)) and the EDM dielectric was sprayed to the working area when MEDM was beginning. The completed micro-tool was 2 mm long and diameter 150 μm. To produce high stress concentration in the workpiece during MUSM, the front end of the micro-tool was reduced in diameter to 20 μm and length 0.2 mm. Fig. 3(b) displays the finished micro-

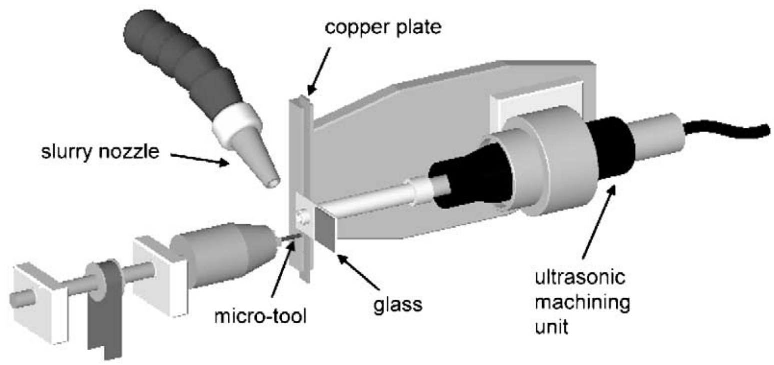



Fig. 2. The detail diagrams of experimental apparatus at MUSM process.

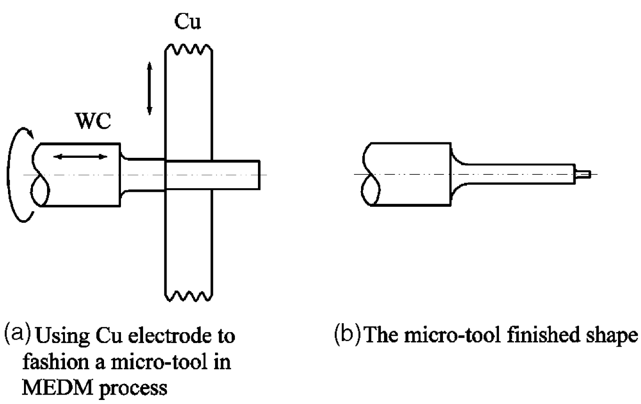



Fig. 3. The micro-tool machining procedure and micro-tool finishing shapes after MEDM. (a) Using Cu electrode to fashion a micro-tool in MEDM process. (b) The micro-tool finished shape.

tool. The experimental parameters for the MEDM processes are listed in Table 1.

With the micro-tool in the chuck, a micro-hole was drilled in the glass using MUSM. To decrease the attrition of the tool at the lower level [15], the tool cannot touch the workpiece before the machining process start, so it existed about 0.1 mm between the tool and glass surface when the machining process was beginning. In micro-hole fabricating procedure, the micro-feeding tool accompanying with spray slurry was utilized to manufacture the glass with ultrasonic vibration (as shown in Fig. 2). The flow rate of slurry was 450 ml/min. Table 2 lists the experimental parameters for the MUSM processes.

Table 1
The experimental MEDM parameters

| | |
|---|---|
| Workpiece | Circular rod of tungsten carbide (K20) |
| Electrode | Copper |
| Working fluid | Kerosene |
| Rotational speed of workpiece (rpm) | 50, 150 |
| Polarity | + (rough); − (finish) |
| The open load voltage (V) | 100 |
| Working voltage (V) | 25 |
| Discharge current (A) | 0.95, 1.45 |
| Pulse duration (μs) | 4, 10 |
| Off time (μs) | 4, 10 |

## 3. Experimental results

In addition to evaluating the size accuracy of high precision micro-holes, the shape precision and surface roughness was estimated. Hence, the following discussion is organized into three main parts: (A) diameter variation between the entrance and exit (DVEE), (B) roundness and (C) surface roughness. The factors affecting the precision of micro-holes include the slurry concentration, abrasive grain size and the MUSM machining parameters.

