*International Conference on Leading Edge Manufacturing in 21st Century*
*Oct. 19-22, 2005, Nagoya, Japan Copyright 2005*

# EDM of Reverse-Tapered Microholes

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Summary

We have performed EDM of reverse-tapered microholes with a diameter of less than 100µm and a high rate of taper. Two methods have been tested for drilling a hole in a 50-µm-thick copper sheet using tungsten electrodes: one uses an electrode moving in planetary motion with planetary-motion diameter gradually increasing; the other employs an electrode bent at a high angle to its original axis. A hole 35µm in entrance diameter and 42µm in exit diameter was drilled by the former method and a hole 50µm in entrance diameter and 115µm in exit diameter was fabricated by the latter.

Keywords: Reverse-tapered hole, Microhole, EDM, Wire electrodischarge grinding

## 1. Introduction

Electrical discharge machining (EDM) has been widely employed for fabricating microholes in various industrial materials, because it can deal with hard materials and the machining force exerted on the workpiece is much smaller than that in mechanical machining processes. The primary applications of such microholes are as nozzles for injecting fuel or forming fibers, and as dies for drawing wires. These holes often need to be tapered with one opening larger than the other. Although a tapered hole is usually drilled from its larger opening for ease of machining, such drilling is difficult work when the design of the part, in which a tapered hole is drilled, does not allow the tool electrode to easily approach the larger opening, as in the case of fabricating a nozzle hole at the tip of a long cylinder. Drilling must be carried out from the smaller opening in such a case, therefore requiring a method of producing reverse-tapered holes.

To fabricate a shape with an overhang such as a reverse-tapered hole, new EDM techniques are necessary. Such methods have been reported: Goto et al. have developed an EDM system with a flexible arm, on whose tip an electrode is fixed [(1)]. Holes similar to mole tunnels were fabricated in aluminum. The method, however, cannot be applied to microholes, because the arm has mechanical parts inside it and minimizing its size is limited. Masuzawa et al. have realized a lathe-type micro-EDM machine, with which boring operation is possible in the tip of a cylindrical workpiece. Microshapes with an overhang were bored as a result [(2) (3)]. However, the fabricated hole was not completely reverse-tapered, having a shape like that of an hourglass. Holes less than 100µm in diameter were not drilled either. Diver et al. have reported that reverse-tapered microholes have been drilled using a conventional EDM machine [(4)]. In their method, the electrode is bent by a guiding collet and then fed into the workpiece. They fabricated a 1-mm-deep reverse-tapered hole 270µm in entrance diameter and 335µm in exit diameter. Holes with a high aspect ratio (hole depth divided by diameter) were achievable. However, they also drilled holes with a diameter of more than 100µm in diameter because the electrode diameters were more than 80µm. A thinner electrode must be used for smaller holes. Furthermore, drilling a hole with a high rate of taper (or a large cone angle, see Fig.1) was impossible because the electrode material was tungsten carbide, which is not ductile and thus cannot be bent at a large angle.

In this study, we therefore attempted EDM of reverse-tapered microholes less than 100µm in diameter with a high rate of taper, using electrodes with a small diameter and a high ductility for allowing them to be bent at a high angle. Two drilling methods have been attempted: one uses an electrode moving in planetary motion with planetary-motion diameter gradually increasing; the other employs an electrode bent at a high angle to its original axis.

