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High-speed imaging of EDM gap phenomena using transparent electrodes

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Abstract

In electrical discharge machining (EDM), discharge occurs with a high frequency in a narrow gap space between parallel plane electrodes filled with a dielectric fluid thus making direct observation of electrical discharge phenomena extremely difficult. On the other hand, SiC single crystals are electrically conductive and optically transparent. This paper describes observation of the EDM gap phenomena through the transparent electrode from the direction normal to the discharge surface using a high speed camera. In consecutive pulse discharges, distribution of discharge locations and volume fraction of bubbles in the working gap were clarified.

Keywords: Electrical Discharge Machining; Transparent Electrode; SiC Single Crystal; Discharge Location; Bubble;

1. Introduction

In electrical discharge machining (EDM), electric discharge occurs at a high frequency between a tool electrode and workpiece in a dielectric fluid such as oil. At the discharge spot, small quantity of material is removed by melting and evaporation of the material due to the heat flux from the electrical discharge. Bubbles and pyrolytic carbon are generated by cracking of the dielectric fluid in the discharge gap. Hence, the gap conditions are being changed every moment.

Many researches have been done about the temperature and diameter of electrical discharge plasma, which exert significant influence on the removal process. Natsu et al. [1] observed the side view of the arc plasma using a high-speed video camera and found that the diameter of arc plasma is several times larger than that of the discharge crater. Kojima et al. [2] measured the temperature distribution in the arc plasma and found that the diameter of arc plasma is five times larger than the crater diameter. In all of these researches however, a needle or thin rod electrode was used as either anode or cathode, or both electrodes, because it is difficult to observe the arc plasma which is generated very deep in the narrow gap between parallel plane electrodes. Moreover, discharge was ignited only once, at the center of the electrode, mostly in air. Hence, findings obtained from single discharge in air may be different from those of consecutive pulse discharges which occur randomly over a large electrode surface, in a gap where exist not only the dielectric liquid, but also bubbles and debris particles.

On the other hand, Miyajima et al. [3] observed the EDM gap through a transparent plastic disk which was embedded in ring-shaped metal electrodes and found that the gap is mostly occupied by bubbles although the discharge gap is under the dielectric liquid surface. Ikeda [4] inserted a fine needle electrodes through a hole pierced at the center of two parallel glass disks separately, and observed the oscillation of the bubble generated by a single pulse discharge ignited between the needle electrodes. It was found that the diameter of the bubble reached several millimeters, which were several tens of times larger than the gap width. However, as the discharge location is limited to the specific place, motion of bubbles generated by consecutive pulse discharges which occur randomly over the working...
surface cannot be observed. Hence, Takeuchi et al. [5] simulated the distribution and movement of the bubbles in an EDM gap based on fluid dynamics and found that most of the gap was filled with bubbles.

Kojima et al. [6] measured the discharge location from the ratio of the currents which flow in four divided feeders, each of which is connected to each side of a square tool electrode. It was observed that when machining depth was shallow and machining was stable, the distribution of discharge location was uniform, and no relationship was observed between consecutive discharge locations, while discharge location became localized with increasing the machining depth. However, it was difficult to determine whether discharge occurs in liquid, in gas, or at the interface between them.

Thus, direct observation of these discharge phenomena using transparent electrodes will be effective to answer the above questions. Recently, SiC single crystal is attracting attention as a new semiconductor used for the next generation power device which has higher electric breakdown strength and higher thermostability than silicon single crystal. Pure SiC single crystal is colorless and transparent, and its electrical conductivity is almost zero. However, the electrical conductivity increases and transmissivity decreases with increasing the impurity concentration. Hence, the present study aims to observe the discharge phenomena from the direction normal to the discharge surface, using SiC single crystal material which has a high electrical conductivity and optical transparency sufficient to conduct the observation.

