Effects of Thin Pipe Electrodes with Grooves in Small Deep Hole EDM

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Abstract

Small hole electrical discharge machining (EDM) typically uses brass or copper pipe electrodes of diameter 0.2–3 mm for machining. However, it has been empirically proven that in high aspect ratio machining, machining speed decreases because of deterioration in the discharge state, which is attributed to insufficient removal of machining debris. This study investigates the usage of straight grooves electrodes in small hole EDM to improve removal of debris and thereby enhance discharge performance during deep hole machining using a commercial small hole EDM machine. Machining experiments were conducted to compare the performance of EDM with normal pipe electrodes and straight grooves electrodes. The electrode was tested for diameters 1 and 3 mm. As a result, the machining of 125 mm height stainless steel using the normal pipe electrode was slower than the case of straight grooves electrode.

Key words: EDM, small deep hole machining, grooves electrode, machining speed, discharge state

1. INTRODUCTION

Electrical discharge machining (EDM), which excels at precision machining of high-hardness materials, is broadly divided into die-sinking EDM and wire EDM. In recent years, EDM has been increasingly used in micro-machining applications because of its non-contact machining ability [1,2]. One of the most widely used applications is the small hole EDM. The small hole EDM typically uses brass pipe electrodes of diameter 0.2–3 mm for machining. Specialized machines that use pipe electrodes to dispense machining fluid through the center of the electrode are commercially available from various companies. Some examples of small hole EDM are machining array of holes for jet engines cooling which is made of difficult-to-cut materials, and deep hole machining for mold cooling.

Various researches have also been reported on small hole EDM, including inner diameter finishing and bent holes [3,4]. In general, however, there are many straight small deep hole machining applications that use pipe electrodes. Straight small hole EDM injects the machining fluid through a brass or copper pipe electrode and removes debris during machining. It has been empirically shown that in deep and small hole machining, machining speed and discharge performance decrease because of insufficient removal of debris at pace with the machining speed. Several studies have been reported to cope with this. One is a device for electrode jump operation [5,6,7]. Furthermore, ultrasonic vibration combined with EDM can improve machining efficiency [8,9]. Some experiments have shown that in micro-hole EDM that uses electrodes with diameter of several hundreds of mm or less, machining speed improves when grooves are drilled into the electrode [10,11]. The machining of these micro holes are often machined after forming the electrodes by WEDG method developed by Prof. Masuzawa. In this case, the pipe electrode is not used because it is molded from the rod shape electrode. Plaza et al. have shown the effectiveness of helical electrodes in micro EDM-drilling of Ti6Al4V [12]. The electrode diameter was 300–800 μm, and the aspect ratio of the machining depth was equal to or less than 10:1. Wang et al. also showed the effect of helical electrodes in micro-EDM on Ti6Al4V [13]. The electrode diameter was 200 μm, the titanium plate thickness was 400 μm, and the aspect ratio was 2:1. The results of the die-sinking EDM with regard to the effect of the electrode shape are presented in [14]. A bottom hole of diameter 30 mm was machined with a 14 mm diameter electrode. In this machining, the EDM characteristics were compared with respect to the various shapes of the tip of the electrode. However, none of the aforementioned studies used pipe electrodes. Therefore, there was no ejection of machining fluid from the center of the electrode. It is thought that the change in electrode shape had a remarkable influence because there was no effect of the machining fluid ejection.

In contrast, this study focuses on small deep hole EDM with pipe electrodes using a commercially available small hole EDM machine. In normal small hole EDM, machining debris is flushed by the dispensing machining fluid through the center of the round pipe electrode. In this study, the straight grooves electrode made by machining a normal pipe electrode was applied on small hole EDM. It was also investigated whether the electrode groove shape would be effective for small deep hole EDM.
when the machining fluid was ejected. In addition, the aspect ratio examined in this paper is very large (40:1 to 125:1). This was used for improving the removal of debris, and the effect on machining speed was verified. Until now, no research has been reported from this perspective. The small hole EDM experiments were conducted by using normal electrode and straight grooves electrode, and their effect was confirmed on the machining speed. Moreover, the effect of straight grooves electrode on the removal of debris was evaluated by analyzing discharge states during machining. Initially, an electrode with a diameter of 3 mm was used, and finally an electrode with a diameter of 1 mm was also confirmed.

