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

(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	**Origins** (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

(1) Magnetic Anisotropy (continued)

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

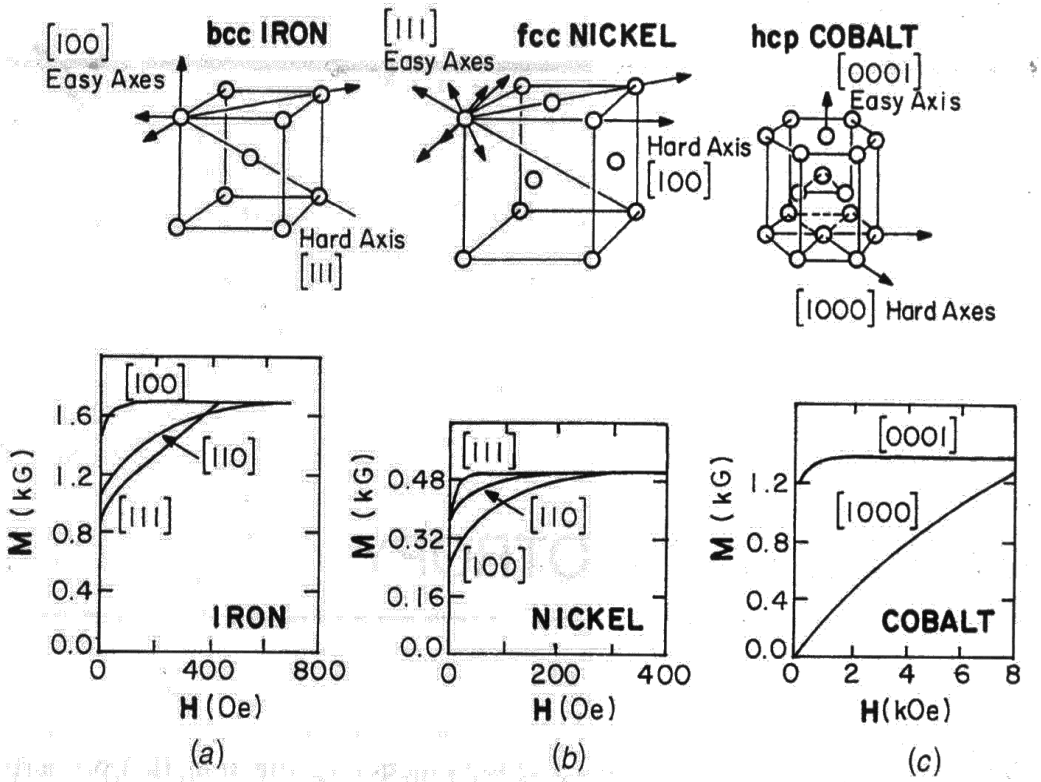


Figure 6.1 Crystal structure showing easy and hard magnetization directions for Fe(*a*), Ni(*b*), and Co(*c*), above. Respective magnetization curves, below.

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

(1st order approximation)

(1) Magnetic Anisotropy (continued)

❑ 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_u 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

$u_a = U_o/V_o = \sum K_{un}\sin^{2n}\theta = K_{uo} + K_{u1}\sin^2\theta + K_{u2}\sin^4\theta + \ldots$

(a power series form)

1st order approximation, $u_a = K_{u1}\sin^2\theta$

where θ is the angle of ***M*** with respect to the unique axis

K_{uo} is independent of the orientation of ***M***

For $K_{u1} > 0$, an oblate spheroid shape of the energy surface

For $K_{u1} < 0$, a prolate spheroid shape of the energy surface

- Experimental data

For Co at RT, $K_{u1} = 4.1\times10^5\ J/m^3$ and $K_{u2} = 1.5\times10^5\ J/m^3$