## 2. Experimental

The present experiments were performed on a machine originally designed for micro-ultrasonic machining (ASWU-1, Creative Technology Corp.) provided with a V-shaped sliding bearing of a micro-EDM machine (MG-ED72, Matsushita Electric Industrial Co., Ltd.). Its three CNC axes are driven by stepping motors and lead screws with a step feed of 0.05µm. The machine is capable of performing EDM with an RC-type electrical-discharge circuit equipped for the on-the-machine fabrication of ultrasonic-

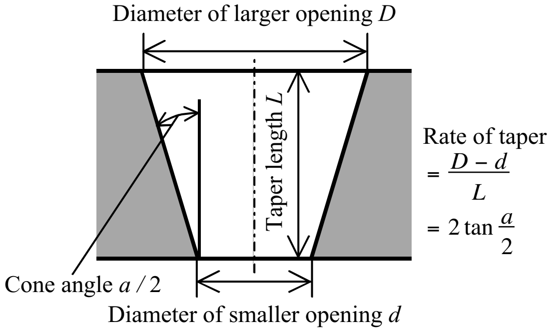
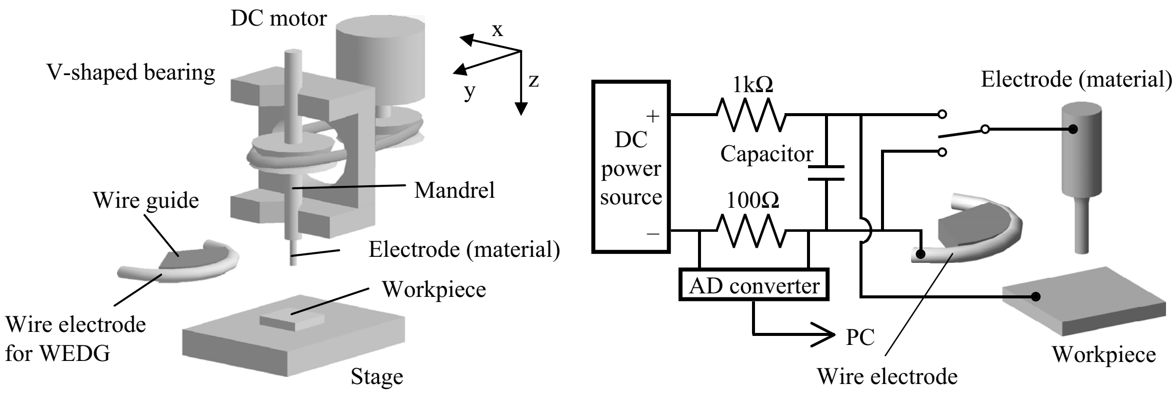



