

# III. Magnetic Anisotropy & Magnetoelastic Effects

참고: Chap. 6, 7 & 12 in O'Handley, Chap. 7, 8, 10 & 11 in Cullity Chap. 5 & 6 in Jiles

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## (1) Magnetic Anisotropy

### **Types and Origin of Magnetic Anisotropy**

Magnetic anisotropy : The preference for the magnetization to lie in a particular direction in a sample

Types of anisotropy	<b>Origins</b> (energy responsible)			
Crystal(or Magnetocrystalline) anisotropy	Crystal symmetry(crystal anisotropy) - the only intrinsic property			
Shape anisotropy	Sample shape (magnetostatic energy)			
Stress anisotropy	Stress (magnetoelastic energy)			
Induced anisotropy	Magnetic annealing : directional order in SS Stress annealing : anisotropic distribution of solute Plastic deformation : residual stress Magnetic irradiation : related to defects generated			
Exchange(or unidirectional) anisotropy	Exchange coupling at the interface of fine particles or through a thin layer			

#### Manetocrystalline Anisotropy

- Anisotropy field  $H_{a}$ : the field needed to saturate the magnetization in the hard direction.
- Anisotropy energy : the energy needed to saturate a materials in a particular direction



**Figure 6.1** Crystal structure showing easy and hard magnetization directions for Fe(a), Ni(b), and Co(c), above. Respective magnetization curves, below.

$$u_a = \mu_o \int_0^{M_s} H(M) dM \approx \mu_o \frac{M_s H_a}{2} (J/m^3)$$

(1st order approximation)

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### Phenomenology of Magnetocrystalline Anisotropy

### 1) Uniaxial Anisotropy (Hexagonal Anisotropy)

Ex) Co, hexagonal rare earths, barium ferrite,  $Nd_2Fe_{14}B_1$ 

- The uniaxial anisotropy energy density = the energy needed to saturate the magnetization in the basal plane (hard axis) - the energy needed to saturate the magnetization along the c axis (easy axis)

- Calculation of the *anisotropy consatant*  $K_{\mu}$  from M-H curve : rough estimation - The minimum energy surface is in the *c* direction(or in the plane normal to the *c* axis) (see Fig. 6.6 in O'Handley)

The uniaxial crystal anisotropy energy density,  $u_a$   $u_a = U_0/V_0 = \sum K_{un} \sin^{2n} \Theta = K_{uo} + K_{u1} \sin^2 \Theta + K_{u2} \sin^4 \Theta + \dots$ (a power series form) 1st order approximation,  $u_a = K_{u1} \sin^2 \Theta$ 

where  $\Theta$  is the angle of M with respect to the unique axis  $K_{uo}$  is independent of the orientation of MFor  $K_{ul} > 0$ , an oblate spheroid shape of the energy surface

For  $K_{ul}^{ul} < 0$ , a prolate spheroid shape of the energy surface

#### - Experimental data

For Co at RT,  $K_{u1} = 4.1 \times 10^5 J/m^3$  and  $K_{u2} = 1.5 \times 10^5 J/m^3$ For  $K_{u1} > 0$ , the min.  $u_a$  is along the c axis For  $K_{u1} < 0$ , the min.  $u_a$  is in the basal plane



**Figure 6.6** First-order anisotropy energy surfaces for iron (*a*), nickel (*b*), and cobalt (*c*). Insert shows the coordinate system. The length of the radius vector to any point on the surface defines the anisotropy energy density in that direction,  $(\theta, \phi)$ .

### Phenomenology of Magnetocrystalline Anisotropy

#### 1) Uniaxial Anisotropy (Hexagonal Anisotropy)

-Legendre polynomials, usually for heavy rare earth metals - Quantitative description of the magnetization process along the hard axis (see Fig. 6.7 in O'Handley) (see Fig. 6.8 in O'Handley)

$$u_a^{hex} = \sum_{l=0}^{\infty} k_l g_l(\alpha) = k_0 + k_2(\alpha^2 - \frac{1}{3}) + k_4(\alpha^4 - \frac{6}{7}\alpha^2 + \frac{3}{35}) + \dots$$

where  $g_l(\alpha) = \sum_{m=-l}^{l} A_l^m Y_l(\alpha)$  and  $\alpha$  = directional cosines



**Figure 6.7** First anisotropy constant,  $k_2$  across the second half of the rare-earth series of metals,  $k_2 > 0$  implies an easy plane. [Values after Rhyne (1972).]

