Effect of Insulating Si₃N₄ Ceramics on Removal Rate by EDM with Piezoelectric Device

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Abstract

This paper describes the machining characteristics of insulating ceramics by EDM (electrical discharge machining) with a piezoelectric device. A piezo scanner that can carry out drive control independently in the X-, Y-, and Z-directions was used for the piezoelectric device. Using the Z-axis as the main axis, dual servo control with a motor drive was applied, with oscillation in the X- and Y-axes, and the effects of these oscillations were examined. In addition to adding these controls to the piezo scanner, the removal rate was considerably improved by independently controlling the gain of the up-and-down motion based on the electrical discharge state of the high-resistance surface. Furthermore, to transmit rotation to the oscillation tool electrode, a magnetic non-contact transfer drive was utilized. Using this combination of controls, we effectively improved the removal rate in micro-hole machining.

Key words: EDM, Insulating ceramics, Piezo scanner, Non-contact transfer drive

1. INTRODUCTION

For EDM (electrical discharge machining) of insulating ceramics, an assisting electrode method was proposed and has been developed by Fukuzawa et al. [1, 2]. Figure 1 shows the machining process for insulating ceramics using the assisting electrode method. The surface of the insulating ceramic is covered by an electrically conductive layer; this layer is called the assisting electrode. In this machining process, surface modification occurs continuously on the workpiece surface. As this surface layer is electrically conductive, continuous discharge phenomena can occur on the EDMed surface.

A long pulse discharge is usually observed in the case of EDM on high-resistivity materials. This long pulse discharge occurs because the real discharge voltage is higher than the threshold level. Therefore, discharge breakdown cannot be detected using the typical settled threshold level. Figure 2 shows the continuous discharge waveform in the EDM of insulating ceramics. A normal discharge and a long pulse discharge occur by turns. Although the duty factor is set at a low value in this experiment, the observed duty factor increases significantly, owing to the generation of this long pulse discharge. In addition, Si₃N₄ ceramics are a low thermal conductivity material; therefore, the discharge point is difficult to cool. For these reasons, it is very difficult to maintain stable machining conditions.

In this study, to stabilize the electrical discharge state in the insulating ceramic, an electrical discharge machine with an installed piezoelectric drive mechanism was utilized. The piezoelectric scanner (used as the scanning probe in an atomic force microscope) was employed for the piezoelectric device. The scanner was designed to be capable of independent control in the X-, Y-, and Z-directions. Using this device, the removal rate was considerably improved by independently controlling the gain of the up-and-down motion based on the electrical discharge state of the high-resistance surface.
microscope) was used for the piezoelectric drive. The tool electrode was driven in all 3 axes using this device. In the Z-axis, the effect of dual servo control with one main axis was examined. To expel the debris from the gap, oscillation was induced in the X- and Y-axes. Moreover, Z-axis control was applied to compensate for the occurrence of long pulse discharge. In addition, the rotation mechanism used for the tool electrode was a non-contact transfer drive in this system; its effects were also examined.

2. EXPERIMENTAL SETUP

The structure of a piezo scanner is shown in Figure 3. Two sets of electrodes are located on the outside upper part of a cylindrical piezoelectric material; the scanner can be driven in the ±X- and ±Y-directions by applying a voltage to these electrodes. Moreover, the electrode for driving in the Z-direction is located on the outside lower part, and the cylindrical inner portion is the GND. Each of these axes can be driven independently.

A diagram of our electrical discharge machine with an installed piezo scanner is shown in Figure 4. In the Z-axis, a dual servo mechanism incorporating a high-response drive for the piezo scanner was constructed. The range of the drive in the Z-axis of the piezo scanner is 15 µm. With this equipment setup, an tool electrode can be oscillated in the X-Y plane in a range of approximately 100 µm. The tool electrode was attached to the tip of the piezo scanner, using a synthetic resin material for insulation.

3. MACHINING WITH PIEZO SCANNER DRIVE

3.1 Effect of dual servomechanism

Under the machining conditions listed in Table 1, the displacement of the tool electrode during the machining of insulating Si3N4 ceramics by the normal and the dual servomechanism is shown in Figure 5. In the dual servomechanism case, the up-and-down motion of the tool electrode decreased relative to the normal servo case, and the processing condition was stabilized. However, when these conditions were compared in terms of the removal rate, as shown in Figure 6, the case of the dual servomechanism showed a significantly lower removal rate. The observed results for the machining surface are also shown in this figure.

Table 1 Machining conditions

<table>
<thead>
<tr>
<th>Tool electrode</th>
<th>Cu (ϕ3mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
<td>Si3N4</td>
</tr>
<tr>
<td>Electrode polarity</td>
<td>negative</td>
</tr>
<tr>
<td>Discharge current</td>
<td>2A</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>8µs</td>
</tr>
<tr>
<td>Pulse interval</td>
<td>64µs</td>
</tr>
<tr>
<td>Open Voltage</td>
<td>110V</td>
</tr>
</tbody>
</table>

![Fig.3 Structure of piezo tube](image)

![Fig.4 EDM system with piezo tube](image)

![Fig.5 Comparison of the displacement of tool electrode for each servo system](image)
Deposited material was observed near the machined hole’s center. The presence of this deposited material caused a decrease in the removal rate. Formation of this deposited material is worthy of consideration, because debris is hard to eliminate when the gap was stabilized so as to vary narrowly. Furthermore, by generating long pulse discharges in this state, the actual duty factor becomes high and discharge concentration appears to have been induced. Significant discharge concentration was observed immediately after the generation of a long pulse discharge.