### *3.1. DVEE of micro holes*

In the MUSM processes, the micro-feeding method of micro-tool was applied to manufacture the micro-holes. In machining micro-holes with high aspect ratios, the tools could touch the walls of the holes for a long time, causing abrasion to the sides of the tools, or inducing irregular expansion of the micro-holes. These conditions will reduce the accuracy of the holes. DVEE of the micro-holes is an essential element in the MUSM process. The following sections utilize several MUSM parameters to study the DVEE forming effects.

Table 2
The experimental MUSM parameters

| | |
|---|---|
| Ultrasonic vibration direction | Longitudinal |
| Ultrasonic vibration frequency | 30 kHz |
| Ultrasonic vibration amplitude (μm) | 1.2, 1.4, 1.6, 1.8,2.0, 2.2 |
| Rotational speed of micro tool (rpm) | 50, 100, 150, 200, 250 |
| Feed rate (μm/min) | 6, 6.7, 7.5, 8.6, 10 |
| Concentration of slurry (wt %) | 10%, 20%, 30% |
| Averaged abrasive size (μm) | 1.2, 3 |

#### 3.1.1. The effects of abrasive slurry concentration and grain size

The abrasive slurry concentration and grain size are the most important factors affecting MUSM machining precision. Abrasive with higher slurry concentrations, the material removed by the abrasive grains at the machining surface will be faster than the lower slurry concentrations. The fast material removal will reduce the friction between the micro-tool front end and the micro-hole wall in the machining process. The DVEE will be lower when higher slurry concentrations are used. Fig. 4 displays that whether the averaged abrasive size was 1.2 μm or 3 μm, a 20% slurry concentration would produce a smaller DVEE than a 10% slurry concentration. But DVEE became larger when the slurry concentration reached 30%. The 20% concentration provided almost double abrasive particles to manufacture the hole than the 10% concentration at an average size of 1.2 μm, causing the DVEE to become smaller. However, because the micro-hole machining was set up in the horizontal mode, the abrasives would gather between the hole entrance and the tool, these particles were be fed into the hole by rotating tool and ultrasonic amplitude. But it would be hindered abrasives to enter the hole when the amount of particles was gathered too much between the hole entrance and tool, thereby influencing the DVEE of the micro holes. At 30% slurry concentration, this situation would become clearer, so the micro-hole drilling effect significantly decreased. Moreover, the average grain size (3 μm) was bigger than the ultrasonic amplitude (1.8 μm), inducing abrasives hard to enter the hole during the MUSM. So the machining effect on DVEE was not obvious than the small grain size. Fig. 4 also shows that employing the 1.2 μm averaged particle size created a better DVEE than the 3 μm averaged particle size. At the same concentration, the small abrasive particles were more uniformly suspended in the slurry and easily entered to the hole than the large one. However, the MRR was less for each grain. Therefore, a smoother machining surface and a straighter cross section of micro-hole could be obtained, improving the DVEE of the micro-holes. To obtain finer finishing effects, the following experiment used a 20% particle concentration with an averaged diameter of 1.2 μm.

#### 3.1.2. The effect of ultrasonic vibration amplitudes

In the USM procedures, larger machining tool amplitudes cause higher MRR [15,16]. The machining tool may bend in the drilling process when the ultrasonic vibration amplitudes are large. This will affect the exactness of the holes. This phenomenon is more apparent during MUSM. In these experiments, ultrasonic amplitude was measured using a tool microscope (1000×) three times (in air), and then took the averaged value as the working amplitude. Fig. 5 presents the effect of ultrasonic vibration amplitudes on DVEE. The figure shows that the DVEE decreased with increasing amplitude from 1.2 μm to 1.8 μm. The DVEE increased when the amplitude increased from 1.8 μm to 2.2 μm. This indicates that the appropriate amplitudes could increase the preciseness of the micro-holes. However, utilizing smaller amplitudes to manufacture micro-holes would increase the machining time and cause more abrasion of the micro-tool, producing a larger DVEE. Further, the machining time became shorter when the amplitudes were increased. This reduced the wear on the micro-tool. A lower DVEE could therefore be found. Owing to a the slender ratio in the MUSM process, micro-tools would be bent because of the greater amplitudes. This induced irregular machining of the micro-holes (as shown in Fig. 6), making DVEE values larger. The micro-tools could also be broken when the irregular hole machining became serious.

