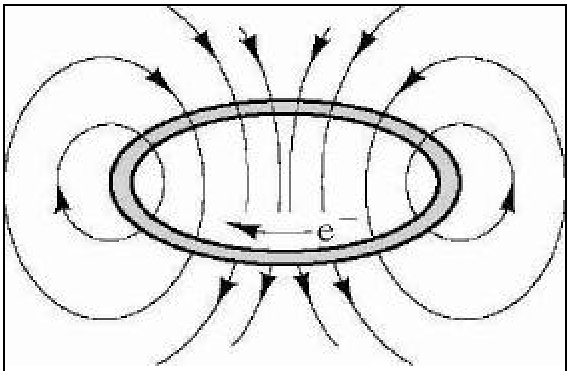
Magnetic behavior

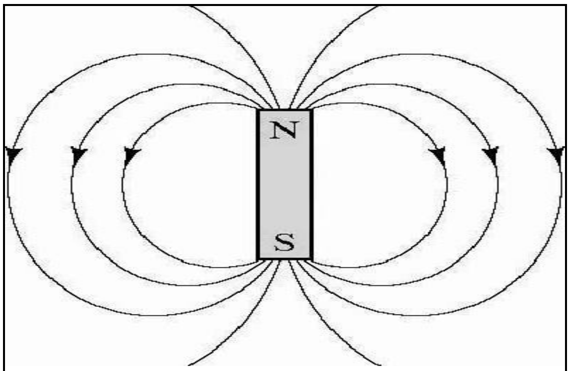
Topic 8

Reading assignment

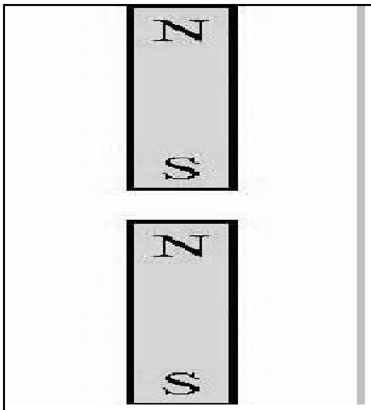
- Askeland and Phule, The Science and Engineering of Materials, 4th Ed., Ch. 19 and Sec. 6-2.
- Shackelford, Materials Science for Engineers, 6th Ed., Ch. 18.
- Chung, Composite Materials, Ch. 9.



Magnetic field generated around an electrical current loop



A magnetic material can generate a magnetic field without an electrical current.

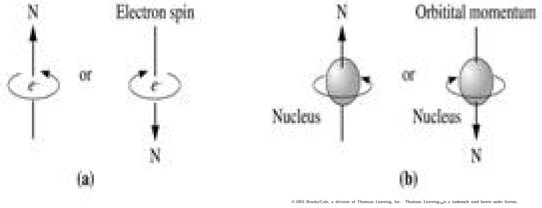


Attraction of two adjacent bar magnets

Applications:

❑electrical motors and generators
❑transformers,
❑to store and retrieve information on magnetic tape or in computers,
❑actuators and sensors,
❑to focus electron beams,
❑medical diagnostic devices: MRIs

Origin of magnetiic dipoles



The spin of the electron produces a magnetic field.

Electrons orbiting around the nucleus creates a magnetic field.

A unit of magnetic moment is simply the strength of the magnetic field associated with the electron. This moment, called the Bohr magneton

$= [(q \cdot h)/(4p \cdot m_e)]$

$= 9.27 \times 10^{-24}\ A \cdot m^2$

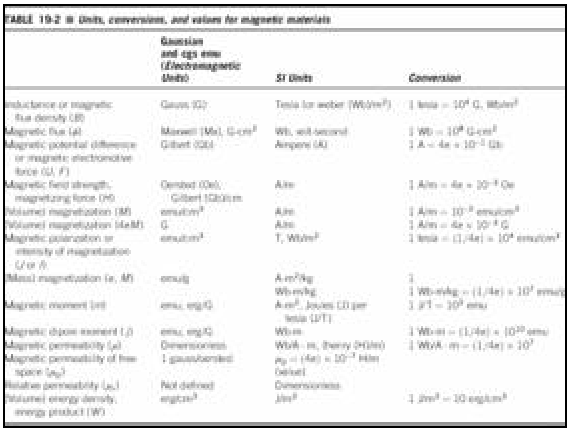
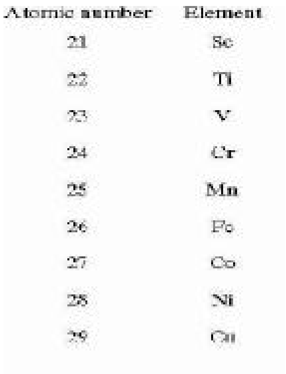


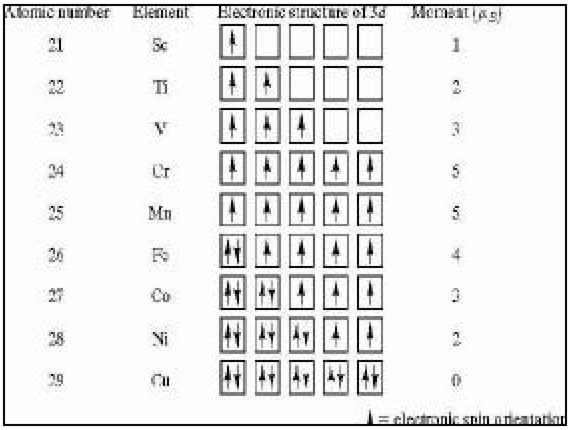
TABLE 19-2 ■ *Units, conversions, and values for magnetic materials*

	Gaussian and cgs emu (Electromagnetic Units)	SI Units	Conversion
nductance or magnetic flux density (B)	Gauss (G)	Tesla (or weber (Wb)/m²)	1 tesla = 10^4 G, Wb/m²
Magnetic flux (φ)	Maxwell (Mx), G·cm²	Wb, volt-second	1 Wb = 10^8 G·cm²
Magnetic potential difference or magnetic electromotive force (U, F)	Gilbert (Gb)	Ampere (A)	1 A = $4\pi \times 10^{-1}$ Gb
Magnetic field strength, magnetizing force (H)	Oersted (Oe), Gilbert (Gb)/cm	A/m	1 A/m = $4\pi \times 10^{-3}$ Oe
(Volume) magnetization (M)	emu/cm³	A/m	1 A/m = 10^{-3} emu/cm³
(Volume) magnetization (4πM)	G	A/m	1 A/m = $4\pi \times 10^{-3}$ G
Magnetic polarization or intensity of magnetization (J or I)	emu/cm³	T, Wb/m²	1 tesla = $(1/4\pi) \times 10^4$ emu/cm³
(Mass) magnetization (σ, M)	emu/g	A·m²/kg Wb·m/kg	1 1 Wb·m/kg = $(1/4\pi) \times 10^7$ emu/g
Magnetic moment (m)	emu, erg/G	A·m², Joules (J) per tesla (J/T)	1 J/T = 10^3 emu
Magnetic dipole moment (j)	emu, erg/G	Wb·m	1 Wb·m = $(1/4\pi) \times 10^{10}$ emu
Magnetic permeability (μ)	Dimensionless	Wb/A·m, Henry (H)/m	1 Wb/A·m = $(1/4\pi) \times 10^7$
Magnetic permeability of free space (μ_0)	1 gauss/oersted	$\mu_0 = (4\pi) \times 10^{-7}$ H/m (Wb/A·m)	
Relative permeability (μ_r)	Not defined	Dimensionless	
(Volume) energy density, energy product (W)	erg/cm³	J/m³	1 J/m³ = 10 erg/cm³

3d transition metals



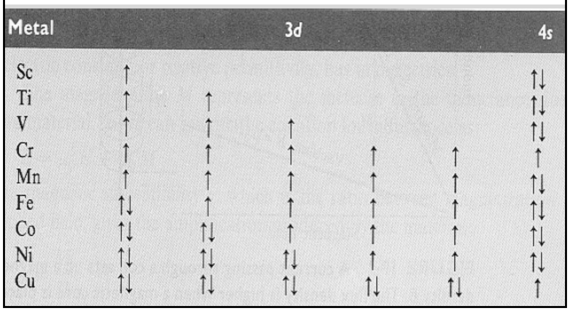
Atomic number	Element
21	Sc
22	Ti
23	V
24	Cr
25	Mn
26	Fe
27	Co
28	Ni
29	Cu



Atomic number	Element	Electronic structure of 3d					Moment (μ_B)
21	Sc	↑					1
22	Ti	↑	↑				2
23	V	↑	↑	↑			3
24	Cr	↑	↑	↑	↑	↑	5
25	Mn	↑	↑	↑	↑	↑	5
26	Fe	↑↓	↑	↑	↑	↑	4
27	Co	↑↓	↑↓	↑	↑	↑	3
28	Ni	↑↓	↑↓	↑↓	↑	↑	2
29	Cu	↑↓	↑↓	↑↓	↑↓	↑↓	0

