Fundamental Investigation on EDM Characteristics of Lanthanum Hexaboride 
Applied for Cathode Parts

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Abstract

Lanthanum hexaboride (LaB$_6$) is highly expected to be applied as high-performance electron emission cathode parts in place of conventional tungsten, since it has high electron emission property due to its low work function. It is considered that EDM has good potential to machine sintered LaB$_6$ with high hardness and brittleness. However, the EDM characteristics have not yet been made clear. In this study, the die-sinker and wire EDM characteristics of sintered LaB$_6$ were experimentally investigated, compared with those of alloy tool steel SKD11. Experimental results clarified that the material removal for LaB$_6$ was processed by material fracture in addition to material melting and boiling, and die-sinker EDM with low electrode wear was possible for LaB$_6$ even under finishing conditions with short pulse durations. It was also made clear that the cutting speed in wire EDM for LaB$_6$ is larger than that for SKD11.

Keywords: EDM, Lanthanum hexaboride, Removal rate, Electrode wear, Surface roughness

1. INTRODUCTION

Recent years, electron beam devices, such as electron gun components and hollow cathodes, require precise shaping of new cathode material with high electron emission property, superior to conventional cathode made of tungsten. Newly developed lanthanum hexaboride (LaB$_6$) is one of refractory ceramic material, and it has high electron emission property, since its work function is as low as around 2.7eV. Furthermore, the filament of LaB$_6$ has 10 to 15 times longer life time, compared with that of tungsten. Therefore, LaB$_6$ has been just begun to be applied as high-performance electron emission cathode parts in place of conventional tungsten. Currently, there are two types of LaB$_6$ material, beside the coating layer by PVD; monocrystalline LaB$_6$ and sintered one, but the monocrystalline LaB$_6$ is difficult to grow to a practically large size so far. Therefore, sintered LaB$_6$ is generally used for industrial products at present. In order to make filaments and hollow cathodes, it is necessary to precisely machine the sintered LaB$_6$ into desired shapes. However, the machining of sintered LaB$_6$ by mechanical machining methods, such as milling, is very difficult due to its high hardness and high brittleness. It is expected that electrical discharge machining (EDM) has a high potential to precisely machine such a hard and brittle material because of noncontact processing with small machining force acting on tool electrode and workpiece. However, the EDM characteristics of LaB$_6$ has not yet been made clear.

Thermal and electrical properties of LaB$_6$ and alloy tool steel SKD11 are listed in Table 1\(^{1,2}\). The melting point and thermal conductivity of LaB$_6$ are higher than those of SKD11. EDM is a thermal removal processing, and the lower melting point and thermal conductivity of workpiece material, the larger the removal volume by a single discharge and the higher the EDM machinability\(^{31}\). Therefore, it is guessed that LaB$_6$ would be more difficult to be machined by EDM than SKD11. On the other hand, LaB$_6$ has high electron emission property because of its low work function. From this point of view, it is expected that the discharge frequency of LaB$_6$ might be higher than that of SKD11, which results in high removal rate. In this study, die-sinker and wire EDM characteristics of LaB$_6$ were experimentally investigated, and compared with those of SKD11.

| Table 1 Thermal and electrical properties of LaB$_6$ |
|-----------------------------------------------|
| Melting point $\theta_m$ [K] | LaB$_6$ | SKD11 |
|-----------------------------------------------|
| 2,803 | 1,698 |
| Thermal conductivity $\Lambda$ [W/(m$\cdot$K)] | 47 | 29.3 |
| Density $d$ [g/cm$^3$] | 4.72 | 7.72 |
| Work function $\Phi$ [eV] | 2.68 | 4.21 |
| Electric resistivity $\rho$ [$\mu$Ω$\cdot$cm] | 15 | 10 - 20 |
2. EXPERIMENTAL PROCEDURE

EDM experiments were carried out by using a die-sinker electrical discharge machine with linear servo motor drive (Sodick AP1L). A cylindrical copper of 10 mm in diameter was used as an electrode. The workpiece materials were sintered LaB$_6$ and alloy tool steel SKD11. Experimental conditions are listed in Table 2. They are based on the EDM maker recommended conditions for steel, and the pulse durations $t_e$ were varied from 3 to 30$\mu$s in order to discuss the effect of pulse durations on removal rate and electrode wear ratio.

