A Study on the Material Removal Mechanism in EDM
- Single Discharge Experiments with Low Melting Temperature Alloy -

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1. Introduction

EDM (electrical discharge machining) is one of advantageous methods to shape very hard materials into complicated form. In EDM, material is removed due to accumulation of a very small crater generated on surface by heat energy of single discharge. In order to fundamentally elucidate mechanism of material removal in EDM, it is necessary to clarify mechanism of the single discharge. It has been reported that craters formed on carbon steel (AISI-1049) or brass by the single discharge are small and they have complicated shapes [1]. It is considered that melting point of these test materials are so high that few volume is removed from test piece in the single discharge. Because the heat energy of the single discharge is very small. Therefore, it was difficult to directly investigate the mechanism of the material removal from these small craters. In this paper, we use low melting temperature alloy (LMTA, melting point 47 degrees Celsius). It is expected that large amount of volume is removed by the single discharge to the LMTA. We observe craters on the LMTA and investigate its removed volume, changing pulse duration, polarity of electrode, dielectric fluid and electrode diameter. We also investigate debris of the LMTA. Based on these experimental results, we discuss the mechanism of material removal in EDM.

2. Single Discharge Experiments on the LMTA

Table 1 shows experimental conditions. We developed power circuit to achieve the single discharge. Fig.1 shows typical SEM images of craters and cross sections under the condition using kerosene oil. The shape of the crater formed on the LMTA is close to a part of sphere as shown in Fig.1 (a). On the other hand, the shape of the crater formed on the carbon steel (AISI-1049) has complicated shape as shown in Fig.1 (b). Fig.2 shows relationship between the pulse duration and diameter (D in Fig.1 (a)) of the craters formed on the LMTA. Fig.3 shows relationship between the pulse duration and depth (H in Fig.1 (a)) of the craters formed on the LMTA. Fig.4 shows relationship between the pulse duration and the removed volume calculated from the diameter and the depth. The diameter increases according to the pulse duration under all conditions. Although it is considered that molten volume by heat energy of discharge increases according to the pulse duration, the removed volume decreases over 200µs pulse duration due to the shallow depth under the condition using negative polarity of electrode and the kerosene oil. In the conventional studies, it was estimated that a part of molten material is blown off by movement of a bubble generated in the dielectric fluid and the rest of them leaves as the resolidified layer [1]. Therefore, in regard to the results of the LMTA, we can estimate that the resolidified layer remains under the craters.

3. The Cross Sections of the Craters on the LMTA

In order to make sure of existence of the resolidified layer, we conduct experiments to observe the cross sections of the craters on the LMTA. Fig.5 shows experimental procedure. In the first step, two workpieces are adhered together. In the second step, single discharge is carried out on the adhesive line between the two workpieces. After that, we divide the adhered workpiece into two parts and observe the cross sections. Fig.6 shows typical SEM images of the cross sections under the condition using the kerosene oil. The resolidified layer remains under the craters when the pulse duration is 200µs or 400µs. Fig.7 shows relationship between the pulse duration and

| Table.1 Single discharge conditions |
|---------------------|---------------------|
| Electrode           | W (φ 0.1mm), polarity : (-), (+) |
| Work piece          | Low melting temperature alloy (LMTA) |
|                     | Carbon steel (AISI-1049) |
| Open voltage        | 100V |
| Current             | 20A |
| Pulse duration      | 25, 50, 100, 200, 400µs |
| Dielectric fluid    | Kerosene oil, De-ionized water |


