Micro Hole Machining by EDM Using Insulated Tool Combined with Ultrasonic Vibration of Dielectric Fluid

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가공액의 초음파 진동 및 절연 공구를 이용한 미세방전가공

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Abstract

This paper describes a micro electrical discharge machining (MEDM) technique that uses an insulated tool in combination with ultrasonic vibration to drill micro holes. As the machining depth becomes deeper, the dispersion of debris and circulation of the dielectric fluid are difficult to occur. Consequently, machining becomes unstable in the machining region and unnecessary electrochemical dissolution and secondary discharge sparking occur at the tool side face. To reduce the amount of unnecessary side machining, an insulated tool was used. Ultrasonic vibration was applied to the MEDM work fluid to better remove debris. Through these methods, a 1000 μm thick stainless steel plate was machined by using a 73 μm diameter electrode. The diameters of the hole entrance and exit were 96 μm and 88 μm, respectively. It took only 351 s to completely drill one hole.

Key Words : MEDM (마이크로 방전 가공), Tool Insulation (공구 절연), Ultrasonic Vibration (초음파진동)

1. Introduction

Production of small holes has become important in applications from biotechnology to automobiles. With the increasing importance of high quality small holes, micro machining technology, especially, the non-traditional machining technologies such as electrical discharge machining (EDM), electrochemical machining (ECM) and ultrasonic machining (USM), has received much attention for their possible application to hard materials, which are difficult to machine by traditional machining technologies. Since the EDM can machine hard materials precisely, it is widely used for making small holes[1]. When high voltage is applied, the dielectric fluid in the gap is partially ionized, thus causing a spark discharge between the workpiece and the electrode. Each discharge produces enough heat to melt and vaporize a small quantity of the workpiece material. As the machined material is ejected from the gap, a tiny crater

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is created on the workpiece surface. In EDM, there is no physical contact between tool and workpiece during the machining process; therefore, it can produce precise holes with good surface quality. However, the EDM has one disadvantage, that is, it has difficulty producing deep micro holes of diameter less than 100 μm. As the hole becomes deeper, it is difficult to expel debris from the machining gap. The debris remaining in the machining gap results in unstable machining, excessive tool wear and unnecessary side machining.

An important factor of hole machining for high aspect ratios is the improvement of debris removal[2,3]. In conventional EDM, a hollow electrode can be used to flush the debris from the machining gap. However, its use is restricted to the hollow electrode in micro-EDM (MEDM). Many researchers have tried to fabricate micro holes of high aspect ratios in various ways. A water-based dielectric solution was used for MEDM[4] and horizontal electrical discharge machining with deionized water and variously shaped electrodes could produce micro holes[5]. However, the resistivity of deionized water quickly decreased with time. As a result, a large machining gap was produced.

Recently, debris has been removed by the application of ultrasonic vibration to the electrode. With a notched shaped electrode, which is favorable for debris removal, a micro hole with an aspect ratio of 15 and diameter of 200 μm was produced on titanium alloy[6]. However, the ultrasonic vibration applied to the electrode made the spindle complex and heavy, and therefore hindered the electrode movement. Also, as the length of the electrode was changed by electrode wear, the characteristics of ultrasonic vibration were changed. Yeo and Tan applied ultrasonic vibration, at 61.5 kHz frequency, to the work tank[7]. The workpiece was submerged and fixed on the base of the work tank. With the system, a blind hole of high aspect ratio was machined on the AISI 401. In this system, the workpiece was vibrated together with the work tank. Accordingly, when the workpiece mass changed, the consistency in ultrasonic vibration transmission was not guaranteed[8].

In this work, ultrasonic vibration was applied indirectly to the workpiece via the dielectric fluid for removing debris and supplying dielectric fluid. To minimize the machining gap, an insulated tool was used. Through this approach, a micro deep hole was drilled precisely.