In addition, wire EDM experiments were carried out by using a wire electrical discharge machine (Sodick AP200L). Working oil was selected as working fluid, and a brass coated steel wire with a diameter of 50$\mu$m was used, since it is necessary to precisely machine the sintered LaB$_6$ for fabricating electron emission parts. The electrical conditions were the EDM maker recommended conditions in normal electrode polarity for 1st-cut of alloy tool steel SKD11.

Table 2 Die-sinker EDM conditions

| Electrode (Polarity $P$) | Copper ø10mm (+) |
|-------------------------|------------------|
| Workpiece              | LaB$_6$, SKD11  |
| Discharge current $t_e$ | 6A               |
| Pulse duration $t_e$    | 3, 9, 15, 30$\mu$s |
| Working fluid           | Oil              |
| Open circuit voltage $V$| 90V              |
| Servo reference voltage $S_v$ | 60V         |
| Duty factor $\tau$      | 60%              |

3. DIE-SINKER EDM CHARACTERISTICS

3.1 Removal Mechanism

EDMed surfaces were observed by using a scanning electron microscope (SEM). The SEM images at various pulse durations are shown in Fig. 1. For comparison, the fractured surface is also shown. The EDMed surface at short pulse duration $t_e=3\mu$s is occupied with resolidified layer, similarly to general EDMed surface of metals. On the other hand, some fractured areas can be found on the surface at long pulse durations $t_e=9$-$30\mu$s, as shown with the white frames in the images. Furthermore, the fractured area becomes wider with the pulse duration.

In order to confirm the material fracture on the EDMed surface, debris generating during the process were observed. Fig.2 shows the SEM and element mapping images of the debris generated in EDM processes for LaB$_6$ and SKD11 at the pulse durations $t_e=3\mu$s and $t_e=30\mu$s.
of 3 and 30 μs. The debris shape of LaB₆ is almost spherical and the particle size is less than 10 μm, similarly to that of SKD11 at the pulse duration of 3 μs. On the other hand, large size debris with non-spherical shape can be observed at 30 μs in EDM for LaB₆. Therefore, these results also indicate that the mechanical fracture occurs in EDM for LaB₆ when the pulse duration is longer than 9 μs.

There are three possible causes resulting in the local fracture. First one is high pressure acting on the EDMed surface by the rapid vaporization of working fluid with high temperature of discharge. Second one is high pressure generation just under the surface by the vaporization of working fluid intruding into pores in the sintered LaB₆ with high temperature of discharge. The other is crack generation and propagation resulting from the residual tensile stress due to resolidification of workpiece material on the surface. Therefore, it is considered that the material removal is done not only by the evaporation and melting of material with high temperature of discharge but also by mechanical fracture for sintered LaB₆ when the pulse duration is longer than 9 μs. Furthermore, it is found that EDM has good potential to precisely machine LaB₆ when the pulse duration is shorter than 3 μs, since the mechanical fracture does not occur in EDM for LaB₆ at the pulse duration of 3 μs shown in Fig. 1.

In addition, it was concerned that the EDMed LaB₆ surface may change its material structure because the surface was subjected to high temperature of electrical discharge. Then, the surface structure of EDMed LaB₆ surface at the pulse duration of 30 μs was evaluated by using an X-ray diffraction (XRD). The XRD spectra for the EDMed surface and ground one are shown in Fig. 3. LaB₆ peaks are clearly detected on EDMed surface, and all peaks appear at the same angles in the case for ground surface. Furthermore, the other crystal structures, such as simple substance of boron or lanthanum, are not detected. Therefore, it is obvious that the crystal structure of LaB₆ surface is kept after EDM.

