

# P1-51 Demagnetization Processes in Nd-Fe-B sintered and Ferrite Magnets Derived from Magnetic Measurement and Soft X-ray Magnetic Circular Dichroism Microscopy

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## 1. Introduction (Angular Dependence of Coercivity (ANDC), Alignment Dependence of Coercivity (ALDC) and Coercivity Mechanism)

### 1-1 Angular dependence of coercivity (ANDC)

(a) Nd<sub>12</sub>B<sub>2</sub>Co<sub>10</sub>Fe<sub>10</sub>, (b) Nd<sub>12</sub>Dy<sub>2</sub>B<sub>2</sub>Co<sub>10</sub>Fe<sub>10</sub>, (c) SrO·6Fe<sub>2</sub>O<sub>3</sub>, (d) Nd<sub>12</sub>B<sub>2</sub>Co<sub>10</sub>Ga<sub>2</sub>Fe<sub>10</sub>.

**Kronmüller Model**  

$$\frac{1}{\cos \theta} = \frac{1}{\cos^2 \theta} \times (1 + (K_1/K_2 + K_3) \tan^2 \theta + (1 + \tan^2 \theta))$$

$$K_1: 4.2 \times 10^6 \text{ J/m}^3, K_2: 0.7 \times 10^6 \text{ J/m}^3, K_3: -2.1 \times 10^6 \text{ J/m}^3$$
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### 1-2 Alignment dependence of coercivity (ALDC)

$\alpha = B_r / J_s$   
 $\beta = ((H_{c2} - H_{c1}) / H_{c1}) \times 100$   
 $H_{c1} = H_{c0} \cos \theta$   
 $H_{c2} = H_{c0} \sin \theta$

(1)  $H_{c2}$  values decrease as the alignments of magnets improve.  
 (2) Extrapolated line of  $\beta$  from  $\alpha > 0.95$  to  $\alpha = 1$  reaches ~30%.

Which models could explain the experimental results of the ALDC?

### 1-3 Schematic drawing of magnetization distribution at residual magnetization ( $B_r$ ), coercivity ( $H_{c2}$ ) and virgin state

(When  $H_{c2} > H_{c1}$ )  
 Coherent Rotation Model (S-W Model):  
 Magnetization Reverse Area at  $H_{c2}$  ( $45^\circ$  /  $\pm 15^\circ$ )  
 Magnetic Domain Wall Motion Model (D-M Model):  
 Magnetization Reverse Area at  $H_{c2}$  ( $\pm 45^\circ$ )

Which state realizes at the  $H_{c2}$ ?

### 1-4 Coercivity derived from the Alignment

Coercivity increase as the alignment improves.  
 Coercivity decrease as the alignment improves.

The ALDC shows that the coercivities of Nd-Fe-B sintered magnets are determined by the magnetic domain wall motion (MDWM).

(1) Whether the ALDC curves could explain by the magnetic domain wall motion with the postulation that every grain reverses by the  $1/\cos \theta$  or not?  
 (2) By what process does the magnetization reversal of Nd-Fe-B sintered and ferrite magnets proceed?

## 2. Discussion of the Demagnetization Process from ANDC, ALDC and Soft X-ray Magnetic Circular Dichroism (XMCD)

### 2-1 Calculation of alignment ( $\alpha$ ) and coercivity change ratio ( $\beta$ )

$$\alpha = B_r / J_s = \frac{1}{2} \int_0^\pi P(\theta) \sin 2\theta d\theta \quad (1)$$

$\alpha$ : Alignment,  $B_r$ : Residual Magnetization,  $J_s$ : Saturation Magnetization,  $P(\theta)$ : Alignment Distribution,  $\theta$ : Angle from easy magnetization direction

$$J = \frac{1}{2} \int_0^\pi P(\theta) \sin 2\theta d\theta - \int_0^{\theta_1} P(\theta) \sin 2\theta d\theta = 0 \quad (2)$$

$\theta_1$  is defined as the magnetization reversal angle at the coercivity ( $J=0$ ).

$$\beta = \left( \frac{1}{\sqrt{2} \cos \theta_1} - 1 \right) \times 100 \quad (3)$$

$\beta$ : Coercivity Change Ratio

$\beta$ s obtained from Eqs. (2) and (3) imply that every grain reverses by the  $1/\cos \theta$  law.