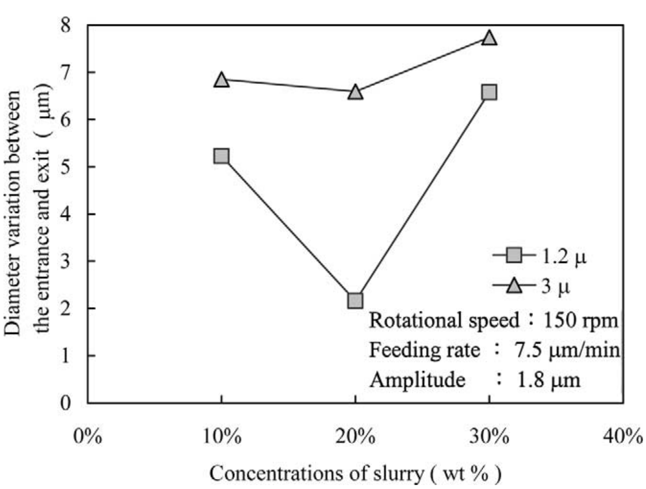



Fig. 4. The abrasive slurry concentration and grain size effect on DVEE through MUSM.

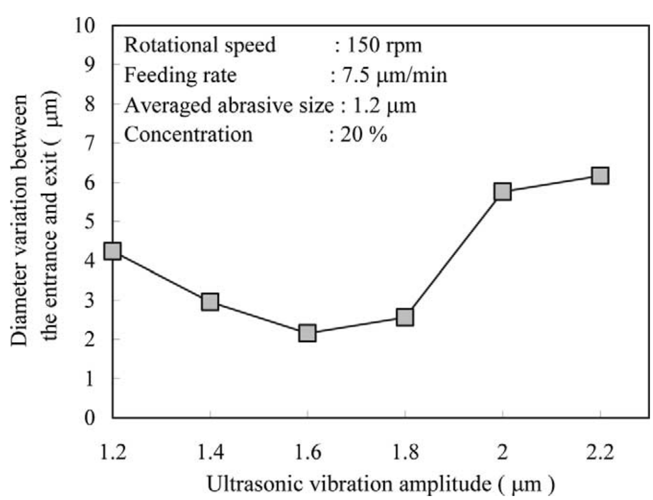



Fig. 5. The ultrasonic vibration amplitude effect on DVEE via MUSM.

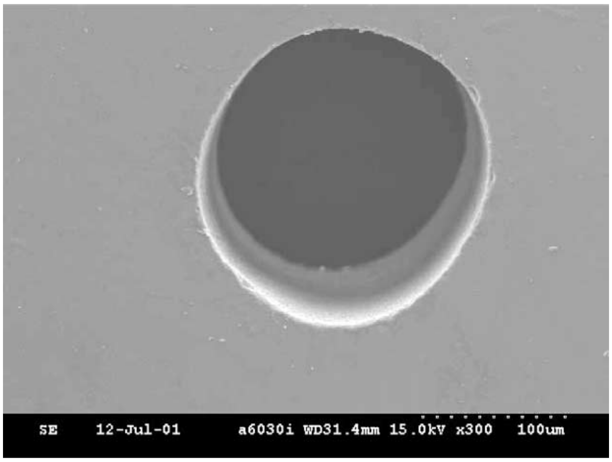



Fig. 6. The irregular expansion of micro-hole produced by ultrasonic amplitude 2.2 μm (averaged abrasive size 3 μm).

### 3.1.3. The effect of rotational speeds of micro-tools

The rotational speed of the micro-tools is also a key parameter affecting the micro-holes accuracy. Because a rotating tool can assist the suspended particles in entering the micro-hole, the arrangement can drive the particles to grind the hole during the MUSM process. Therefore, the DVEE of the micro-holes, produced by rotating tools, will be better if the tools are not rotated. Fig. 7 shows the effect of rotational speed on DVEE. The experiments illustrated that the DVEE became smaller when the rotational speed was increased from 50 rpm to 150 rpm. The DVEE changed greater when the rotational speed was increased from 150 rpm to 250 rpm. This revealed that the correct rotational speed could enhance the micro-holes accuracy. The abrasive particles were fed into the hole via the rotational tool and ultrasonic vibration. At the same vibration mode, the number of abrasive grains fed into the hole when the rotational speeds were increased at the beginning stage. The machining efficiency was therefore enlarged, and micro-tool wear was reduced, so a smaller DVEE could be obtained. The abrasion of the tool side and hole surface will be increased by abrasive particles when rotational speed is increased [17]. This result will be clearer with higher speeds. Moreover, the stability of the cutting process is also affected by high speeds. Due to these reasons, DVEE not only became large but also had obviously changed after 150 rpm.