↑ = electronic spin orientatior

- ❑ **There is a group of elements, transition metals, have an inner energy level that is not completely filled.**

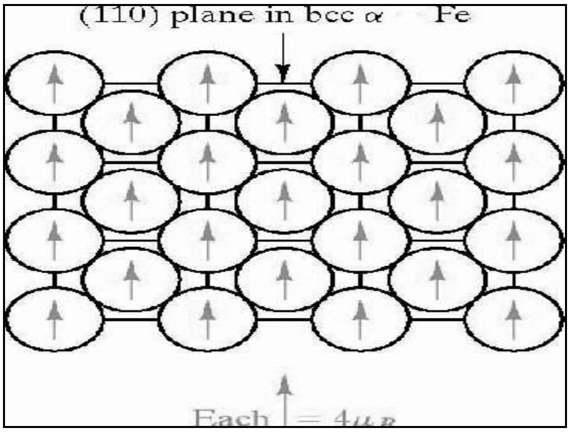


Metal	3d					4s
Sc	↑					↑↓
Ti	↑	↑				↑↓
V	↑	↑	↑			↑↓
Cr	↑	↑	↑	↑	↑	↑
Mn	↑	↑	↑	↑	↑	↑↓
Fe	↑↓	↑	↑	↑	↑	↑↓
Co	↑↓	↑↓	↑	↑	↑	↑↓
Ni	↑↓	↑↓	↑↓	↑	↑	↑↓
Cu	↑↓	↑↓	↑↓	↑↓	↑↓	↑

- **Cu and Cr have unpaired 4s e^{-}_{s} and their magnetic moments is cancelled by their interactions. Cu has a completely filled 3d shell and thus does not display a net moment.**
- **The e^{-}_{s} in the 3d level of remaining transition elements do not enter the shells in pairs. For Mn, the first five e^{-}_{s} have the same spin.**
- **Only after half of the 3d-level is filled, do pairs with opposing spins form.**
- **Therefore, each atom in a transition metal has a permanent magnetic moment, which is related to the number of unpaired electrons ➔ each atom behaves as a magnetic dipole.**

- **Recall that each energy state can contain 2 e^{-}_{s}, with opposite spins. If an energy state is full - no net magnetic moment.**
- **It may be concluded, that any element with an odd atomic # would have a net magnetic moment. Not true!.** ⇨
- **In most of these elements, the unpaired e^{-} is a valence e^{-}, and due to their frequent interactions the magnetic moments, on average, cancel each other and no net magnetic moment is associated with the material.**

- **The response of the atom to an applied magnetic field depends on how magnetic dipoles represented by each atom react to the field.**
- **Most of the transition elements react in such a way that the sum of the individual atoms' magnetic moments is zero.**
- **Nickel, iron, and cobalt undergo an exchange interaction, whereby the orientation of the dipole in one atom influences the surrounding atoms to have the same dipole orientation, producing a desirable amplification of the effect of the magnetic field.**

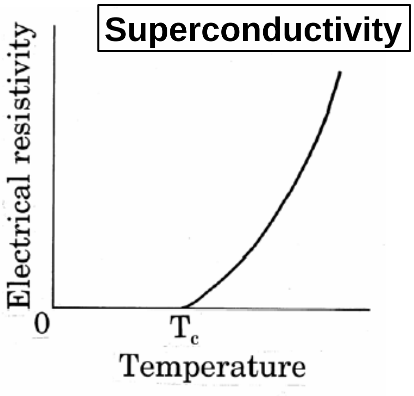


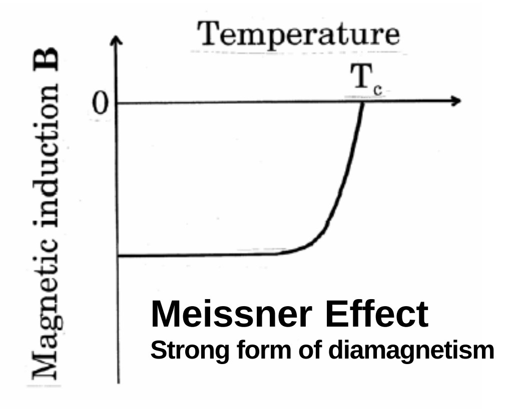
- **Ferromagnetism - Alignment of the magnetic moments of atoms in the same direction so that a net magnetization remains after the magnetic field is removed.**
- **Ferrimagnetism - Magnetic behavior obtained when ions in a material have their magnetic moments aligned in an antiparallel arrangement such that the moments do not completely cancel out and a net magnetization remains.**

- **Most widely used magnetic materials are based on ferromagnetic metals and alloys such as Fe, Ni, and Co or ferrimagnetic ceramics (ferrites & garnets).**
- **Magnetic behavior is determined primarily by the electronic structure of a material, which provides magnetic dipoles.**
- **Interactions between these dipoles determine the type of magnetic behavior that is observed.**
- **Magnetic behavior can be modified by composition, microstructure, and processing of these basic materials.**

Diamagnetism - **The effect caused by the magnetic moment due to the orbiting electrons, which produces a slight opposition to the imposed magnetic field.**

Superconductivity





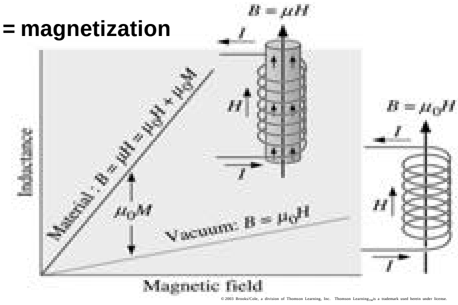
Meissner Effect

Strong form of diamagnetism

Magnetic dipoles and magnetic moments

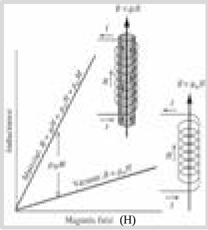
- ❑ **Magnetization occurs when induced or permanent magnetic dipoles are oriented by an interaction between the magnetic material and a magnetic field, H.**
- ❑ **Magnetization enhances the influence of the magnetic field; allows larger magnetic energies to be stored.**
- ❑ **This energy can be stored permanently or temporarily and can be used to do work.**
- ❑ **Each electron in an atom has two magnetic moments (spin and orbital contributions).**

M = magnetization



A current passing through a coil sets up a magnetic field H with a flux density B. The flux density is higher when a magnetic core is placed within the coil.

Magnetization, Permeability, and the Magnetic Field



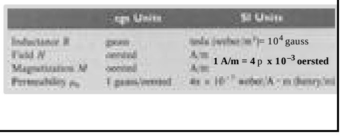
- ❑ A current passing through a coil sets up a magnetic field **H** with a flux density **B**. The flux density is higher when a magnetic core is placed within the coil.

$$\boxed{H = \frac{nI}{l}}$$

# of turns → n

Current, A → I

Coil length, m → l



	cgs Units	SI Units
Inductance B	gauss	tesla (weber/m^2) = 10^4 gauss
Field H	oersted	A/m
Magnetization M	oersted	A/m
Permeability μ_0	1 gauss/oersted	$4\pi \times 10^{-7}$ weber/A · m (henry/m)

1 A/m = 4p **x 10^{-3} oersted**

- **When a magnetic field is applied in a vacuum, lines of magnetic flux are induced. The number of lines of flux, called the flux density, or inductance B, where B = m_o·H.**

magnetic permeability
(vacuum)

- **When we place a material within the magnetic field (H), B is determined by how the induced and permanent magnetic dipoles interact with H. The inductance is now: B = m ·H**

Permeability of material in the field

= 10^4 gauss

- **If the magnetic moments reinforce the applied field, then m > m_o, a greater # of lines of flux are created, and H is magnified.**
- **If the magnetic moments oppose the field, then**

$m < m_o$.

- **The influence of the magnetic material can be described by the relative permeability m_r**

m_r = (m/ m_o). A large m_r means that the material amplifies the effect of the magnetic field.

