Relationship between bulk coercivity and coercivity of surface layer in Nd-Fe-B-based sintered magnet

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The bulk coercivity and coercivity of the polished surface layer of a Nd-Fe-B-based sintered magnet were measured systematically in order to discuss the effectiveness of observing the magnetic domain on the surface of the magnet. It was revealed that the bulk coercivity and coercivity of the polished surface layer were in a proportional relationship even though the coercivity of the surface layer was much smaller than the bulk coercivity. This suggests that the magnetization reversal that occurred in the surface layer has a mechanism similar to that inside of the magnet. The relationship between the bulk coercivity and coercivity of the surface layer was not proportional when the degree of alignment decreased, which can be explained by the increase in the local demagnetizing field on the surface of the magnet.

**Key words:** Nd-Fe-B magnet, coercivity, surface layer, degree of alignment, demagnetizing field

1. Introduction

The coercivity of a Nd-Fe-B-based magnet is an important property, especially for high temperature use, and partially substituting Nd with heavy rare earth elements such as Dy and Tb is an effective way to improve the coercivity. However, decrease in the usage of Dy and Tb has been required recently because of their limited production. The coercivity of a Nd-Fe-B-based magnet is greatly changed not only by the addition of Dy and Tb but also by the microstructure. To understand directly the relationship between the microstructure and magnetic domain structure in the magnet, several methods for evaluating the magnetic domain structure on the surface of the magnet are studied, such as the magneto-optical Kerr microscope\(^1\), magnetic force microscope (MFM)\(^3,4\) and spin-polarized scanning electron microscope (spin-SEM)\(^5,6\). However, on a polished surface of a Nd-Fe-B-based magnet, magnetization reversal progresses with a clearly smaller magnetic field than the bulk coercivity. For this reason, a method for suppressing the reduction in surface coercivity was studied recently by using fractured surface\(^7\). If we could identify the similarities and differences in the magnetic reversal process between the surface and inside of a magnet, it would be very useful for discussing the coercivity. In this study, to clarify the correlation between the surface and inside of the Nd-Fe-B-based sintered magnet, the bulk coercivity and coercivity of the polished surface layer were measured, and the influence of the Dy content, annealing condition, and degree of alignment on these coercivities was investigated.

2. Experimental method

Highly aligned (HA) and moderately aligned (MA) sintered magnets that had compositions of (30.2-x)Nd:xDy-67.6Fe-1.0B-0.9Cr-0.1Al-0.1Cu-0.1Ga (mass%) (x = 0, 1.0, 2.0, 5.0) were prepared by using an ordinary process except for pressing, which applied a different magnitude of magnetic field. Degree of alignment \( \alpha \) was defined as the following formula\(^8,9\).

\[
\alpha = \frac{B_r}{J_s}
\]

where \( B_r \) and \( J_s \) are the remanence and saturation magnetization of each sample. For example, the degree of alignment of HA and MA magnets for \( x = 0 \) was \( \alpha = 0.97 \) and 0.90, respectively. The annealing temperature after sintering was changed from 460 to 540°C. Each sample was set to 7 × 7 × 7 mm under the same grinding condition by using a surface grinder and the demagnetization curve was measured by using a BH tracer. The coercivity of the surface layer was obtained from the differential value of the step appearing in the second quadrant of the demagnetization curve, as shown in Fig. 1. It is supposed that this step in the demagnetization curve is derived from a b planes.

![Fig. 1 Illustration of bulk coercivity and coercivity of surface layer.](image-url)
surface planes located parallel to the orientation direction, which demagnetized independently of the interior of the magnet. When the coercivity was 1600 kA/m or higher, the bulk coercivity was measured by using a pulsed BH tracer. To understand the influence of the demagnetizing field on the magnet surface, a three-dimensional finite element method (3D-FEM) was used to simulate the distribution of the permeance coefficient.

