Realization of micro-EDM under ultra-small discharge energy by applying ultrasonic vibration to machining fluid

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Abstract

Although micro-EDM has its potential in micro tool and part manufacturing, the machining speed is quite low due to short-circuits and abnormal discharges, because of the difficult debris removal from the narrow gap-width. Especially, the machining becomes impossible under ultra-small discharge energy, for example, a low open voltage and the stray capacitor in the RC discharge circuit. In this study, the effect of applying ultrasonic vibration to the machining fluid in micro-EDM was experimentally investigated, in order to realize higher machining speed and deep-hole drilling. It was found that a significant increase in the machining speed was realized by applying ultrasonic vibration. Also, with the vibration of the machining fluid, micro-hole drilling with ultra-small discharge energy became possible. In addition, the experimental results show that the lateral gap width between the tool electrode and workpiece was shortened, and the tool wear ratio became smaller.

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Keywords: micro-EDM, discharge energy, tool wear ratio, ultrasonic vibration, machining speed

1. Introduction

Nowadays industrial products with high performance and precise micro components are required in many fields. For example, ultraprecise die/molds are necessary to produce lenses for digital cameras and motor cores for various kinds of motors. Micro machining technology has therefore become an important issue in fabricating micro components. Electrical discharge machining (EDM) is a promising machining method for micro machining [1]. EDM process is carried out by a series of electric discharges between the tool electrode and the workpiece electrode, which are separated by a dielectric fluid with a gap-width of several submicron to several hundred micron. The workpiece material is removed through melting and evaporation due to the heat generated by electric discharges. Even very hard materials which are difficult to machine with traditional techniques could be machined by EDM, as long as they are electrically conductive. Since pulses with quite small discharge energy and around several dozen nanosecond pulse duration are used in Micro-EDM, it can realize micro processing. Up to now, hole drilling with micro EDM has been adopted for various applications like fuel injection nozzle machining. However micro-EDM has some drawbacks. For instance, tool electrode wear is much more intensive than other machining method. In micro machining, the tool wear could not be ignored when considering the machining accuracy and machining cost. In addition, the machining speed of Micro-EDM is quite lower comparing with cutting and laser machining [2]. These drawbacks are mainly caused by short-circuits and abnormal discharges, because of the difficult debris removal from the narrow gap-width.

Up to now, several methods were proposed in order to deal with the debris in the gap area in the EDM process. For example, the application of ultrasonic vibration to the tool electrode [3-4], the workpiece [5-6] and machining fluid [7] helps circulate the machining fluid and remove the debris from the gap area, and thus reduce short-circuits and abnormal discharges. The characteristics of machining with vibration assisted to the tool and workpiece would change with the shape and weight of the tool and workpiece. Meanwhile, when the vibration is applied to the fluid with the proposed
method mentioned in the literature [7], the machining characteristics changes little even for different tools and workpieces. However, there are no reports about micro-EDM under ultra-small energy conditions, which usually makes the process unstable or even impossible.

In this study, the effect of applying ultrasonic vibration to the machining fluid in micro-EDM was experimentally investigated, in order to realize higher machining speed and deep-hole drilling. Furthermore, the effect of vibration on the machining characteristics of micro-hole drilling with ultra-small discharge energy was investigated.

2. Effect of ultrasonic vibration in micro-EDM

In micro-EDM, debris which generate in the narrow gap-width with processing is difficult to be removed from the narrow gap-width. So the debris remain in the inter-electrode area and cause frequent short-circuit and abnormal discharge. When short-circuits or abnormal discharges occur, the tool electrode is pulled back from machining hole, which greatly reduces the machining speed. In this research, we applied the ultrasonic vibration to the machining fluid, in order to increase the machining speed. The effect of applying ultrasonic vibration to the machining fluid is considered as follows. The ultrasonic vibration to the machining fluid makes a pump effect in the narrow gap area. It helps circulate the machining fluid and remove the debris from the gap area, and thus reduce short-circuits and abnormal discharges, and finally increase the machining speed. In addition, the stir effect caused by the fluid vibration may even the debris and carbon particles distribution in the gap area, and thus reduce the occurrence of short-circuits and abnormal discharges, and therefore increase the machining speed.

