The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)

Change in surface magnetic flux density in EDM of permanent magnets

- Influence of internal temperature and shape on machined magnets

H. Takezawa\textsuperscript{a}\textsuperscript{*}, Y. Ichimura\textsuperscript{a}, N. Yokote\textsuperscript{a}, N. Mohri\textsuperscript{b}

\textsuperscript{a}Kogakuin University, 139 Inume-cho, Hachioji-shi , Tokyo 193-0802, Japan
\textsuperscript{b}National Institution for Academic Degrees and University Evaluation, Gakuen-nishimachi, Kodaira-shi, Tokyo 187-8587, Japan

\textsuperscript{*} Corresponding author. Tel.: +81-42-628-4164; fax: +81-42-628-4164. E-mail address: htake@cc.kogakuin.ac.jp.

Abstract

Traditional machining of a permanent magnet is difficult because of magnetic forces and brittleness of materials. However, electrical discharge machining (EDM), which is a non-contact thermal machining method, has carried out for shape machining of magnetic materials. Magnetic materials have a Curie point. As their magnetic flux density reduces when they are heated to a high temperature. Because EDM is a thermal process, it has the potential to control the magnetic flux density of a machined surface.

In this study, to clarify the relationship between magnetic flux density and temperature distributions in depth direction of permanent magnet by EDM, internal temperatures of magnets were investigated using a K type thermocouple during EDM. Neodymium magnets were used as work-pieces. The magnetic flux density of a machined neodymium magnet was measured. In addition, the effects of duty factor (D.F.) and in Diamagnetic Field were also examined. The results showed that the average temperature inside of the magnet is determined by the input energy, depending on the discharge conditions. A decrease of surface magnetic flux density after EDM is affected by the magnitude of the area and the amount of decrease is due to the increase of the internal temperature of the magnet. In a diamagnetic field EDM, the reduction in magnetic flux density is large compared with a regular magnetic field. However, there is no difference in internal temperature each machining. Therefore, it isn’t determined simply by the magnitude of the input energy. It can be said that combination of heat history and machined magnet shape determine the magnetic flux density.

Keywords: EDM, Permanent Magnet, Surface Magnetic Flux Density, Thermal Influence

1. Introduction

Machining of functional materials such as insulating ceramics and single-crystalline silicon ingots has attracted considerable interest in recent electrical discharge machining (EDM) studies [1,2]. Permanent magnets are examples of such functional materials that have been used in various fields and they have been made in a wide variety of shapes and sizes. A permanent magnet is traditionally produced by powder metallurgy and is characterized by high hardness and brittleness. Hence, it is difficult to machine a permanent magnet by traditional methods such as cutting and drilling. In addition, machining of permanent magnets is difficult owing to the influence of their magnetic forces.

Permanent magnets with complex shapes are first machined by die forming and then magnetized. It is believed that if machining of permanent magnets can be performed after magnetization, their range of applications could expand significantly. In this study, the authors evaluate shape machining of permanent magnets by the non-contact machining methods of EDM. Since EDM is a thermal-energy-based machining process, there is a good possibility that the magnetic flux density of a permanent magnet will change because of heating [3].

In the present report, the change in magnetic flux density in the internal direction of a magnet during 1 mm removal machining. The relationship between the decrease in magnetic flux density and internal temperature were clarified by measuring the internal temperature during the removal of 1 mm of thickness by
EDM. Moreover, the influence of the diamagnetic field was examined by also performing 1 mm removal machining in a diamagnetic field. From these results, it was clarified that internal temperature of the magnet is important in controlling the surface magnetic flux density during thermal machining of a permanent magnet.