2. STRAIGHT GROOVES FORMING METHOD

Straight grooves electrodes were made by cutting grooves on standard brass pipe electrodes. High-speed steel was used for the die for drawing cutting, and it was made by wire EDM. Fig. 1 shows the machined drawing cutting die and its blade. The metal die is 20 mm in diameter with a die shaped design at the center of the die. The metal die thickness is 10 mm; however, to prevent deformation of the electrode, only the die blade portion was machined to 3 mm height. The cutting method is shown in Fig. 2. The metal die was set on a standard lathe chuck; the brass pipe electrode (3 mm in diameter, 400 mm in length, and 0.5 mm in wall thickness) with a thin tip penetrated the mold, and it was fixed to the tool holder. Further, the bite holder was moved in the opposite direction to the chuck and the pipe electrode was pulled to form a groove. At this time, the lathe chuck remained fixed, and thus a straight groove was formed. The rotation of the chuck during pulling results in a spiral groove electrode whose results will be shown section 3.3. Three straight grooves at a target depth of 0.25 mm (actual depth measured at 0.22 mm on average) were cut over a length of 300 mm by this method. There were several concerns related to the bending of the electrode due to drawing. Therefore, only the grooved electrode with straightness of 0.2 mm or less was used for small hole EDM. This result was confirmed by installing the electrodes on the surface plate and preventing the 0.3 mm thickness gauge from entering the gap. In addition, a normal pipe electrode with the same value was used.

3. MACHINING RESULT OF ELECTRODE DIAMETER 3 MM

3.1 Change in main axis position during machining time

Small hole EDM experiments were conducted using a small hole EDM machine (ASTEC Co., Ltd.; A22M). Stainless steel work pieces (AISI 304) with a height of 125 mm were used for the workpiece. Two types of electrodes were used for machining, normal brass pipe electrodes, and brass pipe electrodes with straight grooves shown in Fig. 3. It can be seen that the grooves depth is different in the grooved electrode. This phenomenon occurs because the center of the cutting mold and the center of the electrode are displaced. It was observed that even after several attempts, it never became uniform. Therefore, variable groove depths were used. Due to the imbalance, there were concerns about eccentricity during rotation, but no large vibration was recorded compared to the normal electrode. Discharge conditions are shown.

Fig. 2. Grooves forming technique using a general-purpose lathe.

Fig. 3. Cross section photo of each φ 3 mm electrode.
Table 1 Machining conditions.

|                  | Condition 1 | Condition 2 |
|------------------|-------------|-------------|
| Electrode diameter | \( \phi 3.0 \) | \( \phi 1.0 \) |
| Discharge current  | 8.0 A       | 4.0 A       |
| Pulse duration    | 150 \( \mu \)s | 20 \( \mu \)s |
| Off time          | 10 \( \mu \)s | 20 \( \mu \)s |
| Electrode rotation| 200 rpm     | 200 rpm     |
| Capacitor         | OFF         | ON          |
| Fluid pump pressure | 1.0 MPa     | 5.0 MPa     |

![Grooves electrode Normal electrode](image)

Fig. 4. Photograph of entrance side machining hole.

In condition 1 in Table 1. The discharge circuit is mainly a transistor discharge circuit. Furthermore, it is possible to add a capacitor under the condition that the pulse width is short. Therefore, a capacitor is added under condition 2. The electrode rotation speed of 200 rpm is the highest setting value of the EDM machine. Fig. 4 shows a photograph of the hole on the entrance side using both electrodes. Both these electrodes have a diameter of 3.1 mm or less, and it is not possible to confirm the tendency of the grooved electrode to expand due to vibration. It is also necessary to study the accuracy of machined holes that included the straightness. However, in this paper, we focused on the difference in machining speed depending on the presence or absence of grooves. Therefore, the comparison is limited to the appearance of machined holes.

