Study on Expansion Process of EDM Arc Plasma

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In order to understand the phenomena of electrical discharge machining (EDM), the characteristics of transition arc plasma in EDM were investigated. The arc plasma was directly observed with a high speed video camera. In addition, to learn more about arc plasma expansion, plasma temperature was measured by spectroscopy. The arc plasma temperature was obtained by measuring the radiant fluxes of two different wavelengths from the arc plasma and applying the line pair method. Furthermore, a new expansion model for EDM arc plasma was proposed based on the observations, and validated by comparing experimental and computed results of the discharge crater.

Key Words: EDM, Arc Plasma, Arc Plasma Expansion, Spectroscopy, Plasma Temperature, Discharge Crater

1. Introduction

Electrical discharge machining (EDM) is a method of removing workpiece material by discharges generated between the tool and workpiece electrodes. The diameter of the arc plasma and its temporal change directly influence the shape and volume of the formed crater, removal quantity of the workpiece electrode, and wear amount of the tool electrode. The shape of the discharge crater is generally determined by the power distributed to the electrode and power input area, namely the arc plasma area. The discharge power distributed to the electrode is decided by the discharge current, inter-electrode voltage, and distribution rate of power to the electrode. The discharge current and inter-electrode voltage can simply be measured by the current sensor and voltage probe, and the distribution rate of power to the electrode is provided by literature(1), (2). However, the area of the arc plasma and its temporal change have yet to be clarified. Therefore, the assumed plasma diameter greatly influences the results of the calculated shape and volume of the discharge crater based on the thermal conductivity theory.

Until now, it has been reported that the diameter of the arc plasma in EDM increases with the passage of time after dielectric breakdown because of plasma expansion(3). Furthermore, given that the diameter of the arc plasma at the end of the discharge is equal to that of the crater produced by the discharge(4), the temporal change in EDM plasma diameter has been estimated from the relationship between the crater diameter and pulse duration. That is, through such a relationship obtained by observing the craters produced by discharges with different pulse durations(5), the temporal changes in the arc plasma diameter could be determined. According to this assumption, the arc plasma keeps expanding even after several dozen microseconds from dielectric breakdown. However, from the computed results of unsteady heat conduction analysis using this model, it was found that the analytical result contradicted the experimental one, because the molten area of the electrode was much deeper than that of the actual crater created by a single discharge(6). This result means that the expanding process of the arc plasma in EDM, as well as the assumption that the diameter of the arc plasma is equal to that of the crater, have not been confirmed yet.

In this research, the expansion of the arc plasma and crater formation were therefore investigated analytically and experimentally. That is, the arc plasma was observed with a high-speed video camera, and the plasma temperature after dielectric breakdown was also measured by spectroscopy. In addition, the diameter of the heat affected area and molten area of discharge crater were estimated by the unsteady heat conduction analysis using a new quick...
expanding plasma model, the results of which were compared with experimental ones. Moreover, by comparing the analytical results with experimental ones, the observed expanding process of the arc plasma and crater formation were examined and discussed.

2. Experimental Apparatus and Method for Observing Arc Plasma

2.1 Experimental apparatus

Figure 1 shows the schematic illustration of the experimental apparatus. The arc plasma was photographed with a high-speed video camera (made by Photron Limited). The radiant intensities of specific wavelengths emitted from the plasma were measured with an optical fiber, spectrometer and photo-multiplier. The plasma temperature was then calculated by the line pair method(7). As shown in Fig. 1, the radiant intensities of two wavelengths emitted from plasma were measured simultaneously by a branched bundle of the optical fiber. A current sensor was used to synchronize the photographing and the measurement of the radiant intensities with the discharge.

2.2 Experimental method

Since the inter-electrode area is almost filled with bubbles during the EDM process(8), igniting a single discharge in air is more realistic than in liquid. A single discharge was therefore ignited in air. The discharge conditions were; peak current of 20 A, pulse duration of 300 µs, and open voltage of 500 V. Two copper rods of 2.0 mm in diameter, the discharge surfaces of which were polished to spheres with 2.0 mm curvature radius, were used as the tool and workpiece electrodes. In this research, both tool and workpiece electrodes were just called electrodes for simplicity, because the difference in phenomena between the anode and cathode were not discussed here. The spherical electrodes were used to decrease the obstruction of light emitted from plasma so that more light could enter the high-speed video camera and optical fiber.