(see Fig. 6.8 in O'Handley) The zero-torque condition,  $\partial u_a / \partial \theta = 0$ , Zeeman energy  $= -M_s \cdot H$ and since  $u_a = K_{uo} + K_{u1} \sin^2 \theta + K_{u2} \sin^4 \theta$  (2<sup>nd</sup> order approx.)  $2K_{u1} \sin \theta \cos \theta + 4K_{u2} \sin^3 \theta \cos \theta = M_s H \cos \theta$ Using  $m = M/M_s = \sin \theta$  $HM_s = 2K_{u1}m + 4K_{u2}m^3$ 



**Figure 6.8** Shaded areas indicate  $K_{u1}$  and  $K_{u2}$  values. The fine line represents the linear magnetization process and the bold line is the result of Eq. (6.5) to second order with  $K_{u1} = 1$  and  $K_{u2} = 0.38$  (approximate ratio for Co).

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#### 2) Cubic Anisotropy

Ex) Fe, Ni {110} disk-shaped sample (see Fig. 6.2 & 6.3 in O'Handley)



**Figure 6.2** A (110) sample cut from a cubic crystal contains all three major symmetry directions: {100}, {110}, and {111}.



**Figure 6.3** Schematic of magnetization for iron measured in a field of about 80 Oe as a function of angle from the [001] direction of a sample such as that shown in Figure 6.2.

#### - Case studies

① Square or rectangular (001) plane samples of Fe having domain patterns in demagnetized state (see Fig. 6.4 in O'Handley)

② A spherical sample of Ni along a hard [100] direction (see Fig. 6.1 in O'Handley)

③ A polycrystalline sample of Fe (see Fig. 6.5 in O'Handley)

- The anisotropy energy density of a cubic system

$$u_a = K_0 + K_1(a_1^2 a_2^2 + a_2^2 a_3^2 + a_3^2 a_1^2) + K_2(a_1^2 a_2^2 a_3^2) + \dots$$

where,  $a_1$ ,  $a_2$  and  $a_3$  are direction cosines of the magnetization along three coordinate axes.

- Cubic expansion in the orthonormal polynomials

$$u_a^{\text{cubic}} = k_0 + k_4 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2 - 1/5) + k_6 [\alpha_1^2 \alpha_2^2 \alpha_3^2 - (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2 - 1/5)/11 - 1/105 + \cdots)$$
  

$$k_4 = K_1 + K_2/11 \text{ and } k_6 = K_2$$

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### 2) Cubic Anisotropy

Experimental data

For Fe,  $K_1 = 4.8 \times 10^4 J/m^3$  and  $K_2 = -1.0 \times 10^4 J/m^3$ For Ni,  $K_1 = -4.5 \times 10^3 J/m^3$  and  $K_2 = -2.3 \times 10^3 J/m^3$ 

#### For FCC FeNi alloys (permalloys) (see Fig 6.9(a) in O'Handley)

- Order-disorder transformation at Ni<sub>3</sub>Fe.

Chemical ordering favors <111> magnetization

- Order-disorder transformation at FeCo.

Chemical ordering favors <100> magnetization

For BCC FeCo alloys(permendurs) (see Fig 6.9(b) in O'Handley) Anisotropy constants for selected materials (see Table 6.1 in O'Handley) For Nd<sub>2</sub>Fe<sub>14</sub>B<sub>1</sub> : tetragonal (see Fig. 6.11 in O'Handley)



Figure 6.9 First-order anisotropy constant for (a) FCC NiFe alloys (Bozorth 1993) and (b) BCC FeCo alloys (Hall 1959) at room temperature.

