Bulletin of the Faculty of Engineering,
Hokkaido University, No. 77 (1975)

Angular and Magnitude Dispersion of Uniaxial Anisotropy Resulting from Constraint Energy in Magnetic Films

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(Received March 31, 1975)

Abstract

In an attempt to clarify the origin of the anisotropy dispersion in magnetic films, angular and magnitude dispersion of the uniaxial anisotropy which results from the constraint energy is estimated for nickel and nickel-10% iron films. According to the results obtained, the ranges of magnitude dispersion are $(3\sim5.8)\times10^3$ erg/cc in nickel films and $(0.72\sim0.93)\times10^3$ erg/cc in nickel-10% iron films, and the ranges of angular dispersion are $(0\sim10)$ degrees in nickel film and $(0\sim4)$ degrees in nickel-10% iron film. Angular dispersion obtained in this work is not large enough to explain the experimentally-observed angular dispersion, and it was found that the effects of the magnetocrystalline anisotropy and the internal stress in the films on the anisotropy dispersion should be added to the results obtained in this work.

1. Introduction

It has been known that uniaxial magnetic anisotropy is induced in the film plane when a polycrystalline magnetic film is deposited onto a substrate in the presence of a dc magnetic field. The direction of easy magnetization, in this case, was observed to agree with that of the dc magnetic field. The origin of this induced uniaxial anisotropy in alloy films is best explained[1] by a combination of the short-range directional ordering mechanism of Néel[2] and Taniguchi[3] and the magnetoelastic constraint mechanism of West[4].

On the other hand, angular and magnitude dispersion of the uniaxial anisotropy was observed in nickel, and in nickel-iron alloy films[5,6]. Assuming that a polycrystalline film is an ensemble of randomly oriented crystallites, angular dispersion is attributed to variations in the local anisotropy from crystallite to crystallite[5,7~9]. This local anisotropy is considered to be magnetocrystalline anisotropy and/or anisotropy resulting from magnetoelastic energy which is due to the internal stress in the film[9].

Experimentally-observed angular dispersion is large in nickel and nickel rich nickel-iron films. Cundall and King[7,8], and Maeda and Morimoto[10] have reported the observed values of angular dispersion of approximately 60 and 10 degrees for nickel and nickel-10% iron films, respectively. In nickel film, the Néel-Taniguchi mechanism may not play a role and the constraint mechanism alone will contribute to the uniaxial anisotropy. In nickel-10% iron film, both mechanisms will contribute

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to the uniaxial anisotropy but the contribution of the constraint mechanism is dominant.

If a polycrystalline magnetic film is composed of randomly oriented crystallites and the uniaxial anisotropy results from the constraint mechanism alone, angular and magnitude dispersion of the uniaxial anisotropy is expected without considering the local anisotropy. The purpose of this work is, in an attempt to clarify the origin of the dispersion of the uniaxial anisotropy, to estimate angular and magnitude dispersion of the uniaxial anisotropy which results from the constraint mechanism.

2. Constraint Energy of Crystallite

It is assumed in this work that the polycrystalline magnetic film of volume V is composed of randomly-oriented N small-crystallites of volume v_j:

$$V=\sum_{j=1}^{N} v_j\,, \tag{1}$$

and that each crystallite is a single crystal. The constraint energy density in a cubic crystal, which is due to the constraint mechanism, is given by West[4] as follow;

$$\begin{aligned} w(\alpha_i,\beta_i)= &-(9/4)(C_{11}-C_{12})\lambda_{100}\lambda'_{100}(\alpha_1^2\beta_1^2+\alpha_2^2\beta_2^2+\alpha_3^2\beta_3^2) \\ &-9C_{44}\lambda_{111}\lambda'_{111}(\alpha_1\alpha_2\beta_1\beta_2+\alpha_2\alpha_3\beta_2\beta_3+\alpha_3\alpha_1\beta_3\beta_1)\,, \end{aligned} \tag{2}$$

