Distortion of the Bottom Surface in Micro Cavity Machining Using MEDM

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As mechanical components are miniaturized, the demands on micro die/mold are increasing. Micro mechanical components usually have high hardness and good conductivity. Micro electrical discharge machining (MEDM) can thus be an effective way to machine those components. In micro cavity fabrication using MEDM, it is observed that the bottom surface of the cavity is distorted. Electric charges tend to be concentrated at the sharp edge, and debris cannot be drawn off easily at the center of the bottom surface. These two phenomena make the bottom surface of electrode and workpiece distort. As machining depth increases, the distorted shape of the electrode approaches hemisphere. This process is affected by both capacitance and the size of electrode. By using a smaller electrode than the desired cavity size and appropriate tool movement, bottom shape distortion can be prevented.

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1. Introduction

As mechanical components are miniaturized, the interests for micromachining and microfabrication technologies are increasing. Many research results on micro electrical discharge machining (MEDM) as one of the representative micromachining processes for metals with high hardness have been reported. On the contrary to macro scale EDM, MEDM has been researched in machining simple shapes such as hole and groove.[1-5] To make the micro complex parts and their dies, precise MEDM technique for 3D fabrication has made progress.[6] Yu[7] made the micro cavity by electrode control in 3 axis using MEDM. Machining time is however too long and the tool path selection considering electrode wear is based on the trial and error experiments. In macro scale EDM, electrode with the complex shape is used to form 3D cavity. However, in micro scale EDM, it is not easy to make a free formed shape with one step EDM since the complex shape sculptured on micro electrode tends to be distorted and worn out during machining. For microfabrication by MEDM, electrodes with the simple shapes such as a cylinder, cube, hemisphere are used for step by step machining. To make simple shaped cavity, experiments were conducted with circular and square ended electrodes for the micro cavity by MEDM. During machining micro cavity, it was observed that the center part of micro cavity was protruded. In this research, the causes of bottom surface distortion are discussed and a method that can overcome the center distortion is suggested.

2. The bottom surface distortion in micro electrical discharge machining

In micro cavity machining with a square electrode, it is observed that the center of cavity bottom is protruded. Fig. 1 shows the protrudent bottom by SEM image. Firstly, it may result from the geometric shape of electrode. On the electrically charged conductors, electric charges tend to be concentrated at the sharp edges. Therefore, high electric field is constructed near the sharp edges. Electric discharges occur more frequently through electrode bottom edges for this reason. Secondly, feasibility of debris flushing according to its position can affect the distorted shape generation. Compared with the electrode boundary, debris generated on the center part by the discharge sparks cannot easily be evacuated. The heaped debris obstructs active discharges at the center area and then workpiece material is mainly removed at the edge part.

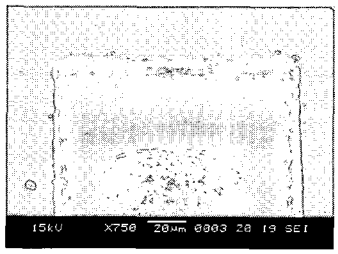


Fig. 1 The distorted shape of bottom surface in MEDM (304 SS, WC electrode, $128 \times 128 \times 100\ \mu m^3$ cavity)

3. Experimental results

The causes of protrusion of the cavity center parts are attributed to electric discharge concentration at electrode edges and debris adhesion after melting on the center of cavity bottom. We conducted a set of experiments to verify our assumptions for the bottom shape distortion. Tungsten carbide electrodes of circular and square shapes are made by wire EDM.[2] Kerosene is used as dielectric and the micro cavity is machined on 304 stainless steel. Table 1 shows experimental machining conditions.

Table 1 Machining condition

Electrode	WC
Workpiece	304 SS
Voltage	100 V
Dielectric fluid	Kerosene

3.1 Micro EDM system

The experimental system is constructed as shown in Fig. 2. System motion is controllable through the 3 linear axis and one rotational axis of spindle. The XY micro stage is 315082 ATMP and Z axis is 404200 XRMP of PARKER Co. The feeding resolution of the each axis is 0.1 μm and the stroke of table is 200 μm. The micro electrode attached on Z axis is fed to machine 304 SS plate by EDM. The RC circuit, shown in Fig. 3, is used for the EDM circuit and the machining gap state is monitored by measuring voltage.