### 2-2 Comparison the ALDC of experiment with those of calculation using the Gaussian distribution for alignment distribution

(1) Calculation results  $\alpha$  agree well with the experimental results.  
 (2) There are significant differences between calculation results and experiments  $\beta$ .  
 (3) These results suggest that every grain does not reverse independently by the  $1/\cos \theta$  law at the coercivity.

A group of grains reverses and forms the cluster of reversed grains at  $H_{c2}$ .

### 2-3 Temperature dependence of the ALDC and the ANDC for Nd-Fe-B sintered magnets

(1) The ALDC and the ANDC vary with temperature.  
 (2) The ALDC and the angular ANDC correlate.  
 (3) As temperature increases, the ALDC and the ANDC is close to the line of  $1/\cos \theta$ .

### 2-4 Temperature dependence of the ANDC for Pr-Fe-B sintered magnets

(1) It is expected that the cluster size increases as  $\theta_1$  increases.  
 (2) When coercivity determined by the magnetic domain wall motion,  $\theta_1$  and  $\beta$  of the ultimate magnet is expected to be  $45^\circ$  and 0 respectively.

### 2-5 ALDC and ANDC for various magnets

(1) The ALDC and the ANDC of Nd-Fe-B sintered and ferrite magnets correlate each other.  
 (2) The ANDC observed in Ga doped Nd-Fe-B sintered magnets and ferrite magnets looks like those of the coherent rotation of magnetization.  
 (3) However, the ALDC of these magnets shows that the coercivities of these magnets decrease as the alignments improve. These results show that the magnetic domain wall motion determines their coercivities.

### 2-6 Comparison of $\theta_1$ obtained from calculation results and experimental results

$$\alpha = Br / J_s = \frac{1}{2} \int_0^\pi P(\theta) \sin 2\theta d\theta \quad (1)$$

$$J = \frac{1}{2} \int_0^\pi P(\theta) \sin 2\theta d\theta - \int_0^{\theta_1} P(\theta) \sin 2\theta d\theta = 0 \quad (2)$$

$$\text{Coercivity Change Ratio } (\beta) = \left( \frac{1}{\sqrt{2} \cos \theta_1} - 1 \right) \times 100 \quad (3)$$

$$\theta_1 = \cos^{-1} \left( \frac{1}{\sqrt{2}(\beta/100 + 1)} \right) \quad (4)$$

Experimental data of  $\beta$  put into Eq. (4)  
 $\beta = (H_{c2} - H_{c1}) / H_{c1} \times 100$

### 2-7 Magnetization reversal angle ( $\theta_1$ )

(1)  $\theta_1$ s of actual magnets are always larger than those of calculation results obtained Eq. (2).  
 (2)  $\theta_1$ s are similar to those with the lower alignment magnets.  
 (3) These results also imply that every grain does not reverse independently without interactions, but the number of grains forms the cluster of reversed grains.

### 2-8 $\theta_1$ , $\beta$ and expected cluster size of reversed grains

Ultimate Magnet	Coercivity Change Ratio ( $\beta$ )	Magnetization Reverse Area ( $\theta_1$ )
Nd <sub>12</sub> Ga <sub>2</sub> B <sub>2</sub> Co <sub>10</sub> Fe <sub>10</sub> ( $\alpha=0.945$ )	-5.3	41.7°
SrO·6Fe <sub>2</sub> O <sub>3</sub> ( $\alpha=0.93$ )	-6.9	40.6°
Nd <sub>12</sub> Dy <sub>2</sub> B <sub>2</sub> Co <sub>10</sub> Fe <sub>10</sub> ( $\alpha=0.96$ )	-13	36°
Nd <sub>12</sub> B <sub>2</sub> Co <sub>10</sub> Fe <sub>10</sub> ( $\alpha=0.95$ )	-18	30°
Calculation using Eq. (3) ( $\alpha=0.95$ )	-27	14°

Cluster size at  $H_{c2}$  becomes larger as  $\theta_1$  increases.