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

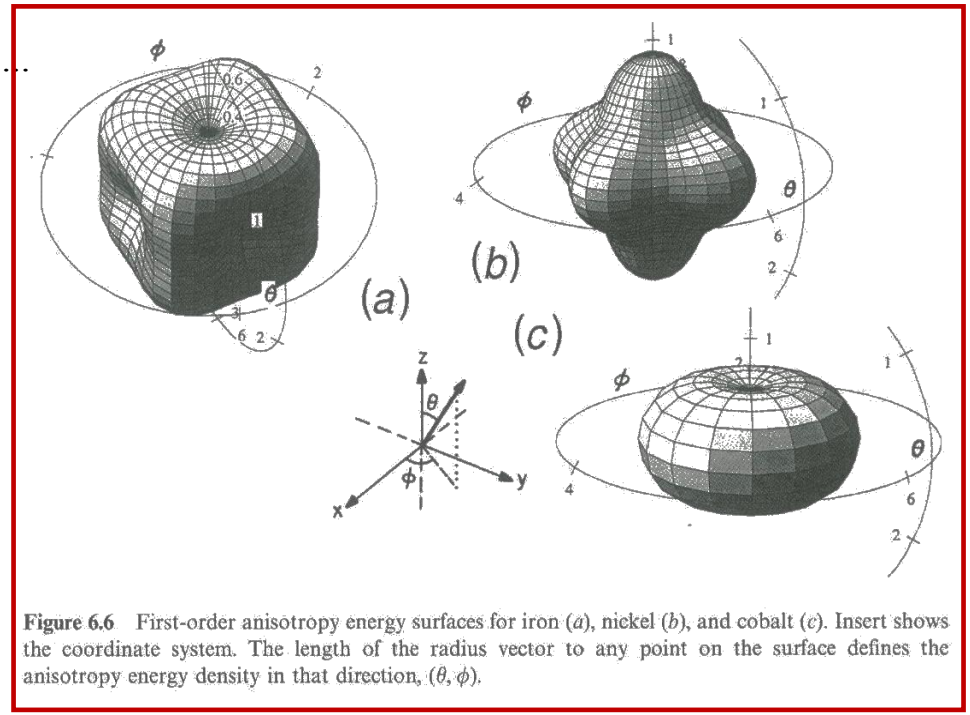


Figure 6.6 First-order anisotropy energy surfaces for iron (*a*), nickel (*b*), and cobalt (*c*). Insert shows the coordinate system. The length of the radius vector to any point on the surface defines the anisotropy energy density in that direction, (θ, ϕ).

(1) Magnetic Anisotropy (continued)

❑ Phenomenology of Magnetocrystalline Anisotropy

1) Uniaxial Anisotropy (Hexagonal Anisotropy)

- **Legendre polynomials**, usually for heavy rare earth metals (see Fig. 6.7 in O'Handley)

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

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

$k_2 = K_{u1} - (8/7)K_{u2}$ and $k_4 = K_{u2}$

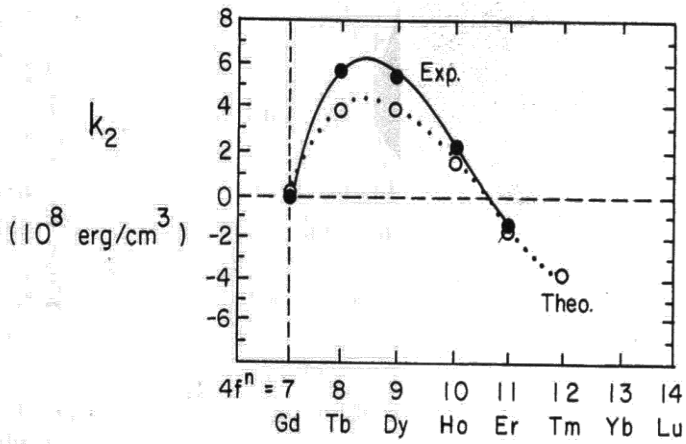


Figure 6.7 First anisotropy constant, k_2 across the second half of the rare-earth series of metals, $k_2 > 0$ implies an easy plane. [Values after Rhyne (1972).]

- Quantitative description of the magnetization process along the hard axis (see Fig. 6.8 in O'Handley)

The zero-torque condition, $\partial u_a / \partial \theta = 0$,

Zeeman energy = $-\boldsymbol{M_s} \cdot \boldsymbol{H}$

and since $u_a = K_{uo} + K_{u1}\sin^2\theta + K_{u2}\sin^4\theta$ *(2nd order approx.)*

$$2K_{u1}\sin\theta\cos\theta + 4K_{u2}\sin^3\theta\cos\theta = M_s H\cos\theta$$

Using $m = M/M_s = \sin\theta$

$$HM_s = 2K_{u1}m + 4K_{u2}m^3$$

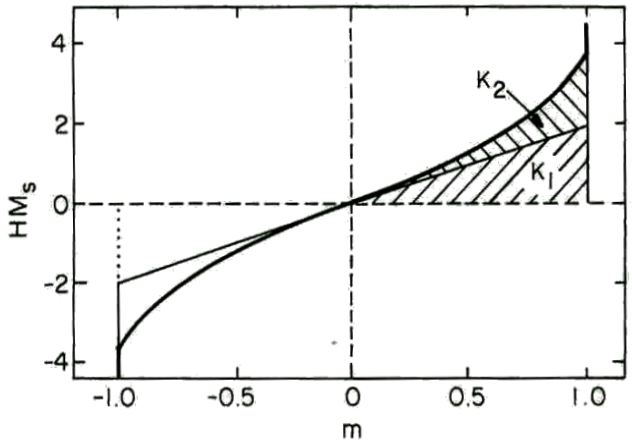


Figure 6.8 Shaded areas indicate K_{u1} and K_{u2} values. The fine line represents the linear magnetization process and the bold line is the result of Eq. (6.5) to second order with $K_{u1} = 1$ and $K_{u2} = 0.38$ (approximate ratio for Co).