where C_{11}, C_{12} and C_{44} are the cubic elastic constants, λ_{100} and λ_{111} are the single crystal magnetostriction constants at a measuring temperature T, λ'_{100} and λ'_{111} are that at a constraint temperature T', and α_i and β_i are the direction cosines of the magnetization relative to the cubic axis at T and T', respectively. The temperature T' is, approximately, the substrate temperature when the film is deposited[10]. Then, the constraint energy density of the crystallite of volume v_j, $w_j(\alpha_i,\beta_i)$, is defined by

$$W=\sum_{j=1}^{N} w_j(\alpha_i,\beta_i)\,v_j\,, \tag{3}$$

where W is the constraint energy of volume V.

To simplify the problem, the surfaces of crystallites, which are parallel to the film plane, are assumed to be composed of {001}, {110}, and {111} planes; $N=N^{\{001\}}+N^{\{110\}}+N^{\{111\}}$. $N^{\{ijk\}}$ is a number of small crystallites whose surfaces parallel to the film plane are $\{ijk\}$ planes. When dc magnetic fields (H_1 during diposition and H_2 during measurement), which are large enough to saturate the magnetization to its own direction, are applied parallel to the film plane, $w_j(\alpha_i,\beta_i)$ is obtained for each crystallite.

For $N^{\{001\}}$ crystallites, we obtain the expression of the constraint energy density from Eq. (2) as

$$w^{\{001\}}(\theta,\xi)=A_{\{001\}}\cos^2\xi+B_{\{001\}}\sin 2\xi+a\ \mathrm{const}\,, \tag{4}$$

where

$$A_{\{001\}}=(9/4)\Big[\Big\{(C_{11}-C_{12})\lambda_{100}\lambda'_{100}-2C_{44}\lambda_{111}\lambda'_{111}\Big\}\sin^2 2\theta-(C_{11}-C_{12})\lambda_{100}\lambda'_{100}\Big]\,, \tag{5}$$

$$B_{\{001\}}=(9/16)\Big\{(C_{11}-C_{12})\lambda_{100}\lambda'_{100}-2C_{44}\lambda_{111}\lambda'_{111}\Big\}\sin 4\theta\,, \tag{6}$$

θ is an angle between ⟨100⟩ and H_1, and ξ is an angle between H_1 and H_2. Because of the random orientation of the crystallite axis in the film plane, θ varies from crystallite to crystallite in the range of 0 to 180 degrees.

For $N^{(110)}$ crystallites, we obtain the expression from Eq. (2) as

$$w^{(110)}(\theta, \xi) = -A_{(110)} \cos^2 \xi + B_{(110)} \sin 2\xi + a \text{ const}, \qquad (7)$$

where

$$A_{(110)} = (9/8)\Big[\big\{(C_{11}-C_{12})\lambda_{100}\lambda'_{100} - 2C_{44}\lambda_{111}\lambda'_{111}\big\}(3\cos^2\theta - 1) \times \cos 2\theta + 4C_{44}\lambda_{111}\lambda'_{111}\Big], \qquad (8)$$

$$B_{(110)} = (9/16)\big\{(C_{11}-C_{12})\lambda_{100}\lambda'_{100} - 2C_{44}\lambda_{111}\lambda'_{111}\big\} \times (3\cos^2\theta - 1)\sin 2\theta, \qquad (9)$$

and θ is an angle between ⟨001⟩ and H_1.

For $N^{(111)}$ crystallites, we obtain the expression from Eq. (2) as

$$w^{(111)}(\theta, \xi) = -A_{(111)} \cos^2 \xi + a \text{ const}, \qquad (10)$$

where

$$A_{(111)} = (3/4)\big\{(C_{11}-C_{12})\lambda_{110}\lambda'_{110} + 4C_{44}\lambda_{111}\lambda'_{111}\big\}. \qquad (11)$$

In this case, θ is taken to be an angle between ⟨1$\bar{1}$0⟩and H_1 but the results given by Eqs, (10) and (11) is independent on θ.

