Synchronized Observation of Machining Phenomena and Discharge Waveform in EDM of Transparent Insulator
-Clarification of Machining Mechanism and Improvement of Machined Shape Accuracy-

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Abstract

The assisting electrode method has enabled the EDM of insulating materials. However, there is a need to change the machining conditions, otherwise the stability of EDM drops. To solve this problem, it is important to clarify the mechanism of EDM for insulating materials. We built a measurement system that enables the synchronized observation of machining phenomena and the discharge waveform. The observation clarified the two facts. The main role of a long pulse discharge is to form a conductive layer on the workpiece surface. Machining of the insulating material progresses with the concentration of normal discharge in the same area after a long pulse discharge. But, when the amount of pyrolytic carbon is large, the machining accuracy will deteriorate due to concentration of the discharge generated. Thus, the discharge conditions were changed according to the amount of pyrolytic carbon generated, resulting in the improvement of the machined shape accuracy.

Key words: EDM, assisting electrode method, silica glass, long pulse discharge, EDMed shape improved

1. INTRODUCTION

The development of the EDM assisting electrode method by Fukuzawa et al. has realized the EDM for insulation materials 1)2) and today it is being applied for machining various insulation materials 3)4). With this method, EDM machining is carried out by repeatedly forming conductive layer made up mainly of carbon on the machined surface of insulation materials from the heat of the arc generated during EDM and removing this layer 4). However, the mechanism of this process has yet to be clarified. For this reason, details of the mechanism by which conductive layer forms and conductive layer thickness appropriate for the EDM of insulation materials are unknown, and this lack of information makes it difficult to select stable EDM conditions. This is one of the reasons why the EDM of insulation using the assisting electrode has not spread that widely. With this method, unlike normal EDM machining, long pulse discharge is generated, and each discharge lasts several times to several tens of times longer than the set time. Goto et al. 7) explain that long pulse discharge contributes to the formation of conductive layers, but this is merely a guess. It is therefore important to directly observe the machining phenomena occurring during long pulse discharge and clarify the mechanism of how conductive layers form. In this study, the authors built a system capable of carrying out EDM on insulating silica glass, videoing the machining phenomenon from the side of the silica glass with a high-speed camera, and observing the discharge waveform using an oscilloscope all at the same time. This paper discusses the results of synchronously observing the arbitrary discharge waveform and the machining phenomenon between the electrodes, and reports on the results of attempting to improve the machined shape accuracy in the EDM of insulators.

2. EXPERIMENT METHOD

2.1 Experiment System

Fig.1 shows an outline of the experiment system. A small transistor power EDM machine for insulator materials was used (Special Electrical Machining Engineering Co., Ltd.). To observe EDM phenomena between the electrodes, a high speed camera (Photron, FAST CAM SA-5), high magnification rate lens (×40, Photron, L-X003), and high luminance lighting (SUMITA, LS-M210) were used. In addition to observe the EDM waveform, an oscilloscope was used (LeCroy, Wavepro 7Zi), and to measure the current by the current transformer (Pearson Electronics, MODEL 110/0.1) was used. For the workpiece, silica glass dimensions 10 mm (thickness) ×50 mm (width) ×10 mm (depth) was used. The surface of the side of the silica glass at which EDM is started was made conductive using copper. Table 1 shows the machining conditions. The silica glass workpiece was taken as the anode and a φ1.0 mm copper rod was used as the cathode and rotated at 60 rpm. For the machining liquid, VITOL2 (Sodick) was used. Table 2 shows the layering conditions of the high speed camera. Under these conditions, about 1.85 s images were recorded with the camera. The shutter
speed was set to 10 μs based on the discharge duration and pause time so that the amount of required image light can be secured and the image and discharge waveform for each discharge can be synchronized. This enables normal discharge to be differentiated from discharge above pulse duration of 20 μs on the images. The depth of field of the lens used this time was about 0.3 mm. As shown in Fig. 2(a), this figure is a side cross-sectional. Therefore, the conductive film formed on the EDM surface is not drawn, so it is not blackened. The focus was adjusted to the middle front of the workpiece. As shown in Fig. 2 (b), the observation example from the high-speed camera side consists of the machining area removed by EDM and the part where the silica glass transmits light.

The black part indicates that it is covered with a conductive film. The broken line represents the tool electrode part. In the EDM of insulating materials, more carbon is generated than in normal EDM, and a large amount of such as machining chips float in the machining liquid. Since normal circulation systems cannot sufficiently remove machining chips and therefore affects stable machining and videoing, an electric static cleaning device was used to circulate the machining liquid (KLEENTEK, EDC-R3P). To realize clarity of images, the surfaces of the workpiece silica glass were polished using a lapping machine, and the silica glass was contacted to the transparent acrylic machining tank during videoing.