(1) Magnetic Anisotropy (continued)

2) Cubic Anisotropy

Ex) Fe, Ni

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

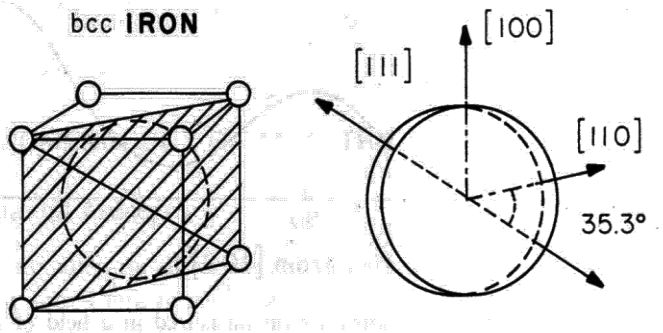


Figure 6.2 A (110) sample cut from a cubic crystal contains all three major symmetry directions: {100}, {110}, and {111}.

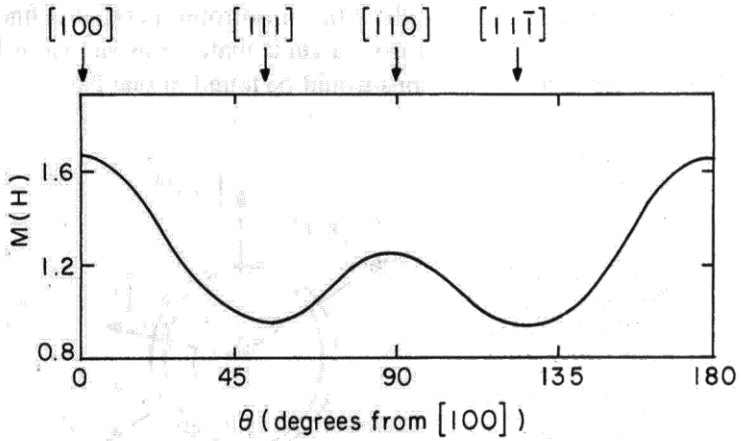


Figure 6.3 Schematic of magnetization for iron measured in a field of about 80 Oe as a function of angle from the [001] direction of a sample such as that shown in Figure 6.2.

- 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

$$u_a = K_0 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + \cdots$$

where, α_1, α_2 and α_3 are direction cosines of the magnetization along three coordinate axes.

- Cubic expansion in the orthonormal polynomials

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

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

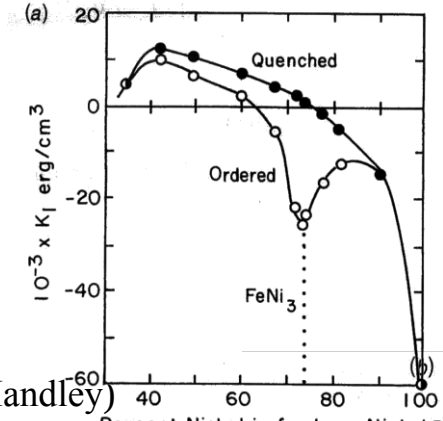
(1) Magnetic Anisotropy (continued)

2) Cubic Anisotropy

Experimental data

For Fe, $K_1 = 4.8\times10^4\ J/m^3$ and $K_2 = -1.0\times10^4\ J/m^3$

For Ni, $K_1 = -4.5\times10^3\ J/m^3$ and $K_2 = -2.3\times10^3\ J/m^3$



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

- Order-disorder transformation at Ni_3Fe.