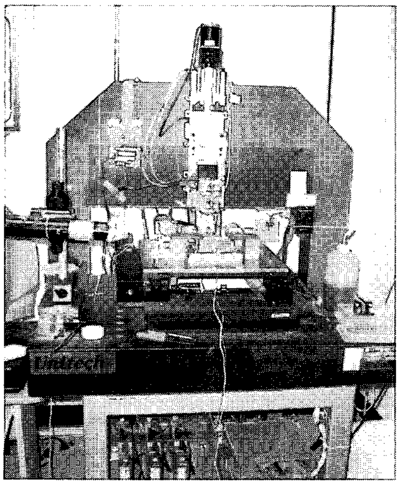


Fig. 2 Micro electrical discharge machining system

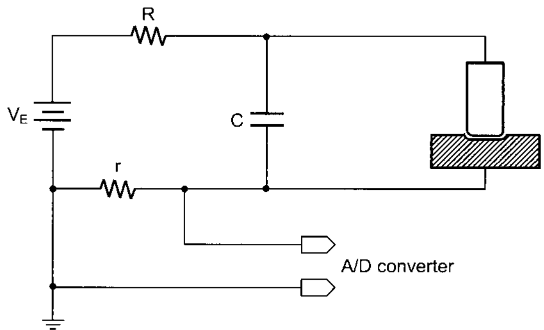


Fig. 3 Electrical discharge circuit

3.2 The effects of electrode rotation

Generally, in micro EDM for the hole generation, electrode is rotated for the debris flushing and the stabilization of discharge state. Based on the previous assumptions about bottom distortion, we infer that the distortion could be magnified when EDM is conducted without electrode rotation since debris adhesion on center area may occur more severely. To investigate the effects of tool rotation on the bottom profile, experiments are carried out with circular electrode of 100 μm in diameter with or without electrode rotation. The capacitance values are varied from 50 pF to 3000 pF. After machining 100 μm in depth, the cavity shape is observed using SEM. The experimental results of the bottom shape, machining time and cavity size are shown in tables 2 and 3.

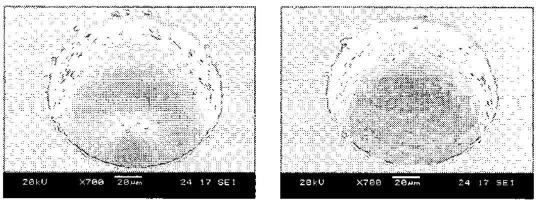
Table 2 Bottom surface distortion according to tool rotation and capacitance

Capacitance	Rotation	No rotation
50 pF	O	O
500 pF	O	O
1000 pF	O	X
3000 pF	X	X

Table 3 Machining results according to tool rotation and capacitance

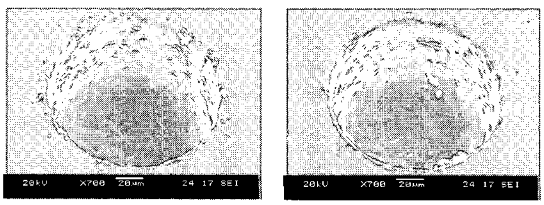
Capacitance	Rotation (time, size)	No rotation (time, size)
50 pF	395.76 sec, ϕ 105 μm	587.79 sec, ϕ 108 μm
500 pF	114.35 sec, ϕ 110 μm	385.19 sec, ϕ 114 μm
1000 pF	113.82 sec, ϕ 112 μm	485.74 sec, ϕ 109 μm
3000 pF	114.30 sec, ϕ 111 μm	446.82 sec, ϕ 112 μm

In table 2, O and X represent the distortion and no distortion of the bottom surface, respectively. Opposite to our expectations, without electrode rotation, the bottom protrusion disappears at the smaller capacitance value. This result might be related with electrode wear characteristics. In the case of no rotation, electrode wear excessively progresses at the boundary of electrode bottom, thus making a tapered electrode. Tapered electrode is suitable for the debris flushing and helps active discharge occurrence at center location. This results indicate that wear mechanism and the shape variation of electrode affect the cavity generation. Fig. 4 represents the machined cavity with or without electrode rotation using ϕ 100 μm WC electrode with 1000pF capacitance. As shown in Fig. 5, with 3000 pF capacitance, regardless of electrode rotation, the bottom shape distortion did not take place.