Note that the discharge circuit of the machine is a non-isopulse type. Therefore, depending on the distance between the electrodes and workpiece, the pulse duration may be shorter than the setting. In addition, the main axis is fed back by means of average gap voltage control. The conditions used were selected in consideration of the conditions that cause machining instability in normal brass pipe electrodes. Under the recommended machining conditions for steel workpiece with an electrode diameter of 3 mm, the fluid pump pressure is equal to or greater than 3.0 MPa.

It was proved that the machining speed does not decrease under such conditions. The results under these conditions were the same as that of the grooved electrode shown in Fig. 5. Because the inner diameter of the 3 mm electrode and flow rate are large, it is assumed that the machining debris is sufficiently removed. However, first, to confirm the effect of the grooved pipe electrode, the condition that makes the normal pipe electrode unstable was selected. Therefore, the injection pressure of the machining fluid was set to a low pressure of 1.0 MPa. In this setting, only the pump protrusion pressure is changed. It is inferred that the injection pressure from the electrode tip during EDM is different. However, because it was difficult to measure the value directly, the amount of machining fluid emission was compared. The machining fluid emission during the entire machining time was collected and the amount emission per minute was measured. As a result, the normal pipe electrode was 276 ml/min and the grooved electrode was 256 ml/min, and there was no significant difference.

In this situation, small hole EDM was performed until the through hole was machined. The machining time and main axis feed were measured. Here, the main axis feed value indicates the sum of machining depth and electrode wear length. Therefore, it is difficult to evaluate the real-time machining depth. However, because the electrode wear rate can be determined after machining, it is possible to predict the change in machining depth. The main axis feed as a function of machining time is shown in Fig. 5. Data sampling was carried out at 1-minute intervals. For normal pipe electrode machining, the machining time increased (i.e., machining speed decreased) as the main axis feed increased. The machining speed decreased from the point where the main axis feed exceeded 100 mm,
Fig. 6. Change in main axis position moved from 45°00" to 45°10" by normal pipe electrode.

Fig. 7. Change in main axis position moved from 45°00" to 45°10" by grooves electrode.

and it took 120 min to penetrate the hole. This is a well-known phenomenon in the machining of small hole EDM, which is attributed to inadequate removal of machining debris, resulting in deterioration of the discharge [15]. In contrast, for straight grooves electrode machining, the stainless steel workpiece was pierced through without a decline in machining speed even when the main axis feed exceeded 100 mm. Total machining time was about 50 min. However, when the main axis feed was 80 mm or less, the machining speed was the same for both normal and straight grooves electrodes. Therefore, a comparison was made between the discharge state of both electrodes in the early and late machining.

The difference between both the experiments was examined at smaller time intervals. The machining time is indicated by the ellipse in Fig. 5. The behavior of the main axis was observed for 10 s after 45 min. The data interval in Fig. 5 was 1 min, but it was further examined at 33 ms intervals. Fig. 6 shows the main axis behavior of the normal electrode, and Fig. 7 shows that of the grooved electrode. From Fig. 6, the normal pipe electrode repeats the up-and-down movement roughly for about 100 to 150 mm, whereas for a grooved electrode, an electrode lifting of about 50 mm can be observed, but the main axis descent continues almost stably. A similar observation was made about 10 min after the start of machining. As a result, a stable main axis descent was observed in both electrodes as well. From this result, it can be inferred that there is no difference in the main axis behavior between the two electrodes for a shallow machining depth. However, as the machining depth increases, the movement of the main axis with respect to the normal pipe electrode changes, and the machining speed decreases, but with the straight grooved electrode, such behavior does not occur and the machining occurs in a stable manner. Therefore, the measurement of the main axis displacement was made until the injection of machining fluid was confirmed from the lower surface of the workpiece. As a result, the hole on the bottom of the workpiece is not completely machined. Therefore, the straightness of the 125 mm drilled hole could not be measured.