  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 $Nd_2Fe_{14}B_1$: tetragonal (see Fig. 6.11 in O'Handley)

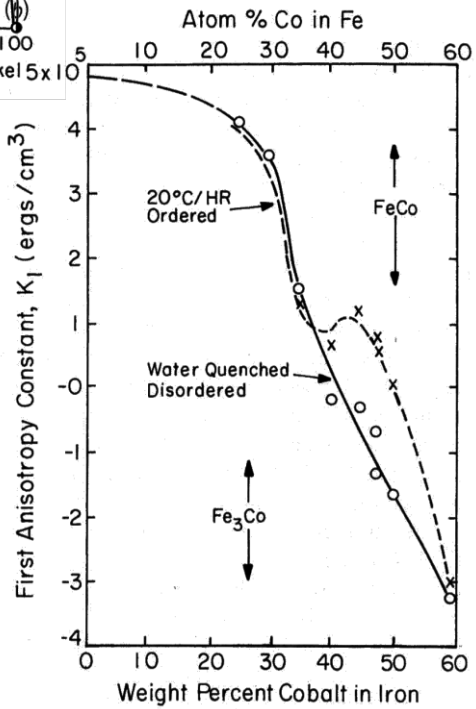


Figure 6.9 First-order anisotropy constant for (*a*) FCC NiFe alloys (Bozorth 199 and (*b*) BCC FeCo alloys (Hall 1959) at room temperature.

(1) Magnetic Anisotropy (continued)

Anisotropy constants for selected materials

(see Table 6.1 in O'Handley)

TABLE 6.1 Magnetic Anisotropy Constants K_1 and K_2 for Selected Materials[a]

	($T = 4.2$ K)		(RT)	
	K_1	K_2	K_1	K_2
		3d Metals		
Fe	5.2×10^5	-1.8×10^5	4.8×10^5	-1.0×10^5
Co[a]	7.0×10^6	1.8×10^6	4.1×10^6	1.5×10^6
Ni	-12×10^5	3.0×10^5	-4.5×10^4	-2.3×10^4
$Ni_{80}Fe_{20}$	—	—	-3×10^3	—
$Fe_{50}Co_{50}$			-1.5×10^5[b]	
		4f Metals		
Gd[a]	-1.2×10^6	$+8.0 \times 10^5$	$+1.3 \times 10^5$	—
Tb[a]	-5.65×10^8	-4.6×10^7	—	—
Dy[a]	-5.5×10^8	-5.4×10^7	—	—
Er[a]	$+1.2 \times 10^8$	-3.9×10^7	—	—
		Spinel Ferrites		
Fe_3O_4	-2×10^5	—	-0.9×10^5	—
$NiFe_2O_4$	-1.2×10^5	—	-0.7×10^5	—
$MnFe_2O_4$	$\approx -4 \times 10^5$	$\approx -3 \times 10^5$	-3×10^4	—
$CoFe_2O_4$	$+10^7$	—	2.6×10^6	—
		Garnets		
YIG	-2.5×10^4	—	1×10^4	—
GdIG	-2.3×10^5	—	—	—
		Hard Magnets		
$BaO{\cdot}6Fe_2O_3$[a]	4.4×10^6	—	3.2×10^6	—
$SmCo_5$[a]	7×10^7	—	$1.1 - 2.0 \times 10^8$	—
$NdCo_5$[a]	-4.0×10^8	—	1.5×10^8	—
$Fe_{14}Nd_2B$[a]	-1.25×10^8[c]	—	5×10^7	—
Sm_2Co_{17}[a]	—	—	3.2×10^7	—
$TbFe_2$	—	—	-7.6×10^7	—

(1) Magnetic Anisotropy (continued)

❑ 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 $\boldsymbol{\mu}_J$ 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 aysmmetric 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

(1) Magnetic Anisotropy (continued)

Application of a field when there is magnetic anisotropy.

A torque is exerted on $\boldsymbol{\mu}_S$, but $\boldsymbol{S}$ may be coupled to $\boldsymbol{L}$.

Two limiting responses

(1) The crystal field energy D (coupling $\boldsymbol{L}$ to the lattice)

(2) The spin-orbit interaction (coupling $\boldsymbol{L}$ to $\boldsymbol{S}$)

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

In case 2, $\xi \boldsymbol{L} \cdot \boldsymbol{S} > D$, (typical in rare-earth system), $\boldsymbol{\mu}_J = \boldsymbol{\mu}_S + \boldsymbol{\mu}_L$ 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).

(1) Magnetic Anisotropy (continued)

❑ Temperature Dependence of Magnetocrystalline Anisotropy

Intimately related to the symmetry of the anisotropy energy function

(see Fig. 6.18-20 in O'Handley)