(a) rotation, ϕ 112 μm cavity (b) without rotation, ϕ 109 μm cavity

Fig. 4 Bottom surface with and without tool rotation. (1000 pF, 100 μm machining depth)



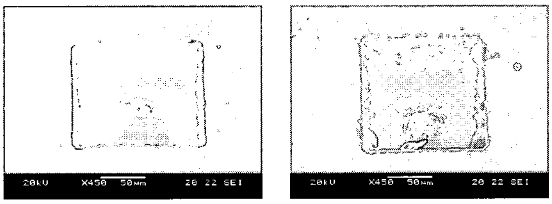
(a) rotation, ϕ 111 μm cavity (b) without rotation, ϕ 112 μm cavity

Fig. 5 Bottom surface with and without tool rotation. (3000 pF, 100 μm machining depth)

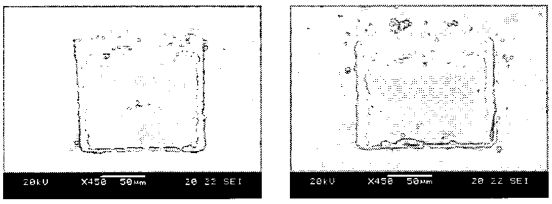
With the higher capacitance, since discharge energy is proportional to capacitance, the discharge mark is bigger and the surface quality is worse. However, machining time is reduced a little when high capacitance is used as shown in table 3. It can also be seen that the machining time is effectively reduced by rotating the electrode.

3.3 The effects of electrode size

In micro EDM, the size of electrode is associated with its amount of wear. In general case, at the same capacitance, the smaller electrode is more rapidly worn during machining. Considering the previous experimental results, we can conjecture that magnitude of bottom shape distortion is reduced when the smaller electrode is used. To explore our surmise, experiments with square electrodes of 50 μm and 100 μm side lengths are conducted by machining micro cavity of 100 μm in depth. The capacitance values are varied from 100 pF to 3000 pF. Workpiece is 304 SS with 300 μm thickness and WC electrodes are used. As we expected, the bottom surface protrusion disappeared with lower capacitance when the smaller size electrode is applied. From the experimental results, we confirmed that the bottom shape protrusion is related with the shape and size of the electrode in the aspects of electrode boundary wear and debris flushing. Fig. 6 shows the SEM image of the machined micro cavity with square electrode of 100×100 μm^2 according to capacitance variation. The smaller capacitance generates the bigger and wider protrusion with smoother surface.



(a) 100 pF (b) 500 pF



(c) 1000 pF (d) 3000 pF

Fig. 6 Bottom surface with square electrode (100×100 μm^2)

Table 4 Electrode wear according to tool size and capacitance (μm)

Capacitance	50×50 μm^2	100×100 μm^2
100 pF	35.05	23.01
500 pF	22.95	17.29
1000 pF	11.90	10.98
3000 pF	10.86	9.95

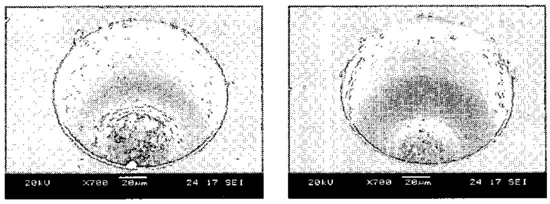
Table 5 Bottom surface distortion according to tool size and capacitance

Capacitance	50×50 μm^2	100×100 μm^2
100 pF	O	O
500 pF	△	O
1000 pF	X	O
3000 pF	X	X

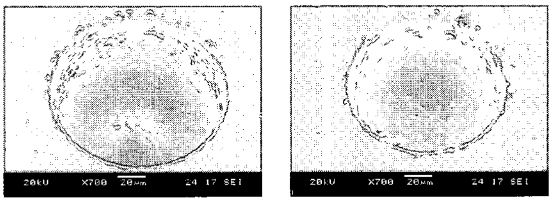
The experimental results are arranged in tables 4 and 5. Table 4 shows the effects of electrode size and capacitance on electrode wear and table 5 shows occurrence of surface protrusion of the cavity bottom. In the table, O means there is surface protrusion and X indicates no protrusion is observed. △ means that it is difficult to determine whether surface protrusion exists or not.