2. Experiments

2.1 Experimental set-up

Fig. 1 shows the schematic diagram of the micro-EDM system. The motion resolutions of motors X, Y and Z were 0.1 μm, 0.1 μm and 0.1 μm, respectively. Micro tool electrodes were machined by wire EDM (WEDG, wire electro-discharge grinding)[9,10]. During electrode fabrication, the wire moves along the guide continuously, while the electrode moves along its axis. Discharge is produced between the electrode and the wire. In this way, the mounting error and the form error of the micro electrode can be eliminated. An RC circuit was used as the discharge pulse supply. The RC circuit is suitable for producing micro holes because it has a short pulse width, high peak current and high discharge frequency. The discharging current, which flows between the tool and the workpiece, is used for feedback. When discharge occurs between a tool electrode and a workpiece, the workpiece melts and evaporates due to high temperature. If kerosene is used as the dielectric fluid, a lot of carbon is generated and causes unstable machining. Since deionized water does not produce carbon, the machining becomes more stable and faster[5,11]. But, the discharge gap becomes wide when the resistivity of the deionized water is low. To supply high resistivity water, a deionized water supplier (Simplicity, Millipore Corp.) was used. But, the resistivity of the deionized water was easily decreased when the water absorbed CO_2 from air. However, if the resistivity reaches a few MΩ·cm, this low resistivity is maintained for a few hours[1]. Therefore, the deionized water, which has a stable resistivity, was used for the experiment. Its resistivity was

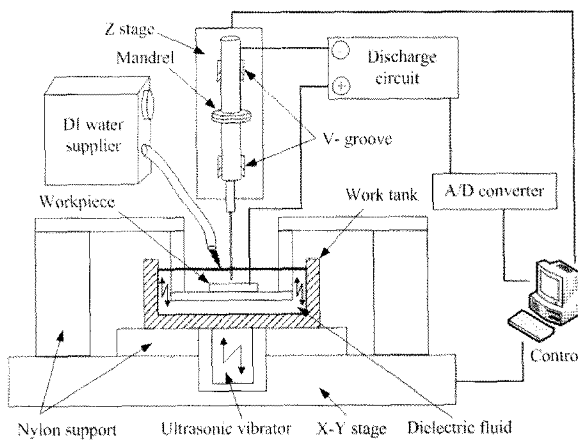


Fig. 1 Schematic diagram of MEDM system

about 1 ~ 2 MΩ·cm.

A BLT type ultrasonic transducer (NTK 4050) was attached at the bottom of the stainless steel work tank. Its resonant frequency was 40 kHz. The stainless steel work tank was coated by Teflon to prevent corrosion of the work tank. Ultrasonic vibration was applied indirectly to the workpiece via the dielectric fluid. Through this approach, ultrasonic vibration was applied to the dielectric fluid, regardless of the workpiece mass. The suspending jig was supported by a nylon leg. Nylon was useful in vibration absorption.

2.2 Tool insulation

In general, MEDM induces side spark erosion, resulting in micro-holes with diameters larger than that of the tool electrode. Especially, the radial clearance becomes larger when deionized water is used as the dielectric fluid because the electrochemical dissolution by the tool side face and the secondary discharge sparking by debris occur during machining. In order to reduce unnecessary side machining, the side face of the tool should be insulated. A tool can be insulated by the following methods.

A few methods can coat a micro electrode with a very thin insulation layer. Glass coating is widely used to insulate the side faces of electrodes, but the coating layer is too thick to use for micro electrodes. To reduce the coating thickness, etching has to be carried out additionally[12]. Polymers such as parylene are used for conformal coatings in a wide variety of applications[13]. Insulation thickness ranges from angstroms to 50 μm. Polymers also give good insulation properties and strong resistance to most chemicals. However, general polymer coating processes through vapor deposition polymerization are carried out under vacuum and require specialized equipment. Nonconductive oxide coating method by vapor deposition also requires additional equipment and the very thin coating it produces may be insufficient to cover an entire rough surface. In this paper, tool insulation was carried out by using diluted enamel.

The chief ingredient of the enamel is nitrocellulose, and the accessory ingredients are solidifying material and some solvents like methyl benzene, toluene and ethyl acetate. Nitrocellulose has characteristics such as acid-resistance, adhesiveness to metal, low electric-conductivity and easy coloring. Methyl benzene hardens easily because of high volatility. Therefore, an insulation layer can be formed by a simple method and removed easily by organic solvents like acetone. One of the important points in insulation coating is that the insulation thickness should be smaller than the machining gap. Therefore, the insulation layer should be a few micrometers thick over the side face of a tool electrode. Enamel evaporates and hardens fast from the surface layer because of the high volatility of the solvent. Therefore, insulation was performed by using the water-drop method[14].