= 10^4 gauss

The magnetization M represents the increase in the inductance due to the core material:

B = m_o H + m_o M

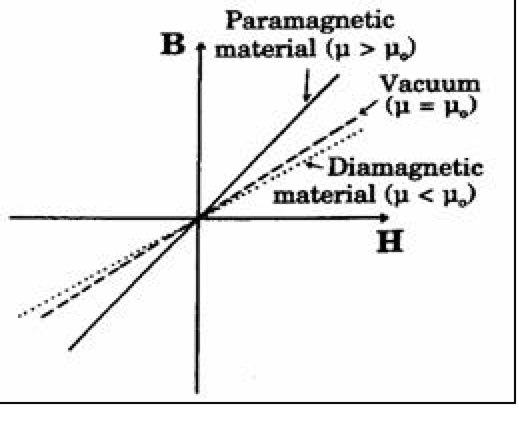
= 10^4 gauss

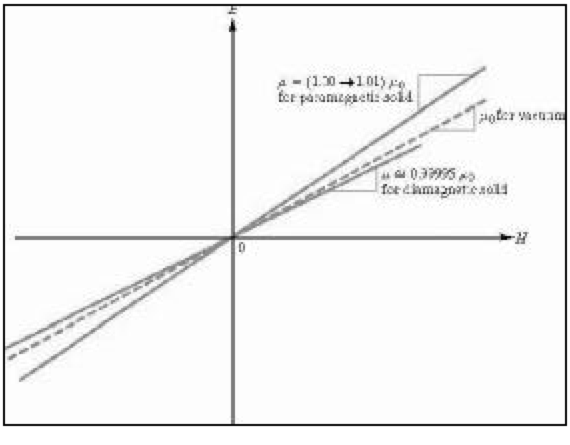
- **For important magnetic materials, the term m_oM >> m_oH, thus:**

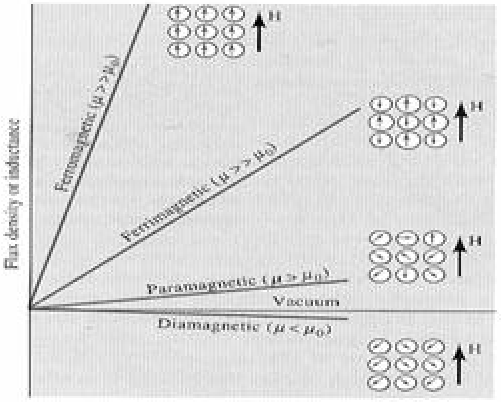
B @ m_o M

- **Inductance, B, or magnetization, M, are sometimes used interchangeably, though they are not the same.**
- **High B or M is achieved by selecting materials with high m_r.**

= 10^4 gauss



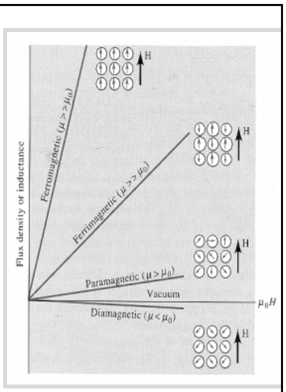




Diamagnetism

Dipoles oppose the H.

- **Magnetization < 0.**
- **m_r = 0.99995**
- **Cu, Ag, Au, and Al_2O_3 are diamagnetic @ R.T.**
- **Superconductors must be diamagnetic.**

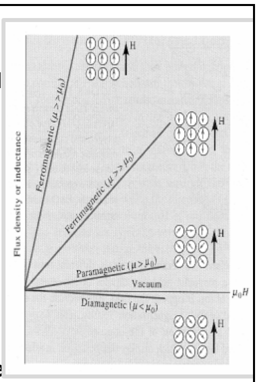


Paramagnetism

- **occurs in materials with unpaired $e^-{}_s$.**
- **a net magnetic moment due to e^- spin is associated with each atom.**
- **when H field is applied the dipoles line up with the field, causing a positive magnetization.**
- **because the dipoles do not interact, extremely large magnetic fields are required to align all of the dipoles.**
- **the effect is lost as soon as the magnetic field is removed.**
- **it is found in Al, Ti, and Cu alloys.**
- **m_r = 1.0 - 1.01**

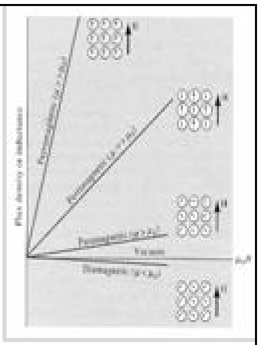
Ferromagnetism

Caused by the unfilled energy levels in the 3d level of Fe, Ni, & Co. Permanent magnetic moments result due to uncancelled e^- spins caused by the e^- structure. In ferromagnetic materials, the permanent unpaired dipoles easily line up with the imposed H due to the exchange interaction, or mutual reinforcement of the dipoles.



Ferromagnetism

- **Coupling interactions develop ⇨ alignment of net spin magnetic moments of adjacent atoms, even when no external field acting.**
- **large magnetizations are obtained even for small magnetic fields.**
- **m_r = very high, 10^6**

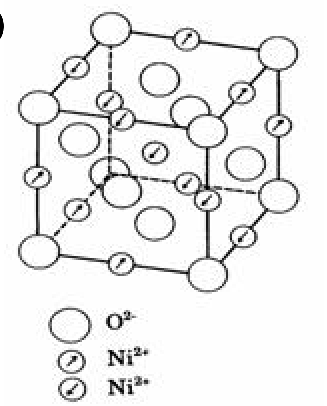


Antiferromagnetism:

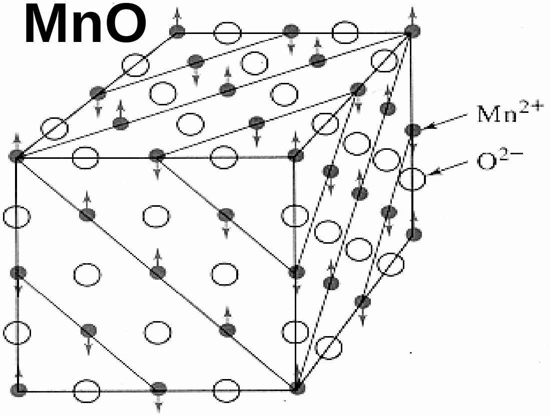
- **It occurs in materials such as Mn, Cr, MnO, and NiO.**
- **The magnetic moments produced in neighboring dipoles line up in opposition to one another in the H. Zero magnetization!!**

Antiferromagnetism - Arrangement of magnetic moments such that the magnetic moments of atoms or ions cancel out causing zero net magnetization.

NiO



MnO



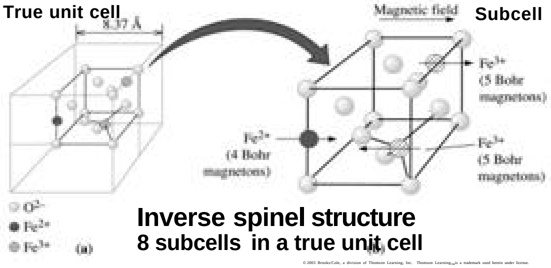
MnO crystal structure: alternating layers of (111) type planes of O and Mn ions. The magnetic moments of the Mn ions in every other (111) plane are oppositely aligned.

Ferrimagnetism

- ❑ It occurs in ceramic materials.
- ❑ Different ions have different magnetic moments.
- ❑ Dipoles of ion A line up with H, while dipoles of ion B oppose H.
- ❑ Since the strengths of the dipoles are different, there is a net magnetization.
- ❑ Ceramic ferrites have this behavior

Fe_3O_4 (magnetite)

For every four O^{2-} ions, there must be one Fe^{2+} ion and two Fe^{3+} ions in order to have electrical neutrality



Inverse spinel structure

8 subcells in a true unit cell

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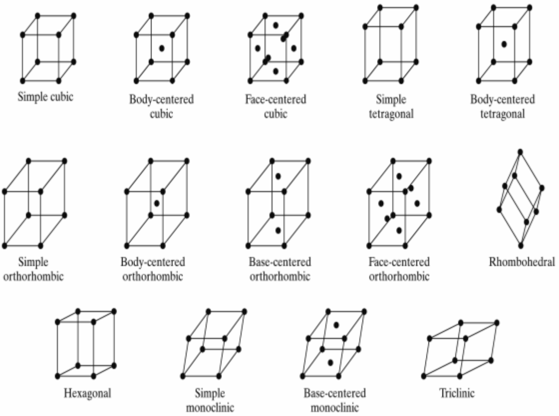
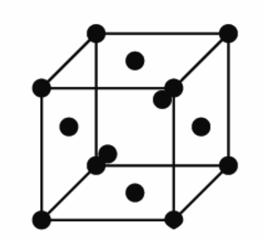
- (a) The structure of magnetite, Fe_30_4. (b) The subcell of magnetite. The magnetic moments of ions in the octahedral sites line up with the magnetic field, but the magnetic moments of ions in tetrahedral sites oppose the field. A net magnetic moment is produced by this ionic arrangement.

Subcell of inverse spinel structure

Based on Cubic F lattice



Cubic F lattice

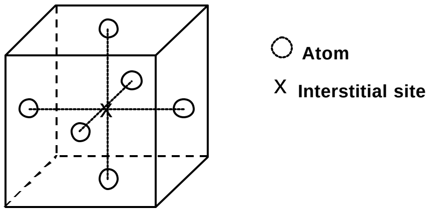


Face-centered cubic (FCC) crystal structure

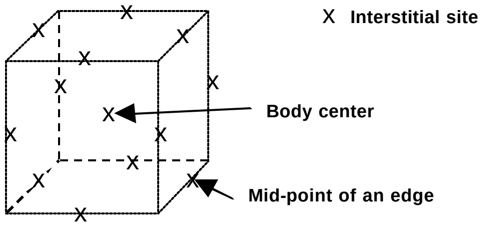
Ion positions in a subcell

- O^{2-} ions occupy the corners and face centers.
- Fe^{2+} ions occupy ¼ of the octahedral interstitital sties (formed by the anion structure)
- Fe^{3+} ions occupy ¼ of the octahedral interstitial sites and 1/8 of the tetrahedral interstitial sites.