2. Experimental setup and method

EDM gap phenomena were observed through a transparent SiC single crystal plate using a high-speed video camera as shown in Figure 1. The experimental apparatus consists of a machining cell, transistor type pulse generator, high-speed video camera, oscilloscope, current sensor, electric micrometer, and PC. The machining cell was installed on the work table of a sinking EDM machine (Sodick C32). Discharge was ignited in the cell filled with an EDM oil. The cathode was a rectangle SiC single crystal plate which was cut out from a commercially available SiC wafer (Nippon Steel Materials Co., Ltd.) using wire EDM, and it was fixed to the cell. The specifications of the SiC single crystal wafer are shown in Table 1. The anode was a rectangle copper plate of 2mm in thickness, fixed to the Z-axis of the machine. Both electrodes were placed in parallel with the discharge area of 5mm×3mm. The gap width was adjusted using the electric micrometer. Immediately after electric breakdown, due to explosive expansion of a bubble, the reaction force acting on electrodes rises up to 50N [7]. Thus, the SiC single crystal plate was supported by a transparent acrylic board to keep the gap width constant and uniform. Table 2 shows high-speed video camera settings used in the experiment. The high-speed video camera was FASTCAM-ultima(Photron) with maximum frame rate of 16,000 frames per second and minimum exposure time of 8 microseconds. When the oscilloscope was triggered by the rise of the discharge current waveform measured by the current sensor, the oscilloscope output a trigger signal, which was sent to the high-speed video camera to freeze the memory which was being refreshed by deleting the first frame and memorizing the last one for each frame capturing cycle. Since the frame capturing was not synchronized with the electric breakdown, the gate signal generated for each frame, gap voltage and discharge current waveforms were recorded together using the oscilloscope.

Table 1. SiC single crystal wafers specifications

<table>
<thead>
<tr>
<th>Polytype</th>
<th>4H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface orientation</td>
<td>(0001)</td>
</tr>
<tr>
<td>Conduction type</td>
<td>N-type</td>
</tr>
<tr>
<td>Resistivity (Ω cm)</td>
<td>0.013~0.025</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>380</td>
</tr>
</tbody>
</table>

Table 2. High-speed video camera settings

<table>
<thead>
<tr>
<th>Resolution (pixel)</th>
<th>1024×512</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate (fps)</td>
<td>1000</td>
</tr>
<tr>
<td>Sutter speed (s)</td>
<td>1/1000</td>
</tr>
</tbody>
</table>

3. Observation of EDM gap phenomena

Under the camera settings shown in Table 2, the recording time was 1.024 second to capture 1024 frames with frame interval of 1 millisecond. Figure 2 shows the discharge gap phenomena observed during the recording time. Figure 3 shows a magnified image of a discharge spot due to a single pulse discharge. The emission of light, generation and expansion of bubble were observed at the discharge spot. In Figure 2, since the frame interval was long, plural discharge spots were observed
in one frame. The light emission at the discharge spot is considered to be the radiation from the arc plasma or cathode spot where temperature of SiC is elevated to melting or evaporating point. Since single crystal is disordered, transparency is lost. Figure 4 shows the area which is occupied by bubbles over the working surface. More than 80% of the working surface was occupied by bubbles at 0.16 seconds after discharge started. Moreover, black smoke like matter was floating in the gap. It was probably debris particles or pyrolytic carbon generated in the working gap.

Fig. 2. High-speed video frames of EDM gap phenomena (i:10A, t_e:10μs, t_o:50μs, u_i:120V)

Fig. 3. Single pulse discharge phenomena

Fig. 4. Volume fraction of bubbles in EDM gap 0.16 seconds after EDM started (i:10A, t_e:10μs, t_o:50μs, u_i:120V)

4. Atmosphere of discharge ignition

For understanding EDM phenomena in real machining, it is interesting to know in what kind of atmosphere electrical discharge is likely to occur. The above results verified that the EDM gap is mostly occupied by bubbles. Moreover, Kunieda et al. [8] found that the debris particles reciprocate with high speed between the anode and cathode in the direction perpendicular to the electrode surfaces due to electrophoresis. They also observed that some particles were linked in series parallel to the electric field and pointed out that this phenomenon could cause an ignition of electric discharge. On the other hand, Yoshida et al. [9] observed the distribution of hundreds of debris particles generated by a single discharge on the workpiece surface and found that most of them were located at the boundary of the generated bubble. Therefore, it is guessed that electrical discharges occur not only in liquid but also in gas and at the interface between liquid and gas. So the atmosphere of discharge ignition was classified into three: liquid, bubble boundary and bubble, and probabilities of occurrence of discharge in the three atmospheres were investigated.