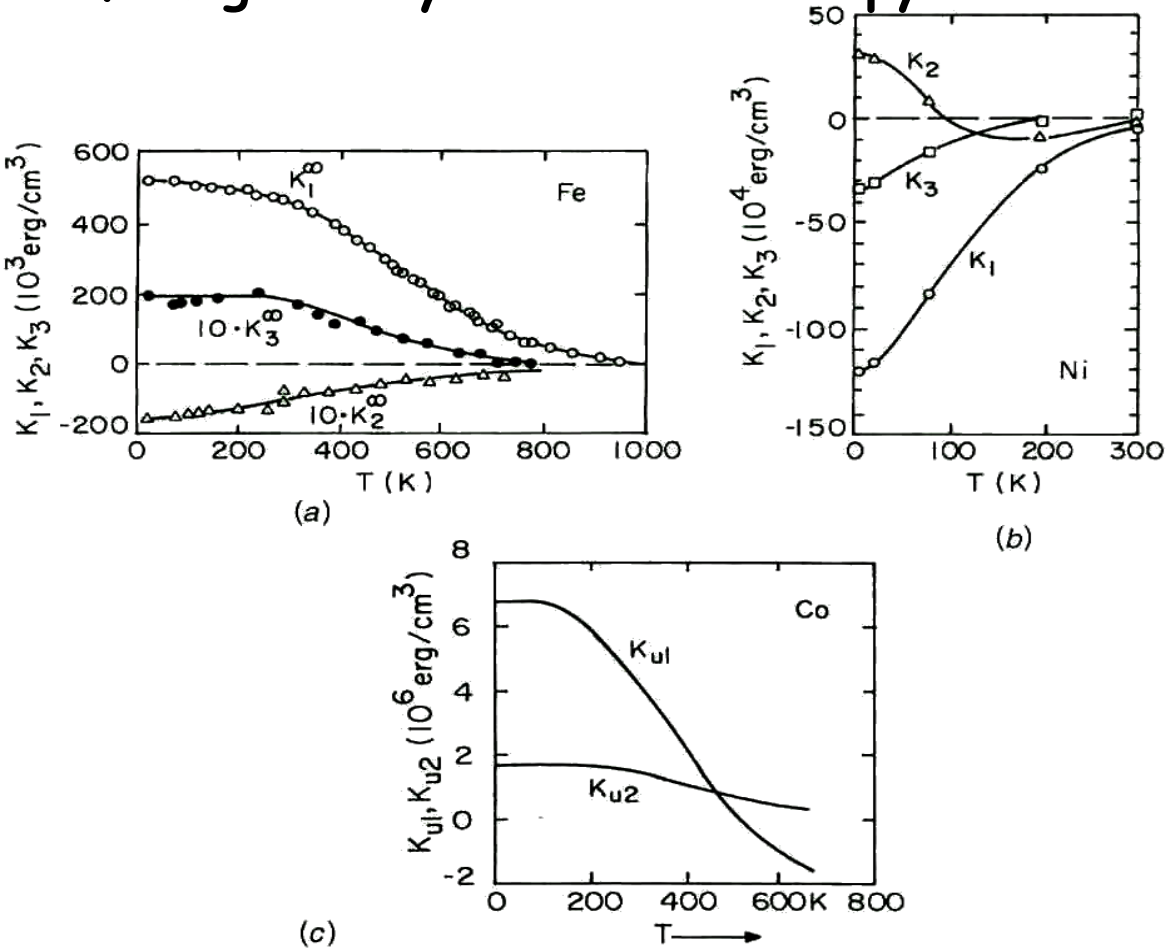


Figure 6.18 Temperature dependence of the principal anisotropy constants of (*a*) Fe (Gengnagel and Hofmann 1968), (*b*) Ni (Franse 1971), and (*c*) Co (Pauthenet et al. 1962).

(1) Magnetic Anisotropy (continued)

❑ 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, $T = -du_a/d\theta = -K_1\sin\theta\cos\theta = -K_1\sin 2\theta$

where, θ = angle between $\boldsymbol{M}_s$ and c-axis(uniaxial axis)

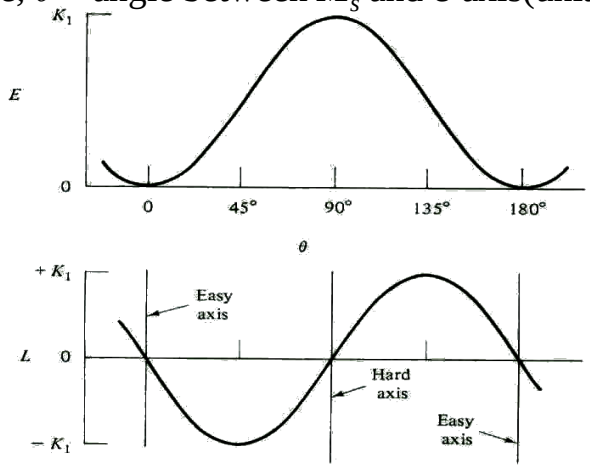


Figure 7.9 Variation with θ of the anisotropy energy E and the torque L (= - dE/dθ) tor a uniaxial crystal. θ is the angle between Ms and the easy axis/

