Paper International Journal of Electrical Machining, No. 2, January 1997

Application of USM to Micromachining by On-the-machine Tool Fabrication

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(Received on May 21, 1996)

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Abstract

Most machining methods have difficulties in machining hard, brittle materials such as glass, ceramics, and silicon. Ultrasonic machining (USM) is a unique method from this point of view, because it easily machines these materials. However, USM has a limitation in its application to micromachining because there are problems in fixing microtools to the machine and maintaining high precision. In this paper we propose a technique of micro-USM by applying on-the-machine tool fabrication by wire electrodischarge grinding (WEDG). As a result, we were able to make microholes as small as 20μm in diameter on a silicon plate. Additional experiments revealed the possibility of wide application.

Key words: ultrasonic machining, micromachining, microholes, WEDG

1. INTRODUCTION

One of the recent trends in industry is high precision and miniaturization in a wide range of machining activities. This requires the machining of microparts made of various materials. Various techniques are fulfilling this requirement. However, hard, brittle and nonconductive materials such as glass, ceramics and silicon are still difficult to machine. EDM is not suitable for nonconductive materials, and etching does not yield high-aspect-ratio structures. On the other hand, USM can be used to machine high-aspect-ratio structures on such materials. The reason is that this method is based on the brittle fracture mechanism which is more easily introduced in these materials than the deformation mechanism is.

Although USM is capable of machining hard, brittle, and nonconductive materials, there are some difficulties in its application to micromachining. One of the problems is its difficulty in handling microtools. Although a microtool can be fabricated by, for instance, EDM, attaching it to a USM machine is a difficult task. Usually, USM tools are directly attached to the horn by soldering or brazing because a normal chuck is easily loosened by the ultrasonic vibration for machining. In such direct attachment, it is difficult to maintain the accuracy of tool attitude and concentricity. Therefore, holes smaller than 100μm in diameter have not been considered as the object of USM. [1]

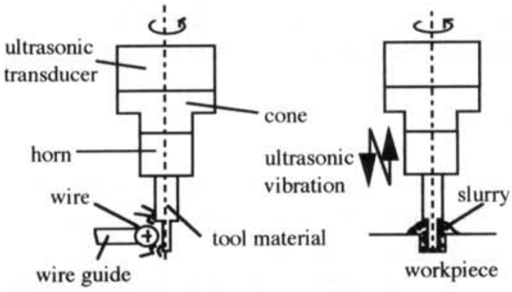
In this paper, a micro-USM technique realized by adding structures for head rotation and WEDG [2] to a conventional USM machine is introduced. WEDG is a kind of micro-EDM method which uses a travelling wire electrode guided by a wire guide. This method yields micropins of 4μm or less in diameter. [3] The aim of this research work is to realize microholes with diameters smaller than 100μm in brittle materials.

2. MICRO-USM ACHIEVED BY FABRICATING MICROTOOLS ON THE MACHINE

In order to solve the problem of fixing microtools onto USM machines, a method has been introduced capable of making microtools directly on the machine. Since an on-the-machine tool-making construction does not include a chucking process after the tool is prepared, a very accurate tool alignment is expected. First, in order to realize this construction, a structure for rotating the machining head is added. The machining head consists of an ultrasonic transducer, a cone and a horn. Second, the WEDG unit was attached to the main body. The

WEDG unit consists of a brass wire, a wire guide, a motor for driving the wire and a breaking system which gives the wire tension.

The microtool fabrication process on this modified machine is as follows. First, a tool material is attached to the horn by soldering. The size of the tool material is large enough to be handled easily. At this time, slight eccentricity and inclination are allowable. Then, as shown in Figure 1(a), the tool material is machined into a microtool by WEDG while rotating the machining head. When we use the microtool in USM, as shown in Figure 1(b),

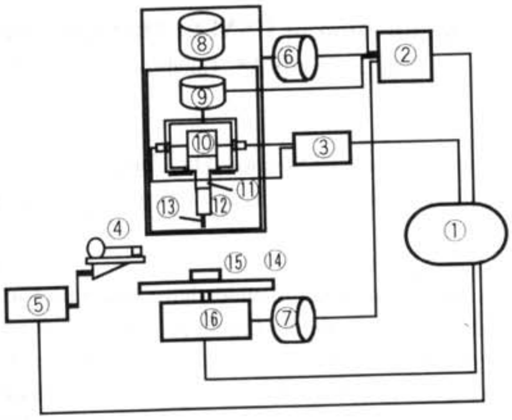


(a) Fabrication of microtool by WEDG

(b) Micro-USM with fabricated tool

Fig.1 Micro-USM achieved by fabricating microtools on the machine.