In the insulation method, a diluted enamel droplet is dropped over the tool electrode, which stands with the bottom surface upward. When the enamel coating dries up,

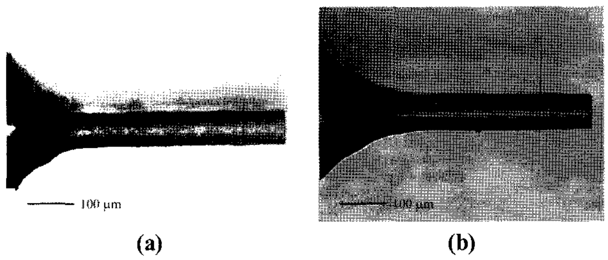


Fig. 2 Tool electrode shape: (a) before coating (diameter: 73 μm), (b) after coating (diameter: 78 μm)

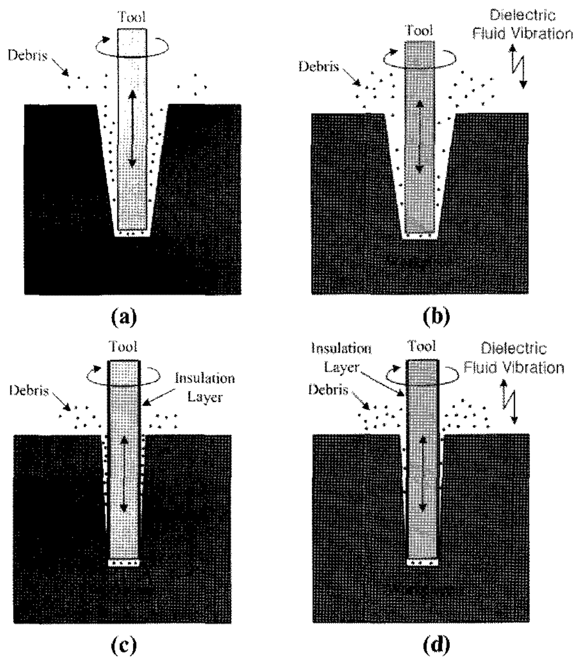


Fig. 3 Schematic diagram of four methods during MEDM drilling: (a) using a cylinder electrode for MEDM (UT-MEDM), (b) using a cylinder electrode for MEDM combined with ultrasonic vibration (UT-MEDM-WV), (c) using an insulated electrode for MEDM (IT-MEDM), (d) using an insulated electrode for MEDM combined with ultrasonic vibration (IT-MEDM-WV)

Table 1 Machining conditions

Electrode	Material	WC
	Diameter (μm)	73
	Shape	Cylinder
Workpiece	Material	304 SS
	Thickness (μm)	300, 1000
	Polarity	(+)
Dielectric fluid	Deionized water (1 ~ 2 MΩ·cm)	
Ultrasonic vibration	Frequency	40 kHz
Electric condition	Applied voltage	70 V DC
	Capacitance (pF)	500
Feed rate	Variable (0.5 ~ 50 μm/sec)	

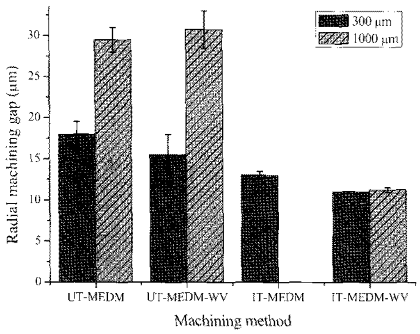


Fig. 4 Machining gap according to various methods

the bottom surface rubs against a hard surface and is machined by EDM (electrical discharge machining) to remove the remaining enamel. Then, the bottom surface, which corresponds to the machining area, is disclosed. Fig. 2 shows an example of an insulated tool electrode. The insulation thickness is about 2.5 μm over the electrode. Machining can be performed using this insulation tool because this thickness is smaller than the general EDM clearance. It takes only a few minutes to form an insulation layer.

2.3 Machining conditions

Tungsten carbide (WC) was used for the tool electrode material and stainless steel (304 SS) plates were used for the workpiece. Tool electrode was machined to 73 μm diameter by WEDG. In order to identify the tendency and repeatability, experiments were performed twice for two kinds of thickness. The electrode feed rate is changed by the machining state. If the machining state is smooth, the feed rate is increased to reduce the machining time. If contact occurs between the tool and workpiece, feed rate is decreased and as a result, the machining stability increases. Table 1 shows the general machining conditions. As shwon in Fig. 3, there are four kinds of different micro-EDM processes according to machining method and tool electrode type: (a) using a cylinder electrode for micro-EDM without ultrasonic vibration (UT-MEDM), (b) using a cylinder electrode for micro-EDM combined with ultrasonic vibration (UT-MEDM-WV), (c) using an insulated electrode for micro-EDM without ultrasonic vibration (IT-MEDM) and (d) using an insulated electrode for micro-EDM combined with ultrasonic vibration (IT-MEDM-WV).