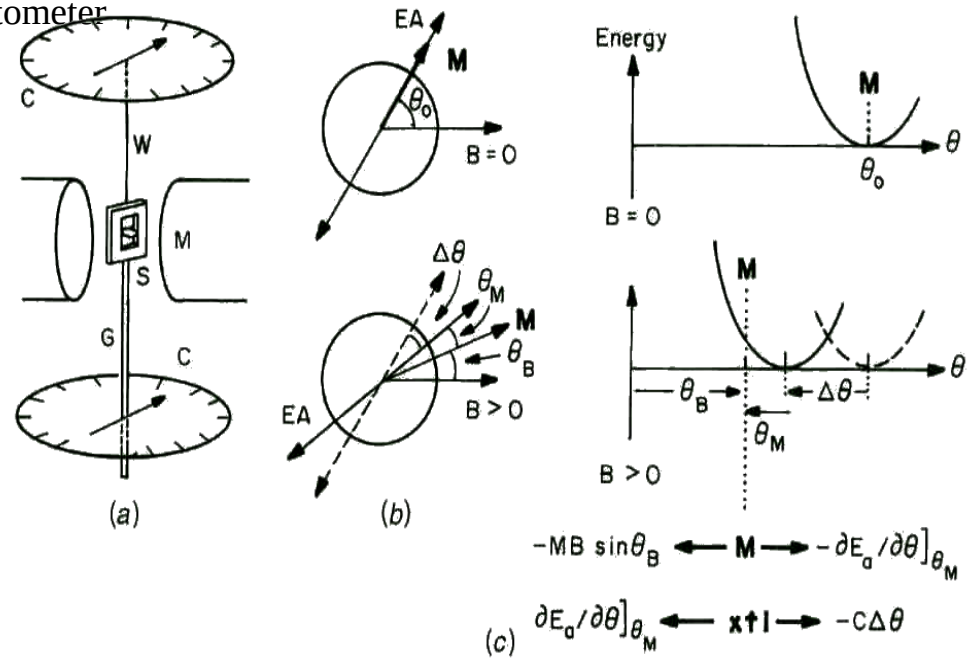


Figure 6.23 Schematic of torque magnetometer, showing (*a*) suspension wire W, guide rod G, sample holder S, calibrated circles C, and magnet pole pieces, M; (*b*) the sample viewed from above (the angles are positive when increasing counterclockwise from the field direction) for $B = 0$ and for $B > 0$; and (*c*) energy diagrams, $E(\theta)$ for $B = 0$, above and $B > 0$ below. For $B = 0$, $\boldsymbol{M}$ coincides with the EA at θ_0. For $B > 0$, the EA is rotated by $\Delta\theta$ and $\boldsymbol{M}$ 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 $\boldsymbol{M}$ and on the crystal (xtl).

(1) Magnetic Anisotropy (continued)

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)

$T = - du_a/d\theta = - (K_1/2)\sin 4\theta$

where, θ = angle between $\boldsymbol{M}_s$ and [100]

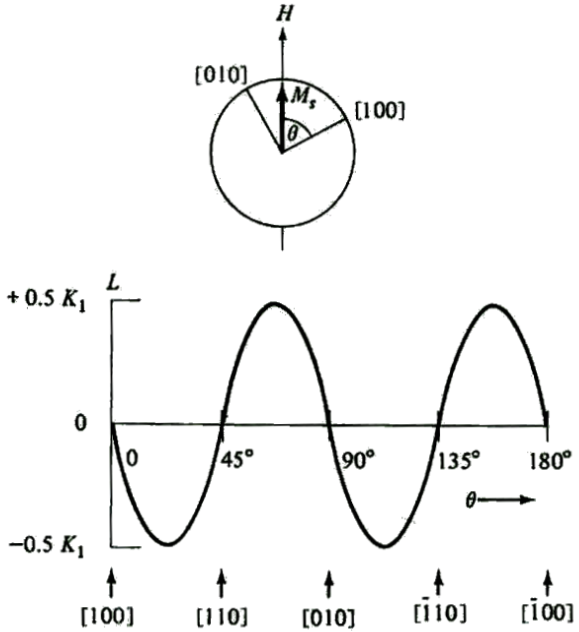


Fig. 7.13 Variation of torque L with angle θ in the (001) Plane of a cubic crystal.