Fig.2 Prototype micro-USM machine.



①personal computer ②motor controller
③ultrasonic generator ④WEDG wire
⑤processing circuits for WEDG ⑥X-axis driver
⑦Y-axis driver ⑧Z-axis driver ⑨C-axis driver
⑩ultrasonic transducer ⑪cone ⑫horn ⑬tool
⑭machining stage ⑮workpiece
⑯electronic balance

Fig.3 Configuration of micro-USM machine.

it is perfectly parallel to the feed axis because the feed axis of USM is the same as that of WEDG. In conventional USM, the tool must be adjusted to be parallel to the feed axis, but this cannot be accomplished at an accuracy as high as several micrometers. The rotation of the machining head is applicable either in tool making or in USM. Good roundness of the products is expected with the application of rotation because the rotation axis is the same in these two processes. The rotation may also be effective in improving the machining rate during the USM process.

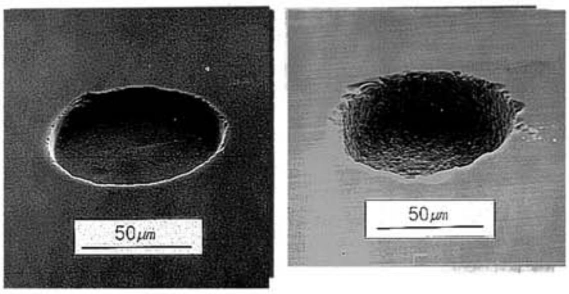
Figure 2 shows the prototype machine used in the experiments in this work, and Figure 3 shows its configuration. The machine has four numerically controllable axes, X, Y, Z and C. The X-, Y-, and Z-axes are driven by stepping motors. The C-axis is driven by a DC servomotor. Machining load is measured by an electronic balance set beneath the machining stage. An ultrasonic frequency of 40kHz was applied. This frequency is higher than those that are usually used in conventional USM. In the case of this higher frequency, a shorter cone and horn can be used. This helps to make the machining head compact and, consequently, convenient for rotation. The whole system is controlled by a personal computer.

3. MACHINING CHARACTERISTICS

Machining characteristics of micro-USM in the dimension range under 100μm have not been previously reported. In this section machining characteristics such as the quality of machined holes, machining rate and tool wear ratio under various conditions are discussed based on experiments.

3.1 Abrasives

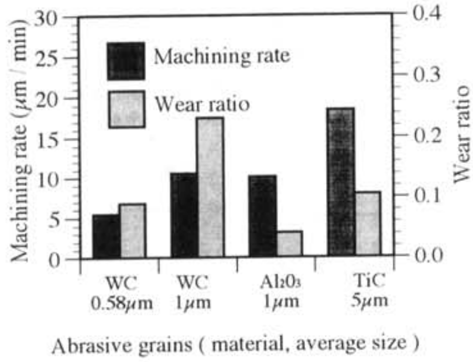
Figure 4 shows the influence of the abrasive size on the quality of machined holes. In the case of TiC 5μm abrasive, large chippings are seen at the hole edge. The roughness of the inside wall is also clearly worse than that in the case of WC 0.58μm abrasive. Figure 5 shows the relationships of abrasive size and abrasive material to machining rate and tool wear ratio. Machining rate here is defined as the depth of a machined hole divided by the machining time. Wear ratio is calculated as the ratio



(a) Size 0.58μm (WC) (b) Size 5μm (TiC)

Workpiece : quartz glass Machining load : 5 - 10 mN
Tool material : WC alloy Tool diameter : 61 – 65 μm
Tool vibration amplitude : 0.8 μm

Fig.4 Influence of abrasive size on surface and edge quality.



