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Relationship between occurrence of material removal and bubble expansion in electrical discharge machining

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Abstract

In this study, we observe the tracks of debris particles scattered from the discharge point and bubble expansion and contraction in a single pulse discharge ignited in the parallel flat gap space in order to discuss the mechanism of material removal in electrical discharge machining (EDM). A metal rod and a transparent flat resin plate with metal wire inserts are used as electrodes, and a single pulse discharge was initiated in EDM oil. The tracks of the debris particles scattered from the discharge point and expansion and contraction of the generated bubble are observed using a high-speed video camera. The discharge duration was varied from 60 to 1000 μs, where the latter condition is intended to maintain the discharge until after the generated bubble expanded and then contracted. By combining the observed results of the scattered debris particles and the generated bubble motion, it is found that material removal occurs while the bubble is expanding, that is, while the pressure at the discharge point is decreasing.

Keywords: Electrical discharge machining; Material removal; Debris particle; Bubble expansion; Discharge duration

1. Introduction

Although electrical discharge machining (EDM) is one of the important machining processes and is widely used in the manufacturing industry, the mechanism of material removal in EDM is not fully understood. To explain the material removal process, many papers have been published. For example, Ikeda [1] observed the behavior of a bubble generated between parallel flat plates. Fujimoto and Toshima [2] investigated the time variation in discharge crater shape using X-ray photography. Motoki et al. [3] discussed the removal mechanism of molten metal using mercury. However, since a condenser-type power supply was used in their experiments, thermal situation, such as power density, is different from that of the presently used EDM process using a transistor-type power supply. Takezawa et al. [4-5] also 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 bubble contraction and collapse process, and that the material removal occurs immediately before bubble collapse. On the other hand, Tamura and Kobayashi [6] reported that the effect of impulsive force caused by the expansion and shrinkage motions of a bubble on the crater formation is insignificant. Yoshida and Kunieda [7] reported that debris particles are scattered even when a pulse discharge is generated in air. Eubank et al. [8] calculated the plasma temperature and pressure, and argued that superheating is the dominant mechanism of the anode and cathode erosion. The authors [9] also reported that material removal occurs intermittently, more than once during the discharge duration, and pointed out that the cavitation is one of the possible causes of the material removal in the EDM process.

In this paper, the flying debris particles, as well as bubble expansion and contraction, generated by a pulse discharge in a parallel flat gap space are observed, and the time when the debris particles are removed from the discharge point is estimated in order to discuss the material removal mechanism in the EDM process.
2. Experimental method

The concept of the experiments conducted in this paper is to observe the scattered debris as well as bubble behaviors, such as expansion and contraction, under conditions where actual EDM gap conditions are reproduced as faithfully as possible. The experimental setup is shown in Figure 1. The parallel flat gap space is composed of a metal rod electrode of 20 mm diameter and a transparent PMMA plate in which a metal wire electrode of 1 mm diameter is inserted. The gap distance is adjusted to 50 \(\mu\)m using a thickness gauge. A single pulse discharge is ignited, and the scattered debris particles 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 shown in section 3, bubble motion is considered to be unaffected by the boundary of the rod electrode.

Experimental conditions are listed in Table 1. The discharge duration was varied from 60 to 1000 \(\mu\)s, where the latter condition (long discharge duration) was intended to maintain the discharge until after the generated bubble turned from expansion to contraction. The discharging surface of the rod electrode is pretreated by buffing or EDM. The gap space is filled with the EDM oil dropped using a syringe. Since a special power control unit for generating a single pulse discharge is not used, some pulse discharges often occur one after another in accordance with the pulse conditions. Therefore, if no subsequent pulse discharge is generated while observing the bubble behavior of the first pulse discharge, the first pulse discharge is regarded as a single pulse discharge.

3. Example of observed results

3.1. Bubble expansion and contraction

Figure 2 shows an example of the observed bubble generated by a single pulse discharge in EDM oil [9]. In this case, the discharging surface of the rod electrode was pretreated by buffing, and the gap width was set at 10 \(\mu\)m. The exposure time of the high-speed video camera was set at 83 \(\mu\)s. The cordlike wire electrode is seen from the center to the top left of each photograph. The time indicated in Figure 2 was determined from the first frame to image the discharge light. It can be observed that a bubble generated immediately after the initiation of electrical discharge (0 \(\mu\)s) expanded in a circular shape and reached its maximum diameter at approximately 400 \(\mu\)s. Then, it began to contract and repeatedly expanded and contracted one more time with a smaller amplitude of diameter. Subsequently, at about 2000 \(\mu\)s, the motion of the bubble ceased.