3. Uniaxial Anisotropy of Crystallite

Magnetic torque, L, which results from the constraint energy density of a crystallite, $w^{(ijk)}(\theta, \xi)$, is given by

$$L = -\frac{\partial w^{(ijk)}(\theta, \xi)}{\partial \xi} \qquad (12)$$

For $N^{(001)}$ crystallites, substitution of Eq. (4) into Eq. (12) gives

$$L^{(001)} = K_u^{(001)} \sin 2(\xi - \varphi^{(001)}), \qquad (13)$$

where $K_u^{(001)}$ is the uniaxial anisotropy constant and

$$K_u^{(001)} = \big\{A^2_{(001)} + (2B_{(001)})^2\big\}^{1/2}, \qquad (14)$$

and

$$2\varphi^{(001)} = \tan^{-1}(2B_{(001)}/A_{(001)}). \qquad (15)$$

For $N^{(110)}$ crystallites, substitution of Eq. (7) into Eq. (12) gives

$$L^{(110)} = -K_u^{(110)} \sin 2(\xi + \varphi^{(110)}), \qquad (16)$$

where $K_u^{(110)}$ is the uniaxial anisotropy constant and

$$K_u^{(110)} = \big\{A^2_{(110)} + (2B_{(110)})^2\big\}^{1/2}, \qquad (17)$$

and

$$2\varphi^{\{110\}} = \tan^{-1}(2B_{\{110\}}/A_{\{110\}})\,. \tag{18}$$

For $N^{\{111\}}$ crystallites, substitution of Eq. (10) into Eq. (12) gives

$$L^{\{111\}} = -K_u^{\{111\}} \sin 2\xi\,, \tag{19}$$

where $K_u^{\{111\}}$ is the uniaxial anisotropy constant and

$$K_u^{\{111\}} = A_{\{111\}}\,. \tag{20}$$

4. Results and Discussions

4.1 Magnitude dispersion

It is seen from Eqs. (5), (6) and (14) that $K_u^{\{001\}}$ is a function of θ. It is also seen from Eqs. (8), (9) and (17) that $K_u^{\{110\}}$ is a function of θ. As was stated in a previous section, θ varies from crystallite to crystallite in the range of 0 to 180 degrees. Accordingly, the values of $K_u^{\{001\}}$ and $K_u^{\{110\}}$ vary from crystallite to crystallite; namely, there is a magnitude dispersion of the uniaxial anisotropy in $N^{\{001\}}$ and $N^{\{110\}}$ crystallites. On the other hand, it is seen from Eqs. (11) and (20) that $K_u^{\{111\}}$ is independent of θ; accordingly, there is no magnitude dispersion of the uniaxial anisotropy in $N^{\{111\}}$ crystallites.

For nickel and nickel-10% iron films, the values of $K_u^{\{001\}}$, $K_u^{\{110\}}$ and $K_u^{\{111\}}$ (for $T=T'=20C$) in each crystallite are calculated from Eqs. (14), (17) and (20), respectively, and the results are shown in Figs. 1 (a) and 1 (b) as functions of θ. Values of the cubic elastic constants were takeh from a paper by Einspruch and Claiborne[11]. Values of the single-crystal magnetostriction constants were taken from a paper by Birss and Lee[12] for nickel, and were interpolated from the curves of Bozorth and Walker[13] for nickel-10% iron. From the results shown in Figs. 1 (a) and 1 (b) the ranges of magnitude dispersion are found to be $(3\sim5.8)\times10^3$ erg/cc in polycrystalline nickel film and $(0.72\sim0.93)\times10^3$ erg/cc in polycrystalline nickel-10% iron film.

