Investigation of Depth-dependent Characteristics in Micro EDM Drilling Based on Direct Inter-electrode Area Observation

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Abstract

In the EDM process of drilling deep blind micro-hole with an aspect ratio larger than 10, machining speed decreases significantly in the last stage of machining due to frequent retreat of the micro tool. Up to now, reasons for the speed decrease were mostly thought to be gradual deterioration of the machining environment in the inter-electrode area, mainly caused by debris accumulation and concentration in the narrow gap area. However, it is difficult to confirm the state of the gap area in micro scale by direct observation. Therefore, an affirmed explanation for the speed decrease in micro EDM drilling has not been reported. In this research, in order to analyze the behaviors of bubble, debris and discharge characteristic in the inter-electrode area and the reason for speed decrease, direct observation of the gap area was carried out with an originally designed sandwich workpiece and a high-speed camera. The characteristics of discharge, bubble behavior and change of discharge area have been investigated and discussed in different hole depths.

Key words: micro-EDM, drilling process, high-speed camera, bubble behavior, discharge.

1. INTRODUCTION

Electrical discharge machining (EDM) has been widely used in the industry as one of non-conventional machining technologies. With the increasing requirement for micro-products, the micro-machining technology has been advanced over the decades. Micro EDM with many unique virtues has proved its capacity in machining varieties of micro features.

Micro hole drilling, one of the applications of micro EDM, has been studied for decades. In EDM, material is removed by the electrical discharge process. The bubble overflows out of the inter-electrode area easily, in the micro hole with aspect ratio less than 5. However, when drilling deep hole with aspect ratio larger than 10, the speed of bubble overflowing out of the gap area decreases seriously, and massive debris accumulates in the inter-electrode area. The accumulation and concentration of debris causes the abnormal discharges such as arc discharges and short-circuits, leading to excessive tool wear and low machining accuracy. Moreover, the weakened insulation strength of dielectric and uneven gap width lead to frequent short circuits, resulting in lower machining speed. Therefore, the exclusion of debris, exchange of dielectric liquid and recovery of insulation strength of gap area are critical to maintain machining precision, high machining speed and low tool wear.

Many researches were focused on improving the flushing process to enhance debris exhaustion and dielectric liquid exchange. For example, the influence of flushing pattern on the distribution of flow field was analyzed. In addition, in order to enhance the mixing effect of dielectric liquid with high-speed rotating tool, single-notch and helical electrodes were used in the drilling process. To enlarge the narrow gap area, decrease the viscous resistance and mix the dielectric unevenly, planetary movement and ultrasonic vibration were applied to improve the escape of bubble and debris from inter-electrode area.

However, the mechanism of bubble and debris behavior is still unknown in micro EDM for deep hole drilling, because it is difficult to quantitatively investigate the behavior of bubble and debris under extreme conditions: debris in nano-micro scale of 1nm-10μm, massive bubbles generated in a significant short period of time, and the narrow gap width about 10μm.

Direct observation is an effective way to clarify the behavior of bubble and debris in the inter-electrode area. To observe the discharge phenomenon in gap area, the observation using high-speed camera and transparent workpiece, or transparent electrode made of material of SiC or Ga2O3, were performed in sinking EDM. However, none reports have been published so far about the observation of inter-electrode area in micro hole drilling. On the other hand, due to the difficulty in directly observing the whole gap area, most researches were focused on the observation of bottom of the gap area or simulation of the drilling process.
process by using hot-melt adhesive with a copper wire inside\textsuperscript{13}. Even so, the light transmissivity of transparent material significantly reduced after being heated in the discharge process, due to the destruction of crystallographic texture. Therefore, in order to obtain a clear image of the observation area, the observation was performed in a very short period of time just at the beginning stage of machining or in specific conditions. Thus, it is necessary to investigate the depth-dependent characteristics of discharge process, debris and bubble in deep hole drilling.

The purpose of this paper is to investigate the depth-dependent characteristics of discharge and bubble behavior, which play the dominate role in micro deep hole drilling, by means of direct observation of inter-electrode area. In order to realize the purpose, an originally designed novel sandwich workpiece and a high-speed camera were adopted. Based on the observation results, the depth-dependent behavior of discharge and bubble and their influences on the deep micro hole drilling with EDM were analyzed.

2. THE METHOD TO OBSERVE THE GAP AREA

In this paper, a method was put forward for the long-time observation of gap area from the side wall, by using an original sandwich workpiece. The schematic was shown in Figure 1, where R is radius of micro tool, g is the width of gap area. The high-speed camera is focus on the observation area A. The micro tool with the diameter equal to the thickness of the sheet workpiece was used. During the discharging, the material in the gap area with the cross section area of $\pi(r^2+g)^2$ was completely removed so that the details of gap area can be observed through the area B of side wall.

![Fig. 1 Method for observing the gap area](image)

Two projects were put forward to create the sandwich workpiece. In the first project, the sheet workpiece was pressed by two pieces of glass plates from both sides. The micro clearance between the glass plate and sheet workpiece can hold the debris. If the bubble can flush the debris, the debris will move into the clearance from the discharge spot, and this phenomenon can be observed by the high-speed camera. Therefore, the first project was to confirm the flushing effect of bubble on debris exhaustion. The figures of workpiece in project 1 are shown in Fig. 2.