Fig.1 Tapered hole




(a) Schematic configuration (b) Electrical-discharge circuit

Fig.2 Experimental setup

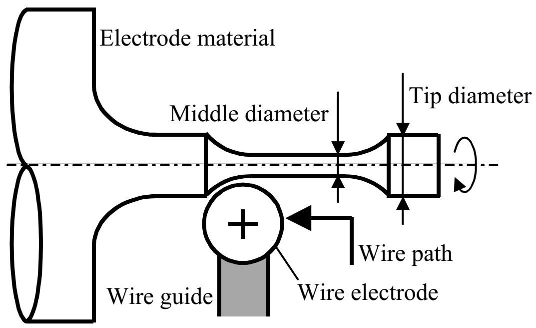



Fig.3 Electrode shape and wire motion in WEDG

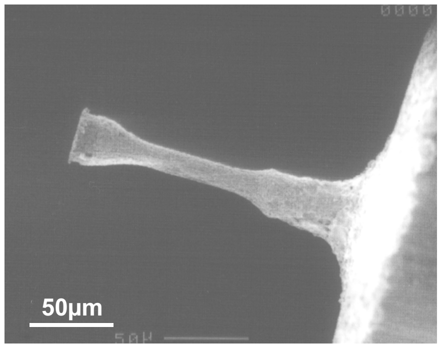



Fig.4 Electrode (30μm in tip diameter and 15μm in middle diameter) for method A

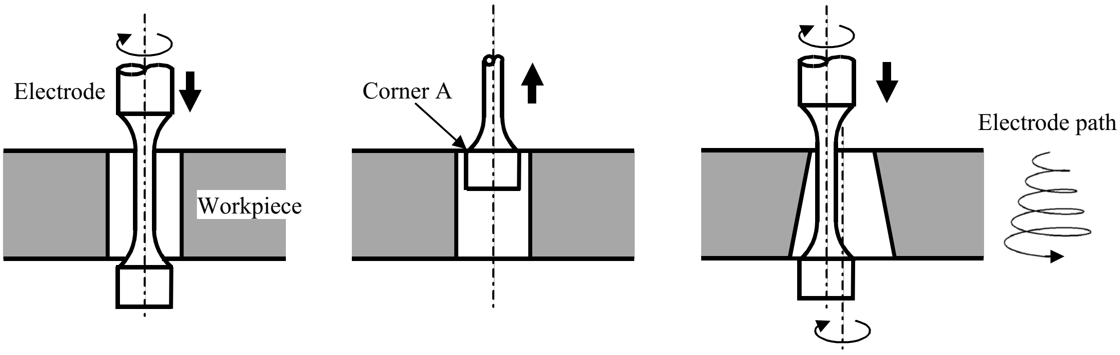
machining tools [5]. The circuit is used for fabricating electrodes and drilling using them. Figure 2 shows the schematic configuration of the main parts of the setup and the electrical-discharge circuit. Feeding the electrode is controlled by monitoring the average charging current, which is calculated from the average voltage over a charging resistance of 100Ω. EDM oil is used as working fluid in all the EDM steps.

In preparing an electrode, a 300-μm-diameter tungsten rod, which is used as electrode material, is first held by a mandrel mounted on the bearing. The cylindricality of the mandrel is set such that the rotation run-out of the mandrel is less than 0.5μm [6]. A DC motor rotates the mandrel at a rotational speed of 3000rpm. A unit for WEDG (wire electrodischarge grinding) [7], which includes a wire electrode and a wire guide, is also installed on the machine. The wire diameter and running speed are 90μm and 3mm/min, respectively. WEDG is one of the EDM methods that can fabricate thin pins with a diameter of several micrometers. In fabricating electrodes, the electrode material is the anode and the wire is the cathode, while the electrode is the cathode and the workpiece is the anode in drilling. A 50-μm-thick copper sheet is used as workpiece material.

## 3. Drilling by planetary EDM (method A)

A normal tapered hole can be drilled by planetary EDM, in which a simple cylindrical electrode not only is vertically fed into the workpiece but also revolves around the axis of the hole to be drilled. The planetary-motion diameter is gradually reduced as the electrode penetrates into the workpiece. In drilling a reverse-tapered hole, the diameter must be increased, thus, the electrode shape has to be changed. Figure 3 shows the shape of the electrode used in the present method, which is hereafter referred to as method A, and the wire-electrode path in fabricating the electrode by WEDG. A cylindrical electrode is first processed, and then fabricated into the final shape with a wire moving along the path shown in the figure. Figure 4 shows a micrograph of the fabricated electrode. The diameters of the tip and middle of the electrode are 30μm and 15μm, respectively.

The drilling steps for a reverse-tapered hole are shown in Fig.5. After a straight hole is drilled in the workpiece (Fig.5 (a)), the electrode is retracted until its corner A reaches the height of the hole entrance (Fig.5 (b)). It then begins planetary motion and is fed into the workpiece again (Fig.5 (c)), while continuously rotating around its axis. The hole is processed into a reverse-tapered one with planetary-motion diameter gradually increasing from zero. The side surface of the electrode's tip removes most of the material. Such drilling is possible because all the surfaces of the electrode can remove material in EDM.




