Observation of Scattered Debris Generated by Pulse Discharge in Bubble in Electrical Discharge Machining

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Abstract:
In this paper we investigate the scattered debris generated in a bubble during a pulse discharge in order to discuss the material removal phenomena in the EDM process. A single pulse discharge is generated between a parallel gap and the motion of the scattered debris as well as the bubble expansion is observed using a high-speed video camera. It is found for the case of discharge in a bubble that material removal occurs during the discharge duration but does not occur after the discharge duration, whereas material removal occurs during and after the discharge duration for the case of discharge in a dielectric liquid.

Keywords: Electrical Discharge Machining, Material removal, Debris, Bubble, High-speed video camera

1. Introduction
Although electrical discharge machining (EDM) is one of the important machining processes and widely used in the manufacturing industry, the mechanism of material removal in the EDM process is not fully understood. In order to explain the material removal process, many studies have been reported. For example, Ikeda [1] observed the behavior of a bubble generated between parallel flat plates. Motoki et al. [2] discussed the removal mechanism of molten metal using mercury. However, since a condenser-type power supply was used in their experiments, the thermal state, such as power density, is different from that of the presently used EDM process using a transistor-type power supply. Takeuchi and Kunieda [3] reported that the gap width can be expressed as a function of the debris concentration, and the gap width is affected by discharge area and debris diameter. Yanatori and Kunieda [4] calculated the movement of debris caused by the electrostatic force in the narrow gap. The calculated results were compared with the experimental results for the movement of debris observed by a high-speed camera. Takezawa et al. [5][6] observed bubble behavior and investigated the relationship between bubble motion and material removal volume using a low-melting-temperature alloy. They inferred that the material removal of the molten volume is affected by the process of bubble contraction and collapse, and that material removal occurs immediately before bubble collapse. Hayakawa et al. [7] observed bubble behavior and scattered debris generated by a pulse discharge under actual EDM conditions using a high-speed camera and reported that debris is generated during discharge duration and scattered at a speed of 20-70 m/s and that after scattering the debris drifts with the boundary of the dielectric liquid.

In the actual EDM process, a large proportion of the volume of the gap is thought to be filled with the generated bubbles [8]. Adachi et al. [9] calculated the process reaction force by considering the bubble behavior and pressure distribution in a dielectric liquid in a gap. They concluded that the reaction force in a series of pulse discharges decreases with time as the gap is filled with generated bubbles in place of the dielectric liquid. On the other hand, Yoshida and Kunieda [10] reported that debris is scattered even when a pulse discharge occurs in air.

However, the effect of the presence of bubbles on material removal by a pulse discharge generated in a bubble requires investigation in order to discuss the effect mentioned above. In this paper we investigate the scattered debris generated in a bubble during a pulse discharge in order to discuss the material removal phenomena in the EDM process.

2. Experimental Method
The concept of the experiments is to observe scattered debris as well as bubble behavior, such as expansion and contraction, under conditions where actual EDM gap conditions are reproduced as faithfully as possible. The experimental setup is shown in Fig.1. A parallel flat gap is located between a metal rod electrode A of 20 mm diameter and a transparent PMMA plate, in which a metal wire electrode B of 0.3 mm or 1 mm diameter is inserted. The gap distance is adjusted to 10 µm or 50 µm using a thickness gauge. A single pulse discharge is ignited, and scattered debris and bubble behavior are observed using a high-speed video camera from the direction normal to the discharging surface through the transparent PMMA plate and the observation hole of the jig. Waveforms of discharge current and gap voltage are also recorded using a digital oscilloscope. Since the maximum diameter of the bubble is smaller than the rod electrode diameter under the present experimental conditions, as discussed in section 3, bubble motion is considered to be unaffected by the boundary of the rod electrode.
In this paper, material removal when a discharge occurs in a bubble is discussed by the comparison of discharge in air at atmospheric pressure and in a dielectric liquid. Experimental conditions are listed in Table 1. The discharging surface of rod electrode A was pretreated by buffing or EDM and cleaned using an ultrasonic cleaning machine before each experiment. In the case of discharge in a dielectric liquid, the gap is filled with EDM oil, which was dropped using a syringe. The frame rate of the video camera is set to 20,000fps or 30,000fps in order to observe 4-7 frames during the discharge duration.