4.2 Angular dispersion

Eq. (13) includes $\varphi^{\{001\}}$ which is given by Eq. (15), and Eq. (16) includes $\varphi^{\{110\}}$ which is given by Eq. (18). It is seen from Eqs. (5), (6) and (15) that $\varphi^{\{001\}}$ is a function of θ. It is also seen from Eqs. (8), (9) and (18) that $\varphi^{\{110\}}$ is a function of θ. Accordingly, the values of $\varphi^{\{001\}}$ and $\varphi^{\{110\}}$ vary from crystallite to crystallite; easy direction of the magnetization changes from crystallite to crystallite; that is, there is an angular dispersion of the uniaxial anisotropy in $N^{\{001\}}$ and $N^{\{110\}}$ crystallites. On the other hand, it is seen from Eq. (19) that there is no angular dispersion in $N^{\{111\}}$ crystallites.

For nickel and nickel-10% iron films, easy directions of the magnetization (for $T=T'=20C$) in each crystallite are calculated from Eqs. (13) and (15) for $N^{\{001\}}$ crystallites and from Eqs. (16) and (18) for $N^{\{110\}}$ crystallites. The values of angular dispersion, α, which is the angle between the easy direction of the magnetization and the direction of dc magnetic field which is applied during deposition, are shown in Figs. 2 (a) and 2 (b) as functions of θ. From the results shown in Figs. 2 (a) and

2 (b) the ranges of angular dispersion are found to be (0~10) degrees in polycrystalline nickel film and (0~4) degrees in polycrystalline nickel-10% iron film.

In conclusion, the presence of angular and magnitude dispersion of the Uniaxial anisotropy which results from the constraint energy in magnetic film was pointed out. However, the estimated values of the angular dispersion is not large enough to explain the experimentally-observed angular dispersion. To explain the experimentally-observed anisotropy dispersion, the effects of the magnetocrystalline ani-

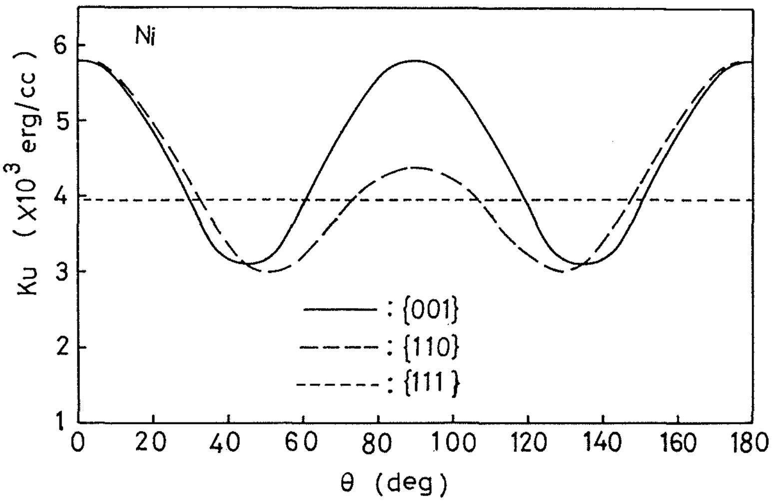

Fig. 1 (a)

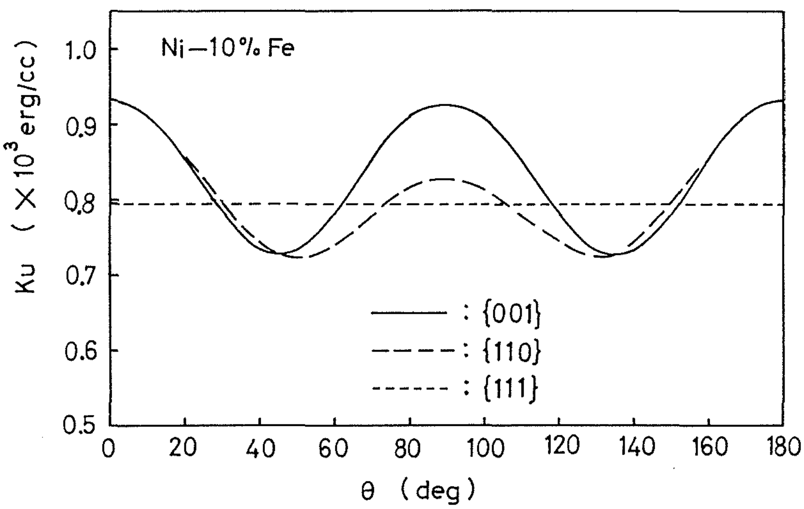

Fig. 1 (b)