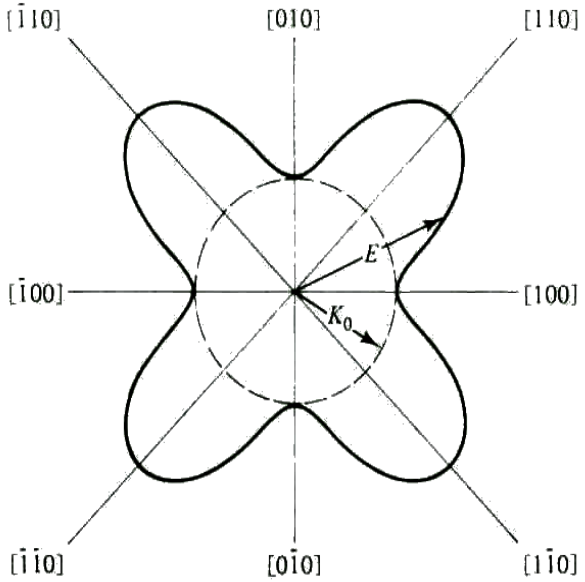


Fig. 7.14 Polar plot of the crystal anisotropy energy E as a function of direction in the (001) plane. K_1 is positive and equal to 5 K_0.

(1) Magnetic Anisotropy (continued)

ii) For a cubic crystal (continued)

O'Handley)

Fig. 7.15 in Cullity (see also Fig. 6.24 in

- 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, θ = angle between $\boldsymbol{M}_s$ and [100]

- Sample of {111} surface plane

$u_a = K_o + K_1/4 + (K_2/108)(1 - \cos 6\theta)$

$T = -du_d/d\theta$

where, θ = angle between $\boldsymbol{M}_s$ and [100]

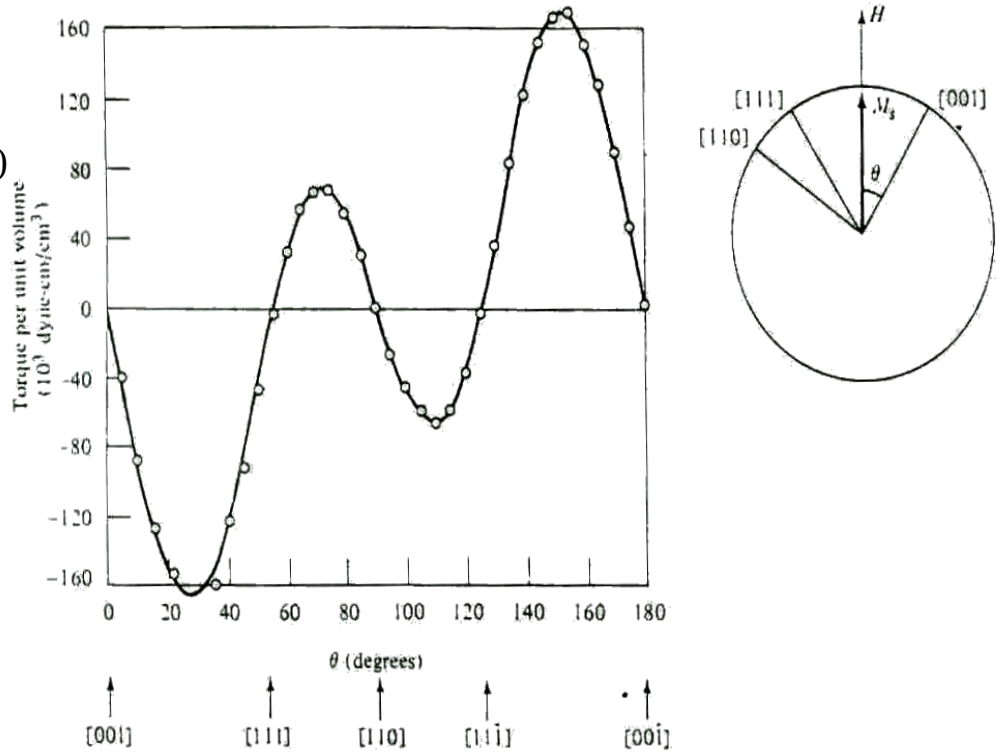


Fig. 7.15 Torque measurements on a {110} disk of an Fe-Si crystal. The curve is drawn for K_1 = 2.87 x 10^5 ergs/cm^3 and K_2 = 1.00 x 10^5 ergs/cm^3. After Bozorth [G.4], from measurements by Williams [7.8]

(1) Magnetic Anisotropy (continued)

❑ 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.