Since a special power control unit for generating a single pulse discharge was not used, pulse discharges often occurred one after another in accordance with the pulse conditions. Therefore, if a subsequent pulse discharge was not generated after the first pulse discharge while the bubble behavior was being observed, the first pulse discharge was regarded as a single pulse discharge.

3. Observation of Scattered Debris

3.1 Discharge in a gas

The scattered debris was observed when a pulse discharge was generated in air. Figure 2 shows sequential photographs of the observed discharge. In this experiment copper was used for the rod electrode, and iron was used for the wire electrode. The discharging surface of the rod electrode was pretreated by EDM and the gap distance was set to 10μm. The wire electrode can be seen at the center of each photograph. Tracks glowing red and radiating in all directions from the point of discharge were also imaged. The authors judged these tracks to be debris scattered from the point of discharge. It is found that the debris is generated at latest 33μs after the initiation of the electrical discharge and that the scattering of debris continues during the discharge duration. It is also found that no new debris was generated after the discharge duration.

3.2 Discharge in a dielectric liquid

The scattered debris and bubble behavior were observed when a pulse discharge was generated in a dielectric liquid. Figure 3 shows sequential photographs of the observed result. In this experiment, copper was used for the rod electrode and iron was used for the wire electrode. The discharging surface of the rod electrode was pretreated by buffing and the gap distance was set to 50μm. The experimental results show that a bubble is generated immediately after the initiation of electrical discharge (0μs) and expands concentrically. Figure 4 shows the time variation of bubble radius and debris position. It is found that the bubble reached a maximum diameter at approximately 300μs. The rate of bubble expansion was estimated to be 15-25m/s. It is also found that the debris moves in the generated bubble at the speed at which the bubble expands. Scattered debris follows the boundary of the expanding bubble, and after rising into the dielectric liquid, it decelerates and drifts with the boundary.

![Diagram](https://example.com/diagram.png)

Table 1 Experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>In gas</th>
<th>In liquid</th>
<th>In bubble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod electrode A</td>
<td>020mm Cu</td>
<td>020mm Cu</td>
<td>020mm S45C</td>
</tr>
<tr>
<td>Wire electrode B</td>
<td>03mm, 1mm Fe</td>
<td>03mm, 1mm Fe</td>
<td>01mm Cu</td>
</tr>
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<td>Dielectric fluid</td>
<td>Air</td>
<td>EDM oil</td>
<td>EDM oil</td>
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<tr>
<td>Gap distance</td>
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<td>50μm</td>
<td>50μm</td>
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<td>Applied voltage</td>
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<td>Discharge current</td>
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<td></td>
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<tr>
<td>Discharge duration</td>
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<td>200μs</td>
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<td>Frame rate</td>
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<tr>
<td>Exposure time</td>
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</tr>
</tbody>
</table>
Fig. 2 Debris generated by discharge in gas

Fig. 3 Bubble and debris generated by discharge in liquid

Fig. 4 Time variation of bubble radius and debris position

Fig. 5 Bubble and debris generated by discharge in bubble
Fig.6 Relationship between debris position and time in the case of discharge in air (discharge duration 20μs)

Fig.7 Relationship between debris position and time in the case of discharge in air (discharge duration 70μs)

Fig.8 Relationship between debris position and time in the case of discharge in air (Discharge duration 130μs)

Fig.9 Relationship between debris position and time in the case of discharge in air (discharge duration 200μs)

Fig.10 Relationship between debris position and time in the case of discharge in dielectric liquid (discharge duration 200μs)

Fig.11 Relationship between debris position and time in the case of discharge in bubble (discharge duration 200μs)
3.3 Discharge in a bubble

The scattered debris and bubble behavior were observed when a pulse discharge was generated in a bubble generated by a previous pulse discharge. Figure 5 shows sequential photographs of the observed result. In this experiment, S45C was used for the rod electrode and copper was used for the wire electrode. The discharging surface of the rod electrode was pretreated by buffing and the gap distance was set to 50μm. It is found that when a pulse discharge is generated in a bubble, the bubble diameter and shape hardly change. Scattered debris was observed even when a pulse discharge was generated in the bubble. The debris rushed into the dielectric liquid, and drifted with the boundary without adhering to the electrode surface. This is the same behavior as that of debris when a pulse discharge was generated in a dielectric liquid. Therefore, it appears that material removal may occur when a discharge is generated in a bubble in the actual EDM process.