Machining conditions used in the experiment are shown in Table 3. The high-speed video camera settings were the same as in Table 2. In order not to capture more than one electrical discharge in each frame, the pulse interval time was set equivalent to the frame interval. When the surface of SiC is covered by discharge craters, whole surface becomes opaque, making the observation of bubbles difficult. Hence, a clear SiC plate with no discharge craters was used. The atmosphere of discharge ignition was determined from the consecutive video
frames. However, when movement of bubble boundary was too quick, the still image of the boundary was not obtained. In this case, the atmosphere was classified as unknown. Figure 5 shows the result of the classification of the atmosphere of discharge ignition. It is found that discharge can occur in any atmosphere. However, the probability of discharge in liquid was higher than 50%, and 35% of discharge occurred at the boundary. Discharge probability in bubbles was low.

Table 3. Machining conditions

<table>
<thead>
<tr>
<th>Polarity</th>
<th>Cu (+), SiC (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge duration (μs)</td>
<td>10</td>
</tr>
<tr>
<td>Pulse interval time (μs)</td>
<td>1000</td>
</tr>
<tr>
<td>Discharge current (A)</td>
<td>10</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
<td>120</td>
</tr>
</tbody>
</table>

![Classification of atmosphere of discharge ignition](image)

Yoshida et al. [9] compared the size of discharge crater due to a single pulse discharge which occurred in a gap filled with liquid or air, and found that the craters generated in liquid were smaller. This is because plasma expansion is prevented by the inertia of liquid. Takeuchi et al. [5] found that diameters of craters generated by consecutive pulse discharges were intermediate between those of the craters generated by a single pulse discharge in a single phase liquid and gas. Hence, in consecutive pulse discharge, the relation between the atmosphere of discharge ignition and the size and shape of discharge craters was obtained. On the other hand, for comparison, a single pulse discharge was ignited between a SiC cathode plate and copper rod anode with 3mm in diameter in a single phase liquid and gas, respectively, and the discharge craters formed on the SiC surface were observed.

Figure 6 shows the craters generated in each atmosphere. Comparing the single pulse discharge crater generated in liquid with that in gas, it is found that the shape of the crater in liquid is more circular than that in gas. The shape of crater generated by consecutive pulse discharges in liquid atmosphere is similar to the single pulse discharge crater in liquid. On the other hand, the shape of crater generated by consecutive pulse discharges in bubble is similar to the single pulse discharge crater in gas. The shape of the crater generated by consecutive pulse discharges at the interface between liquid and gas is intermediate between those generated in liquid and bubble. Figure 7 shows comparison of the area of discharge craters generated in different atmospheres. It was found that the area of electrical discharge craters generated by consecutive pulse discharges were intermediate between those generated by single pulse discharges in a single phase liquid and gas, and that the area tends to become large as the atmosphere changes from liquid to gas. These results are in agreement with the researches of Yoshida et al. [9] and Takeuchi et al. [5] described above.

![Discharge craters generated in different atmospheres](image)

![Area of discharge craters generated in different atmospheres](image)

Next, the influence of the atmosphere of discharge ignition on the volume of bubble generated by the discharge was investigated. When electrical discharge occurs, the dielectric fluid and electrode materials are evaporated by the heat of arc plasma. Large molecules are dissociated into small molecules or atoms, which are further ionized to generate ions and electrons. Thus, a bubble is formed and its volume expands explosively. Figure 8 shows the side view of the bubble generated by a single pulse discharge in dielectric fluid [10]. It is found that the bubble boundary is parabolic and the electrode surface is wet even inside the bubble. Hence, even if discharge is ignited in the bubble, small amount of gas may be generated. For simplicity, the bubble shape was approximated as a pillar, and in crease in the bubble volume due to each discharge was measured. The bubble volume here was obtained by multiplying the area of bubble and the gap width. Figure 9 compares the increase in bubble volume due to discharge generated in
different atmospheres. It was found that the bubble volume increased most in liquid, least in bubble, and intermediate at the interface between liquid and bubble. Therefore, it can be concluded that even if most of the working gap is occupied by bubbles, dielectric fluid exist on the working surface, and gas volume increases due to discharge in the bubble.