![Fig. 2 Sandwich workpiece in project 1](image)

In the project 2, the sheet workpiece was glued together with two pieces of glass plates from both sides by using a transparent resin adhesive. Therefore, the clearance between the sheet workpiece and glass plate was totally blocked and the condition is similar to the actual blind hole drilling. Therefore, this project was attempted to simulate blind hole drilling process and investigate bubble behavior and discharge characteristics. On the other hand, in order to ensure that project 2 is similar to the actual micro drilling process, thickness of the adhesive layer should be close to the width of gap area. The thickness of adhesive layer is shown in Fig. 3, measured by a surface profiler (CV-3100S4/MM, Mitutoyo) from three locations. It was found that the thickness of adhesive layer was about 15\textmu m, similar to the gap width\textsuperscript{14} in the experimental conditions of Table 1.

![Fig. 3 Thickness of adhesive layer](image)

3. EXPERIMENTAL EQUIPMENT AND CONDITIONS

The experiments planned in two projects were carried out to drill micro holes in sandwich workpiece with sheet workpiece of SiC and stainless steel SUS304. The experimental conditions are shown in Table 1.
Table 1 Machining conditions

| Parameter          | Value                  |
|--------------------|------------------------|
| Tool electrode     | Tungsten rod           |
| The diameter of tool | 300μm                  |
| Thickness of sheet | 300μm                  |
| Tool feed rate     | 5μm/s                  |
| Open voltage       | 110V                   |
| Capacitance        | 1000pF                 |
| Dielectric         | Deionized water        |

The experiment equipment is shown in Fig. 4. The experiment was carried out in the micro-EDM machine (MG-ED71, Panasonic) with a RC circuit. During experiments, the dielectric was supplied gently through a nozzle to the machining area as shown in Fig.1 (a). The laser distance sensor (LK-G80, Keyence) was used to record the position of Z axis from a reference point without regard to tool wear, called feed depth in this paper. The current sensor was for the detection of current signal. The high-speed camera (VW9000, Keyence) was for the observation of gap area. The frame rate in SiC sheet workpiece was 4000fps and the shutter speed was 1/8000s. In the case of the opaque stainless steel workpiece, the frame rate and shutter speed was 1000fps and 1/8000s respectively, in order to obtain high quality images.

4 FLUSHING EFFECT OF BUBBLE ON DEBRIS EXHAUSTION

In micro drilling, generally the diameter of micro hole is less than 500μm. The influence of surface tension makes it difficult for the exchange of dielectric, especially at the deep depth. The rotation of micro tool and bubble movement significantly improve the flow of dielectric in the gap area. In the discharge, high temperature of the plasma makes the dielectric liquid evaporate instantly. The bubble behavior, such as expansion, contraction and movement, improves the flowing of dielectric and debris exhaustion. However, the phenomenon has not been confirmed yet because it is difficult to observe the gap area directly.

In this part, the experiment of project 1 was carried out and the phenomenon was confirmed. The stainless steel SUS304 was used for sheet workpiece because more debris was generated in machining stainless steel than SiC, so that the movement of debris was very obvious in the micro clearance flushed by bubble.

The movement of debris was predicted in Fig. 5. The machining area was divided into three parts: gap area, flushing area and debris accumulation area. Due to the existence of micro clearance between glass plates and the sheet workpiece, the debris was flushed out of the gap area and accumulated in an area far away from the gap area, called the debris accumulation area in this paper. The flushing area, where bubbles expand and move, has little debris in the beginning of machining because the bubble in the discharge spot have enough pressure to force the debris in the bottom to move towards the outer area, resulting in the enlarging of debris accumulation area. With the increase of hole depth, more debris accumulated in the bottom of gap area and blocked the bottom totally. In a threshold, the bubble pressure is not enough to enlarge the debris accumulation area so that the debris was flushed into the flushing area from the bottom of gap area. In deeper hole depth, most of the flushing area was occupied by the debris as shown in Fig. 5 (b) except the bottom area where the discharge occurred.

The result obtained from the observation by the high-speed camera is shown in Fig. 6. It is found that the result is consistent with previous prediction. In the feed depth of 584μm, the flushing area and debris...
accumulation area is distinguished obviously. However, in 972μm, most of the flushing area has been occupied by the debris, except for the bottom area because of bubble flushing. Actually, the bubble and debris are nearly generated at the same time in the discharge. Once the debris is generated, it will be flushed away by the bubble immediately.

![Image](image_url)

(a) Feed depth: 584μm  (b) Feed depth: 972μm

Fig. 6 Observation of machining area

However, when short circuits occur, the discharge process stops, and the machining area is full of debris as shown in Fig. 7 (a). Then, the tool is retreated and fed again after insulation of gap area recovers. The discharge occurs again and the flushing of bubble to debris was shown in Fig. 7 (b) and (c). This control process for the tool feed and retreat based on the short-circuit signal was determined by the servo system of the micro EDM machine.