### 3.1.4. The effect of feed rate on the micro-tools

DVEE is influenced by changes in the feed rates during MUSM. In these experiments, feed rates utilized the program interface to control motor Z and optical scale, producing constant feed rates. Fig. 8 details the effect of feed rates on DVEE. This figure shows that DVEE was smaller when a lower feed rate was employed. DVEE became large when a large feed rate was used. However, the gap between the micro-tool end surface and glass face became smaller when a larger feed rate was used. This smaller gap induced poor slurry circulation. When this occurred, fewer abrasive particles entered the gap through MUSM, inducing a not very good working effect; the front end of the tool produced more abrasion during this machining process. Hence, the DVEE became large. Fig. 9 shows a SEM photograph of the worn micro-tool. Fig. 9(a) represents the small circular step at the front end of the micro-tool seriously abraded from a larger feed rate machining (8.6 μm/min). The tool suffered less wear at the same position when a smaller feed rate was used (6 μm/min), as shown in Fig. 9(b).

## 3.2. Roundness

In the USM processes, tool rotation or not, definitely influences the roundness of the holes [15,18]. Tool rotation aids the suspended particles to enter the holes, thereby increasing the working efficiency of the USM. Rotating tools can also induce the particles to grind the holes, thereby improving the roundness of the holes. In

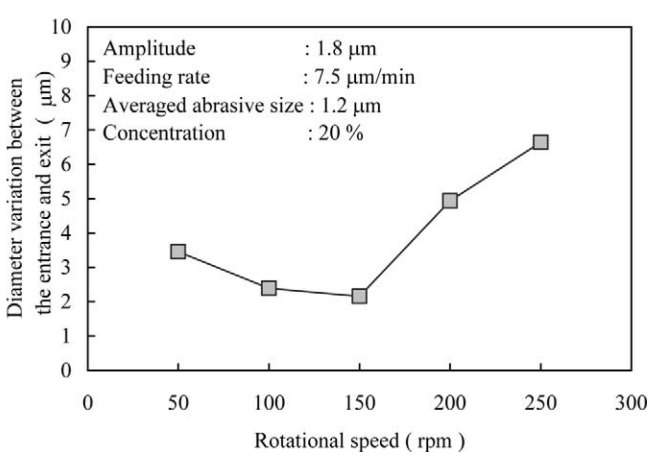



Fig. 7. The rotational speed effect on DVEE by MUSM.

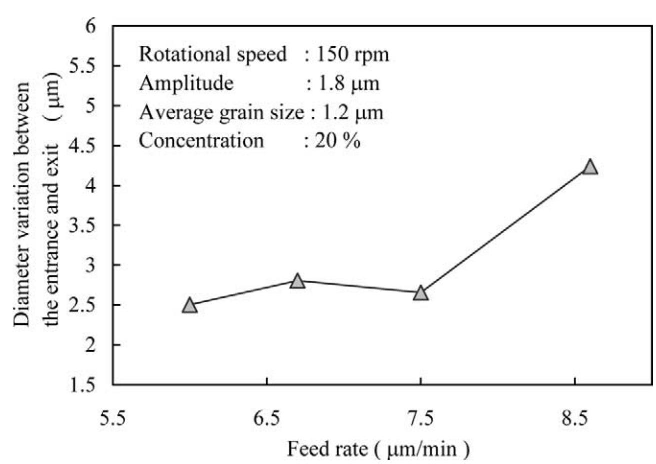
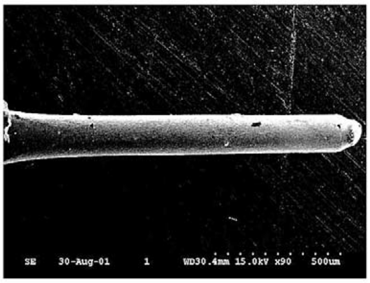