(see Fig. 7.29 in Cullity)

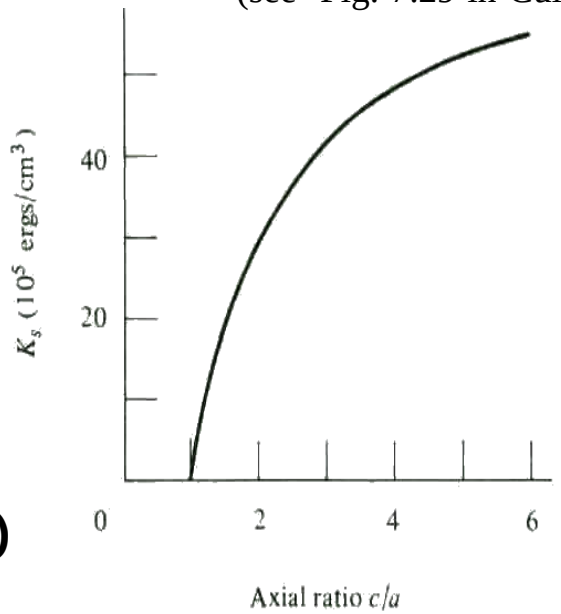


Fig. 7.29 Shape-anisotropy constant *Ks* for saturated cobalt in the form of a prolate spheroid.

❑ 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.

(1) Magnetic Anisotropy (continued)

❑ Exchange(or unidirectional) anisotropy

(see Fig. 11.25 & Fig. 11.27 in Cullity)

- 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.

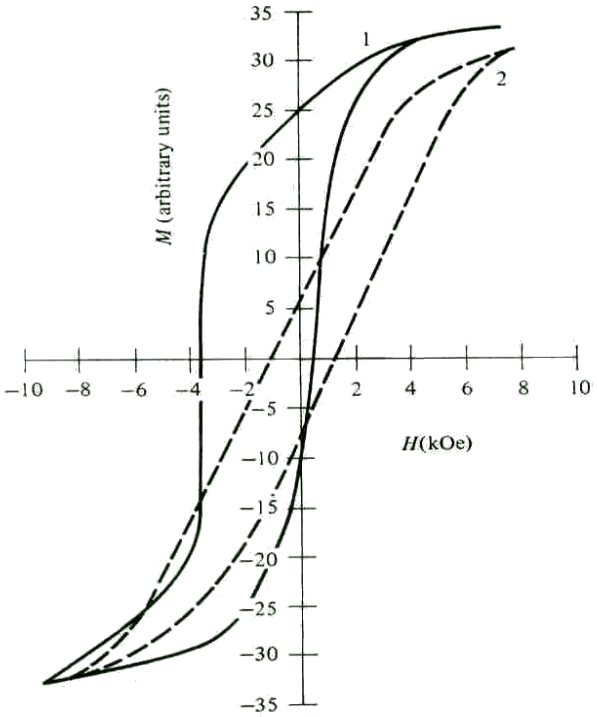


Fig. 11.25 Hysteresis loops measured at 77K of oxide-coated cobalt particles. Loop (1) results from cooling in a 10 kOe field in the positive direction, and loop (2) from cooling in zero field. Meiklejohn and Dean [11.28]

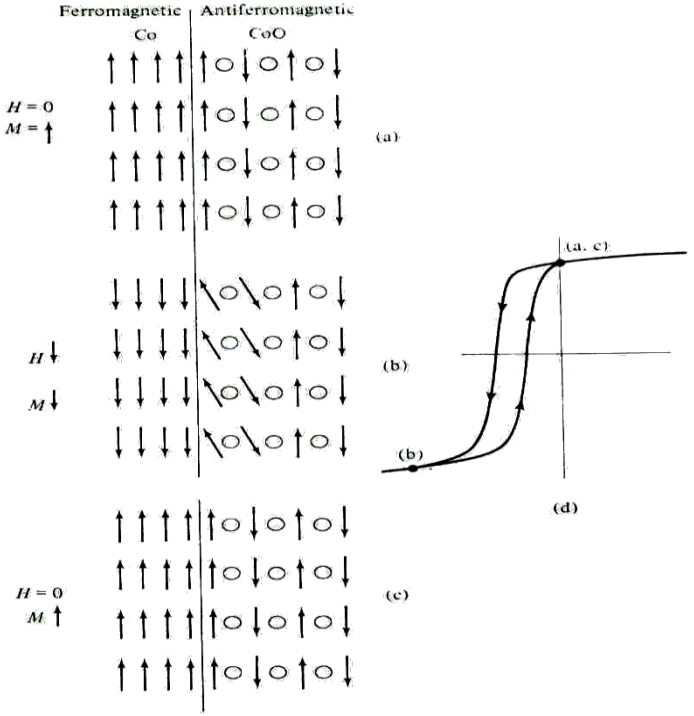


Fig. 11.26 Hysteresis loops measured at 4.2K of an alloy of Ni + 26.5 atomic percent Mn after cooling with and without a field of 5 kOe in the positive direction. Kouvel *et al.* [11.29]