Fig. 1. Uniaxial magnetic anisotropy constant K_u which results from the constraint energy plotted as a function of θ for (a) nickel and (b) nickel-10% iron films with {001}, {110} and {111} surfaces. θ is the angle between the direction of dc magnetic field during deposition and ⟨100⟩, ⟨001⟩, and ⟨1$\bar{1}$0⟩ for {001}, {110}, and {111} surfaces, respectively.

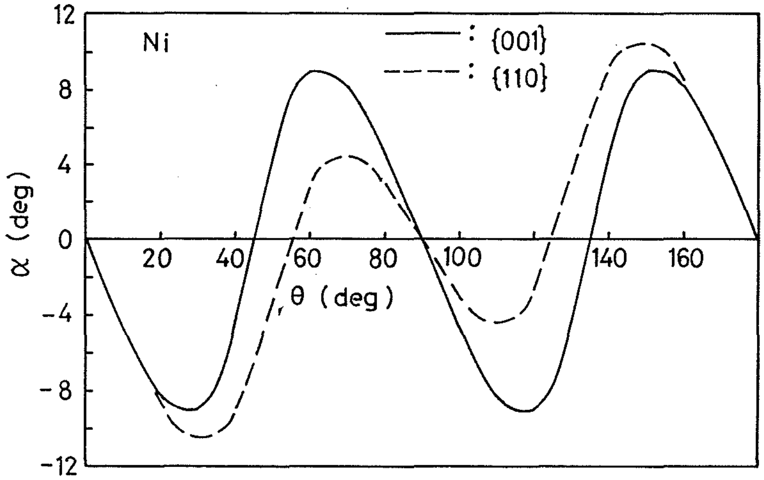

Fig. 2(a)

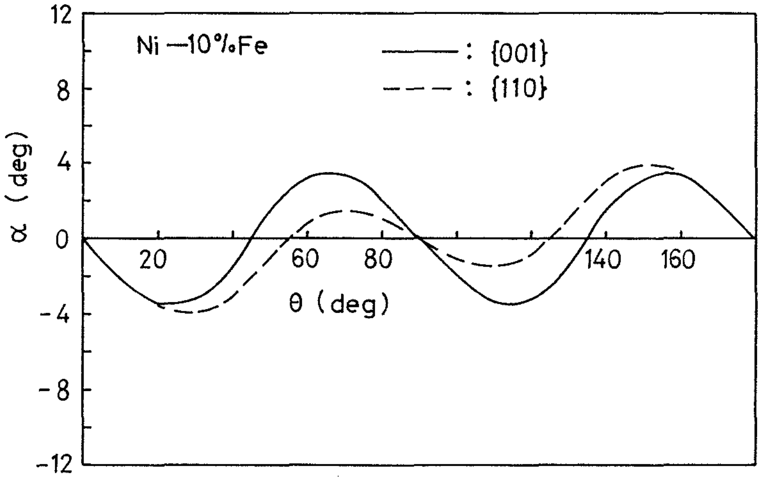

Fig. 2(b)

Fig. 2. Angular dispersion α of the uniaxial magnetic anisotropy which results from the constraint energy plotted as a function of θ for (a) nickel and (b) nickel-10% iron films with {001}, {110}, and {111} surfaces. θ is the angle between the direction of dc magnetic field during deposition and ⟨100⟩, ⟨001⟩, and ⟨1$\bar{1}$0⟩ for {001}, {110}, and {111} surfaces, respectively.

sotropy energy and the magnetoelastic energy which results from the internal stress in the film on the anisotropy dispersion should be added to the anisotropy dispersion obtained in this work.

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