Figure 3 shows the observed results of the time variation in bubble diameter for discharge durations of 60, 120 and 1000 \(\mu\)s. It was found that the time when the bubble diameter becomes maximum is approximately 400 \(\mu\)s regardless of the discharge duration.

3.2. Debris particles

Figure 4 shows the flying debris particles observed using a high-speed video camera. In this figure, the dark circle located in the center of the image indicates the wire electrode and the bright line segments going from the center to the lower right indicate the tracks of flying debris particles scattered from the discharge point. Since the scattered debris particles are moving during the exposure time of the high-speed video camera, the particles are observed as the line segment. Although a large number of small (fast and relatively dark) debris...
particles are observed in most pulse discharges, especially just after the discharge initiation, only the clearly observed large (bright) particles were analyzed in this paper.

4. Estimation of material removal time

4.1. Discharge location

In order to estimate the time when a debris particle was removed from the discharge point, the location of the discharge point on the discharging surface was determined first. The method of determining the location of a discharge based on the recorded images is also shown in Figure 4. Although the discharge point cannot be seen because it is shielded by the wire electrode, the intersection point of the trajectories of two or more flying debris particles scattered by the same discharge can be determined as the discharge point.

4.2. Material removal time

Figure 5 shows the time variation of distance from the estimated discharge point for three flying debris particles. The horizontal axis of this figure indicates time from occurrence of electrical breakdown. The location of each debris particle in a frame is defined as the position of the upstream edge point of the line segment drawn by the debris particle. From the change in the distance of each debris particle, the time when each debris particle was
removed from the discharge point can be estimated as the intersection point of the extrapolated line and the horizontal axis. Although the change in the distance should be approximated by some curve, it was expressed with a line graph in order to simplify the analysis, and the trend between the first and second plots was used to read the removal time. Therefore, the estimated removal time tends to be slightly earlier than the actual time.

4.3. Experimental results

Figure 6 shows the distribution of the obtained material removal time for discharge durations of 60, 120 and 1000 μs. In this figure, each graph adds up the experimental results for five or six pulse discharges. It is found that the material removal occurs at different times, which distribute from 0 to 400 μs.

Figure 7 shows the material removal time standardized by the discharge duration. In this figure, the dots plotted between 0 to 1 indicate the material removal occurred during the discharge duration, whereas that plotted over 1 indicate the material removal occurred after the discharge duration. It is found that material removal can occur not only during the discharge duration but also just after the discharge duration, for the cases of the discharge duration of 60 and 120 μs. On the other hand, for the case of the discharge duration of 1000 μs, there is the time period when material removal does not occur even while the discharge continues. This result indicates that whether the discharge continues or not is not the dominant factor of the material removal.

Figure 8 shows the material removal time standardized by the time when the generated bubble reaches its maximum diameter. The dots plotted between 0 to 1 indicate the material removal occurred while the generated bubble is expanding, whereas that plotted over 1 indicate the material removal occurred while the bubble is contracting. As shown in Figure 3, the generated bubble expands and reaches its maximum diameter at approximately 400 μs regardless of the discharge duration, and then it begins to contract. It is found from Figure 8 that the material removal occurs
while the bubble is expanding, whereas no debris particle is removed while the bubble is contracting. Although the effect of shear force and that of pressure drop can be considered as the possible material removal mechanisms associated with the bubble expansion, the authors believe that latter is the dominant factor. The reason of this is discussed in the next section.

5. Discussion

In this section, the mechanism of material removal in the EDM process is discussed on the basis of the obtained results. As mentioned in the previous section, it was found that the material removal occurs intermittently while the generated bubble is expanding. However, since the material removal occurs even when a pulse discharge is generated in air [7], the effect of shear force caused by the bubble expansion, which is one of the usual theories, is considered to be not significant.

When bubble motion, namely, expansion and contraction, is calculated using a simple model [10][11], the decrease and increase in the pressure in bubble coincides with the increase and decrease in the bubble radius, as shown in Figure 9. Therefore, the effect of
pressure drop, such as cavitation of the molten metal and degassing of solution gas in the molten metal, could be pointed out as one of the possible causes of the material removal.

Although superheating [8] is also considered to occur at different times in a pulse discharge, it is unknown whether it can occur more than once in a pulse discharge.

6. Conclusions

In this paper, we observed the scattered debris particles, as well as bubble expansion and contraction, using a high-speed video camera and estimated the material removal time for each debris particle in order to discuss the mechanism of material removal in the EDM process. The following conclusions were obtained.

(1) Material removal occurs intermittently during or just after the discharge duration.

(2) Material removal occurs while the generated bubble is expanding, whereas no debris particle is removed while the bubble is contracting.

(3) The effect of pressure drop, such as cavitation of the molten metal and degassing of solution gas in the molten metal, was pointed out as one of the possible causes of the material removal.

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