2. Relationship between Change in Magnetic Flux Density and Discharge Conditions

A Neodymium magnet (N42, recommended temperature below 80°C) 10 mm in diameter, and 10 mm in height (manufacturer offer: 530 mT) was used for the experiment. Table 1 lists the characteristics of the Neodymium magnet. It was machined to a 1-mm depth by EDM (Sodic Co. AM3L). The electrode was made of copper and had a diameter of 11 mm. The electrode polarity was positive, and an electrode jump-up motion was applied twice per second during all machining. Each jump-up motion time was 0.2 s. A jet flow (0.12 MPa) originated from the side of the machining position. Table 2 shows the 4 types of discharge conditions. Machining of the first 1 mm depth was conducted under two conditions: slow and high machining speeds (Nos. 1 and 2 in Table 2, respectively). In subsequent processes, each 1-mm machining was conducted under the first machining condition. After each 1-mm machining, the surface magnetic flux density was measured using a Tesla meter on the machine. The measurements were obtained along a straight line passing through the center of the samples.

Figure 1 shows the change in magnetic flux density in the depth direction the EDM machining conditions Nos. 1–4. The horizontal axis represents the height of the machined magnet. The vertical axis represents the magnetic flux density of the center position after EDM machining condition No. 1. From the result of No. 3, the surface magnetic flux density decreased progressively (Fig. 1). This decrease according to the height of the magnet shows that the decrease of thermal influence is less. Because it shows almost similar value with initial magnetic flux density in each height new magnets.

However, under condition No. 2, magnetic flux density decreased to 270 mT during the first 1 mm removal. Subsequent removals were completed under condition No. 1. The magnetic flux density increased until the height of the magnet reached 6 mm. The difference in magnetic flux density after the first 1-mm removal EDM is believed to be the thermal influence caused by the discharge condition. The influence range of condition No. 2 is inferred to be an approximately 3-mm-thick domain. Subsequent removals were completed under condition No. 1 to measure the change in magnetic flux density beneath the machined surface.

Incidentally, the decrease in surface magnetic flux density after the initial 1 mm of machining under condition No. 2 was thought to be due to the large thermal influence of EDM. Therefore, the condition under which the duty factor (D.F.) is changed is considered to influence the surface magnetic flux density. The D.F. for condition Nos. 1 and 2 were set to 50%, and that for conditions No. 3 and No. 4 was set as described below. The current value and the pulse duration in condition Nos. 1 and 3 were the same; however, it was thought that thermal influence is affected by a change in heat energy input due to changing the pulse interval. Condition No. 3 used same current value and pulse duration as No. 1; however, the D.F. was increased to 90% by shortening the pulse interval. The heat energy input was 90 W. Condition No. 4 used the same current value and pulse duration as No. 1; however, the D.F. was increased to 90% by shortening the pulse interval. The heat energy input was 40 W. The initial 1-mm removal was machined under both conditions. Subsequent removals were completed under EDM condition No. 1. From the result of No. 3, the surface

Table 1. Characteristics of Neodymium magnet

<table>
<thead>
<tr>
<th>Surface magnetic flux density</th>
<th>Density</th>
<th>Thermal Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>520 mT</td>
<td>7.5 ~ 7.65 g/cm³</td>
<td>0.11 ~ 0.12 °C⁻¹</td>
</tr>
<tr>
<td>Curie Temperature</td>
<td>310 ~ 380 °C</td>
<td></td>
</tr>
<tr>
<td>Coercive Force (BHc)</td>
<td>876 ~ 923 kA/m</td>
<td>955 kA/m</td>
</tr>
</tbody>
</table>

Table 2. EDM machining conditions

<table>
<thead>
<tr>
<th>Discharge current (A)</th>
<th>Pulse duration (µs)</th>
<th>Pulse interval (µs)</th>
<th>D.F. (%)</th>
<th>Input energy (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>5</td>
<td>32</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>No.2</td>
<td>5</td>
<td>128</td>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>No.3</td>
<td>20</td>
<td>128</td>
<td>1152</td>
<td>10</td>
</tr>
<tr>
<td>No.4</td>
<td>20</td>
<td>128</td>
<td>4</td>
<td>90</td>
</tr>
</tbody>
</table>

Fig. 1 Change in magnetic flux density in the depth direction
magnetic flux density decreased with a longer D.F., although that condition used a smaller energy input per pulse. For a large energy input per pulse, the reduction in the value of magnetic flux density is reduced by a shorter D.F.. In this case, the reduction in the magnetic flux density depended on the height of the magnet, and both of the thermal influence layers were expected to be about 1 mm.