3.2 Analysis of the discharge waveform

As discussed above, in the normal electrode machining of stainless steel, the machining speed decreased when the main axis feed reached a certain depth. It is believed that the discharge state becomes unstable due to the volume of unremoved debris in the deep machining region. In contrast, because machining speed did not decrease for the electrode straight grooves, it can be inferred that a stable discharge state was maintained even at a greater machining depth. To verify these results, discharge waveforms during machining of stainless steel with normal and straight grooves electrodes were recorded and analyzed using an oscilloscope (LeCroy WaveSurfer 424). The current sensor is a Pearson model 110. Fig. 8 is an example of a recorded discharge waveform. The discharge occurs continuously under the set discharge condition 1 without any delay. A state classification based on
discharge waveform is performed for a long time [16]. This is further used for adaptive control of the main axis by grasping the discharge state [17,18,19]. Further, it is also used for fuzzy control [20,21]. In this paper, the state classification was carried out for the purpose of understanding the discharge state. The discharge waveform was acquired as follows. The oscilloscope recorded both the discharge voltage and current waveforms for 5 ms duration at every 3 s interval. Waveforms classification was performed for 5 min after the main axis reached 70 mm. At this instant, the machining speed did not decline. Further, this classification was done for 5 min after reaching 120 mm. At this instant, the machining speed decreased with the normal pipe electrodes. The total number of discharge waveforms observed was 2850. Waveforms were classified into five discharge waveforms as shown in Fig. 9. The waveforms in the figure are schematically shown only for explaining the five states. The normal discharge waveform has a time duration of 150 $\mu$s, and it is usually preferred. The second waveform, which is the ignition delayed, has a shorter discharge duration time because of ignition delay time. This occurs due to the presence of a non-isopulse circuit. No discharge occurs in the open circuit. The short circuit waveform indicates a short circuit between the electrode and the workpiece. The “Other” waveform was observed when both short circuit and discharge occurred.

Fig. 10 and Fig. 11 show the results of classification of discharge waveforms. Fig. 10 shows the results that are observed for 5 min when the main axis reached 70 mm and Fig. 11 shows the results of data that were observed for 5 min after the main axis reached 120 mm. In Fig. 10, there are no significant differences in the number of normal discharges between normal and grooves electrodes. As can be seen from Fig. 5, this can be deemed appropriate because the machining speed is the same. On the contrary, in the region where the main axis feed was large, the normal discharge frequency decreased and open state frequency increased when the normal electrode was used as shown in Fig. 11. However, the number of normal discharges did not decrease on straight grooves electrode data as compared with Fig. 7. From these results, it can be inferred that as the machining depth increases, the machining speed of the normal electrode decreases because the number of normal discharges was reduced. It was observed that the main axis was repeatedly pulled in a region where the machining speed declined. This phenomenon occurs when the discharge state becomes unstable, and it is the cause behind the frequent open waveform. In other words, it can be inferred that the discharge becomes unstable because the removal of debris was stagnant. The main axis is pulled up in machining, as conventionally shown. Conversely, in the case of straight grooves electrode, the discharge state was stable even when the machining speed increased. This result shows that the removal of debris was favorable, and the discharge state remains stable during the machining, including the deep region.
3.3 Results for spiral grooves 3 mm electrode

The results of straight grooves are shown in section 2. The spiral grooves are expected to witness a higher debris discharging effect, which is similar to a drill shape. Therefore, we attempted to form a spiral groove using a lathe as in Section 2. In the case of spiral grooves, a mold was made with two grooves at a depth of 0.25 mm. When the mold was fixed to the lathe spindle and the pipe electrode was pulled out, the spindle rotated slowly. Although the torsion interval is not exactly accurate, one rotation was observed at 270 mm. The small hole EDM was performed in a similar manner shown in Fig. 5, and the change in the main axis descent amount over time was examined. Fig. 12 shows the results when the spiral grooves were added to Fig. 5. However, to study the grooving results, a machining time of up to 60 min was considered. From the figure, the effect of the grooves can be confirmed without any reduction in the machining speed in the region where the machining depth is large even in the spiral grooves. In addition, the same result is obtained even if the rotation direction of the electrode is reversed. However, the result was similar to the one with straight grooves. It was also confirmed that the addition of straight grooves or spiral grooves on the outer periphery of the pipe electrode can improve the machining speed in deep hole electric discharge machining. In addition, the wear ratio of each electrode was as follows. It was 31% for normal pipe electrodes, 26% for straight grooves, and 28% for spiral grooves. The high consumption ratio of normal pipe electrodes is due to the long total machining time. From these values, it can be inferred that there is no significant difference in the electrode wear ratio due to the electrode cross-sectional shape.