![Image](image_url)

(a) t  (b) t+0.12s  (c) t+0.522s

Fig. 7 Flushing of bubble to debris

(t, a certain machining time; Feed depth: 972μm)

In this part, by using the sandwiched workpiece of project 1, the movement of massive debris becomes visible due to the existence of micro clearance between the glass plate and the sheet workpiece. The flushing effect of bubble on debris exhaustion has been confirmed.

5 BEHAVIOR OF BUBBLE IN GAP AREA

In project 2, the bubble behavior in gap area was observed. The sheet workpiece was glued together with the glass plates by a transparent resin adhesive. Since the melting point of adhesive is much lower than that of the SiC and stainless steel SUS304 workpiece, the adhesive film was much easier to be removed during discharging. Therefore, the gap area was a bit larger than that in actual blind hole drilling.

![Image](image_url)

The phenomenon can be observed in the case of using the stainless steel SUS304 as shown in Fig. 8 (a). During the observation, the strong light was irradiated on the machining area so that the adhesive film cannot be observed on the SiC sheet because of its transparency, as shown in Fig. 8 (b).

![Image](image_url)

(a) Stainless steel SUS304  (b) SiC

Fig. 8 State of machining area in project 2

In the discharge process, massive bubbles were generated in the gap area. With the increase of hole depth, since bubbles cannot escape from the gap area immediately, they grow up or merge with other bubbles to become a larger bubble. One example is shown in Fig. 9 that two bubbles in Fig. 9 (a) merged together to become a big bubble in Fig. 9 (b).

![Image](image_url)

(a) t  (b) t+0.2011s

Fig. 9 Merging of two bubbles

(t, a certain machining time; Feed depth: 1117μm)

Moreover, the accumulation of bubble leads to the increase in bubble occupancy area and the decrease in the area of dielectric liquid and debris in the limited gap area, resulting in the concentration of debris. In Fig. 10, the states of gap area in different hole depths were shown. Since only a part of the gap area was observed, and the observation result might not reflect the bubble state in the whole gap area. However, the result definitely shows that the bubble occupancy area becomes larger with increase of hole depth.

![Image](image_url)

(a) Feed depth: 500μm  (b) Feed depth: 1149μm

Fig. 10 Bubble occupancy area
In Fig. 10 (a), since the hole depth is shallow, bubble escapes from the gap area quickly. However, in Fig. 10 (b), the deeper hole depth leads to the increase of path length resulting in bubble needs much more time to go through the path. On the other hand, the surface tension and viscosity resistance are also influenced by the hole depth. Therefore, the bubble escaping speed becomes lower than the bubble generation speed so that many bubbles accumulate in the gap area and merge together to become a larger bubble.

6 DISCHARGE CHARACTERISTICS IN DIFFERENT HOLE DEPTHS

With the increase of hole depth, the environment of gap area deteriorates significantly because of debris accumulation and tool wear. These elements change the insulation strength of gap area and leads to the non-uniform gap width. The moving conductive debris in gap area causes random discharges. These suppositions have never been confirmed by direct observation. In this part, discharge characteristics were analyzed based on the observation with the high-speed camera.

The images of machining area in project 1 and 2 are shown in Fig. 11 and 12, respectively. The images in project 1 showed that massive debris accumulated in the clearance of both stainless steel and SiC sheet, which indicates that massive debris are generated in micro EDM. In project 2, due to the debris accumulation and the shelter of the micro tool, the gap area is not very clear. Even so, massive debris was also found in the gap area.

The accumulation of debris decreased the insulation strength of gap area significantly. It makes the discharge occurs more frequently and easily. Compared to the discharge in the beginning of machining (Fig. 13 (a) and 14 (a)), more discharges occurred in the larger area in Fig. 14 (b). In addition, the weakened insulation strength of dielectric liquid makes the electric bridge was easier to be built. When massive debris existed in gap area, it can be polarized by cathode and anode respectively to result in the discharge occurred in debris. As shown in Fig. 13 (b), the discharge even occurs in debris in stainless steel SUS304.

Moreover, the debris behavior leads to the changing gap width. Once the debris moves, forced by the bubble flushing and tool rotation, the insulation strength of gap area also changes. These phenomena cause a decrease in the machining accuracy and speed.

7. CONCLUSIONS

In this paper, the inter-electrode area in micro-hole drilling with EDM was observed directly from the side wall by a high-speed camera and using an originally designed sandwich workpiece. The flushing effect of bubble on debris has been confirmed. The bubble behavior and discharge characteristic in different hole depths have been analyzed. The following conclusions are drawn:

(1) In micro-hole drilling, bubble flushing has dominated influence on debris exhaustion.

(2) With the increase of hole depth, the bubble grows
up or merge with other bubbles to become a big bubble, and the bubble occupancy area also increases resulting in the debris concentration.

(3) In deeper hole depth (Feed depth is larger than 972μm in stainless steel SUS304 in this paper), massive debris accumulated in the gap area.

(4) The debris accumulation leads to frequent short circuits and discharges in larger area. The discharge can even occur in debris.

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