### 3.2 Material Removal Rate

Fig. 4 shows the variations of removal rate with pulse duration for LaB₆ and SKD11. As shown in the figure, the removal rate increases with an increase of pulse duration for both materials. The removal rate for LaB₆ is smaller than that for SKD11 when the pulse duration is shorter than 15 μs, since LaB₆ is more difficult to be machined by EDM than SKD11 because of its higher melting point and thermal conductivity, which follows the conventional theory of EDM machinability. On the other hand, the removal rate for LaB₆ is larger than that for SKD11 at the pulse duration of 30 μs. In this case, the material removal is carried out not only by the evaporation and melting with high temperature of discharge but also by mechanical fracture as proved with the SEM observation in Fig. 1.

### 3.3 Electrode Wear

The variations of electrode wear ratio with pulse duration in EDM for LaB₆ and SKD11 are shown in Fig. 5. The electrode wear ratios decrease with an increase of pulse duration for both materials. The
electrode wear ratio in EDM for LaB₆ is lower than that for SKD11 at any pulse duration, and the difference between those for LaB₆ and SKD11 becomes larger as the pulse duration is shorter. In general, the electrode wear ratio is large under finishing condition at the pulse duration of 3μs, but it is found that EDM finishing with low electrode wear ratio is possible for LaB₆, differently from the case for metal material including SKD11.

Cross-sections of copper electrode surface after EDM at the pulse duration of 3μs for LaB₆ and SKD11 were observed by using SEM, in order to investigate the cause of low electrode wear ratio for LaB₆. Fig. 6 shows the SEM and element mapping images. While iron is not detected so much on the copper electrode surface after EDM for SKD11, much lanthanum is distributed on the electrode surface after EDM for LaB₆. This result indicates that the workpiece material easily adheres to the electrode surface when LaB₆ is EDMed.

Furthermore, in order to investigate the thickness of the adhesion layers, line component analyses along the lines shown in Fig. 6 were done. Fig. 7 shows the component distributions with the distance from the surface. It is clear that the lanthanum component on the electrode surface after EDM for LaB₆ is higher than the iron one for SKD11.

When the adhesion layer thicknesses with less than 80% copper electrode component are compared, the adhesion thickness for LaB₆ is three times thicker than that for SKD11.

From these results, it was made clear that EDM with low electrode wear was possible for LaB₆ even under finishing condition at the pulse duration of 3μs, since thick LaB₆ layer adhered on the electrode surface during the EDM, and protected the electrode from the high temperature and pressure associated with discharge generation.

4. WIRE-EDM CHARACTERISTICS

4.1 Removal Mechanism

Fig. 8 shows the SEM images of wire EDMed surface of LaB₆ and SKD11 under 1st cut condition. The wire EDMed surface of SKD11 is occupied with resolidified layer. On the other hand, some fractured area, as shown with the white flames in the image, can be confirmed on the surface of LaB₆, similarly to the die-sinker EDMed surface of LaB₆ at long pulse durations shown in Fig. 1. It indicates that mechanical fracture occurs also in wire EDM for LaB₆.

Cross-sections of wire EDMed surface under 1st cut condition for LaB₆ and SKD11 were observed by using SEM, in order to investigate the cause leading to mechanical fracture in EDM for LaB₆. Fig. 9 show the SEM images, BSE (backscattered electron) images (compositional images), and element mapping images of workpiece material components. It can be confirmed that chromium carbide grains are distributed on the base material of SKD11 below the white line. It indicates that the layer from the surface to the white line is resolidified layer. On the other hand, the border between resolidified layer and base material cannot be found on the cross-section of wire EDMed surface for LaB₆, because the component distributions of lanthanum and boron with the distance from the surface are not changed. It is found that the cracks propagate parallel to the wire EDMed surface for LaB₆, while the crack propagate mostly perpendicular to the wire EDMed surface for SKD11.
Furthermore, the cross-section of wire EDM'ed surface under 1st cut condition for LaB₆ was observed by using TEM, in order to investigate the removal mechanism in detail. Fig. 10 shows the SEM image of wire EDM'ed surface for LaB₆, and the TEM image of cross-section of the surface shown with the white line in the SEM image. It is considered that the area shown with the white dotted frame in the SEM image is fractured area because the area has very smooth surface without cracks. As shown in the TEM image, it can be judged that left side part with curved surface is resolidified layer, and right side with flat surface is fractured surface. Focusing on the crystal structure of cross-section, it is obvious that the white dotted line in the image would be the border between resolidified layer and base material, because the crystal structure changes at the line. Furthermore, it can be confirmed that the crack starts just from the border around the surface. From these results, it was made clear that mechanical fracture occurs in EDM for LaB₆, since volume shrinkage occurs after the material melting and resolidification, and cracks propagate parallel to the EDM'ed surface due to the residual tensile stress.