Octahedral interstitial site in FCC

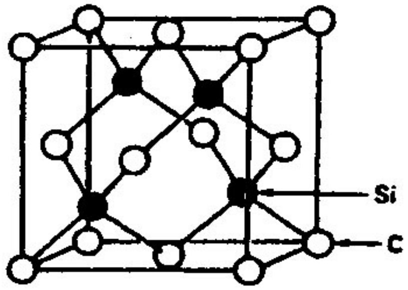


Octahedral interstitial sites in FCC

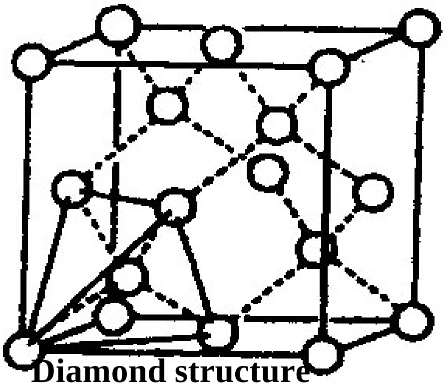


No. of octahedral interstitial sites / unit cell

$$= \underbrace{1}_{\text{Body-centered site}} + \underbrace{12(1/4)}_{\text{Edge-centered sites; 12 edges, each shared by 4 cubes.}} = 4$$

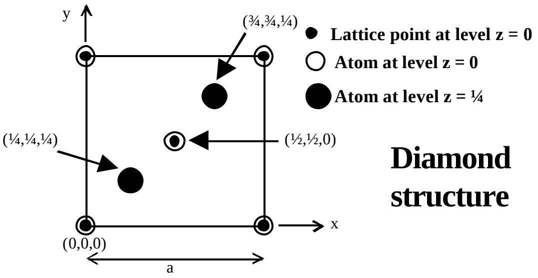


Zinc blende structure



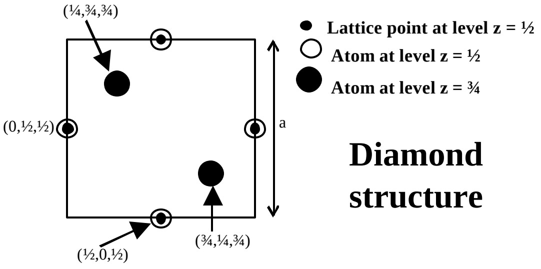
Diamond structure

Consider the lattice points in the bottom square of the cubic unit cell.



Diamond structure

Next, consider the lattice points at the z = ½ level.



Diamond structure

Tetrahedral interstitial sites in FCC

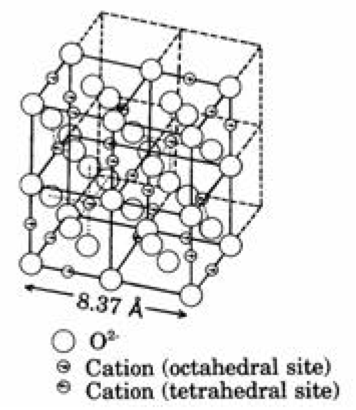
4 X 2 = 8 per unit cell

No. of ions per subcell

- Fe^{2+} ions: 4 octahedral interstitial sites per subcell times ¼ = 1
- Fe^{3+} ions: 4 octahedral interstitial sites per subcell times ¼ + 8 tetrahedral interstitial sites per subcell times 1/8 = 2

Magnetic alignment of ions

- O^{2-} ions have zero magnetic moment.
- The ions in the octahedral interstitial sites and those in the tetrahedral interstitial sites are opposing alignment.



Magnetic moment of the ions

- Fe^{2+} ion ($3d^6$) 4 Bohr magnetons
- Fe^{3+} ion ($3d^5$) 5 Bohr magnetons

Magnetic moment per cell

- **Octahedral Fe^{2+} (1 per subcell) (spin up): +4 Bohr magnetons**
- **Octahedral Fe^{3+} (1 per subcell) (spin up): +5 Bohr magnetons**
- **Tetrahedral Fe^{3+} (1 per subcell) (spin down): -5 Bohr magnetons**
- **Total per subcell = +4+5-5**
  = +4 Bohr magnetons
- **Total per true unit cell = +4 X 8 = +32 Bohr magnetons.**

Saturation magetization

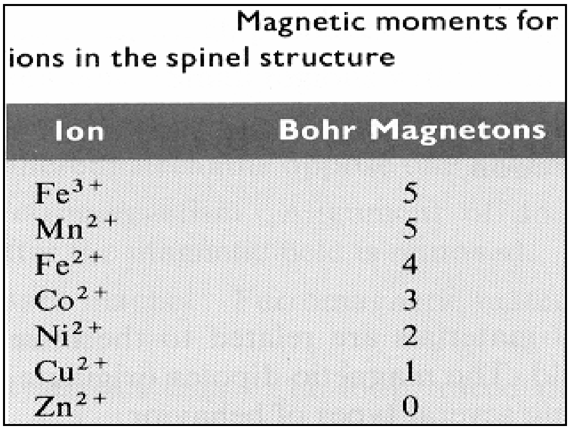
Magnetic moment per unit cell, divided by volume of unit cell

= 32 (9.27 X 10^{-24} A.m^2)/(8.37 X 10^{-10} m)^3

= 5 X 10^5 A.m^{-1}

$NiFe_2O_4$ (nickel ferrite)

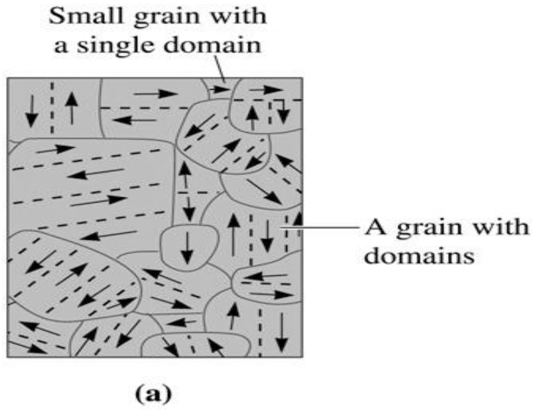
- Ni^{2+} instead of Fe^{2+}
- Magnetic moment for a Ni^{2+} ion = 2 Bohr magneton
- Magnetic moment per true unit cell
  = +16 Bohr magnetons



Magnetic moments for ions in the spinel structure

Ion	Bohr Magnetons
Fe^{3+}	5
Mn^{2+}	5
Fe^{2+}	4
Co^{2+}	3
Ni^{2+}	2
Cu^{2+}	1
Zn^{2+}	0

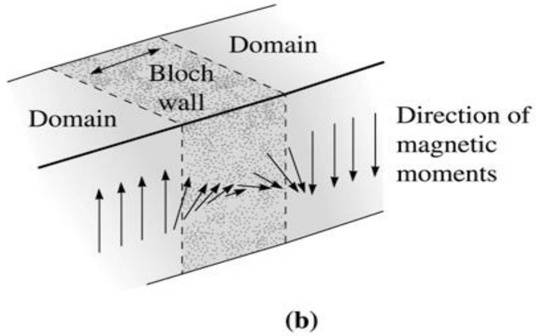
The high electrical resistivity of these ceramic compounds helps minimize eddy currents and allows the materials to operate at high frequencies.



(a) A qualitative sketch of magnetic domains in a polycrystalline material. The dashed lines show demarcation between different magnetic domains; the dark curves show the grain boundaries.

Domain structure

- ❑ **Ferromagnetic materials have a powerful influence on magnetization because of the positive interaction between the dipoles of neighboring atoms.**
- ❑ **A substructure composed of magnetic domains is produced within the grain structure of a ferromagnetic material, even in the absence of an external field.**
- ❑ **Domains are regions in the material in which all of the dipoles are aligned.**
- ❑ **In a material that has never been exposed to a magnetic field, the individual domains have a random orientation.**

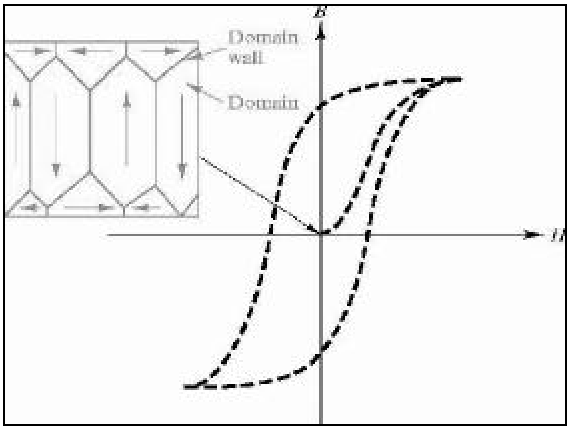


(b)

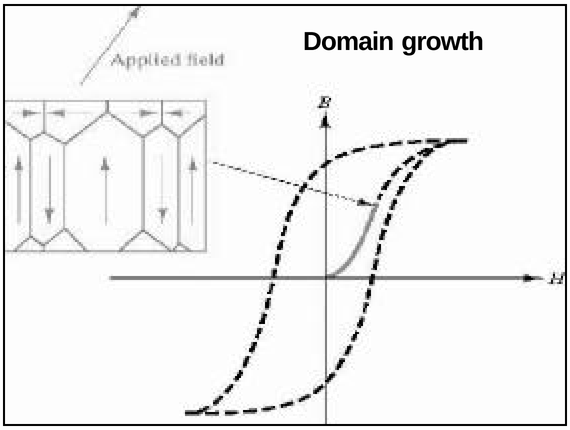
(b) The magnetic moments in adjoining atoms change direction continuously across the boundary between domains.