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Anisotropy constants for selected materials	TABLE 6.1 Magnetic Anisotropy Constants $K_1$ and $K_2$ for Selected Materials <sup>a</sup>					
		$(T = 4.2 \mathrm{K})$		(RT	(RT)	
	-	$K_1$	K 2	Κ1	K <sub>2</sub>	
(see Table 6.1 in O'Handley) Fe Co' Ni Ni Fe Fe Gd Tb' Dy Er" Fe Nil Min Co Yl <sup>4</sup> Gd Sm Tb			3d Metals			
	Fe Co <sup>u</sup> Ni Ni <sub>80</sub> Fe <sub>20</sub> Fe <sub>50</sub> Co <sub>50</sub>	$5.2 \times 10^{5}$ $7.0 \times 10^{6}$ $-12 \times 10^{5}$	$-1.8 \times 10^{5}$ $1.8 \times 10^{6}$ $3.0 \times 10^{5}$	$\begin{array}{r} 4.8 \times 10^{5} \\ 4.1 \times 10^{6} \\ -4.5 \times 10^{4} \\ -3 \times 10^{3} \\ -1.5 \times 10^{5b} \end{array}$	$ \begin{array}{c} -1.0 \times 10^{5} \\ 1.5 \times 10^{6} \\ -2.3 \times 10^{4} \end{array} $	
	4f Metals					
	Gd" Tb" Dy" Er"	$\begin{array}{r} -1.2 \times 10^6 \\ -5.65 \times 10^8 \\ -5.5 \times 10^8 \\ +1.2 \times 10^8 \end{array}$	$+8.0 \times 10^{5}$ -4.6 × 10 <sup>7</sup> -5.4 × 10 <sup>7</sup> -3.9 × 10 <sup>7</sup>	$+1.3 \times 10^{5}$		
	Spinel Ferrites					
	Fe <sub>3</sub> O <sub>4</sub> NiFe <sub>2</sub> O <sub>4</sub> MnFe <sub>2</sub> O <sub>4</sub> CoFe <sub>2</sub> O <sub>4</sub>	$\begin{array}{r} -2 \times 10^{5} \\ -1.2 \times 10^{5} \\ \approx -4 \times 10^{5} \\ +10^{7} \end{array}$	$\approx -3 \times 10^5$	$\begin{array}{r} -0.9 \times 10^{5} \\ -0.7 \times 10^{5} \\ -3 \times 10^{4} \\ 2.6 \times 10^{6} \end{array}$		
	Garnets					
	YIG GdIG	$-2.5 \times 10^4$ $-2.3 \times 10^5$	=	$1 \times 10^{4}$		
	Hard Magnets					
	$BaO·6Fe_2O''_3$ Sm"Co_5 Nd"Co_5 Fe_14Nd_2B"	$\begin{array}{r} 4.4 \times 10^{6} \\ 7 \times 10^{7} \\ -4.0 \times 10^{8} \\ -1.25 \times 10^{8c} \end{array}$		$\begin{array}{r} 3.2 \times 10^{6} \\ 1.1 - 2.0 \times 10^{8} \\ 1.5 \times 10^{8} \\ 5 \times 10^{7} \end{array}$		
	$Sm_2Co'_{17}$ TbFe <sub>2</sub>			$3.2 \times 10^{7}$ - 7.6 × 10 <sup>7</sup>		

### Physical Origin of Magnetocrystalline Anisotropy (Microscopic origin)

How does the local magnetic moment distinguish between different crystallographic directions? In other words, how is the net atomic moment  $\mu_I$  coupled to the lattice?

<Ans> The coupling of the spin part of the magnetic moment to the electron orbital shape and orientation (*spin-orbit coupling*) as well as chemical bonding of the orbitals on a given atom with their local environment(*crystal electric field*).

If the local crystal field seen by an atom is of low symmetry and if the bonding electrons of that atom have an aysymmetric charge distribution ( $L_z \neq 0$ ), then the atomic orbitals interact anisotropically with the crystal field. In other words, certain orientations for the molecular orbitals (or bonding electron charge distributions) are energetically preferred.

- A low symmetry crystal field
- A non-zero spin-orbit interaction

Crystal field symmetry from a magnetic pair interaction Crystal Field Splitting

Crystal Field Splitting

### Application of a field when there is magnetic anisotropy.

A torque is exerted on  $\mu_S$ , but S may be coupled to L.

Two limiting responses

- (1) The crystal field energy D (coupling L to the lattice)
- (2) The spin-orbit interaction (coupling L to S)

In case 1,  $D > \xi L \cdot S$  (typical in 3d transition metals and alloys),  $\mu_S$  will show a weakly anisotropic response to  $H_{ext}$  while  $\mu_L$  is mostly quenched, that is locked to a fixed direction by D.  $\rightarrow$  a nonzero orbital angular momentum for the highest occupied electronic state so that the orbital senses the crystal field symmetry.

In case 2,  $\mathcal{J}L \cdot S > D$ , (typical in rare-earth system),  $\mu_J = \mu_S + \mu_L$  will respond to  $H_{ext}$ , but the pull of the crystal field in certain directions may be strong if it is of low symmetry, leading to very large magnetocrystalline anisotropy. The rotation of the anisotropic orbital charge distribution causes large anisotropic strains (magnetostriction).

### **Temperature Dependence of Magnetocrystalline Anisotropy**

Intimately related to the symmetry of the anisotropy energy function (see Fig. 6.18-20 in O'Handley)





### Measurements of Anisotropy

- Magnetization measurements using a conventional magnetometer

- Torque magnetometer
- Torsion pendulum
- Magnetic resonance

-Other techniques: Ferromagnetic resonances,

Mössbauer spectroscopy

#### **Interpretation of torque curves** i) For a uniaxial crystal

If  $K_2$  is negligible,  $u_a = K_{uo} + K_{u1} \sin^2 \Theta$ Torque,  $T = -\frac{du_d}{d\Theta} = -K_1 \sin \Theta \cos \Theta = -K_1 \sin 2\Theta$ where,  $\Theta =$  angle between  $M_s$  and c-axis(uniaxial axis)



그림 7.9 일축결정에서 θ의 변화에따른 이방에너지 E와 토오크 L(=-dE/ dθ)의 변화. θ는 M<sub>s</sub>와 자화용이축간의 각도임.