3. Results and discussion

3.1 Radial EDM gap

From Fig. 4, radial machining gap is defined by equation (1).

$$Radial\ machining\ gap_{IN} = \frac{1}{2}(D_{IN} - d) \quad (1)$$

In equation (1), d is the diameter of electrode, and D_{IN} is the diameter of machined hole. In general, MEDM induces side spark erosion, resulting in micro-holes with diameters larger than that of the tool electrode. This side machining occurred by electrochemical dissolution of the deionized water and secondary discharge sparking of debris. Fig. 4 shows the average radial machining gap according to various methods. Experiments were performed twice for each method and error bar means the results of each test. The EDM gap of a micro-hole with a depth of 300 μm produced by using a cylindrical electrode is larger than that produced by other methods. This phenomenon can be seen distinctly when drilling a hole with a depth of 1000 μm. Radial gap was reduced slightly when ultrasonic vibration applied during the machining period because the debris can be dispersed out of the gap. Radial gap was reduced remarkably when an insulated electrode was used as a tool because side face machining was constrained. But, it was impossible to drill 1000 μm depth completely by the IT-MEDM method. If the tool was not insulated, side machining occurred intensively. Therefore, the circulation of debris and dielectric fluid frequently occur because the radial machining gap becomes large. However, the circulation

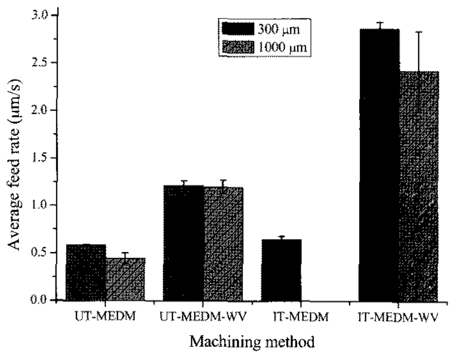


Fig. 5 Machining rate according to various methods

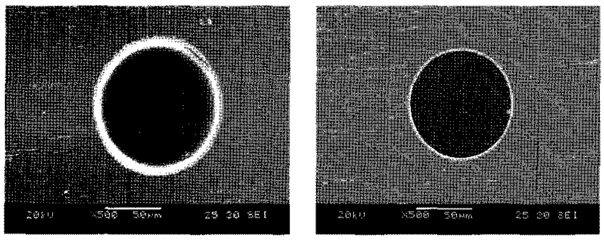
of debris and dielectric fluid was not smooth with the increase of machining depth when side face machining was restrained. It was impossible to drill deep hole completely by the IT-MEDM method. On the other hand, when using IT-MEDM-WV method, the average machining gap was reduced 62% compared with UT-MEDM method for drilling 1000 μm. Therefore, IT-MEDM-WV was the suitable machining method for reducing the EDM gap.

3.2 Machining rate

Tool feed rate is controlled according to machining state. If machining state is smooth, feed rate is increased to reduce the machining time. If contact occurs between the tool and workpiece, feed rate is decreased to increase machining stability. Fig. 5 shows the average machining rate according to various machining methods. The average feed rate is defined as the increase of depth of the hole in unit time. Debris can be removed well from the machining gap by applying ultrasonic vibration additionally. Consequently, machining time can be reduced because the unnecessary secondary discharge sparking can be decreased at the bottom surface. However, the secondary discharge at the tool side face still occurs. In order to decrease side machining, the tool electrode was insulated. As shown in Fig. 5, IT-MEDM-WV method can increase the machining rate greatly because the side face machining is restrained. Namely, machining rate can be increased because machining can be concentrated in the direction of depth without unnecessary machining. But, the machining rate was low when the insulated tool was used without ultrasonic vibration for the following reason: debris, which cannot be dispersed well from the bottom surface, disturbs the machining in the direction of depth even when the side machining is repressed. Therefore, when using IT-MEDM-WV method, the average machining rate was increased 446% compared with UT-MEDM method for drilling 1000 μm. Accordingly, the average machining time of a micro-hole of 1000 μm depth is substantially reduced, from 2288 s by UT-MEDM to 425 s by IT-MEDM-WV.