3. Experimental setup

In this study, micro-hole drilling was carried out with a micro-EDM machine (MG-ED71, made by Panasonic) with an RC discharge power supply to investigate the machining characteristics of ultrasonic vibration assisted micro-EDM. A tungsten electrode with a diameter of 40 μm, fabricated with the wire electrical discharge grinding (WEDG) method [8], was used in this experiment. The tool electrode was mounted on the rotation spindle whose position was controlled in the Z-direction, while the workpiece was mounted on the NC XY stage. The schematic layout of the ultrasonic vibration device (SC-450SP, made by Taga Electric Co.), the tool electrode, and the workpeice is shown in Figure 1. The ultrasonic vibration was applied to the machining fluid through the vibrating horn in Z direction. In the horn tip there is a circular hole of diameter 5mm. Since the tool electrode was fed through this hole, ultrasonic vibration could be applied to machining fluid without the contact between the tool electrode and the vibrating horn.

4. Characteristics of ultrasonic vibration assisted micro-EDM

It was predicted that the ultrasonic vibration applied to the machining fluid would help circulate the machining fluid and remove the debris from the gap area, and thus improve the machining speed. In order to investigate the effect, experiments under the following two situations were carried out: using rotation only, and using both rotation and ultrasonic vibration under different preset tool feed rates. The micro-holes were machined with an open voltage of 110 V and a capacitance of 1000 pF. The distance between the horn and workpiece was 2.5 mm and the tool electrode was fed 1000 μm. The other machining conditions are shown in Table 1. One example of the electrode used in the machining is shown in Fig.2. Figure 3 shows the change in the electrode position with the machining time under preset feed rates 10 μm/s and 100 μm/s. It is found that the machining time is shortened over 90% by applying ultrasonic vibration to the machining fluid. Figure 4 shows the relationship between the average tool feed rate and the preset feed rate. Here, the average tool feed rate is defined as the ratio between the electrode feed distance and the machining time. It is found that in the absence of

| Table 1. Machining condition |
|-----------------------------|
| **Tool electrode**           | Tungsten, φ 40 μm |
| **Workpiece**                | SUS304            |
| **Frequency**                | 43±1.5 kHz        |
| **Vibration amplitude**      | 4 μm (p-p)        |
| **Machining oil**            | CASTY-LUBE EDS    |
ultrasonic vibration, the average tool feed rate is quite low and changes slightly. However, in the case of applying ultrasonic vibration, the average tool feed rate increases with an increase in the preset feed rate up to 100 μm/s, and then decreases. The reason is attributed to the faster feed of the tool electrode because of the effective removal of debris and less short-circuits, due to the ultrasonic vibration of the machining fluid. Meanwhile, when the preset tool feed rate becomes larger than 100 μm/s, short-circuits occur frequently because of the faster tool feed rate, thus leading to a decrease in the average tool feed rate.