2.2 Synchronization of Images between Electrodes and Discharge Waveform

Fig. 3 shows the outline of the operations of the synchronous observation system composed of a high-speed camera, PC for controlling the high-speed camera, and oscilloscope. Each observation step ① to ⑤ in the figure is described in the following. ① The discharge waveform, high speed camera images, and state during EDM were observed using the naked eye. ② The high speed camera shutter signals for control PC were input manually at the timing at the generation of EDM phenomena was confirmed in the layered area. ③ The high-speed camera inputting shutter signals was stopped at this point. ④ Trigger was output from the high speed camera at the timing at which videoing ends. ⑤ The trigger signal output from the high speed camera was input to the oscilloscope to record the discharge waveform data until the input of the trigger signal for confirming the reception of the shooting end signal output from the high-speed camera. This enables the synchronized recording of the images of the EDM.
phenomenon observed between the electrodes recorded using the high speed camera and discharged waveform recorded using the oscilloscope. However, complete synchronization was difficult due to time lag between the processing times of the shutter signals and trigger signals of the high speed camera and oscilloscope. Results of preliminary experiments showed that this time lag is about 100 μs each time. In this study, the time lag was corrected according to the observed images between the electrodes during the generation of long pulse discharges and discharge waveform. Fig. 5 shows the correction method, and Fig. 6 shows an example of the synchronized observation of the revised images of the phenomena between the electrodes and discharge waveform. Here, the discharge voltage waveform in Fig. 5 decreases with the passage of time, and the discharge current waveform rises because the resistance of the arc column decreases due to the expansion of the discharge arc column. As shown in the figure, long pulse discharge with pulse duration of 50 μs was generated, after which normal discharge occurred. The light of the long pulse discharge was captured in 6-frame images when the long pulse discharge occurred, and the light of normal discharge which occurred after this was found to be synchronized with the discharge waveform. This enabled the synchronization of discharge waveform and images.

### 3. EXPERIMENT RESULTS

Fig. 7 shows the example of observation of the photographed machining. Given that the machined area removed by EDM is black and non-transparent, it is assumed that a conductive layer is formed here. At other parts, there are parts where light is seen to pass through the silica glass, or parts where shadows are formed outside the machined areas. Shadows are generated on transparent bodies such as glass when stress or heat is added. Fig. 7(a) shows the image immediately after a shadow has formed and (b) 2.3 ms after the shadow has formed. This shadow decreases and eventually disappears after the discharge point move. Consequently, this shadow is
said to have occurred at the discharge point. The type of stress occurring at the discharge point is thermal stress resulting from the discharge arc column and machining reaction force. A dynamics model on the application of impact force to a silica glass workpiece was built. The machining reactive force was set to 100 N and the natural frequency of the system was calculated by adding the reaction force to the center of the workpiece and found to be about 53.3 MHz. Based on these results, the time at which stress is removed and the workpiece becomes undistorted was found to be sufficiently faster than the shutter speed of 10 μs. Consequently, shadows formed by machining reactive force are said to be layered only on 2-frame images at the most. The machining reactive force peaked at several ten μs after the generation of the arc column, and became 0 N about 100 μs later. Next, when the tool electrode and workpiece are in contact with each other and a shadow is generated by the stress, the response of the Z-axis of the EDM machine is about several tens of Hz. This is thought to form a shadow measuring several ms in the whole videoed area. Such a phenomenon has not been observed. These results suggest that these shadows were not formed by machining reactive force, but due to heat.

Fig. 8 shows the machined area which increased during videoing. To show the increase in the machined area, the colors of the image before the increase were reversed so that the machined area becomes white, the increased area and area outside the machined area were synthesized. The images used for comparing the increased area were also synthesized in the same way. As seen in these images, even when the tool electrode is rotated, only one part is machined considerably. From the recorded images, it can be seen that for about 0.185 s, after long pulse discharge occurs, the phenomenon where normal discharge concentrates at the same place (hereafter called normal concentration) occurred at a high probability. The waveform which occurs here is not general concentrated discharge waveform which rises to the open voltage, but normal discharge waveform with very short discharge time delay which occurs concentratedly at the same place. To clarify the details of this phenomenon, a detailed analysis of the synchronized discharge waveform and machining phenomenon was performed. As a result, it was found that the machining area may or may not increase with normal concentration. The following describes the two cases.

Fig. 9 shows the scene where the machined area increased due to normal concentration. Here, long pulse discharge with pulse duration of 100 μs is seen to occur. In the figure, (a) shows the image before the generation of long pulse discharge, while (b) shows the image after generation. To check if machining has progressed by long pulse discharge, (a) and (b) were synthesized to form (d). The black area is the increased part. In (d), if the contour is removed, more or less no changes can be seen. This indicates that machining does not occur with long pulse discharge alone. After this normal concentration occurred for 0.0181 s in the place where long pulse discharge occurred. (c) shows the image after normal concentration ends, (e) is the comparison of (a) and (c), and the black part in the figure is the increased part of the machined area. This indicates that machining progresses due to normal concentration.