### 2-9 Spherical trigonometry

$$J = \frac{1}{2\pi} \int_0^\pi \int_0^{2\pi} Q(\omega, \tau) \sin 2\omega d\omega d\tau - \frac{1}{2\pi} \int_0^{\theta_1} \int_0^{2\pi} Q(\omega, \tau) \sin 2\omega d\omega d\tau = 0 \quad (1)$$

$$\frac{H_{c2}(\theta \geq 0)}{H_{c2}(\theta = 0)} = \frac{\cos \omega_1(\theta = 0)}{\cos \omega_1(\theta \geq 0)} \quad (2)$$

### 2-10 Calculation of the ANDC using various alignment distribution

The calculation results of the ANDC are effective at a low angle because the information obtained from the ALDC is the information of  $\theta_1$ .

The ANDC agrees well with the calculation results in a low angle ( $\theta$ ) region.

### 2-11 ANDC of Pr-Fe-B sintered magnets, the ANDC of $\theta_1 = 45^\circ$ and the Stoner-Wohlfarth model (S. W.)

(1) The ANDCs of Pr-Fe-B sintered magnets decrease from  $0^\circ$  in low temperature. (175K and 4.2K)  
 (2) It is expected that the limit of ANDC by the magnetic domain wall is expected that  $\theta_1$  is  $45^\circ$ .  
 (3) The ANDC of Pr-Fe-B is not exceed the expected ANDC from  $\theta_1 = 45^\circ$  until  $40^\circ$ . The ANDC of 4.2K is agree well with the ANDC of  $\theta_1 = 45^\circ$  until  $40^\circ$ .  
 (4) The ANDC of 4.2K is quite different from the ANDC of S.W.  
 (5) It speculates that the coercivity of Pr-Fe-B sintered magnets is determined by the magnetic domain wall motion even at 4.2K

### 2-12 The ANDC of Nd-Fe-B isotropy magnets obtained from the ALDC

The ANDCs of isotropy magnets agree well with the calculated ANDC from  $\theta_1 = 45^\circ$  until  $50^\circ$

### 2-13 X-ray magnetic circular dichroism microscopy (XMCD) and magnetization curve measures by magnetization measurement

1. From XMCD, discrete reverse grains are observe in lower demagnetization field than their coercivities.  
 2. At -0.7T for Nd-Fe-B sintered magnets and -0.2T for ferrite magnets, cluster of reversed grains is formed.  
 3. These demagnetization field is close to the  $H_d$  of these magnets in the demagnetization curve. ( $H_d$  is the demagnetization field at  $0.9B_r$ .)

### Summary (1)

Temperature	Low	High
Composition	(Pr <sub>17</sub> Fe <sub>73</sub> ) <sub>2</sub> B <sub>2</sub> (Pr <sub>17</sub> Fe <sub>73</sub> B <sub>2</sub> ) <sub>2</sub> at R.T.	Nd <sub>12</sub> Ga <sub>2</sub> B <sub>2</sub> Co <sub>10</sub> Fe <sub>10</sub> at R.T., SrO·6Fe <sub>2</sub> O <sub>3</sub> at R.T., Nd <sub>12</sub> Dy <sub>2</sub> B <sub>2</sub> Co <sub>10</sub> Fe <sub>10</sub> at R.T., Nd <sub>12</sub> B <sub>2</sub> Co <sub>10</sub> Fe <sub>10</sub> at R.T.
Magnetization Reverse Area ( $\theta_1$ )	(-45°)	41.7°, 40.6°, 36°, 30°
Cluster size of reversed grains at $H_{c2}$	Large	Small
Number of discretely reverse grains before cluster formation	Few	Many
Alignment dependence of $H_{c2}$ ( $\beta$ )	Alignment( $\alpha$ )	Alignment( $\alpha$ )
Angular dependence of $H_{c2}$ ( $H_{c2}(\theta) / H_{c2}(0)$ )	Angle ( $\theta$ )	Angle ( $\theta$ )

### Summary (2)

In magnetization reversal, discrete reversals of crystal grains occurred first in the demagnetized field region, which was lower than the coercivity. In the next step, clusters of reversed grains were formed by reversals in crystal grains around the discrete reversed grains. For highly aligned magnets, the cluster sizes at the coercivity increased with decreasing temperature, and also varied with composition. The alignment and angular dependences of the coercivity varied with cluster size, which depended on the number of discrete magnetization reversal grains that occurred in the demagnetizing field that was lower than the coercivity. Hence, if the number of discrete reversal grains was large, the cluster size was small; conversely, if the number of discrete reversal grains was small, the cluster size was significant.

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