3.4 The effects of capacitance

From the experiments of capacitance variation from 50 pF to 3000 pF, it is confirmed that the higher capacitance reduces protrusion magnitude of the bottom surface. Bottom distortion disappeared with 3000 pF capacitance regardless of electrode shape and electrode rotation. This result implies that the larger forces by discharge explosions with the higher capacitance remove debris at nearby center area and block debris adhesion on the cavity bottom. Fig. 7 shows the machined micro cavity with ϕ 100 μm electrode in the capacitance range from 50 pF to 3000 pF. In each case, cavity depth is equal as 100 μm. With 3000 pF capacitance, the smaller cavity is made and compared with that made by other capacitances. This phenomenon results from the fact that the higher capacitance causes the higher electrode wear and makes electrode small. Machining time is remarkably reduced but surface quality gets worse with the higher capacitance.



(a) 50 pF, ϕ 115 μm cavity, 652.95 sec machining time (b) 500 pF, ϕ 119 μm cavity, 170.26 sec machining time

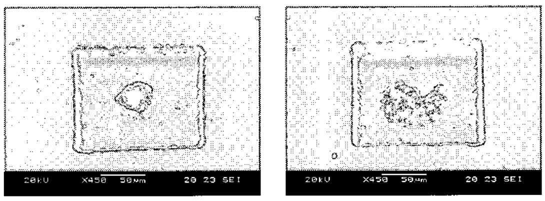


(c) 1000 pF, ϕ 125 μm cavity, 161.45 sec machining time (d) 3000 pF, ϕ 110 μm cavity, 132.25 sec machining time

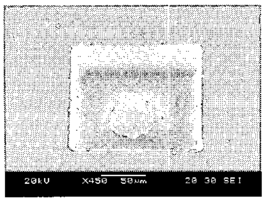
Fig. 7 Bottom surface according to capacitance

3.5 The effects of machining depth

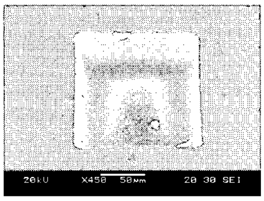
To investigate the procedure of the bottom protrusion, we observed the cavity shape according to machining depths from 20 μm to 100 μm with 20 μm step. Square electrode with 100 μm side length is used and capacitance value is fixed at 100 pF. Fig. 8 represents the cavity shape according to machining depth. At initial time of machining, as shown in Fig. 8(a), a lump is formed on surface center of the cavity. It is found that debris is the main components of the lump. Melted debris formed by the discharge sparks is adhered on the cavity bottom because it is hard to be drawn off at center region.



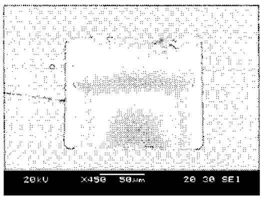
(a) 20 μm machining depth, 61.23 sec machining time (b) 40 μm machining depth, 145.79 sec machining time



(c) 60 μm machining depth, 287.64 sec machining time



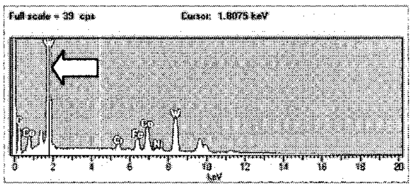
(d) 80 μm machining depth, 549.85 sec machining time



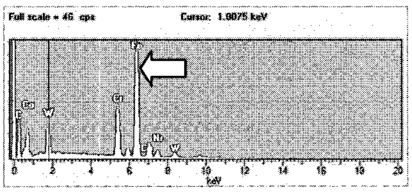
(e) 100 μm machining depth, 852.07 sec machining time

Fig. 8 Bottom surface according to machining depth

As machining proceeds, the lump is gradually grown up. The normal discharges at center area are prevented by stacked debris. Finally, the micro cavity with shape of center protrusion is formed through these processes. We can see that the lump of debris is eliminated as machining depth increases and unremoved cavity center rises in Fig. 8. Fig. 9 represents the EDS spectra at center and boundary of the cavity bottom surface after machining of 20 μm in depth. The analysis shows that the ratio of W is definitely high at the cavity center region compared with boundary area. On the contrary, Fe ratio is higher at center than at boundary. If we remind that electrode material is W and workpiece is 304 SS, the assumption is appropriate that melted debris is adhered at center and that causes the bottom protrusion.