Meanwhile, for discharges in air, dielectric breakdown usually does not occur unless the gap width is shortened to several micrometers, which is different from the actual gap width in the EDM process. Therefore, in order to make the gap width in air nearly equal to that in the actual EDM process, spherical copper particles used as dummy debris were placed on the electrode surface. The particle diameter was about 20 µm. The dummy debris enabled discharge at a gap width of about 100 µm. On the other hand, high-speed video camera settings were; frame rate of 16,000 fps and exposure time of 1/128,000 s (about 8 µs). Figure 2 shows the time relationship between the photographing gate signal of the high-speed video camera and the waveform of discharge current. As shown in the figure, the exposure was carried out just before the photographing gate signal.

3. Experimental Results and Discussions

3.1 Direct observation of EDM arc plasma

Figure 3 shows the timing of photographing gate signals for photographed frames using the high-speed video camera. In this study, the single discharge was carried out many times in order to observe the change in the arc plasma with the passage of time after dielectric breakdown. Figure 4 is the photographing results. The frame (0) in Fig. 4 shows the electrodes before breakdown, and frames (1) to (14) show the arc plasma which was observed in the time shown in Fig. 3. It was found that the diameter of the emitting area already expanded to 0.6 mm or
0.7 mm in a few microseconds from the beginning, though the intensity of the plasma light in the first stage after the breakdown was weak. These results show that the expansion of plasma completed within a few microseconds after the dielectric breakdown. This fact is quite different from the theory that the arc plasma in EDM keeps expanding even after several dozen microseconds from the dielectric breakdown, which has been believed true until now.

3.2 Observation of discharge crater

In order to observe the diameter change of the crater produced by a single discharge with the passage of time, the crater diameters corresponding to different pulse durations were measured. Figure 5 shows the relationship between the discharge duration and the diameter of the molten and heat affected areas of the anode, while the crater picture in Fig. 6 shows the difference between the molten and heat affected areas. As shown in Fig. 6, the molten area indicates the region where the electrode material melted due to the heat of the plasma, while the heat affected area indicates the region where the electrode surface discolored due to the heat, though the material did not melt. From Fig. 5, it was found that the crater, especially the heat affected area kept growing even in several dozen microseconds after the breakdown. The fact obtained from the above section that the plasma diameter expands to 0.6 mm or 0.7 mm within a few microseconds after breakdown shows that the diameter of the arc plasma differs from that of the formed crater. In addition, Fig. 5 also shows that the diameter of the heat affected area became almost constant from 10 µs to 50 µs after breakdown.

3.3 Measured plasma temperature and discussions

To study the results that the expansion of the plasma completes within a few microseconds after breakdown, the changes in the arc plasma temperature with the passage of time were investigated. The measurement of the plasma temperature was carried out by measuring the radiant intensities of two different wavelengths of the light emitted from the arc plasma. This measurement principle is called the line pair method\(^{(7)}\). Since copper material was used for both electrodes in this study, the measured wavelengths were set to two representative wavelengths of neutral copper atom, 510.554 nm and 521.820 nm.

Figure 7 shows the measured plasma temperature and the waveform of the discharge current. It was found that the plasma temperature was almost constant with the pas-
sage of time after dielectric breakdown. If the plasma keeps expanding even after several dozen microseconds from the breakdown as it has been considered until now, the plasma temperature would decrease with the passage of time, because of the current density decrease. That is, the higher the current density was, the higher the temperature would be. However, the plasma temperature, in the period from several to several dozen microseconds after breakdown, did not show such a tendency (see Fig. 7). This may indicate that the current density was also constant during that period, namely the plasma area did not expand anymore after several microseconds from the dielectric breakdown, because the plasma temperature was almost constant with the passage of time. From the viewpoint of temperature, it may also be considered that the arc plasma finishes expanding at the first stage of breakdown.

4. Proposition and Confirmation of New Arc Plasma Expansion Model

According to the above results and discussions, a new expansion model for EDM arc plasma was proposed. This model was confirmed by comparing experimental and computed results of the formed discharge crater.