4. Comparison of Debris Generation Time

4.1 Discharge in a gas

From the observation results for the debris, the debris generation time is investigated for discharge of in air, in a dielectric liquid, and in a bubble. The phenomena of material removal due to a pulse discharge in a dielectric liquid should be different from those in the EDM process because a considerable proportion of the gap in the actual EDM process is filled with generated bubbles. Therefore, the behavior of the debris may be affected by the presence of the bubbles.

First, the time at which debris is first observed is investigated. Figures 6-9 show the results obtained for the case of discharge in air, in a dielectric liquid, and in a bubble. In this experiment, the discharge duration is varied from 20μs to 200μs. The observed debris particles are classified into two categories in term of the intensity of light emitted from the particles. Particles emitting intense light were defined as large debris and particles emitting weak light were defined as small debris. It is found for the case of discharge in air that most of the debris particles are generated during the discharge duration. For the case of 20μs discharge duration, shown in Fig.6, the authors observed the plotted results as being those of debris generated during the discharge duration because there is some error in determining the time of the initiation of electrical discharge due to the exposure time of the video camera. On the other hand, there are few debris newly observed after the discharge duration.

In Fig.9, the result for the case that the discharging surface of the rod electrode A was pretreated by buffing is plotted. It is found that the roughness of the discharging surface does not affect the debris generation time. The speed of large debris was estimated to be about 20-30m/s and that of small debris was estimated to be about 40-80m/s.

4.2 Discharge in a dielectric liquid

Next, the time when the debris is first observed is investigated for the case of discharge in a dielectric liquid. Figure 10 shows the results obtained for the discharge duration of 200μs. It is found that material removal occurs during the discharge duration. The reason that debris is first observed 100μs after the initiation of electrical discharge, whereas debris can be observed 33μs after the initiation of electrical discharge for the case of discharge in air, is thought to be that the debris is difficult to observe immediately after the electrical breakdown due to diffused reflection of the light by the generated bubble.

It is also found from Fig.10 that some scattered debris particles are generated after the discharge duration in the case of discharge in a dielectric liquid, whereas no debris is generated after the discharge duration in the case of air.

4.3 Discharge in a bubble

Next, the time at which the debris is first observed is investigated for the case of discharge in a bubble. Figure 11 shows the results in the case of that discharge duration of 200μs. It is found that debris particles are generated during the discharge duration and that no debris is generated after the discharge duration, which is the same result as that for the case of air.

4.4 Discussion

Since a considerable proportion of the gap is filled with generated bubbles in the actual EDM process [8], pulse discharges may occur not only in the dielectric liquid but in the generated bubbles. Therefore, the material removal phenomena when a pulse discharge occurs in the bubble should be discussed.

For the case of discharge in a bubble, it is found from the observed results that material removal undoubtedly occurs during the discharge duration, but that does not occur after the discharge duration. On the other hand, for the case of discharge in a dielectric liquid, debris is generated during and after the discharge duration. When a discharge occurs in the dielectric liquid, the pressure at the point of discharge would become very high because a marked increase in volume must occur caused by the evaporation and decomposition of the dielectric liquid. The fact that the expansion of the bubble is obstructed by the surrounding liquid should also affect the pressure rising. Even after the discharge duration, the bubble continues to expand beyond the equilibrium state due to inertia, and the pressure in the bubble is thought to become lower than atmospheric pressure. This variation of pressure should affect the material removal. On the other hand, when a discharge occurs in a bubble, pressure rising at the point of discharge appears to be smaller than that in case of the dielectric liquid, because the decomposition of the bubble components appears to bring small amount of increase in volume. Therefore, the inertia of the expanding bubble would be low and the variation of pressure would cease earlier than that in the case of the dielectric liquid. The fact that scattered debris was not observed after the discharge duration for the case of discharge in a bubble appears to reflect the small variation of pressure mentioned above.
5. Conclusions

In this paper we investigated bubble behavior and scattered debris generated by discharge in air, in a dielectric liquid, and in a bubble under actual EDM conditions using a high-speed video camera in order to discuss the material removal mechanism in the EDM process. The following conclusions were obtained.

1) Scattered debris is observed in the case of discharge in a bubble.
2) The debris is first generated during the discharge duration.
3) Some scattered debris is generated after the discharge duration for the case of discharge in a dielectric liquid, whereas no debris is generated after the discharge duration for the cases of discharge in air and in a bubble.

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References