3. Result and discussion

Figure 2 shows the bulk coercivity and coercivity of the surface layer of the HA magnets when changing the Dy content and annealing temperature. The bulk coercivity increased as the Dy content increased and reached the maximum value when the annealing temperature was 500°C or 520°C in each composition. It was found that the coercivity of the surface layer also varied depending on these conditions with the same tendency as the bulk coercivity, even though the
coercivity of the surface layer was much smaller than the bulk coercivity. Figure 3 shows the relationship between the bulk coercivity and the coercivity of the surface layer when the degree of alignment, the Dy content, and the annealing temperature were changed. The coercivity of the surface layer changed in proportion to the change in the bulk coercivity depending on the Dy content and the annealing temperature under the same degree of alignment. This suggests that the coercivity of the surface layer also depends on the magnetocrystalline anisotropy of the (Nd,Dy)2Fe14B main phase and the microstructure, especially around the grain boundary. This result means that the magnetization reversal occurring in the polished surface layer has a similar mechanism to the inside of the magnet. Comparing each HA magnet and MA magnet under the same composition and annealing condition, the coercivity of the surface layer had about the same value, even though the bulk coercivity in the MA magnet was larger than that in the HA magnet. When the degree of alignment decreases, it is expected that the number of grains that incline its easy axis of magnetization in the out-of-plane direction increases on the magnet surface. This may lead to an increase in the local demagnetizing field and induce magnetization reversal in the magnet surface.

To clarify the change in the demagnetizing field due to the inclination of the easy axis of magnetization on the magnet surface, we assumed the simple model shown in Fig. 4(a) and calculated the demagnetizing field by 3D-FEM. First, a $3 \times 3 \times 3$ mm cubic Nd-Fe-B magnet that was fully magnetized in the $Y$ direction was created. The mesh size had a 0.1 mm pitch, and the total number of units was 27000. Each unit was affected by the static magnetic field from the surrounding units, but there was no exchange interaction among units. Next, we focused on a $1 \times 1 \times 1$ mm of cubic Nd-Fe-B particle that existed in one plane that was parallel to the easy magnetization direction in the $3 \times 3 \times 3$ mm of cubic Nd-Fe-B magnet. The direction of the magnetization of this particle changed independently in the in-plane direction ($Y$ to $X$) and out-of-plane direction ($Y$ to $Z$) at angles of $\theta_{XY}$ and $\theta_{YZ}$, respectively. Figure 4(b) shows distributions of permeance coefficient $P$ when $\theta_{XY}$ and $\theta_{YZ}$ were changed from 0 to 45°. When $\theta_{XY} = \theta_{YZ} = 0$, the distribution of $P$ in a surface area of 1 mm square, indicated by a square line in Fig. 4(b), was relatively even. When $\theta_{YZ}$ was increased, the distribution of $P$ in the area changed greatly compared with the case in which $\theta_{XY}$ was increased. Figure 5 shows the change in average $P$ in the area with respect to $\theta_{XY}$ and $\theta_{YZ}$. The average $P$ decreased as $\theta_{YZ}$ increased, whereas it hardly changed when $\theta_{XY}$ varied. From the relation of $N = 1 / (1 + P)$, where $N$ is a demagnetizing factor, it is suggested that the local demagnetizing field becomes large when the easy axis of magnetization is tilted in the out-of-plane direction on the magnet surface. Therefore, the increase in the local demagnetizing field may promote magnetization reversal may decrease the coercivity on the magnet surface, which is the reason for the non-proportional relationship between the bulk coercivity and the surface layer coercivity when comparing HA and MA magnets.

4. Conclusion

To clarify the correlation between the surface and the inside of a Nd-Fe-B-based sintered magnet, the bulk coercivity and coercivity of the polished surface layer were measured systematically. It was revealed that the bulk coercivity and coercivity of the surface layer were in a proportional relationship, which suggests that the magnetization reversal occurring in the surface layer has a mechanism similar to the inside of the magnet. The relationship between the bulk coercivity and coercivity of the surface layer was not proportional when the degree of alignment decreased, which can be explained as the increase in the local demagnetizing field due to the low degree of alignment promoting the magnetization reversal and decreasing the coercivity on the magnet surface.

References


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