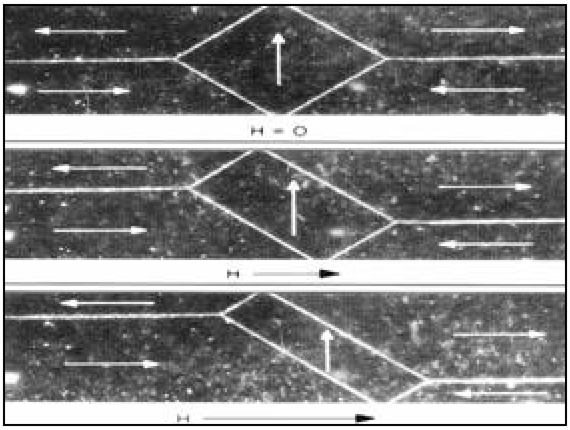
- ❑The net magnetization in the material as a whole is zero.
- ❑Boundaries, called Bloch walls separate the individual domains.
- ❑The Bloch walls are narrow zones in which the direction of the magnetic moment gradually and continuously changes from that of one domain to that of the next.
- ❑The domains are typically very small, about 0.005 cm or less.
- ❑The Bloch walls are about 100 nm thick.

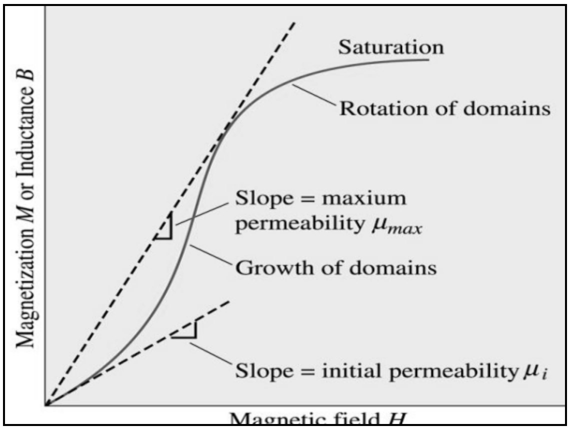
- ❑When a H is imposed on the material, domains that are nearly lined up with the field grow at the expense of unaligned domains.
- ❑For the domains to grow, the Bloch walls must move; H provides the force required for this movement.
- ❑Initially the domains grow with difficulty, and relatively large increases in the field are required to produce even a little magnetization.



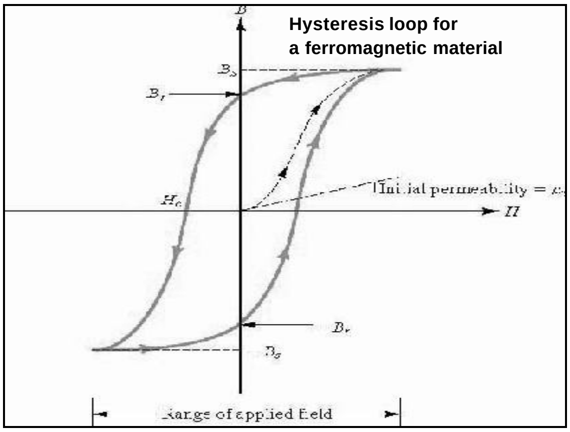
Domain growth



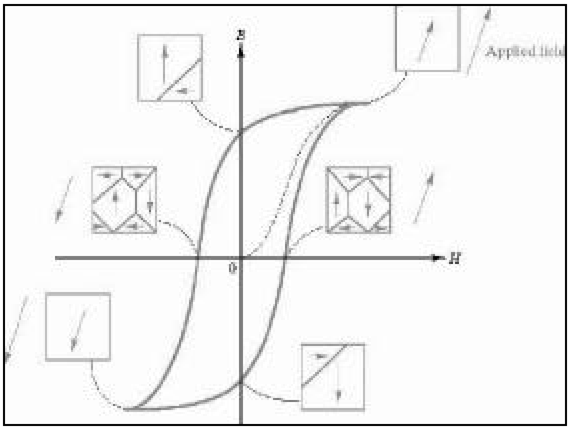


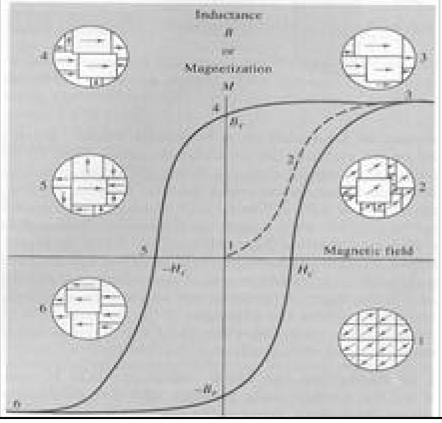


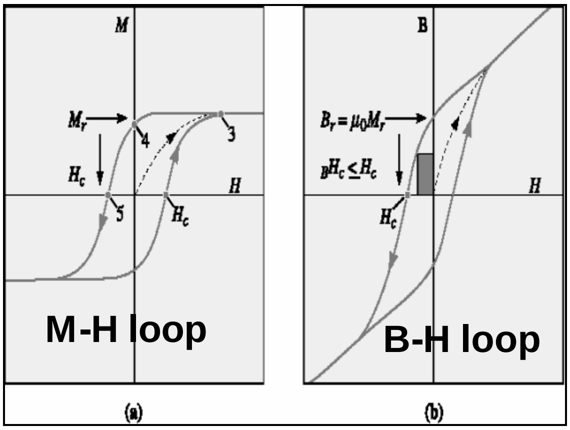
When a magnetic field is first applied to a magnetic material, magnetization initially increases slowly, then more rapidly as the domains begin to grow. Later, magnetization slows, as domains must eventually rotate to reach saturation. Notice the permeability values depend upon the magnitude of H.



Hysteresis loop for a ferromagnetic material







(a) The ferromagnetic hysteresis M-H loop showing the effect of the magnetic field on inductance or magnetization. The dipole alignment leads to saturation magnetization (point 3), a remanance (point 4), and a coercive field (point 5).

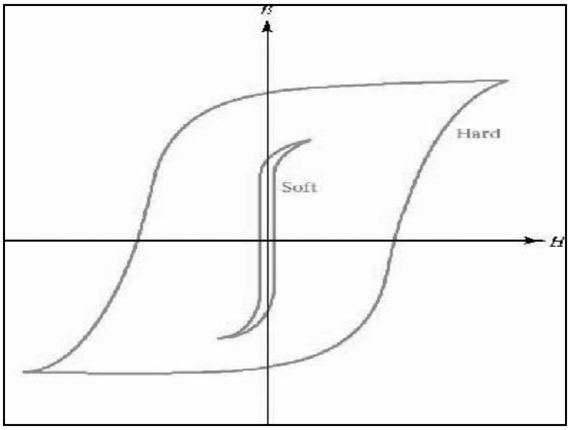
(b) The corresponding B-H loop. Notice the end of the B-H loop, the B value does not saturate since B = $\mu_0 H + \mu_0 M$.

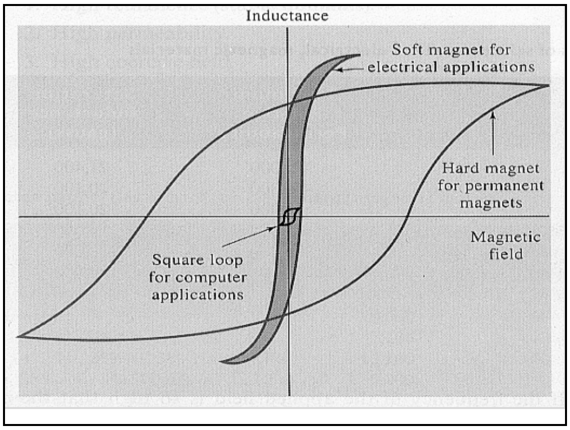
Effect of removing the magnetic field

- ❑Because of the resistance by the domain walls, domains do not regrow into random orientations.
- ❑Many domains remain oriented near the direction of the original field.
- ❑Residual magnetization, remanence, (B_r) is present in the material.