(a) center of bottom surface



(b) boundary of bottom surface

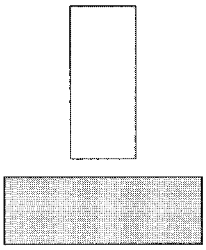
Fig. 9 EDS spectra of the bottom surface at 20 μm machining depth

4. Discussions

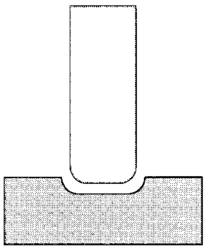
4.1 Electrode wear and the bottom distortion

Based on the previous experimental results, in micro cavity machining using MEDM, electrode wear and the bottom surface generation can be briefly explained as follows: Firstly, by discharge concentration at the electrode edges, the edge boundary is worn, thus the electrode is tapered. Debris generated by electrode wear and by removed material is stacked on the cavity center because debris in the middle area of electrode bottom is scarcely drawn off. The stacked debris is adhered on the cavity bottom in high temperature environment formed by discharge sparks. About melting and adhesion process of debris, it is necessary to consider the chemical components of electrode material. WC is a sintered material of W and C with Co bond and melting temperature of Co is quite lower than that of W. Thus Co bond may help easy formation of debris lump. The lump of adhered debris causes wear of bottom center of electrode and prevents material removal at cavity center by EDM. This process makes protrusion of the cavity center. As electrode feeding and machining progress, electrode bottom center is reversely worn by the protrudent cavity bottom and that makes a pit on electrode bottom surface. The heaped debris is removed as machining goes on. Finally, electrode edge becomes rounded by wear, thus edges of cavity having a little curvature.

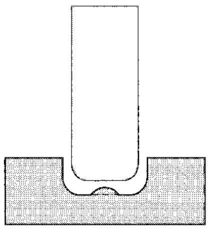
Fig. 10 represents the schematics of electrode wear process at initial machining by piled up debris. To verify our hypothesis, electrode bottom is observed by SEM after machining each cavity of 20 ~ 100 μm in depth with ϕ 100 μm electrode. The SEM images of electrode bottoms and machined cavities are shown in Fig. 11. As expected, the center of electrode bottom becomes pitted by the protrudent cavity center as machining progresses. Also, edge boundary of electrode is blunted by discharge sparks concentration. Based on the experimental results, it is confirmed that our hypothesis about cavity shape distortion is quite persuasive.



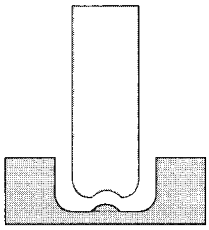
(a) before machining



(b) growth of corner wear

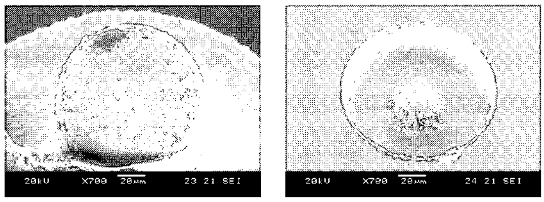


(c) piling up of debris at bottom surface

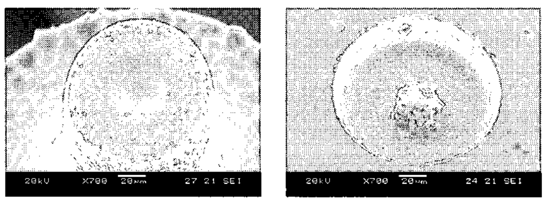


(d) distortion of bottom surface and wear of electrode center

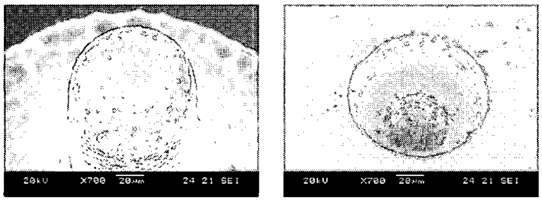
Fig. 10 Changes of electrode shape and bottom surface as machining progresses