3. Internal temperature of the magnet during 1-mm removal EDM

In the previous section, the decrease in magnetic flux density was considered to be due to the discharge conditions. Therefore, in order to compare the conditions, the internal temperature of the magnet during 1-mm removal machining was measured. A K-type thermocouple with a tip diameter of ~0.5 mm was used for the internal temperature measurement. The measurement points are shown in Fig. 2. Under discharge condition Nos. 1 and 2, to investigate the change in temperature in the depth direction, the internal temperature was measured at distances of 2, 3, 4, and 5 mm from the top of the magnet. A hole, 1 mm in diameter and 5 mm in depth, was machined into the sidewall at each height from the top surface of the magnet by EDM, and a K-type thermocouple was embedded in the magnet. The inside of the hole was filled with silicon grease for heat conduction (thermal conductivity: 0.84 W/m·K). Hence, the magnet which had experienced a great deal of cavity machining was concerned an influence to thermal conductivity. Cavity machining at each height was carried out for each magnet. This study was divided into 4 experiments, and the change in temperature in the depth direction was measured. Here, 1-mm removal machining was performed. Thus, the distance between the thermocouple, and the machined surface approached 1 mm just before the end of the machining process. The output from the thermocouple was acquired at a sampling interval of 0.1 s using a data logger (KEYENCE NR-1000) until the end of the machining process.

Figure 3 shows the internal temperature recorded during the course of each experiment. Machining time under condition No. 1 was ~50 min, and under No. 2 it was ~5 min. As shown in condition No. 1 of Fig. 3 (a), 2 mm below the top of the magnet (just after machining 1 mm), the internal temperature was approximately 80°C. However, under condition No. 2, the internal temperature at the same measurement position as that in condition No. 1 increased from 130°C to 180°C at the end of machining. The distance between the machined surface and the thermocouple reduced from 2 mm to 1 mm, and this was one of the reasons for the increase temperature. Similarly, under condition No. 1, internal temperatures were 65–55°C at distances of 3–5 mm from the top (Figs. 3 (b–d)). However, under condition No. 2, the internal temperatures rose to 130°C at 3 mm (just after machining 2 mm) from the top (Fig. 3 (b)), 110°C at 4 mm (just before machining 3 mm) (Fig. 3 (c)), 70°C at 5 mm (just before machining 4 mm) (Fig. 3 (d)). At 4 mm depth and 6 mm magnet height, the internal temperature reached over 100°C. It was confirmed that it reached a high enough temperature to decrease the magnetic flux density.

4. Relationship between Magnetic Flux Density and Internal Temperature under Different D.F. Conditions

In previous experiments, the influence of different input energies was considered. A D.F. of 50% was considered, and the values of the current and pulse duration were changed. As a result, the decrease in magnetic flux density became more pronounced when input energy increased. However, the internal temperature was considered to depend on input energy. Thus, the internal temperature is closely related to the decrease in magnetic flux density.

In this section, in order to confirm the relationship described above, the machining input energy was...
changed according to the D.F.. The changes in magnetic flux density and internal temperature were measured. Machining conditions were Nos. 3 and 4 in Table 1. These machining conditions were set as follows. Condition No. 3 used similar discharge current and pulse duration as that in condition No.1. The D.F. rose to 90% (input energy: 90 W) when the pulse off time was reduced to 4 μs. Condition No. 4 was the same as condition No. 2 in that the same heat input per pulse was 10% lower in the D.F. and a longer pulse of 1152 μs was used (input energy: 40 W). The first 1 mm was removed under these EDM conditions. The magnetic flux density was measured after machining. The results are shown in Fig. 1. In addition, the internal temperatures during the first 1-mm machining under condition Nos. 3 and 4 were measured. The measurement positions and measuring conditions were the same as those described in the previous section. The temperature records under conditions Nos. 3 and 4 are shown in Figs. 4 (a–d).