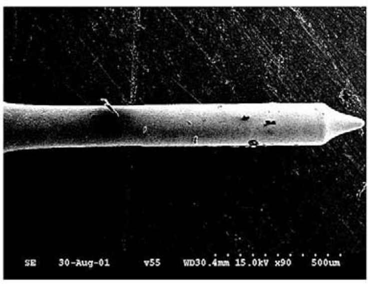

Fig. 8. The feed rate effect on DVEE via MUSM.

(a)




The photograph of micro-tool wear at higher feed rate of 8.6 μm/min

(b)




The photograph of micro-tool wear at appropriate feed rate of 6 μm/min

Fig. 9. The SEM of micro-tool wear after MUSM. (a) At higher feed rate of 8.6 μm/min. (b) At appropriate feed rate of 6 μm/min.

these experiments, the roundness of exits is discussed herein, because the exits, such as nozzles, adequately affect the micro holes performance. The roundness computation used the measuring program to gauge the SEM images of micro-holes, taking the max. radius minus the min. radius as roundness values. Fig. 10 displays the effect of rotational speed on the roundness of micro-holes. This figure illustrates that micro-hole roundness

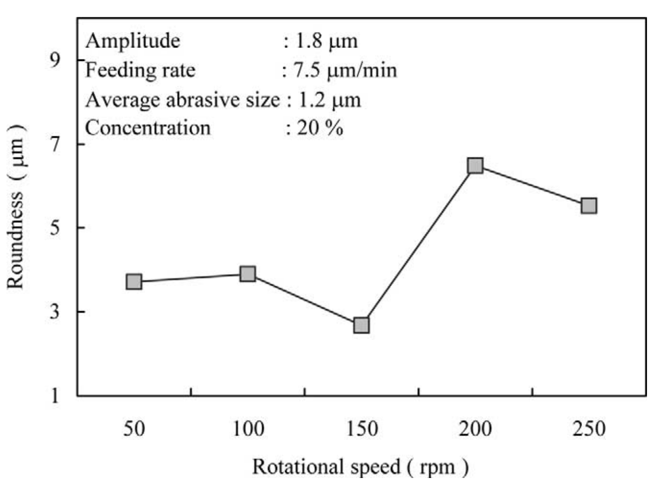
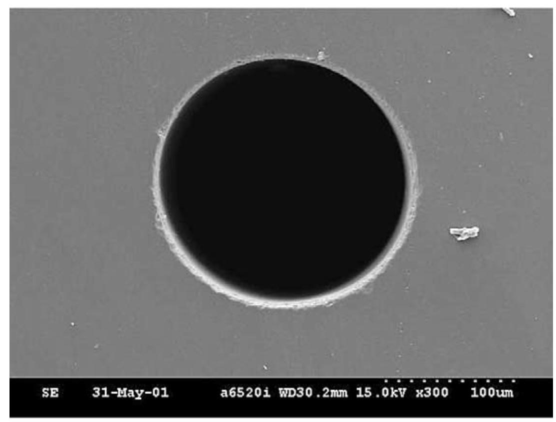



Fig. 10. The rotational speed effect on roundness by MUSM.

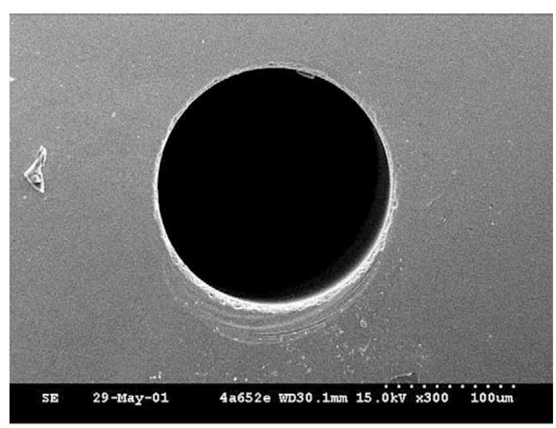
was better with rotational speeds from 50 to 150 rpm. The roundness values became larger when the rotational speed was increased from 150 to 250 rpm. This was similar to the rotational speed effect on DVEE. However, high rotational speed not only caused more abrasion at the tool but also induced instability in the cutting process, prompting clearly out-of-round micro-holes after 150 rpm. In these experiments, the best roundness value found in this study was about 2 μm. Fig. 11 presents micro-holes with acceptable entrances and exits produced at 150 rpm rotational speed.