3.2 Effect of the oscillation in the X- and Y-directions

The oscillation on the X- and Y-axes, which can eliminate debris from the gap and distribute the electrical discharge, was applied to the tool electrode. The frequency and the phase of the sine wave that are inputted into the X electrode and the Y electrode of the piezo scanner were adjusted to produce two types of oscillation patterns, (a) and (b), shown in Figure 7. The removal rates for the total amplitude of oscillations of 20, 40, and 60 µm of the tool electrode are shown in Figure 8. This figure shows that at a total amplitude of 0 µm, there is no oscillation. The position in the Z-axis was controlled using the dual servomechanism. Results for the normal servomechanism for pattern (b) are also shown in the figure for comparison. Oscillation patterns (a) and (b) showed improved removal rates with an increasing amplitude. The removal rate improved using this method, particularly for oscillation pattern (b). With regard to the formation of the deposited material, the resultant total amplitude of oscillation was not observed at 40 µm or more. We believe that the elimination of debris from the gap and the distribution of electrical discharge occurred. Moreover, in the region in which the total amplitude of the oscillation was comparatively large, the dual servomechanism yielded a high removal rate. When the deposited material is not formed, the dual servomechanism also effectively improves the removal rate. The removal rate can be improved by choosing a suitable oscillation pattern and amplitude based on the above results.

3.3 Control based on the high resistance case

The gap voltage, average voltage, and displacement of the tool electrode during the EDM of an insulating ceramic are shown in Figure 9. As mentioned above, a long pulse discharge occurs in the machining of the insulating ceramics. The discharge voltage of a long pulse discharge is approximately 50 V, which is higher than the servo reference voltage. For this reason, during the long pulse electric discharge, the tool electrode is set to allow motion in the descending direction. Using such a motion, it is thought that discharge
concentration and a short circuit state occur. Moreover, because the machining surface has a resistance, a high voltage is generated in the short circuit state. Therefore, the movement of raising the tool electrode is not fully performed.

In this section, the servo gains upward and downward in the Z-axis were adjusted independently, and stabilization of the machining was attempted. The downward gain was initially set low so as to decrease the amount of descent in the Z-axis during long pulse discharge generation. On the other hand, the upward gain was considerably increased to fully withdraw the tool electrode when in the short circuit state on a high-resistance surface. Our results are shown in Figure 10. In addition, the servo gain 1 is 0.15 μm/V, it has a given total amplitude of 60 μm, and it uses the oscillation pattern (b) in the X- and Y-axis directions. When an upward gain was set to 1.5 and the downward gain was set to 0.75, the removal rate improved by approximately 1.2 times. Therefore, adjustment of the independent upward and downward gains can improve the removal rate.

4. EFFECT OF A ROTATING ELECTRODE

4.1 Tool Electrode rotation by non-contact transfer drive

It is known experientially that the rotation of the tool electrode has an effect on the stability of electrical discharge machining. Because the wire connection to the piezo scanner is carried out to the driver for exclusive use, one cannot rotate the piezo scanner itself. Therefore, a non-contact transfer drive using a magnetic gear was used to rotate the tool electrode. The experimental setup of the tool electrode component is shown in Figure 11. The rotation of the motor was transmitted to tool electrode by a magnetic gear, which is made of N- and S-pole magnetizations along the circumference. Using this mechanism, even if the piezo scanner oscillates, rotation can be transmitted to the tool electrodes. The relation between the transfer
distance and the oscillation state of the tool electrodes is shown in Figure 12. When the transfer distance is short, the gear is attracted to a driving wheel. By selecting a moderate transfer distance, one can achieve oscillation that maintains the center of oscillation.

4.2 Machining characteristics with tool electrode rotation

The removal rates with 100 rpm tool electrode rotation and using the piezo scanner drive are shown in Figure 13. Even if the non-contact transfer drive is used, the tool electrode was able to rotate during electrical discharge machining, and the removal rate improved. By combining the drive control of the piezo scanner with rotation, approximately 3 times the removal rate was obtained, relative to the conventional method.

The displacement of the tool electrode during hole machining using an electrode with a diameter of \( \phi 1 \) mm is shown in Figure 14. Additionally, in micro-electrical discharge machining, the piezo scanner can be effectively controlled; this effectiveness can be increased by rotating the tool electrode. However, it is necessary to examine the machining hole shape accompanying oscillation in the X- and Y-directions.

5. CONCLUSIONS

The machining characteristics of insulating ceramics by EDM with a piezoelectric device were investigated. The results obtained are as follows:

1. Under the conditions in which no deposited material is formed, the dual servomechanism was effectively able to improve the removal rate.

2. A deposited material is not formed by oscillations of moderate amplitude in the X- and Y-directions. Furthermore, the removal rate improved by adding gain control based on the electrical discharge state on the high-resistance surface.

3. Rotation of the tool electrode was performed by a non-contact transfer drive using a magnetic gear. Even though the device used a non-contact transfer drive, the tool electrode rotated during electrical discharge machining, and the removal rate improved by approximately 3 times in the piezo scanner drive control condition.

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REFERENCE
