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자화곤란축의 초기자화율을 이용한 1차 자기이방성상수 결정법

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Determination of the first anisotropy constant of uniaxial anisotropic material from initial susceptibility of magnetization hard direction

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1. Introduction

Many of ferromagnetic materials with low symmetric crystal structure such as hexagonal, tetragonal or trigonal show uniaxial magnetocrystalline anisotropy. In principle, the initial part of magnetization process in uniaxial anisotropy system is mainly governed by the first order anisotropy constant. In this work, we suggest a method to determine the first anisotropy constant from the initial susceptibility of magnetization hard direction.

2. Rigid coupled magnetization model

A) Single crystal : The first anisotropy constant K_1 is easely obtained from the equilibrium condition of free energy in H applied perpendicular to easy axis,

$$K_1 = M_s^2 / 2\ \chi_i(\perp) \qquad (1)$$

B) Powders aligned by magnetic field : If we assume a powder system with the misorientation angle of easy axis of each powder against to the alignment direction being θ_c , the free energy of the system in H applied perpendicular to the alignment direction is

$$E = K_1 \sin^2\theta_M - HM_s \cos(\gamma_c - \theta_M) \qquad (2)$$

Here, γ_c is the angle between magnetization easy axis and the applied field direction. Under equilibrium condition of free energy, and if we assume the gaussian distribution of powders

$$M(\perp) = M_0(\perp) + \frac{M_s^2 H}{2K_1} P \qquad (3)$$

where, $M_0(\perp) = M_s \dfrac{\int_{\theta_c=0}^{\pi/2}\int_{\varphi_c=0}^{\pi/2} \sin^2\theta_c \cos\varphi_c \exp\left(-\frac{\theta_c^2}{2\theta_0^2}\right) d\theta_c d\varphi_c}{\int_{\theta_c=0}^{\pi/2}\int_{\varphi_c=0}^{\pi/2} \exp\left(-\frac{\theta_c^2}{2\theta_0^2}\right) \sin\theta_c d\theta_c d\varphi_c}$ $\quad P = \dfrac{\int_{\theta_c=0}^{\pi/2}\int_{\varphi_c=0}^{\pi/2} (1-\sin^2\theta_c\cos^2\varphi_c) \exp\left(-\frac{\theta_c^2}{2\theta_0^2}\right) \sin\theta_c d\theta_c d\varphi_c}{\int_{\theta_c=0}^{\pi/2}\int_{\varphi_c=0}^{\pi/2} \exp\left(-\frac{\theta_c^2}{2\theta_0^2}\right) \sin\theta_c d\theta_c d\varphi_c}$

If we define the initial susceptibility as $\chi_i^p(\perp) = [M(\perp) - M_0(\perp)]/H$ near $H=0$, then,

$$K_1 = \frac{M_s^2}{2\ \chi_i^p(\perp)} P \qquad (4)$$

3. Two sublattice model

A) Single crystal

The free energy of a two sublattice system in H applied perpendicular to easy axis is

$$E = K_{1A}\sin^2\theta_{MA} + K_{1B}\sin^2\theta_{MB} - M_A H \sin\theta_{MA} - M_B H \sin\theta_{MB} + N_{RT} M_A M_B (\sin\theta_{MA}\sin\theta_{MB} + \cos\theta_{MA}\cos\theta_{MB}) \quad (5)$$

Here, A and B represents the sublattice A and B, respectively. N_{AB} is the macroscopic exchange interaction coefficient. From equilibrium conditions,

$$2K_{1A}\theta_{MA} - M_A H + N_{AB} M_A M_B (\theta_{MB} - \theta_{MA}) = 0 \quad (6)$$

$$2K_{1B}\theta_{MB} - M_B H - N_{AB} M_A M_B (\theta_{MB} - \theta_{MA}) = 0 \quad . (7)$$

Since the total magnetization is $M(\perp) = M_A \sin\theta_{MA} + M_B \sin\theta_{MB} \approx M_A\theta_{MA} + M_B\theta_{MB}$,

$$K_{1B} = \frac{2K_{1A}M_B^2 - N_{AB}M_A M_B (M_A + M_B)^2 + 2N_{AB}K_{1A}M_A M_B \chi_i(\perp)}{4K_{1A}\chi_i(\perp) - 2N_{AB}M_A M_B \chi_i(\perp) - 2M_A^2} \quad (8)$$

B) Powders aligned by magnetic field : The free energy of the two sublattice powder in H applied perpendicular to the alignment direction can be expressed by

$$E = K_{1A}\sin^2\theta_{MA} + K_{1B}\sin^2\theta_{MB} - M_A H \cos(\gamma_c - \theta_{MA}) - M_B H \cos(\gamma_c - \theta_{MB}) + N_{AB} M_A M_B (\sin\theta_{MA}\sin\theta_{MB} + \cos\theta_{MA}\cos\theta_{MB}) \quad (9)$$

From equilibrium conditions,

$$2K_{1A}\theta_{MA} - M_A H \sin\gamma_c + N_{AB} M_A M_B (\theta_{MB} - \theta_{MA}) = 0 \quad (10)$$

$$2K_{1B}\theta_{MB} - M_B H \sin\gamma_c - N_{AB} M_A M_B (\theta_{MB} - \theta_{MA}) = 0 \quad . (11)$$

The magnetization observed in field direction is

$$M_j(\perp) = \sin\theta_c \cos\varphi_c (M_A + M_B) + (1 - \sin^2\theta_c \cos^2\varphi_c)(C_A^L M_A + C_B^L M_B) H \quad (12)$$

where, $C_A^L = \frac{2K_{1B}M_A - N_{RT}M_A M_B (M_A + M_B)}{4K_{1A}K_{1B} - 2N_{RT}(K_{1A} + K_{1B}) M_A M_B}$ and $C_B^L = \frac{2K_{1A}M_B - N_{RT}M_A M_B (M_A + M_B)}{4K_{1A}K_{1B} - 2N_{RT}(K_{1A} + K_{1B}) M_A M_B}$

Therefore,

$$K_{1B} = \frac{2K_{1A}M_B^2 P - N_{AB}M_A M_B (M_A + M_B)^2 P + 2N_{AB}K_{1A}M_A M_B \chi_i^p(\perp)}{4K_{1A}\chi_i^p(\perp) - 2N_{AB}M_A M_B \chi_i^p(\perp) - 2M_A^2 P} \quad (13)$$

Table 1. The magnetic parameters, K_1 and K_{1RE} of $RE_2Fe_{14}B$ at 4.2 K

$RE_2Fe_{14}B$ (RE=)	σ_s^+ [Am^2/kg]	$\chi_i(\perp)$ [Am^2kg^{-1}/T]	N_{RT}^{++} [T/Am^2kg^{-1}]	K_1 [J/kg]/[MJ/m^3]	K_{1RE} [J/kg]/[MJ/m^3]
Ce	153.8	48	-	-	-
Pr	193.2	5.4	-2.59	2300 / 17s	4800 / 36
Gd	88.9	41	1.48	100 / 0.8	-
Tb	66.2	2.5	1.42	870 / 6.9	1500 / 12
Dy	56.5	2.7	1.36	590 / 4.8	860 / 6.9