4.1 First-stage-expansion model

The diameter of plasma was assumed to expand to 0.6 mm within three microseconds after breakdown based on the observation. This proposed model is called first-stage-expansion model, because it assumes the arc plasma expands completely in the first stage of discharge. Figure 8 shows the method for analyzing electrode temperature. The 2 mm diameter electrode was segmented to meshes. The adiabatic boundary was used for the electrode side surface. On the discharge surface, a heat flux Q was supplied to the plasma area, while other areas were adiabatic. The heat flux in the arc plasma is highest at the plasma center, and it follows the normal distribution in the plasma area, considering the arc temperature is highest at center and decreases away from the center(9). The temperature of meshes 10 mm from the discharge surface was set at the ambient temperature. Besides, the power distribution rate to the electrode is set at 35% according to literature(2). The electrode material is copper, same as that used in experiments.

4.2 Computed results

The diameter of the area which reaches the melting point of 1 358 K is shown in Fig. 9. In this study, the region where the temperature has exceeded the melting point during the electric discharge duration is considered the molten area. That means, even if the molten material re-solidifies afterwards, the region is also called molten area. From these results, it was found that the diameter of the molten area did not grow with time in this analysis. The reason why the diameter of molten area did not change is considered as follows; In the first stage of discharge, the temperature at the discharge point exceeds the melting point, because the heat flux is large for small arc plasma. However, with the passage of time the arc plasma expands quickly and the heat flux to the electrode surface becomes much lower, and finally the molten material re-solidifies and the area where the temperature exceeds the melting point disappears because the heat flux becomes too week.

As for the heat affected area on the electrode discharge surface shown in Fig. 6, the temperature at which the electrode surface changes its color is not clear yet. In this study, analysis was conducted assuming that the region where the temperature has exceeded over 750 K was the heat affected area. The relationship between the computed diameter of the heat affected area and time passage after breakdown is also shown in Fig. 9. The result shows that the diameter of the heat affected area keeps growing even after several dozen microseconds. It was also found that the diameter of the heat affected area was almost constant in the first stage of discharge, which agreed with the experimental result shown in Fig. 5. In order to investigate the phenomena occurring in the first stage of discharge, the change in temperature at electrode center was analyzed. The result shown in Fig. 10 indicates that,
in the first stage, the temperature is high because of strong heat flux, while it becomes low due to arc plasma expansion and weak heat flux. After a certain time, the temperature increases gradually again due to continued supply of heat energy to the electrode with the passage of time. The expanding process of the arc plasma and the increasing energy distributed to electrodes with the passage of time explain the phenomenon that there exists a period when the diameter of the heat affected area remains constant.

4.3 Discussions on arc plasma expansion

In order to demonstrate that the first-stage-expansion model is nearer to the actual situation, the molten areas under the conventional and the proposed models were computed. Because the relationship between the diameter of discharge crater and the pulse duration\(^5\) was obtained when carbon steel was used as the electrode material, computation was carried out for carbon steel electrode. The expansion of the arc plasma diameter is shown in Fig. 11. The computed diameter and depth of the molten area is shown in Fig. 12. The figures show that the diameter of obtained diameter of the molten area is considerably smaller than that of arc plasma in the new model, and close to that of the experimentally obtained discharge crater. This result proves that the diameter of molten area could differ from that of arc plasma. Furthermore, it is found that the molten area of the first-stage-expansion model is much shallower than that of the conventional model, although the diameters do not differ greatly. The ratio of the depth to diameter is 0.17 for the new model and 0.42 for the conventional one at 200 µs. Considering that the depth/diameter ratio of most discharge craters is about 0.1, it is rational to say that the first-stage-expansion model proposed in this study is closer to the actual EDM process than the conventional model.

5. Conclusions

In this research, observations of the arc plasma with a high-speed video camera showed that the expansion of the arc plasma in the EDM process completed within only a few microseconds after dielectric breakdown, which was quite different from what has been accepted until now. Based on this observation, a new model of EDM arc plasma expansion, called first-stage-expansion model, was proposed. This new model of arc plasma expansion was verified experimentally by the measurement results of plasma temperature. Furthermore, the computed discharge crater shows that the first-stage-expansion model is closer to the actual EDM process than the conventional model.

References