Effect of an alternating magnetic field

- ❑If the field is applied in the reverse direction, the domains grow along the new applied direction.
- ❑A coercive field H_C (coercivity) is needed to force the domains to orient randomly and cancel one another's effect.
- ❑Further increases in the strength of the field eventually align the domains to saturation in the opposite direction.
- ❑By alternating the applied field a hysteresis loop results.





Soft magnetic materials

- used to enhance the magnetic flux density (B) produced when an electric current is passed through the material. Applications include cores for electromagnets, electric motors, transformers, generators, and other electrical equipment.

Magnetic materials for electrical applications

- ☐ Electrical magnetic materials are called ***soft magnets.***
- ☐ Characteristics:
  1. **High saturation magnetization ➔ allows a material to do work.**
  2. **High permeability ➔ saturation magnetization reached @ small $H_{applied}$**
  3. **Small coercive field. ➔ domains can reoriented with small $H_{applied}$**
  4. **Small remanence ➔ desired, so that no magnetization remains when $H_{applied}$ is removed.**
  5. **Small hysteresis loop ➔ minimizes energy losses.**
  6. **Rapid response to high-frequency magnetic fields.**
  7. **High electrical resistivity.**

Magnetic materials for electrical applications

- ☐ If frequency of $H_{applied}$ is too high that domains do not realign in each cycle ➔ device may heat due to dipole friction.
- ☐ Higher frequencies produce more heating!!
  - ➔ material cycles through the hysteresis loop more often.
  - ➔ energy is lost during each cycle.
- ☐ Energy can also be lost by heating if eddy currents are produced.
- ☐ During operation, electrical currents can be induced into the magnetic material ➔ these currents produce power losses and Joule heating (I^2R).

Magnetic materials for electrical applications

- ☐ **If the electrical resistivity is high, eddy current losses can be held to a minimum.**
- ☐ **Soft magnets produced from ceramic materials have a high resistivity and therefore are less likely to heat than metallic magnets.**

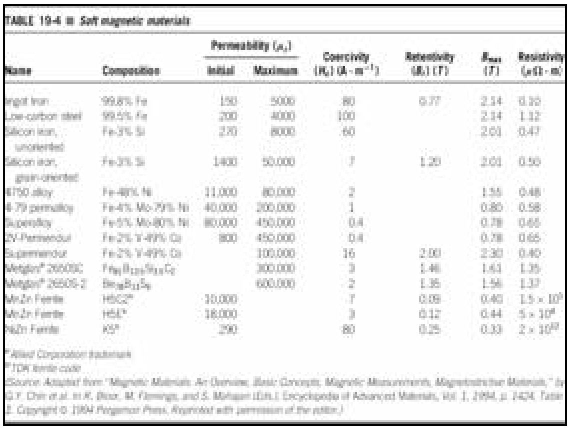


TABLE 19-4 ■ *Soft magnetic materials*

Name	Composition	Permeability (μ_r) Initial	Permeability (μ_r) Maximum	Coercivity (H_c) (A · m^{-1})	Retentivity (B_r) (T)	B_{max} (T)	Resistivity ($\mu\Omega$ · m)
Ingot iron	99.8% Fe	150	5000	80	0.77	2.14	0.10
Low-carbon steel	99.5% Fe	200	4000	100		2.14	1.12
Silicon iron, unoriented	Fe-3% Si	270	8000	60		2.01	0.47
Silicon iron, grain-oriented	Fe-3% Si	1400	50,000	7	1.20	2.01	0.50
4750 alloy	Fe-48% Ni	11,000	80,000	2		1.55	0.48
4-79 permalloy	Fe-4% Mo-79% Ni	40,000	200,000	1		0.80	0.58
Superalloy	Fe-5% Mo-80% Ni	80,000	450,000	0.4		0.78	0.65
2V-Permendur	Fe-2% V-49% Co	800	450,000	0.4		0.78	0.65
Supermendur	Fe-2% V-49% Co		100,000	16	2.00	2.30	0.40
Metglas[a] 2605SC	$Fe_{81}B_{13.5}Si_{3.5}C_2$		300,000	3	1.46	1.61	1.35
Metglas[a] 2605S-2	$Fe_{78}B_{13}Si_9$		600,000	2	1.35	1.56	1.37
MnZn Ferrite	H5C2[b]	10,000		7	0.09	0.40	1.5×10^5
MnZn Ferrite	H5E[b]	18,000		3	0.12	0.44	5×10^6
NiZn Ferrite	K5[b]	290		80	0.25	0.33	2×10^{12}

[a] Allied Corporation trademark

[b] TDK ferrite code

(Source: Adapted from "Magnetic Materials: An Overview, Basic Concepts, Magnetic Measurements, Magnetostrictive Materials," by G.Y. Chin et al. In K. Bloor, M. Flemings, and S. Mahajan (Eds.), Encyclopedia of Advanced Materials, Vol. 1, 1994, p. 1424, Table 2. Copyright © 1994 Pergamon Press. Reprinted with permission of the editor.)

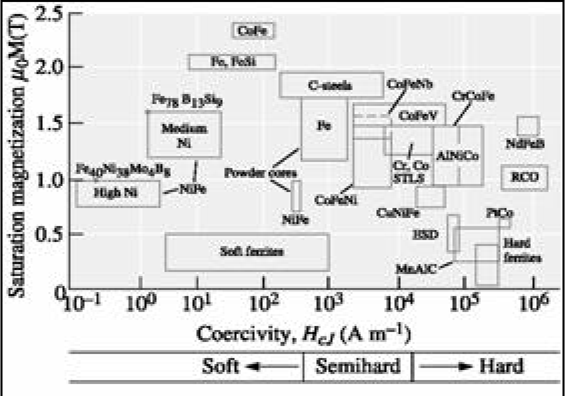
Hard magnetic materials –

used to make strong permanent magnets

- ❑ **Strong permanent magnets, often called hard magnets.**
- ❑ **Requirements:**
  1. **High remanence (stable domains).**
  2. **High permeability.**
  3. **High coercive field.**
  4. **Large hysteresis loop.**
  5. **High power (or BH product).**

Hard magnet –

Ferromagnetic or ferrimagnetic material that has a coercivity $> 10^4$ A . m^{-1}.



(b)

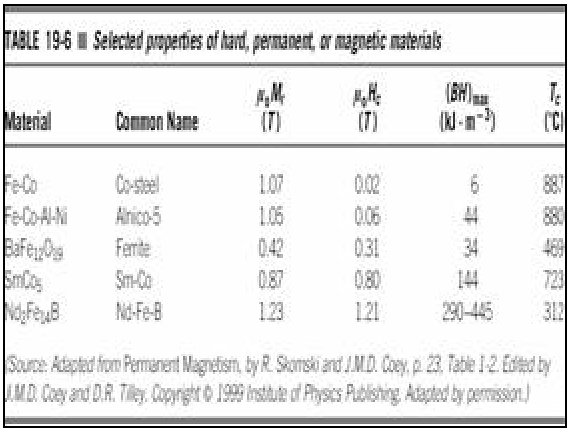


TABLE 19-6 ▪ *Selected properties of hard, permanent, or magnetic materials*

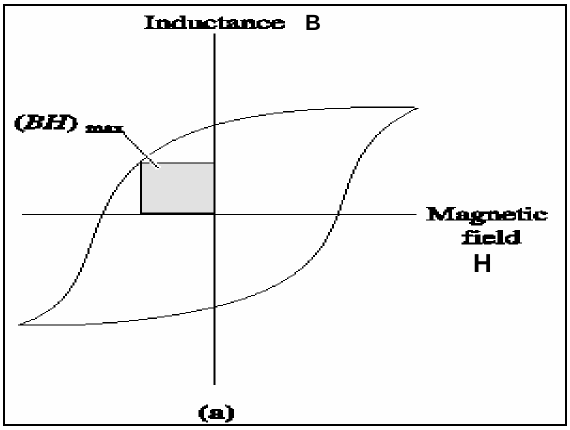
Material	Common Name	$\mu_0 M_r$ (T)	$\mu_0 H_c$ (T)	$(BH)_{max}$ (kJ · m^{-3})	T_c (°C)
Fe-Co	Co-steel	1.07	0.02	6	887
Fe-Co-Al-Ni	Alnico-5	1.05	0.06	44	880
$BaFe_{12}O_{19}$	Ferrite	0.42	0.31	34	469
$SmCo_5$	Sm-Co	0.87	0.80	144	723
$Nd_2Fe_{14}B$	Nd-Fe-B	1.23	1.21	290–445	312

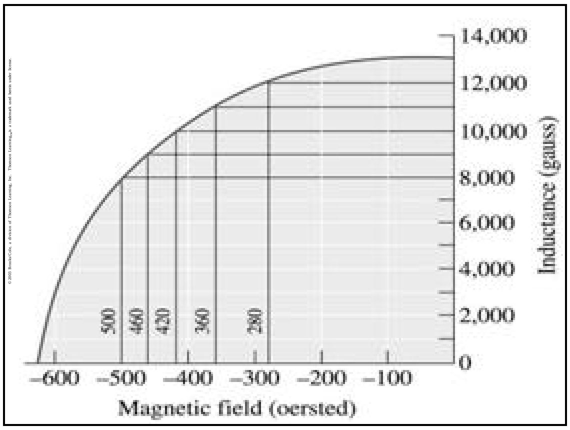
(Source: Adapted from Permanent Magnetism, by R. Skomski and J.M.D. Coey, p. 23, Table 1-2. Edited by J.M.D. Coey and D.R. Tilley. Copyright © 1999 Institute of Physics Publishing. Adapted by permission.)