**Figure 6.23** Schematic of torque magnetometer, showing (*a*) suspension wire W, guide rod G, sample holder S, calibrated circles C, and magnet pole pieces, M; (*b*) the sample viewed from above (the angles are positive when increasing counterclockwise from the field direction) for B = 0 and for B > 0; and (*c*) energy diagrams,  $E(\theta)$  for B = 0, above and B > 0 below. For B = 0, *M* coincides with the EA at  $\theta_0$ . For B > 0, the EA is rotated by  $\Delta \theta$  and *M* is rotated by  $\Delta \theta + \theta_M$  so that it experiences a counterclockwise torque from the crystal anisotropy energy, which balances the clockwise torque it experiences from the field. Below the B > 0 energy surface we schematically show the torque balance conditions on the magnetization vector *M* and on the crystal (xtl).



### ii) For a cubic crystal

- Sample of (001) surface plane

 $u_a = K_o + K_1 \sin^2 \Theta \sin^2(\pi/2 - \Theta)$  (independent of  $K_2$ )

 $T = -\frac{du_d}{d\theta} = -\frac{(K_1/2)\sin 4\theta}{1}$ 







그림 7.14 (001)면에서 방향에따른 결정이방에너지 E의 polar plot. K<sub>1</sub>이 양 의 값을 가지며 5K<sub>0</sub>와 같다.

#### ii) For a cubic crystal (continued)

### - Sample of {110} surface plane $u_a = K_o + (K_1/4) (\sin^4 \Theta + \sin^2 2 \Theta) + (K_2/4) (\sin^4 \Theta \cos^2 \Theta)$ $T = - du_d d\Theta$

where,  $\theta =$  angle between  $M_s$  and [100]

#### - Sample of {111} surface plane

 $u_a = K_o + K_1/4 + (K_2/108)(1 - \cos \theta)$  $T = - du_d/d\theta$ 

where,  $\theta =$  angle between  $M_s$  and [100]

#### Fig. 7.15 in Cullity (see also Fig. 6.24 in O'Handley)



### □ Shape Anisotropy : a uniaxial anisotropy

Magntostatic energy,  $E_{ms} = (1/2)N_d M^2$  (in cgs)  $E_{ms} = K_s \sin^2 \theta$ Shape-anisotropy constant,  $K_s = (N_a - N_c)M^2/2$ for a prolate spheroid (a < c) The easy axis is along the c axis and hard along any axis normal to c.

### □ Stress Anisotropy : a uniaxial anisotropy

Magnetoelastic energy,  $E_{me} = K_{\sigma} \sin^2 \theta$ If stress-anisotropy constant  $K_{\sigma} = 3\lambda \sigma/2 > 0$ , the axis of stress is an easy axis

### □ Induced Anisotropy (ref. Chap. 10 in Cullity)

- Magnetic annealing
- Stress annealing
- Plastic deformation
- Magnetic Irradiation

### Exchange(or unidirectional) anisotropy

- Exchange coupling refers to a preference for specific relative orientations of the moments of two different magnetic materials when they are in intimate contact with each other or are separated by a layer thin enough (< 60) to allow spin information to be communicated between the two materials, leading to unidirectional anisotropy.



#### Exchange(or unidirectional) anisotropy

-Exchange coupling refers to a preference for specific relative orientations of the moments of two different magnetic materials when they are in intimate contact with each other or are separated by a layer thin enough (< 60) to allow spin information to be communicated between the two materials, leading to unidirectional anisotropy. (see Fig. 11.25 & Fig. 11.27 in Cullity)



그림 11.25 77°K 에서 측정한 산화물이 피복된 코발트입자의 자기이력곡선. 루프(1)은 + 10KOe의 자장하에서 냉각된 결과이며 (2)는 무자장 하에서 냉각된 결과이다. Meiklejohn 과 Bean[11.28]



그림 11.27 Co-CoO입자에서 루프가 이동하는 기구. 화살표는 코발트원자 또는 이온의 스핀을 표시하며 동그라미는 산소이온을 표시한다. 이력곡선에서의 (a),(b),(c)는 왼편의 3가지 상태에 해당되는 점 이다. Graham[10.1]