Fig. 1 SEM images of the craters and cross section profile

Fig. 2 Relationship between pulse duration and diameter of discharge crater

Fig. 3 Relationship between pulse duration and depth of discharge crater

Fig. 4 Relationship between pulse duration and removed volume per discharge

Fig. 5 The observation method of cross sections of craters

Fig. 6 Cross sections of the craters

<table>
<thead>
<tr>
<th>Pulse duration</th>
<th>Electrode(−)</th>
<th>Electrode(+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25μs</td>
<td>Removal</td>
<td>Removal</td>
</tr>
<tr>
<td>200μs</td>
<td>Resolidified layer</td>
<td>Resolidified layer</td>
</tr>
<tr>
<td>400μs</td>
<td>Resolidified layer</td>
<td>Resolidified layer</td>
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</tbody>
</table>
the removed or molten volume under the negative polarity in the kerosene oil. Under this condition, the
volume of the resolidified layer increases according to the pulse duration as shown in Fig.7. Fig.8 shows
relationship between the pulse duration and the removed or the molten volume under the positive polarity in
the kerosene oil. The volume of the resolidified layer does not increase extremely. In de-ionized water, the
volume of the resolidified layer shows the same tendency as Fig.8. If the time required for all molten part to
be resolidified is same under the all conditions, we can estimate that timing of the material removal is late
only under the positive polarity in the kerosene oil.

3. The Debris of the LMTA

The debris of the LMTA is expected to involve information regarding the timing of the material
removal and molten state at that time. So, we conduct the experiments to observe of the debris. Fig.9 shows
SEM images of the debris of the LMTA under the condition using the kerosene oil. Fig.10 shows shapes of
the each debris. The debris consists of a lot of spherical debris and some non-spherical ones over 100µm long.
It is considered that the debris become spherical when the temperature of the molten part is high at the
moment of removal, on the contrary, the debris become non-spherical when the temperature of the molten
part is low at the moment of removal. Fig.11 shows relationship between the pulse duration and number of
the non-spherical debris per unit removal volume. Under the negative polarity in the kerosene oil, the
number of the non-spherical debris increases extremely at 400µs pulse duration. Considering increase of
both the resolidified layer and the non-spherical debris under the negative polarity in the kerosene oil, we
can estimate that the material is removed after the temperature of the molten part drops around melting
point, and most of the molten part is resolidified. The reason that the number of the non-spherical debris is
much more under the positive polarity in de-ionized water than the other conditions has not been cleared
yet.

4. Effect of Electrode Diameter

The maximum diameter of the bubble generated in the dielectric fluid by single discharge is a few
millimeters [2]. It is considered that electrode of 0.1mm in diameter is so thin that effect of the bubble on the
material removal decrease. In order to investigate the effect of the electrode diameter, we conduct single
discharge experiments using tungsten electrode of 3mm in diameter under the negative polarity in the
kerosene oil. Fig.12 shows the effect of the electrode diameter on the depth of the craters. Fig.13 shows the
effect on the removed volume. In the case of using the thick tungsten electrode, the removed volume does not
decrease over 200µs pulse duration. We can estimate that the timing of the material removal is fast, or the
effect of the bubble on the material removal increases because of large area of the electrode facing workpiece.

5. Conclusions

From the single discharge experiments with LMTA, following results are obtained.
(1) The craters on the LMTA are close to a part of sphere regardless of the polarity of electrode or a kind of
the dielectric fluid.
(2) The removed volume generally increases according to the pulse duration. It decreases over 200µs pulse
duration only under the negative polarity of electrode in kerosene oil.
(3) The number of non-spherical debris increases when the resolidified layer increases.
(4) It seems that the timing of the material removal is fast, or the effect of the bubble on the material
removal increases when the electrode diameter is larger than the bubble diameter.

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References
**Fig. 7** Relationship between pulse duration and removed or molten volume (Kerosene oil, Electrode: -)

**Fig. 8** Relationship between pulse duration and removed or molten volume (Kerosene oil, Electrode: +)

**Fig. 9** Wide SEM images of debris of LMTA

(a) 25µs
(Kerosene oil, Electrode: -, I:20A)

(b) 400µs
(Kerosene oil, Electrode: +)

**Fig. 10** Shape of debris of LMTA

(a) Spherical debris

(b) Non-spherical debris

**Fig. 11** Relationship between pulse durations and the number of non-spherical debris per unit removed volume

**Fig. 12** The effect of the electrode diameter on the depth of discharge crater (Kerosene oil, Electrode: -)

**Fig. 13** The effect of the electrode diameter on the removed volume per discharge (Kerosene oil, Electrode: -)