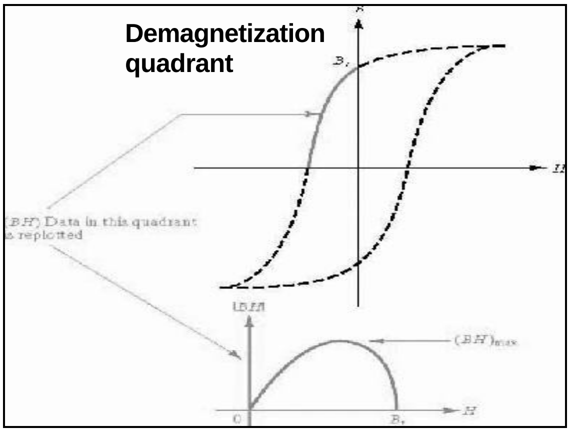
The behavior of a material in a magnetic field is related to the size and shape of hysteresis loop.

Magnetic materials for permanent magnets

- ❑ **Strong permanent magnets, often called hard magnets.**
- ❑ **Requirements:**
  1. **High remanence (stable domains).**
  2. **High permeability.**
  3. **High coercive field.**
  4. **Large hysteresis loop.**
  5. **High power (or BH product).**



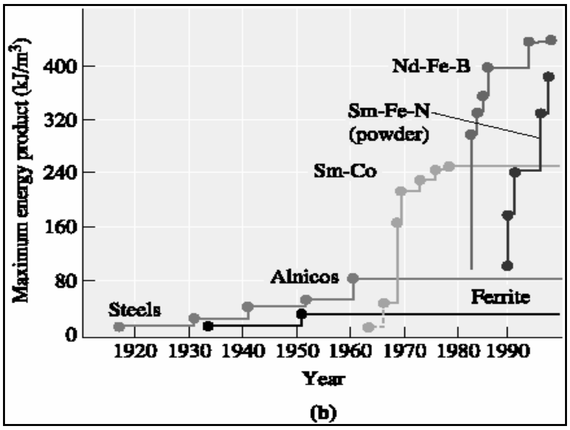




Power - The strength of a permanent magnet as expressed by the maximum product of the inductance and magnetic field, i.e., the BH product.

BH product is related to the power, or energy, required to demagnetize the permanent magnet.

- ❑The power of the magnet is related to the size of the hysteresis loop, or the maximum product of B and H.
- ❑The area of the largest rectangle that can be drawn in the second or fourth quadrants of the B-H curve is related to the energy required to demagnetize the magnet.
- ❑For the product to be large, both the remanence and the coercive field should be large.

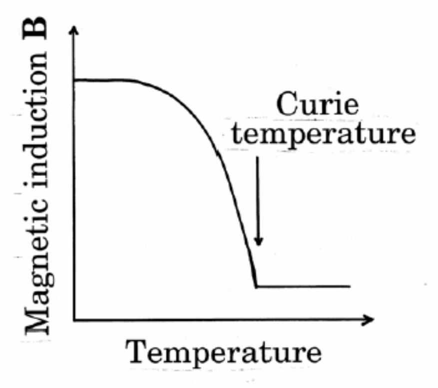


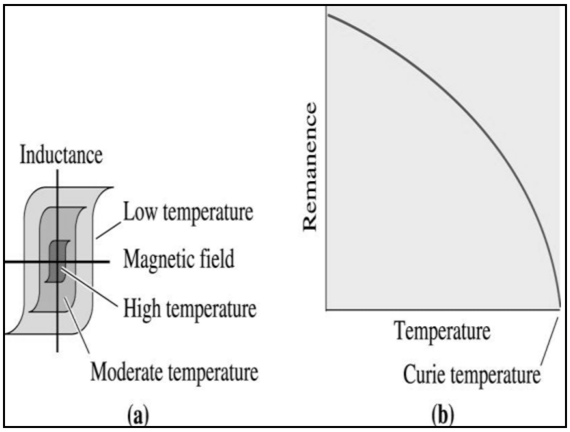
The Curie temperature

- ❑In ferromagnetic materials as T - s, the mobility of the domains - s, making it easier to become aligned, but this also prevents them to remain aligned when the field is removed.
- ❑ \ saturation magnetization, remanence, and the coercive field are all ¯ed at T_{high}.
- ❑If $T > T_{curie}$ ➔ ferromagnetic behavior changes to paramagnetic behavior

Curie temperature (T_c)

The temperature above which a ferromagnetic or ferrimagnetic material becomes paramagnetic.





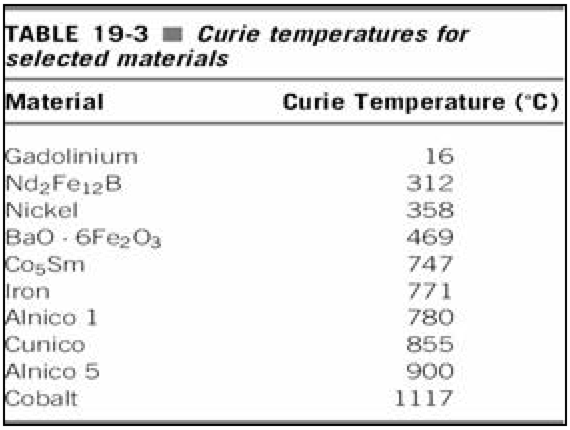
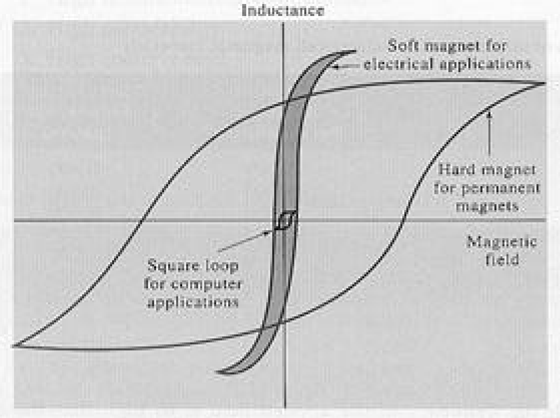


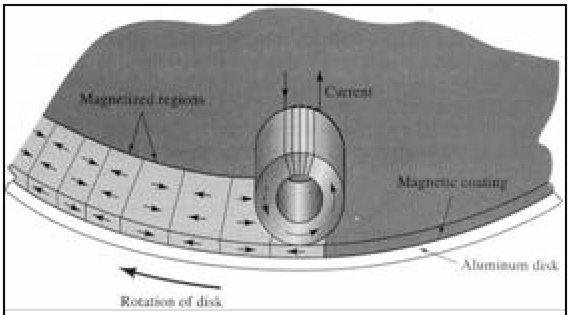
TABLE 19-3 ■ *Curie temperatures for selected materials*

Material	Curie Temperature (°C)
Gadolinium	16
$Nd_2Fe_{12}B$	312
Nickel	358
$BaO \cdot 6Fe_2O_3$	469
Co_5Sm	747
Iron	771
Alnico 1	780
Cunico	855
Alnico 5	900
Cobalt	1117

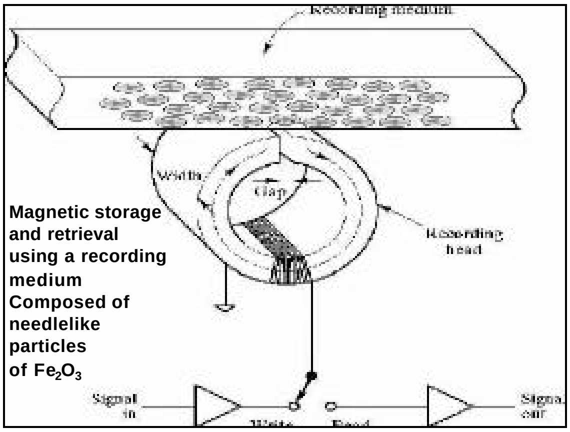


Magnetic materials for computer memories

- Used to store bits of information in computers.
- Memory is stored by magnetizing the material in a certain direction.
- Materials with a square hysteresis loop, a low remanence, a low saturation magnetization, and a low coercive field are preferable.
- Ferrites containing Mn, Mg, or Co may satisfy these requirements.
- The square loop assures that a bit of information placed in the material by a field remains stored.



Information can be stored or retrieved from a magnetic disk by use of an electromagnetic head. A current in the head magnetizes domains in the disk during storage; the domains in the disk induce a current in the head during retrieval.