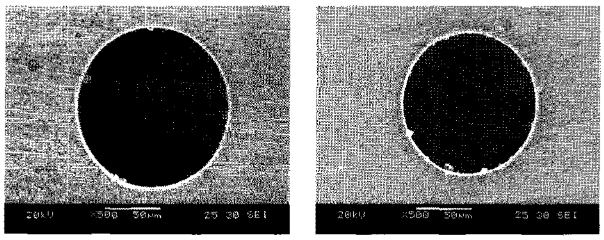
3.3 Micro hole machining

Fig. 6 shows the SEM image of a drilled hole using UT-MEDM method. The thickness of the 304 SS plate is 300 μm. The edge of the hole entrance is round shape because of electrochemical dissolution. This side machining occurs clearly when the machining time is long. Fig. 7 shows the SEM image of a 1000 μm thick drilled hole. Round edge shape, shown in Fig. 6, cannot be seen because side machining occurred sufficiently. But, radial machining gap was large because the secondary discharge and electrochemical dissolution occurred for a long time. The diameter of the hole exit was also large because the machining rate was very low near the hole exit. Namely, the dispersion of debris and the circulation of dielectric fluid were not smooth with the increase of machining depth. For these reasons, side machining occurred greatly near the hole exit. However, side machining was almost restrained when the IT-MEDM-WV method was used. Fig. 8 and 9 show the SEM image of 300



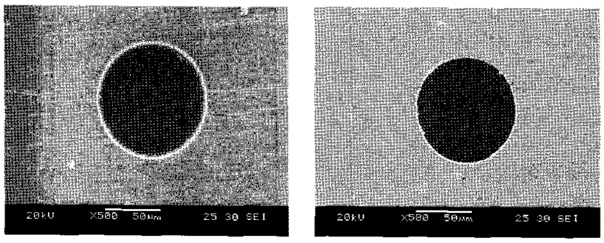
(a) (b)

Fig. 6 Drilling a hole using UT-MEDM method (workpiece: 300 μm thick 304 SS): (a) hole entrance (diameter: 106 μm), (b) hole exit (diameter: 90 μm)



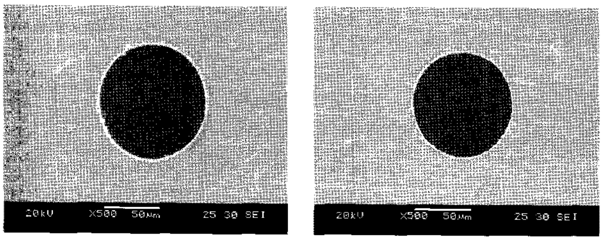
(a) (b)

Fig. 7 Drilling a hole using UT-MEDM method (workpiece: 1000 μm thick 304 SS): (a) hole entrance (diameter: 135 μm), (b) hole exit (diameter: 120 μm)



(a) (b)

Fig. 8 Drilling a hole using IT-MEDM-WV method (workpiece: 300 μm thick 304 SS): (a) hole entrance (diameter: 95 μm), (b) hole exit (diameter: 88 μm)



(a) (b)

Fig. 9 Drilling a hole using IT-MEDM-WV method (workpiece: 1000 μm thick 304 SS): (a) hole entrance (diameter: 96 μm), (b) hole exit (diameter: 88 μm)

μm and 1000 μm thick drilled holes obtained by using IT-MEDM-WV method, respectively. Sharp edge and small machining gap were acquired. Namely, side machining was restrained by the tool insulation. The dispersion of debris and circulation of the dielectric fluid were smooth because of the ultrasonic vibration. A 1000 μm thick stainless steel plate was machined with 73 μm diameter electrode by the IT-MEDM-WV method. The diameter of hole entrance and exit were 96 μm and 88 μm, respectively. It took only 351 s to completely drill one hole.

4. Conclusions

In this paper, ultrasonic vibration and insulated tool were used for MEDM to fabricate a micro hole at a high machining rate. Ultrasonic vibration was transmitted through the dielectric fluid to the workpiece. A suspending jig was designed to isolate the workpiece from the vibrating work tank. The vibration increased the debris elimination in the MEDM. Diluted enamel was used for tool insulation. Unnecessary side machining was reduced greatly by tool insulation. With this approach, hole was drilled smoothly because machining was concentrated in the direction of depth. Using an insulated micro-tool electrode with micro-EDM combined with ultrasonic vibration (IT-MEDM-WV) can substantially reduce the EDM gap and machining time, especially for deep micro-hole drilling. The average machining gap and machining rate were reduced 62% and 82% compared with UT-MEDM method for drilling 1000 μm, respectively. Accordingly, the IT-MEDM-WV method using deionized water was very effective for machining micro holes.

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