Workpiece : quartz glass Tool diameter : 28 – 32 μm
Machining load : 3 – 6 mN Tool vibration amplitude : 0.8 μm
Tool material : WC alloy Tool rotating speed : 200 rpm

Fig.5 Relationships of abrasive size and material to machining rate and wear ratio.

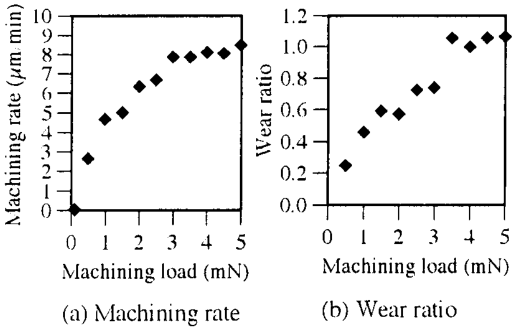
of the length of tool wear to the depth of the hole. As shown in Figure 5, machining rate increases with the size of abrasives. Therefore, we should choose the abrasive size considering the balance between the quality of machined holes and machining rate. Wear ratio is strongly influenced by the abrasive material.

3.2 Machining load

Figure 6 shows the influence of machining load on machining rate and tool wear ratio. Machining rate increases when machining load increases but saturates at the load of 3mN. This means that the increase of tool wear is larger than that of hole depth when higher load is applied. The reason may be that high machining rate causes debris accumulation at the bottom of the hole. This absorbs the impact of abrasives and the selective removal of the workpiece material is deteriorated.

3.3 Vibration amplitude

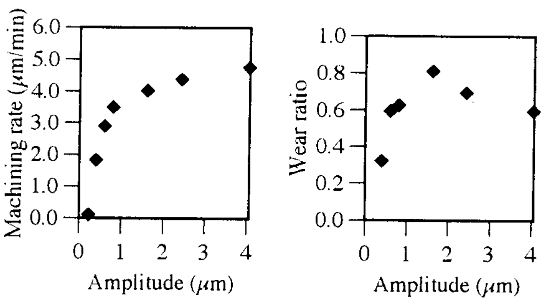
Figure 7 shows the influence of tool vibration amplitude on machining rate and tool wear ratio. Similarly to changing machining load, both parameters increase when the amplitude increases, although wear ratio saturates more clearly. Basically the same phenomenon is assumed to occur as in the case of debris increase upon load increase.



(a) Machining rate (b) Wear ratio

Workpiece : silicon
Abrasive : WC, 0.58μm
Tool material : WC alloy
Machined hole diameters : 26 – 28 μm
Tool vibration amplitude : 0.8 μm
Tool rotating speed : 100 rpm

Fig.6 Relationships of machining load to machining rate and wear ratio.



(a) Machinig rate (b) Wear ratio

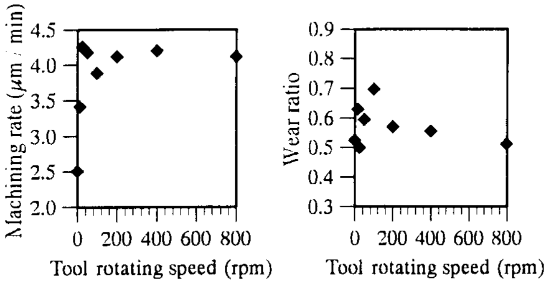
Workpiece : silicon
Machining load : 1 – 2 mN
Tool material : WC alloy
Tool diameter : 25 – 30 μm
Abrasive : WC, 0.58μm
Tool rotating speed : 100 rpm

Fig.7 Influence of tool vibration amplitude on machining rate and wear ratio.

3.4 Rotating speed

The influence of the tool rotating speed on machining rate and tool wear ratio is shown in Figure 8. The rotating speed was changed from 0rpm (the tool was not rotated) to 800rpm. At higher speeds ultrasonic power supply to the tool through the slip ring becomes so unstable that the ultrasonic transducer does not work continuously.

