3.15 Magnetic Fundamentals

C.A. Ross, DMSE, MIT

References:

Jiles, Introduction to Magnetism and Magnetic Materials

Magnetic quantities and units

H = magnetic field, A/m –represents energy gradient, or torque on a dipole

B = magnetic flux density, T or Wb/m^2 –number of magnetic field lines per unit area

M = magnetization, A/m –the magnetic moment, the response of a material to a field.

H comes from a current: current i produces tangential field $H = i/2\pi r$ at radius r
or from a magnetic material.

B depends on H: in free space		$B = \mu_o H$	$\mu_o = 4\pi\ 10^{-7}$ Henry/m
but inside a material		$B = \mu_o(H + M)$	
	or	$B = \mu_o \mu_r H$	μ_r = relative permeability
	or	$M = H(\mu_r - 1)$	
	or	$M = \chi H$	$\chi = (\mu_r - 1)$ = susceptibility

M and B both indicate how a material responds to a field H. Lines of B are continuous.

Note the same relation expressed in cgs units:

$B\ (Gauss) = H\ (Oersted) + 4\pi M\ (emu/cc)$

where

$1\ Oe = (1000/4\pi)\ A/m = 79.6\ A/m$

$1\ G = 10^{-4}\ T$

$1\ emu/cc = 1\ kA/m$

Different types of materials

Diamagnet: atom has no net magnetic moment, but a field induces a small moment opposite to the field. Susceptibility is negative ($\mu_r < 1$)

Paramagnet: atoms have a net moment but the spin directions are randomly arranged. An applied field can give weak alignment, hence a small susceptibility that varies with 1/T. ($\mu_r > 1$)

Ferromagnets have spontaneous magnetization, a large permeability which depends on the history of the sample, and nonlinear, hysteretic behavior.

Origin of magnetic behavior

Angular momentum of electrons produces magnetization due to moving charges.
Magnetization comes from 1) electron spin, 2) electron orbital motion.
Contributions from paired electrons cancel out, so strong magnetic effects are found in materials with unpaired electrons.

One electron has a moment of 1 μ_{B_B} (Bohr magneton) = $9.27\ 10^{-24}\ Am^2$

Stern-Gerlach and Zeeman experiments indicate the quantization of the magnetization in atoms.

We expect large magnetic effects in transition metals (unfilled 3d) and rare earths (unfilled 4f) because these can have a large net spin.

e.g. Fe^{3+} has $3d^5$: expect 5 μ_B per atom (neglecting orbital contributions)
Fe has $4s^2 3d^6$: in the metal, because of the way the s and d hybridize, the structure is actually $4s^{0.95}\ 3d^{7.05}$ with 4.62 spin-up and 2.42 spin-down electrons, giving a net 2.2μ_B

Ferromagnets have spontaneous ordering of the spins in neighboring atoms due to exchange coupling. If spins make angle θ,

exchange energy = A (1 – cos θ)

where A is the exchange constant, e.g. $1.4\ 10^{-20}$ J for Fe

Negative A gives antiparallel alignment: material is antiferromagnetic or ferrimagnetic. Above the Curie temperature T_c, the spins are disordered, so $kT_c \sim A$. (770˚C for Fe)

In ferro/ferrimagnets, aligned spins form domains which usually point in different directions, giving no net moment to the sample. However, the domains can be oriented (i.e. the domain walls can be moved) by a relatively small field giving a large net moment, so the permeability is very high. The shape of the M-H curve is hysteretic; important loop parameters include

area within the curve (the energy expended as the field is cycled back and forth)
saturation magnetization (the magnetization in a large field)
remanence (the magnetization remaining at zero field)
coercivity (field needed to bring the magnetization to zero).

Anisotropy and Domains

Magnetic energy consists of the following terms:

exchange energy (minimise by having all spins parallel)
magnetostatic energy (minimise by having domains pointing in different directions so there is no external field)
Zeeman energy (potential energy due to an external magnetic field, E = M.H)
magnetocrystalline energy (lower if the magnetization is pointing in certain crystallographic directions, eg the c-axis in Co)

Domain structures form to minimise energy. Domains are typically microns or larger; domain wall widths ~ 100 nm.

Magnetocrystalline anisotropy represents the energy needed to 'pull' the magnetization away from the preferred (easy) axis.

e.g. Co $K_u = 4.1\ 10^5$ J/m^3 uniaxial, [0001] is easy
Fe $K_1 = 4.8\ 10^4$ J/m^3 cubic, <100> is easy
Ni $K_1 = -4.5\ 10^3$ J/m^3 cubic, <111> is easy

Uniaxial: energy $E = K_u \sin^2 \phi$ ϕ = angle between M and easy axis

Cubic: $E = K_1 (\cos^2\phi_1 \cos^2\phi_2 + \cos^2\phi_2 \cos^2\phi_3 + \cos^2\phi_3 \cos^2\phi_1)$ + higher order terms

ϕ_i = angle between M and the i axis

Domain wall width is determined by a balance between exchange (favors wide walls) and magnetocrystalline anisotropy (favors narrow walls). (a = lattice parameter)

wall width $d = \pi\sqrt{A/2Ka}$

wall energy $E_w = \pi\sqrt{2AK/a}$

For small enough particles it is not worth establishing a wall because the savings in magnetostatic energy are less than the wall energy. These are 'single domain' particles. Very small particles are thermally unstable because the net magnetic energy $K_{tot}V < 25kT$. (here V is the volume of the particle)

Magnetostatic energy (a.k.a. self-energy or demagnetizing energy)
The energy in the field surrounding the magnetized object depends on the way the object is magnetized. For instance, a long thin object has less magnetostatic energy if it is magnetized along its length, compared to across its length. This can be expressed in the same way as a uniaxial anisotropy: if the long axis is z and the short axis is x then

$E = K_{shape} \sin^2 \phi$ ϕ = angle between M and z axis

where $K_{shape} = 0.5(N_x - N_z)M_s^2$

The Ns are called demagnetizing factors and depend on the shape of the object. For instance for an infinite cylinder with length in the z direction, $N_z = 0$ and $N_x = N_y = 0.5$.

The field inside the object along the i axis due to its own magnetization is

$H_d = -N_i M_s$ M_s = saturation magnetization.

Hard and soft materials
In a soft material, walls are easy to nucleate (low energy, i.e. low A and magnetocrystalline anisotropy) and move (few pinning sites), magnetization is easy to rotate (low magnetocrystalline anisotropy). Hard materials have opposite properties: high energy walls, pinning sites, high anisotropy, often made of single-domain particles.