(a) Drilling straight hole (b) Retracting electrode (c) Tapering sidewall

Fig.5 Drilling steps of method A

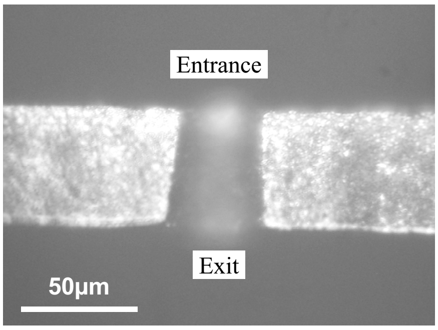


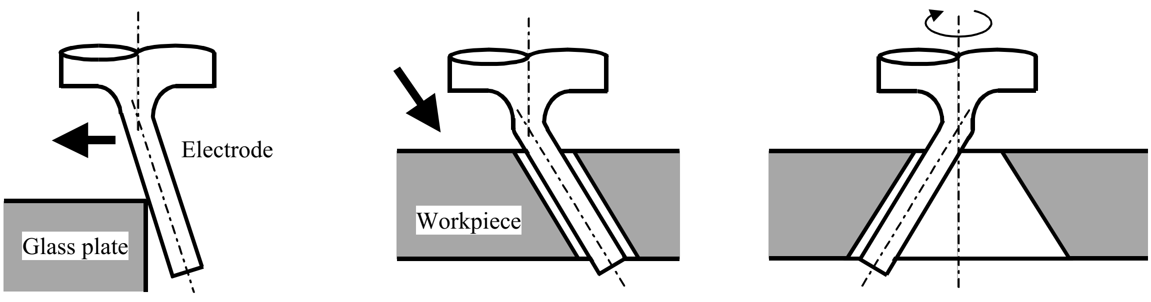

Fig.6 Cross section of reverse-tapered hole drilled by method A in 50-μm-thick plate

Figure 6 shows the cross section of a reverse-tapered hole drilled by method A, using an electrode of the same dimensions as that shown in Fig.4. Its entrance and exit diameters are 35μm and 42μm, respectively. The drilling time was 3min. The electrical conditions in all the processes were an open-circuit voltage of 80V and a capacitance equal to the stray capacitance of the machine. The stray capacitance was approximately 30pF. This hole is the smallest reverse-tapered hole drilled in EDM, to the best of our knowledge. Drilling holes other than a circular one is also possible with a noncircular planetary-motion path.

4. Drilling using bent electrode (method B)

The method described in the previous section cannot drill a reverse-tapered hole with a high diameter ratio of the larger opening to the smaller opening. Even if it were not for electrode wear and the middle diameter of the electrode were almost zero, the diameter ratio would not be more than 2:1. Because the electrode wears and its middle part cannot be very thin in actual drilling processes, the achievable diameter ratios are much smaller. It is impossible for a hole with a long taper length to obtain a high rate of taper. Other techniques are necessary for drilling such holes. The second method, namely method B, has therefore been attempted.

The method uses an electrode bent at a certain angle to its original axis. Hereafter, the angle is referred to as the bending angle. Bending angle corresponds to half the cone angle of the hole to be drilled. Figure 7 illustrates the drilling steps. A cylindrical electrode fabricated by WEDG is bent using the edge of a glass plate (Fig.7 (a)). It is pushed against the plate until its bending angle reaches half the cone angle of the hole. The ductility of its material (tungsten) allows it to be bent at a high angle. The bent electrode is then fed into the workpiece in its axial direction (Fig.7 (b)). It begins rotating after penetrating through the workpiece, thereby generating a reverse-tapered hole (Fig.7 (c)). This process of rotating the electrode is carried out two times; the second is for finish machining. Rotational motion is manually controlled by monitoring the average charging current, because of the difficulty in controlling the rotational angle of the DC motor, and thus that of the mandrel. Figure 8 shows an example of a processed electrode, which is 18μm in diameter and 32˚ in bending angle.