Yoshida et al. [9] found that most of discharge debris particles ejected from the crater were reattached to the working surface when the electrode surfaces were perfectly dried. In the case of EDM in liquid, however, although the working gap is nearly occupied by bubbles, the wet working surfaces prevent adhesion of debris particles, enabling successful machining.

Fig. 8. Side view of bubble generated by discharge in oil (i:20A, t:100μs, gap width:0.1mm) [10]

Fig. 9. Volume of gas generated in different atmosphere

5. Correlation between discharge locations of consecutive pulse discharges

It was reported that discharge location is determined not deterministically but probabilistically in a way that shorter gap width or higher debris concentration increases the discharge probability per unit area [11]. If discharge location is determined deterministically, discharge will be ignited in the vicinity of the last discharge spot, because ridge of the crater is protruded and debris particles are scattered around the crater. This tendency will especially be true, when a SiC wafer is used as an electrode due to its perfect flatness. Figure 10(a) shows the correlation between discharge locations of two consecutive discharges using a new SiC plate without a discharge crater. Among the 183 discharges ignited in 1.024 seconds, the number of electrical discharge which occurred in the same place as the previous discharge was only 25 events (14%). Thus, it was confirmed that discharge location is determined probabilistically. In contrast, the same experiment was performed using a SiC plate whose surface was fully covered by discharge craters.

Figure 11 shows an image taken by the high-speed camera using the SiC plate fully covered by discharge craters. Since all the working surface was damaged, there is no place where the plate is transparent. However, since the single crystal nature is not spoiled inside the material, discharge spot could be found from the radiation at the discharge spot. Figure 10(b) shows the correlation between two consecutive discharges using the SiC plate covered by discharge craters. Compared with the new SiC plate, the crater distribution is more dispersed over the whole working surface. Among 322 discharges, only 2% of discharge occurred at the same place as the previous discharge. After the whole working surface was covered by discharge craters, a lot of debris particles were existent and whole surface was covered by large asperities. As a result discharging locations were distributed at random. This result was in agreement with that obtained from the electrical measurement method described in Introduction [6].

Fig. 10. Discharge locations

Fig. 11. Emission of light from discharge location generated on SiC surface covered densely by discharge craters
6. Difference from normal EDM conditions

Use of single crystal SiC plates enabled direct observation of the EDM gap in process. However, results of the observation should be carefully analyzed, because the present experiments were conducted under the following conditions which are different from the normal EDM conditions:

- When the gap was observed at the beginning of machining using a new SiC plate, the gap conditions were not in the steady state.
- The working surface was not fully covered by discharge craters.
- Debris particles distribution was not fully developed.
- Joule heating at the discharge spot affects the discharge phenomena because specific resistivity of SiC is high.
- Discharge interval was longer than that normally used in EDM processes.

7. Conclusions

The EDM gap phenomena were observed through an optically transparent SiC single crystal plate from the direction normal to the discharge surface. The results are summarized below:

1) Using a SiC single crystal plate, the direct observation of light radiation, bubbles, and debris particles was possible.
2) Although damage caused by discharge made the SiC plate opaque, the discharge spot could be observed even after the whole surface was covered by discharge craters.
3) In consecutive pulse discharges, it was observed that the gap is mostly occupied by bubbles.
4) In consecutive pulse discharges, discharge can occur most often in liquid, least in gas, and intermediate at the interface between liquid and gas.
5) The shape and size of discharge craters vary depending on the atmosphere of discharge ignition.
6) The probability of discharge which occurs at the same location as the previous discharge is significantly low in a steady state of machining.

References