When machined under condition No. 3, (Fig. 4 (a)), the internal temperature 2 mm from the top of the magnet surface (1 mm just after machining) was about 110°C. This was about 30°C higher than the internal temperature at the same position in Fig. 3 (a) under condition No. 1. The decrease in magnetic flux density was found to be due to the increase in temperature. In addition, the average temperature was high because of the high input energy. However, under condition No. 4, the discharge current was 20 A, the pulse duration was 128 μs, and the heat input energy per pulse was the same as that in condition No. 2. As shown in Fig. 4 (a), the internal temperature 2 mm from the top of the magnet (1 mm just after machining) was about 60°C. Compared with in Fig. 3 (a), it was verified that the average internal temperature tended to be lower in spite of low energy input. However, the temperature was below 80°C at the same position in Fig. 3 (a). Therefore, the decrease in magnetic flux density was greater than the decrease in magnetic flux density under condition No. 1. It was inferred that the decrease in magnetic flux density occurred in a layer directly beneath the machined surface.

5. EDM for Permanent Magnet in Diamagnetic Field

Next, the same experiment was carried out in a diamagnetic field, and the magnetic flux density and internal temperature were measured. Discharge condition Nos. 1 and 2 were used for the initial 1 mm removal. Measuring positions of the internal temperature of the magnet are shown in Figs. 2 (a–c). In order to work in a diamagnetic field, a jig as shown in Fig. 5 was used. When working in a diamagnetic field, Neodymium magnets were locked in the opposite polar direction below the magnet being machined. In this case, magnetic flux density at the top of the magnet being machined was decreased to about 450 mT.

The change in magnetic flux density in the depth direction of the material is shown in Fig. 6 for the initial 1-mm machining under condition Nos. 1 and 2 in a diamagnetic field or a regular field. In either case, after the initial 1-mm machining, the external magnetic field was removed, and 1-mm removal machining continued under condition No. 1. Furthermore, the surface magnetic flux density was measured in situ in each case. From this figure, after 1-mm machining in a diamagnetic field under condition No. 2, the surface magnetic flux density decreased about 50 mT compared with the case without a diamagnetic field. However, after 1-mm machining under condition No. 1, the surface magnetic flux density stood at the same value, and it was equal value with 9 mm height of magnet at the new magnet. Further, in change of magnetic flux density of depth direction, under the condition No.1 stand at almost same change of magnetic flux density, it found that there is no influence in diamagnetic field EDM. However, under condition No. 2, the tendency of the increase in the surface magnetic flux density was similar to that in the case with a regular magnetic field. In these results, however, the magnetic field does not increase to the same value as under condition No. 1, even after removal machining.

![Fig. 4 Internal temperature in conditions Nos. 3 and 4](image)

![Fig. 5 Schematic for the diamagnetic field jig](image)
In this study, EDM of permanent magnets, which are difficult to machine by traditional machining methods, was attempted. The change in magnetic flux density, supposedly caused by the thermal effect of EDM machining, was measured using a K-type thermocouple. In addition, magnetic flux density and internal temperature were measured for EDM carried out in a diamagnetic field. The following conclusions were derived:

1. The average temperature inside the magnet is determined by the average input energy, depending on the discharge conditions.
2. The decrease in surface magnetic flux density after EDM is influenced by the magnitude of the magnetic flux density in the diamagnetic field. The following conclusions were
determined simply by the magnitude of the input energy.
3. For EDM in a diamagnetic field, the reduction in magnetic flux density is large compared with EDM in a regular magnetic field. However, there is no difference in internal temperature due to the type of magnetic field.

These conclusions suggest that the characteristics of a magnet can be controlled during EDM machining.

Acknowledgements
This study is financially supported by the Grant-in-Aid for Scientific Research (C) (23560134) of the Ministry of Education, Science, Sports, and Culture, Japan, and the Machine Tool Engineering Foundation.

References