On the other hand, Fig. 10 shows the scene where the machined area does not increase. In this case, long pulse discharge with pulse duration of 60 μs is seen to occur. There is more or less no increase in the machined area before and after the long pulse (d). Like earlier, after the long pulse discharge, normal discharge is seen to concentrate, but there is no increase in the machined area as shown in the figure.

Scenes differing the above two, where the machining area increased due to a single long pulse discharge, were also confirmed. As shown in Fig. 11, the number of machined areas increased after a long pulse discharge with a pulse width of about 50 μs. Such increase in the machined area due to the occurrence of long pulse discharge is seen in less than 1% of all recorded images. Figure 12 shows an example of the shadow observed when a long pulse was generated. At this time, the pulse width of the long pulse discharge is about 70 μs. A shadow accompanying it can be observed. After this
shadow was formed, normal discharge light was observed at the same location. In other words, the normal discharge is thought to concentrate at the same location after the long pulse discharge described above. However, it was observed that the shadow area did not expand after the occurrence of the long pulse discharge and was steadily decreasing. After that, the discharge point moved to another location.

4. DISCUSSION

As described in the previous chapter, the experiment results confirmed that machining does not progress with the single occurrence of long pulse discharge. In other words, the discharge energy of long pulse discharge is mostly used for the generation of carbon and not for the elimination of the workpiece. In most cases, normal concentration occurs triggered by the generation of long pulses discharge. It is thought that more carbon than normal discharge is produced due to the long pulse discharge11), indicating that machining scraps made up mainly of carbon are not discharged, but remain between the electrodes, thus the dielectric breakdown drops conspicuously.

Based on the results of Fig. 12, it is thought that the shadow disappeared because a thick conductive layer was formed by the long pulse discharge, and the heat energy of the arc column of the normal discharge after that did not reach the glass, as shown in Fig. 13. This suggests that when machining does not progress due to normal discharge concentration, the carbon produced by the long pulse discharge forms a thick conductive layer.
on the workpiece surface. Tani et al.\textsuperscript{11,12} confirmed that a continuous normal discharge and long pulse discharge occur alternately in the EDM of insulation materials using the assisting electrode method. It is thought that the process progresses with the removal of the workpiece by long pulse discharge and formation of conductive layer. On the other hand, in this study, it was confirmed that normal discharge concentration occurred after the long pulse discharge, the insulating workpiece was machined as a result of this. Until now, it was thought that the insulating workpiece was machined by the long pulse discharge, but in fact, the machining progressed due to the concentration of normal discharge after the occurrence of the long pulse discharge.

5. ATTEMPTS TO IMPROVE MACHINED SHAPE ACCURACY OF INSULATING MATERIALS

As described above, the deterioration of the machining shape accuracy due to the EDM of the insulator is speculated to be due to local concentrated discharge from the excessive amount of generated carbon. We therefore attempted machining under machining conditions to reduce the amount of carbon generated during long pulse discharge, and improve the machined shape accuracy of EDM of insulators. Table 3 shows the machining conditions and Figure 14 shows the change in the ratio of discharge types caused by changing the machining conditions. This indicates that the ratio of long pulse discharge and normal concentrated discharge decreased and the ratio of normal discharge increased. Fig. 15 shows the progress of machining after machining for 720 seconds. It can be seen that the discharge is distributed and the machined shape is flat, clarifying that it is effective to reduce the amount of carbon generated during long pulse discharge and reduce local concentrated discharge in order to improve the machined shape accuracy in the EDM of insulators.

6. CONCLUSION

To clarify the machining mechanism of EDM of insulation materials using the assisting electrode method, we constructed a system to synchronously observe discharge machining phenomena between electrodes during the EDM of silica glass and discharge waveform. Based on the results, attempts were made to improve machining accuracy in the EDM of insulators. The following results were obtained.

(1) The synchronized observation system enables synchronized observation of discharge waveform and EDM machining phenomenon.

\begin{table}[h]
\centering
\caption{Changing processing conditions}
\begin{tabular}{|c|c|}
\hline
Discharge duration[μs] & 5→10 \\
\hline
Off time[μs] & 43→86 \\
\hline
Current [A] & 2.5→1.7 \\
\hline
Open voltage [V] & 100 \\
\hline
Servo voltage [V] & 55→85 \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig14.pdf}
\caption{Improvement of rate of concentration discharge}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig15.pdf}
\caption{Result of machining progress}
\end{figure}

(2) Observations focusing on machining phenomena caused by long pulse discharge showed that in the EDM of silica glass, normal concentration occurs only in one place with a very short delay time after long pulse discharge, and machining progresses as a result. It was clarified that there are two patterns of machining processes; one with the normal discharge and one with machining progress. In addition, there is very little progress in machining with a single long pulse discharge.

(3) It was confirmed that if machining does not proceed during normal concentration, the formed carbon coating may be thick.

(4) To improve the machined shape accuracy, it is effective to reduce the amount of carbon generated during long pulse discharge and reduce local concentrated discharge.

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