(a) Bending electrode (b) Feeding electrode in its axial direction (c) Rotating the electrode

Fig.7 Drilling steps of method B

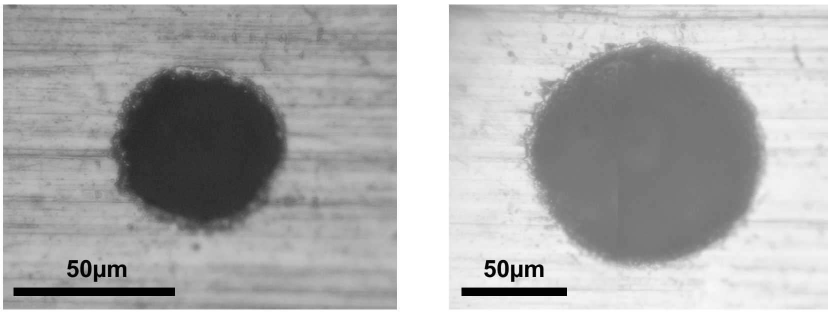
Figure 9 shows a reverse-tapered hole drilled by method B using an electrode with a diameter of 18μm and a bending angle of 33˚. The electrical conditions in all the processes were an open-circuit voltage of 100V and a capacitance of 220pF. The drilling time was 15min. The hole's entrance and exit diameters are 50μm and 115μm, respectively. The hole's rate of taper is larger than unity, proving that method B can be used to produce reverse-tapered microholes with a high rate of taper.


Fig.8 Electrode with diameter of 18μm and bending angle of 32˚ for method B

5. Summary and conclusions

We have performed EDM of reverse-tapered microholes with a diameter of less than 100μm and a high rate of taper. Two methods have been tested for drilling holes in a 50-μm-thick copper sheet using tungsten electrodes. The following results were obtained:

1) The first method used an electrode moving in planetary motion. The tip diameter of the electrode was larger than the middle-electrode diameter for fabricating the overhang of a reverse-tapered shape. Planetary-motion diameter was gradually increased as the electrode penetrated into the hole. As a result, with an electrode 30μm in tip diameter and 15μm in middle diameter, a microhole 35μm in entrance diameter and 42μm in exit diameter was drilled. This was the smallest reverse-tapered hole drilled in EDM, to the best of our knowledge.
2) The second method employed an electrode bent at a certain angle to its original axis. In the drilling process, the electrode first penetrated through the workpiece at a feed angle equal to its bending angle to the hole axis. It was then rotated around the hole axis, thereby fabricating a reverse-tapered shape. Using an 18-μm-diameter electrode with a bending angle of 33˚, a hole 50μm in entrance diameter and 115μm in exit diameter was fabricated. Its rate of taper was larger than unity, proving the ability of the method to obtain a high rate of taper.




(a) Entrance (b) Exit

Fig.9 Reverse-tapered hole drilled by method B in 50-μm-thick plate

6. References

(1) Goto A., Watanabe K. and Takeuchi A., A Method to Machine a Curved Tunnel with EDM, International Journal of Electrical Machining No.7, (2002), pp.43-46.
(2) Masuzawa T., Okajima K. and Fujino M., EDM-lathe for Micromachining, Annals of the CIRP, Vol.51, No.1, (2002), pp.355-358.
(3) Uchimura A., Masuzawa T. and Fujino M., Development of Micro EDM-lathe, Proceedings of the Annual Meeting of the Japan Society of Electrical Machining Engineers, (in Japanese), (2004), pp.13-14.
(4) Diver C., Atkinson J., Helml H. J. and Li L., Micro-EDM Drilling of Tapered Holes for Industrial Applications, Journal of Materials Processing Technology, Vol.149, No.1-3, (2004), pp.296-303.
(5) Egashira K. and Masuzawa T., Microultrasonic Machining by the Application of Workpiece Vibration, Annals of the CIRP, Vol.48, No.1, (1999), pp.131-134.
(6) Sato T., Mizutani T. and Kawata K., Electro-discharge Machine for Micro-hole Boring, National Technical Report, (in Japanese), Vol.31, No.5, (1985), pp.105-113.
(7) Masuzawa T., Fujino M. and Kobayashi M., Wire Electrodischarge Grinding for Micromachining, Annals of the CIRP, Vol.34, No.1, (1985), pp.431-434.