4. MACHINING RESULT OF ELECTRODE DIAMETER 1 MM

A similar machining to the one in the previous section was performed with an electrode of diameter 1 mm. The workpiece used is stainless steel (AISI 304) with a height of 125 mm. Condition 2 from Table 1 was used. Condition 2 is recommended for steel with electrode diameters of 1 mm. Unlike condition 1, the pump pressure is set to a maximum value of 5.0 MPa. The straight grooves electrode was cut with a die, similar to the one in section 2. The cutting die used here was specifically designed for a diameter of 1 mm. Fig. 13 shows a cross-sectional photograph of a normal electrode and a straight grooves electrode. The grooves depth was set at about 0.2 mm. Although the grooves depth was shallow, there was a difference from normal electrodes in actual machining. As with the diameter of 3 mm, the straightness is equivalent to that of a normal pipe electrode. In addition, the grooved electrode did not vibrate during machining. The main axis feed as a function of machining time is shown in Fig. 14. With normal electrodes, the machining speed decreased from the main axis feed exceeded 180 mm. The phenomenon that the machining speed decreases with the normal electrode is the same as in the case with an electrode diameter of 3 mm. On
the other hand, for the electrode straight grooves, the machining speed did not decrease, and it was completed in about 30 min. Although the depth of the grooves was shallow, there was a clear difference in the machining results. The electrode wear ratio was 73 % and 63 % for normal pipe electrode and straight grooves electrode, respectively. It is assumed that the large consumption ratio of the normal pipe electrode is due to the long machining time, same as the 3 mm electrode.

The classification of the discharge state was performed in a similar way to the one in the previous section. The discharge waveform was recorded for 5 min from the main axis feed of 40 and 180 mm. Unlike in the results of the case with the 3 mm electrode, the sampling frequency is increased. This is because the discharge pulse width is 20 μs. Therefore, the oscilloscope recorded both discharge voltage and current waveforms for 1 ms at an interval of 3 s. The total number of observed discharge waveforms was 2400.

The classification of both discharge states is shown in Fig. 15 and 16. In Fig. 14 where the machining depth is shallow and the machining speed is almost the same, there is no significant difference between the results of the normal and the straight grooves electrode. Because the number of normal discharges is almost the same, the machining speed is the same. On the other hand, in Fig. 16 where the machining depth increases, the number of normal discharges in the normal electrode reduces. However, the straight grooves electrode does not change when the machining depth is shallow. As in the previous section, it is surmised that the discharge was stable because of the ejection of machining. The effect of the straight grooves was confirmed even with a 1 mm diameter electrode.

5. CONCLUSIONS

For a stainless steel workpiece height of 125 mm, small hole EDM with electrodes of diameter 1 and 3 mm were used. The effect of straight grooves electrode on machining speed and stabilizing discharge state was observed, and the following inferences were made.

1) A straight grooves could be formed on the outer periphery of the pipe electrode by the drawing-cutting method.

2) There was a region where the machining speed declined when the normal pipe electrode was used. However, the reduction of the machining speed could be suppressed in machining of electrodes with straight grooves.

3) From the detailed observation of the main axis displacement, the normal pipe electrode was usually greatly displaced in an upward and downward direction in the region where the machining depth was low.

4) In the discharge waveform analysis, it was observed that the electrode with straight grooves had a larger number of normal discharges as compared to the normal electrode in the region where the machining depth was more. It is assumed that the machining debris was removed for the electrode with grooves.

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