Figure 8(a) indicates that even a slow rotation drastically improves the machining rate. However, speeds higher than 50rpm seem to be useless. No significant influence on tool wear ratio was observed as is shown in Figure 8(b). This result suggests that the tool rotation is effective for abrasive circulation and debris removal from the machining gap.



(a) Machining rate (b) Wear ratio

Workpiece : silicon
Machining load : 1 – 2 mN
Tool material : WC alloy
Tool diameter : 26 – 31 μm
Tool vibration amplitude : 0.8 μm
Abrasive : WC, 0.58μm

Fig. 8 Influence of tool rotating speed on machining rate and wear ratio.

3.5 Summary of the influence of machining conditions

The characteristics confirmed from the above experiments are summarized as follows.

1. Small abrasive size improves surface roughness and suppresses chipping but gives a low machining rate.
2. Increase of machining load and vibration amplitude improves the machining rate but introduces high tool wear ratio.
3. Tool rotation is effective for improving machining rate with little influence on tool wear ratio.

Under the conditions used in these experiments, the following are the recommended parameters.

Abrasive grain size: smaller than 1μm.
Machining load: 1 – 3 mN.
Vibration amplitude: around 1μm.
Rotation speed: 200 – 500 rpm.

4. MACHINING EXAMPLES

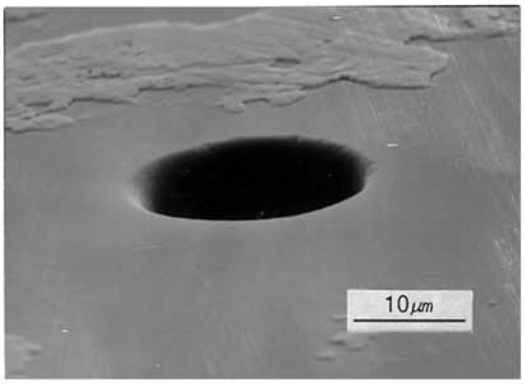
In order to show the possible areas of application of micro-USM, we carried out test machining. Typical examples are shown in Figures 9 to 14.

Figure 9 shows a microhole machined on a silicon plate. Its diameter is 20μm and depth is 50μm. This is a previously unreported size for work with USM. Figure 10 is a microhole made on quartz glass. Its diameter is about 33μm and the depth is about 120μm.

Figure 11 shows a 20 x 20 μm^2 square hole with a depth of around 30μm. Machining of such a square hole has become possible with the use of a tool with square-section awing in the WEDG technique. In this case the tool is not rotated during USM. As a similar application, a triangular hole is shown in Figure 12. Each side is 50μm long and the depth is about 30μm.

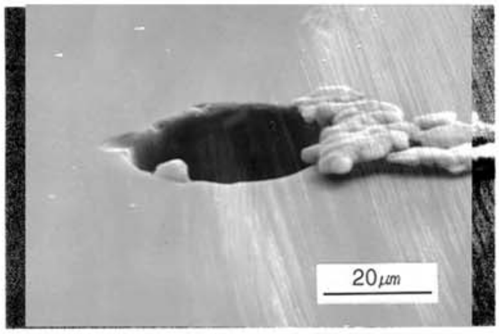
Figure 13 is a trench on silicon. It is 50μm wide, 250μm long and 150μm deep. This trench was obtained by repeatedly moving the rotating tool parallel to the workpiece surface.

Combining holes and trenches, we could make more complex 3D structures. As an example, Figure 14 shows a microturbine chamber. The center hole in which to put the turbine shaft is about 80μm in diameter and the channels for air flow are 200μm deep and 100μm wide.



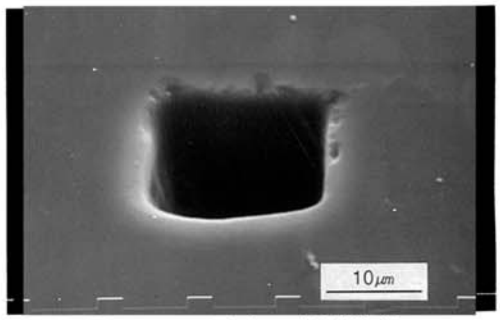
Diameter : 20 μm
Depth : 50 μm
Tool material : WC alloy
Abrasive : WC, 0.58μm
Machining load : 0.5 – 1 mN
Tool rotating speed : 200 rpm
Tool vibration amplitude : 0.8 μm
Machining time : around 12 min

Fig.9 Microhole on silicon.