### 3.3. Roughness

In the USM process, the rotation effect of the tool can drive the abrasive particles to grind the hole surface. Therefore, the surface roughness value is generally less




(a) The entrance of the micro-hole

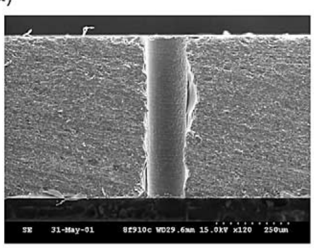



(b) The exit of the micro-hole

Fig. 11. The shapes of micro-holes at rotational speed of 150 rpm through MUSM. (a) The entrance of the micro-hole. (b) The exit of the micro-hole.

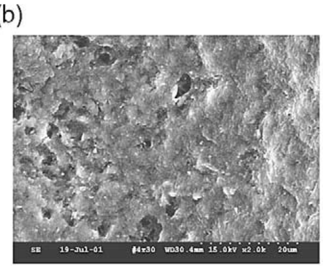
than the abrasive particle size [4,15,18]. Because no equipment was available to measure the surface roughness of micro-holes in this research, SEM photographs are used to discuss the grain size effects. Fig. 12 shows a cross section of a micro-hole and the hole surface. In Fig. 12(a), a cross section of a micro-hole with a fair and straight shape was obtained. Fig. 12(b) and (c) show the magnified photographs of the hole surfaces when machining with different abrasive particle sizes. The surface of (b) was manufactured using averaged grain 3 μm; (c) was finished using an averaged grain of 1.2 μm. These two figures clearly illustrate that the working surface still has a few craters and is not very smooth when the large grain size was used. The surface was very smooth with almost no craters when the small grain size was applied. Hence, the smaller abrasive particle sizes have a better effect on the micro-hole surface roughness.

(a)



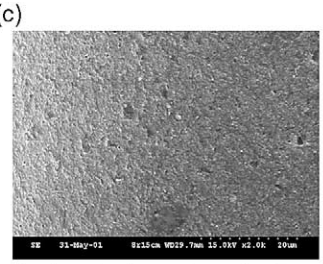
A cross section of micro-hole

(b)



The surface of micro-hole produced using averaged size 3 μm

(c)



The surface of micro-hole produced using averaged size 1.2 μm

Fig. 12. The cross section and the surfaces of micro-holes via MUSM. (a) A cross section of micro-hole. (b) The surface of micro-hole produced using averaged size 3 μm. (c) The surface of micro-hole produced using averaged size 1.2 μm.

## 4. Conclusions

For drilling micro-holes with high aspect ratios in borosilicate glass, a working method combining MEDM with MUSM was developed. Because the micro-tool was not dismantled from the clamping apparatus through varied working processes, a good tool concentricity level could be maintained in the machining procedures. Highly accurate micro-holes with diameters of about 150 μm and depth of 500 μm were manufactured via the MUSM method.

The experiments revealed that the DVEE is influenced by the slurry concentration, ultrasonic vibration amplitude or rotational speed of the micro-tool. Values of these parameters exist at which DVEE is a minimum. Larger or smaller values cause DVEE to increase. Furthermore, smaller particle sizes or micro-tool feed rates produced better DVEE.

In the MUSM processes, the micro-hole roundness had a close relationship to the micro-tool rotational speed. Experiments show the rotational speed effect on roundness is similar to the rotational speed effect on DVEE. Hence, for better micro-hole roundness, choosing the proper rotational speed is important.

Moreover, the surface roughness of micro-holes was clearly affected by the size of the abrasive particles. Results obtained show that a finer surface roughness could be obtained when smaller abrasive particle sizes were used.

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