4.2 Cutting Speed and Discharge Frequency

The cutting speeds for LaB₆ and SKD11 under 1st cut condition and the discharge frequencies during the wire EDM are shown in Fig. 11. The discharge frequencies for each discharge current peak value are shown with different hatching patterns. At first, it was expected that the discharge frequency in wire EDM for LaB₆ would be high, since it has high electron emission property due to its low work function. However, in this experiment, the discharge frequency for LaB₆ is slightly lower than that for SKD11, and the ratio of discharge number with high discharge current peak values is also lower. On the other hand, the cutting speed for LaB₆ is two times larger than that for SKD11 in spite of difficulty in EDM machinability guessed by its high thermal conductivity and high melting point. It is considered that the material removal is carried out not only by the evaporation and melting with high temperature of discharge but also by mechanical fracture as shown in Fig. 8, similarly to the case for die-sinker EDM at long pulse durations for LaB₆.

![Fig. 10 SEM image of wire EDM'ed LaB₆ surface and TEM images of cross-section](image)

![Fig. 11 Cutting speed and discharge frequency in wire EDM on LaB₆ and SKD11](image)
4.3 Surface Roughness

Fig. 12 shows the surface roughness of wire EDMed surface for LaB₆ and SKD11 at 1st, 2nd, and 4th cut conditions. The surface roughness for LaB₆ is 20% smaller than that for SKD11 under any conditions. Fig. 13 shows the SEM images of 2nd and 4th cut wire EDMed surfaces for LaB₆ and SKD11. The fractured area cannot be found on the 2nd and 4th cut wire EDMed surfaces for LaB₆, differently from the 1st cut wire EDMed surface shown in Fig. 8. While the pile up is formed at the periphery of craters on the wire EDMed surface for SKD11 by resolidification of workpiece material, the pile up can hardly be observed on the wire EDMed surface for LaB₆ under any conditions. Furthermore, as shown in Fig. 9, if the thickness from the surface to the crack is defined as the resolidified layer thickness of LaB₆, the resolidified layer thickness of LaB₆ would be thinner than that of SKD11. Therefore, it is considered that the surface roughness for LaB₆ became smaller than that for SKD11 due to difficulty in formation of the pile up in wire EDM for LaB₆.

5. CONCLUSIONS

In this study, die-sinker and wire EDM characteristics of LaB₆ were experimentally investigated and compared with those of SKD11. Main conclusions obtained in this study are as follows;

1. The removal rate in die-sinker EDM for LaB₆ under long pulse duration condition is larger than that for SKD11 against thermal machining theory of poor EDM machinability with its high thermal conductivity and high melting point, since the material removal for LaB₆ is processed by material fracture in addition to material melting and boiling.

2. EDM with low electrode wear is possible for LaB₆ even under finishing condition with short pulse duration, since thin LaB₆ layer adheres on the electrode surface during the EDM and protects the electrode from the high temperature and pressure associated with discharge generation.

3. Mechanical fracture occurs in EDM for LaB₆, since cracks propagate parallel to the EDMed surface.

4. The cutting speed in wire EDM for LaB₆ is larger than that for SKD11, since the material removal for LaB₆ is processed by material fracture in addition to material melting and boiling.

5. The surface roughness of wire EDMed surface for LaB₆ is smaller than that for SKD11, since the resolidified layer thickness of LaB₆ is thinner than that of SKD11 in addition to difficulty in formation of pile up at the periphery of craters on wire EDMed surface of LaB₆.

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