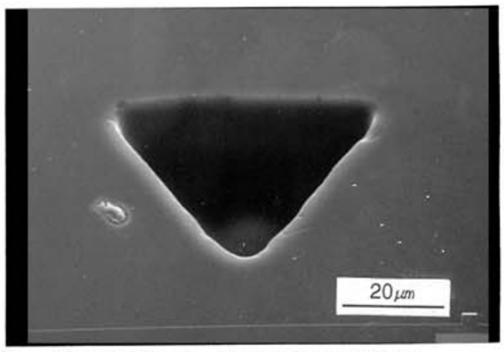
Diameter : about 33 μm
Depth : about 120 μm
Tool material : WC alloy
Abrasive : WC, 0.58μm
Machining load : 0.5 – 1.5 mN
Tool rotating speed : 200 rpm
Tool vibration amplitude : 0.8 μm
Machining time : around 30 min

Fig.10 Microhole on quartz glass.



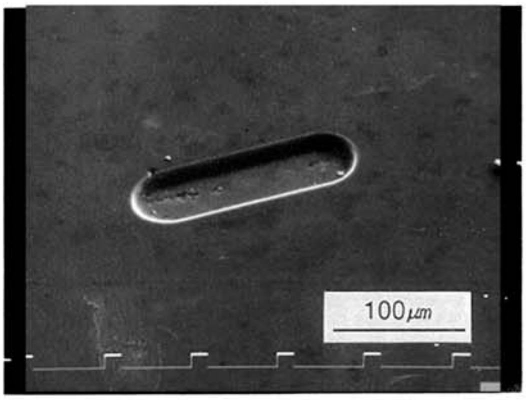
Size : 20 x 20 μm
Depth : 30 μm
Abrasive : WC, 0.58μm
Tool material : WC alloy
Machining load : 0.5 – 1 mN
Tool vibration amplitude : 0.65 μm
Machining time : around 20 min

Fig.11 Square microhole on silicon.



Size : Each side 50 μm
Depth : 30 μm
Abrasive : WC, 0.58μm
Tool material : WC alloy
Machining load : 3 - 6 mN
Tool vibration amplitude : 0.8 μm
Machining time : around 10 min

Fig.12 Triangular microhole on silicon.



50μm wide, 250μm long, 30μm deep

Fig. 13 Trench on silicon.

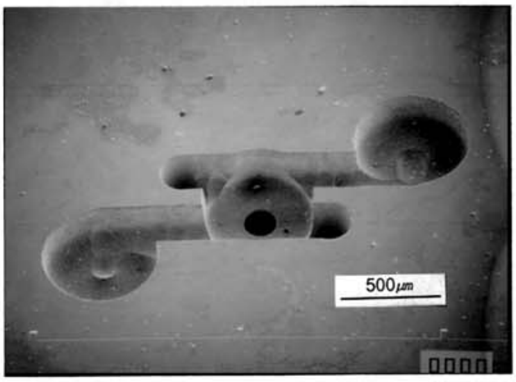


Fig.14 Microturbine chamber on silicon

5. CONCLUSION

A micro-USM technique has been developed by introducing an on-the-machine tool-making system. In order to fabricate microtools on the USM machine, we added structures for head rotation and WEDG to the machine. These features enabled us to prepare USM tools that are microsized, parallel to the feed axis and concentric to the rotation axis. The WEDG facility also offers a wide choice of tool shape.

Experiments were carried out using a prototype machine, and machining characteristics under the conditions applicable for holes smaller than 100μm were analyzed.

Following points were found to be important in the application of USM in micromachining.

1. Very fine abrasive should be used.
2. Millinewton order is suitable for the machining load.
3. Tool rotation is strongly recommended.

In practice, we succeeded in machining holes as small as to 20μm in diameter, while conventional USM machines can only machine holes larger than 100μm. A wide possibility of applications was also proved by machining examples of various shapes including complex 3D structures.

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