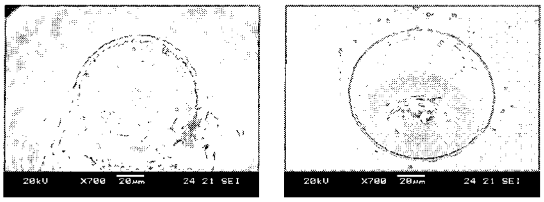
(a) 20 μm machining depth



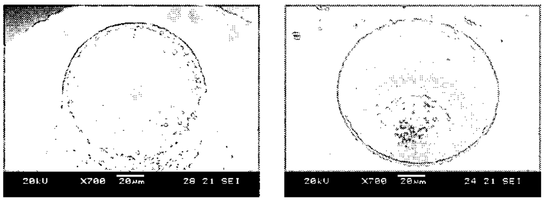
(b) 40 μm machining depth



(c) 60 μm machining depth



(d) 80 μm machining depth



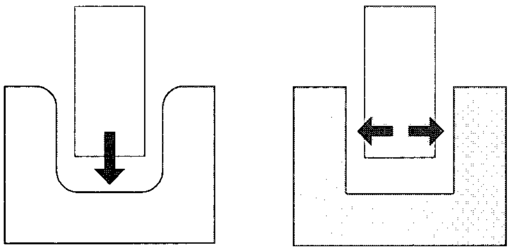
(e) 100 μm machining depth

Fig. 11 Bottom shapes of electrode and machined cavity according to machining depth

4.2 Prevention of the cavity shape distortion

In micro cavity machining by EDM, capacitance and electrode size are closely related with the cavity shape distortion. To avoid the cavity shape distortion, high capacitance and small size electrode should be used. However, because electrode size is determined by the required cavity size, variation of capacitance value is only proper solution for avoiding cavity distortion. Increase of capacitance is also limited because higher capacitance makes surface roughness worse.

In this research, a new method is suggested for the undistorted cavity fabrication without losing surface quality. To make a square cavity of 100 μm in side length, square electrode of 80 μm in side length is introduced. In the first step, the cavity is machined to final depth with 3000 pF capacitance. This process makes the smaller cavity with coarse surface texture without the bottom surface distortion. In the next step, after changing capacitance to 100 pF, electrode is fed about 5 μm in forward and backward in X and Y directions considering machining gap as the finishing process. The suggested method is composed of roughing and finishing in EDM. The schematic is drawn in Fig. 12 and the machined cavity through these processes is shown in Fig. 13.



(a) first step (b) second step

Fig. 12 Method for prevention of bottom surface distortion

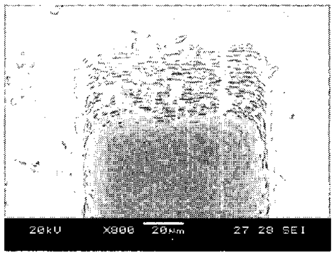


Fig. 13 Micro cavity without bottom surface distortion. (92.0×93.7 μm^2 cavity, 100 μm machining depth, and 479.1 sec machining time)

5. Conclusions

Fabrication of micro cavity by electrical discharge machining is investigated in this paper. The bottom surface distortion occurs during cavity machining. We analyzed the characteristics of cavity shape distortion from a series of experiments according to electrode size, electrode shape, capacitance and electrode rotation. An effective method for making undistorted micro cavity with good surface quality is suggested. The research can be concluded as follows:

1) At initial stage of EDM, the boundary of electrode bottom is rapidly worn by concentration of electric charges at the sharp edges.

2) Debris located on cavity center is scarcely drawn off. Melted and adhered debris on the cavity bottom composes a lump and it grows up as machining progresses. This heap makes a pit on electrode bottom surface.

3) Using the higher capacitance, the bottom surface distortion can be avoided but surface roughness gets worse. As electrode size decreases, the magnitude of distortion reduces at small capacitance because of electrode wear characteristics.

4) After roughing with a smaller electrode than the desired cavity using high capacitance, finishing with small capacitance can make a micro cavity with good surface quality.

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