5. Effect of ultrasonic vibration under ultra-small energy conditions

Accurate micro-holes can be machined with ultra-small discharge energy [9], for example, a low open voltage and the stray capacitor in the RC discharge circuit. However, machining with ultra-small discharge energy is difficult as the removal of debris from the gap area becomes difficult because of the small energy and the narrow gap-width. The effect of applying ultrasonic vibration is thought to become obvious under ultra-small energy conditions. Experiments under the following four situations were then carried out: (a) without rotation and ultrasonic vibration, (b) with only rotation, (c) with only ultrasonic vibration, and (d) with both rotation and ultrasonic vibration. The distance between the horn and workpiece was 2.5 mm. The micro-holes were machined with an open voltage of 40, 30, 20, 16 and a stray capacitor as ultra-small discharge energy. The hole drilling was stopped when the tool electrode was fed 100 μm, or the machining time reached 30 min, under the same machining conditions as shown in Table 1. Figure 5 shows the relationship between the electrode position and machining time under an open voltage of 40 V. It was found that the hole drilling finished after only 1 minute with rotation and ultrasonic vibration; extremely faster than other situations. The reason is considered to be that the rotation and ultrasonic vibration helps circulate the machining fluid and therefore efficiently remove the debris from the gap area. In addition, the electrode feed in the case of both rotation and ultrasonic vibration coincide well with that of only rotation until the electrode was fed about 35 μm. Subsequently, only the machining with rotation and ultrasonic vibration could maintain a constant feed rate. The combination effect appears after the micro-hole is drilled to a certain depth.
Figure 6 shows the relationship between the electrode position and the machining time under an open voltage of 16 V, which is the lowest voltage that can be set in our machine. It is found that hole drilling is impossible without the assistance of ultrasonic vibration under this smallest discharge energy condition. The smoother feed in Fig. 6 also shows that the combination of ultrasonic vibration and rotation helps to reduce short circuits. Figure 7 shows the average tool feed rate under an open voltage of 40 V. This average tool feed rate was calculated by dividing electrode feed distance by machining time until the electrode was fed 40 µm under each situation. It is found that average feed rate with rotation and ultrasonic vibration is 33 times faster than that with only rotation, as conventional assisting method. Figure 8 (a) shows the lateral gap width under an open voltage 40 V. The lateral gap width is the half of the diameter deference between the tool electrode and the machined hole. Since the experimental result changed even under the same conditions, experiments under the same condition were carried out several times and the standard deviation was obtained and showed with the error bar in the figure. If the tool electrode vibrates during machining under the influence of the fluid ultrasonic vibration, the lateral gap width will increase comparing to the machining without ultrasonic vibration. However, the experimental result in Fig.8 (a) shows that the lateral gap width of the machining with both rotation and ultrasonic vibration is the smallest one. This is because the multiplier effect of debris removal due to the combination of rotation and vibration makes the dielectric clean, thus the lateral gap-width decreases. In addition the standard deviation under the normal condition is quite small. The reason is considered that ultrasonic vibration and rotation caused the tool electrode to vibrate, while in the normal condition, there is no influence of these two factors. Therefore, the standard deviation under the normal condition becomes quite small. Figure 8(b) shows the effect of applying ultrasonic vibration on the tool wear ratio, under an open voltage of 40V. Here, the tool wear ratio is defined as the ratio between the tool electrode wear length and machining hole depth. It is found that the tool wear ratio becomes smaller by applying ultrasonic vibration. The reason is considered that reduction of short-circuits and abnormal discharges caused by applying vibration is helpful to reduce the tool wear. Moreover, it is found that little difference of standard deviation among all conditions.
6. Effect of amplitude of ultrasonic vibration

Although the vibration amplitude of the device used in this research can be slightly changed, the frequency is fixed at 43 kHz. Since the effect of the vibration on the machining characteristics may change with the vibration amplitude, experiments under the following three situations were carried out: ultrasonic vibration with 4 \( \mu \text{m} \) (p-p) amplitude, ultrasonic vibration with 6 \( \mu \text{m} \) (p-p) amplitude, and without ultrasonic vibration. The distance between horn and workpiece was 2.0 mm, and the tool electrode was fed 500 \( \mu \text{m} \). Because deep micro-hole drilling under ultra-small discharge energy was difficult, the micro-holes were machined with an open voltage 80 V and a capacitor 220 pF. The other machining conditions are the same in Table 1. Figure 9 shows the relationship between the electrode position and the machining time under each situation. It is found that there is no clear difference between the amplitude 4 \( \mu \text{m} \) (p-p) and 6 \( \mu \text{m} \) (p-p). The result shows that in these two conditions, there was no significant pullback motion of the tool electrode and the machining process was quite stable. Figure 10 shows the average tool feed rate under each situation. This average tool feed rate was calculated by dividing the electrode feed distance 500 \( \mu \text{m} \) with the machining time. It is found that the average feed rate under 4.0 \( \mu \text{m} \) (p-p) increased by 5\% than that of 6.0 \( \mu \text{m} \) (p-p). Figure 11 shows the lateral gap width under each situation. It is found that the lateral gap width of 4.0 \( \mu \text{m} \) (p-p) slightly decreased comparing with that of 6.0 \( \mu \text{m} \) (p-p). This reason is considered that larger amplitude of vibration causes the tool electrode vibration and thus increases the hole diameter. Figure 12 shows the effect of ultrasonic vibration amplitude on the tool wear ratio. It is found that ultrasonic vibration amplitude does not have a big effect on the tool wear ratio. Moreover it is found that little difference of standard deviation exists between the conditions of the amplitude 4 \( \mu \text{m} \) (p-p) and 6 \( \mu \text{m} \) (p-p).

7. Conclusion

In this study, to improve the machining speed, micro-hole drilling was carried out by applying ultrasonic vibration to machining fluid. The effects of ultrasonic vibration on hole drilling were investigated and discussed. The following conclusions were obtained.

1. The machining time was greatly shortened.
2. Machining under ultra-small discharge energy was realized.
3. The lateral gap width was decreased.
4. Tool wear ratio became smaller.
5. The ultrasonic vibration amplitude does not have a significant effect on the machining characteristic.
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