Magnetic storage and retrieval using a recording medium Composed of needlelike particles of Fe_2O_3

- Information can be stored or retrieved from a magnetic disk by use of an electromagnetic head.
- A current in the head magnetizes domains in the disk during storage.
- The domains in the disk induce a current in the head during retrieval.

Data storage applications

- Memory
- Stripe on credit cards
- Audio-cassettes

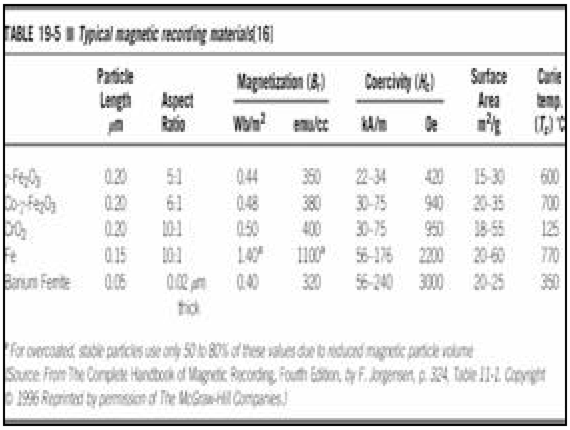


TABLE 19-5 ■ *Typical magnetic recording materials*[16]

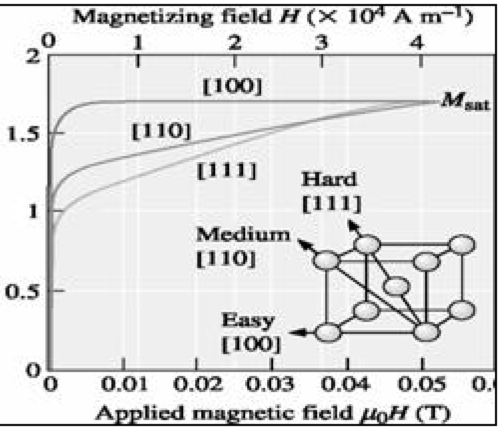
	Particle Length μm	Aspect Ratio	Magnetization (B_s) Wb/m^2	Magnetization (B_s) emu/cc	Coercivity (H_c) kA/m	Coercivity (H_c) Oe	Surface Area m^2/g	Curie temp. (T_c) °C
γ-Fe_2O_3	0.20	5:1	0.44	350	22–34	420	15–30	600
Co-γ-Fe_2O_3	0.20	6:1	0.48	380	30–75	940	20–35	700
CrO_2	0.20	10:1	0.50	400	30–75	950	18–55	125
Fe	0.15	10:1	1.40*	1100*	56–176	2200	20–60	770
Barium Ferrite	0.05	0.02 μm thick	0.40	320	56–240	3000	20–25	350

*For overcoated, stable particles use only 50 to 80% of these values due to reduced magnetic particle volume

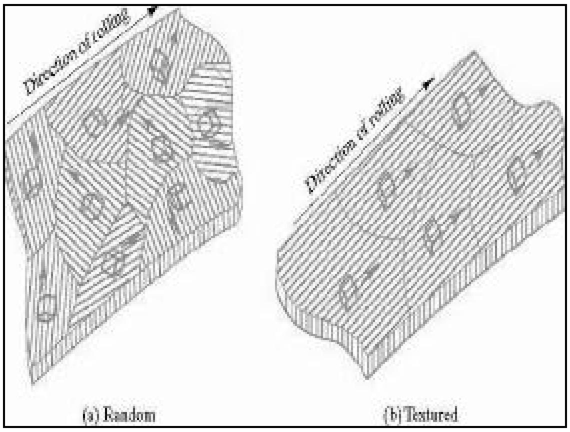
(Source: From *The Complete Handbook of Magnetic Recording*, Fourth Edition, by F. Jorgensen, p. 324, Table 11-1. Copyright © 1996 Reprinted by permission of The McGraw-Hill Companies.)

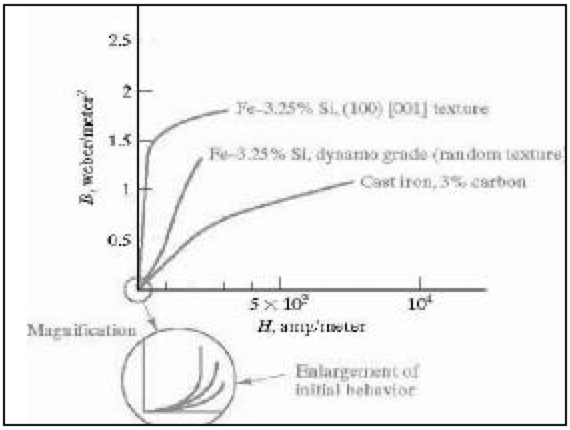
Magnetocrystalline anisotropy - In single crystals, the coercivity depends upon crystallographic direction creating easy and hard axes of magnetization.

Iron



The initial magnetization curve for iron is highly anisotropic; magnetization is easiest when the <100> directions are aligned with the field and hardest along [111].



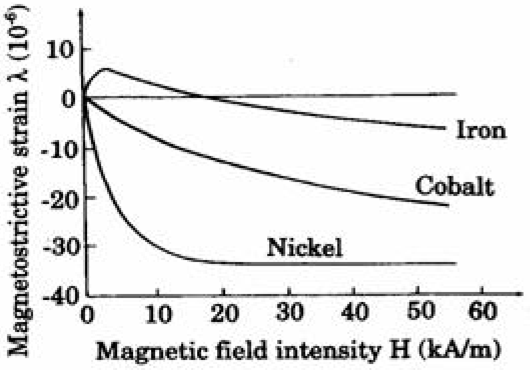


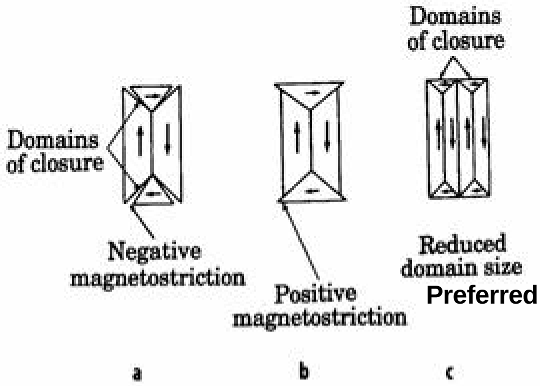
Magnetoresistance

- **Phenomenon in which the electrical resistivity changes with the magnetic field**
- **Due to interaction of magnetic field with electrons**
- **Useful for magnetic field sensing**

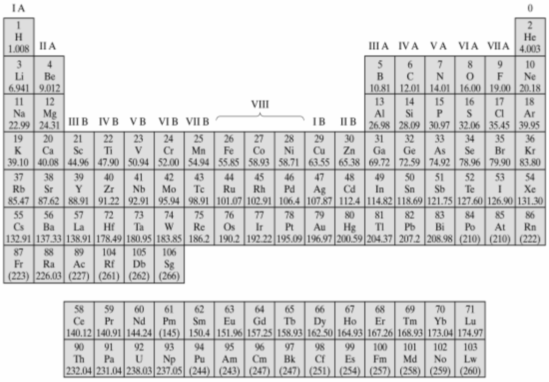
Magnetostriction

- **Strain due to change in magnetic state (by changing the magnetic field or the temperature)**
- **Due to interaction of the magnetic field with the electron orbit**
- **Examples of magnetostrictive materials: iron nickel, Fe_3O_4, $TbFe_2$, $DyFe_2$, $SmFe_2$.**
- **Useful for actuation**





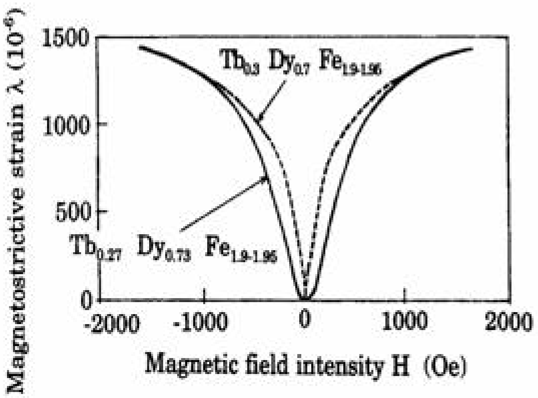
Preferred



I A	II A	III B	IV B	V B	VI B	VII B	VIII			I B	II B	III A	IV A	V A	VI A	VII A	0
1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.4	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.22	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.2	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra 226.03	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)												
		58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97		
		90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (254)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lw (260)		

Terfenol-D

- **Terbium (Tb)**
- **Iron (Fe)**
- **Dysprosium (Dy)**
- **Naval Ordnance Laboratory (NOL)**
- **Composition: ~$Tb_xDy_{1-x}Fe_y$**
  x ranging from 0.27 to 0.30
  y ranging from 1.9 to 2.

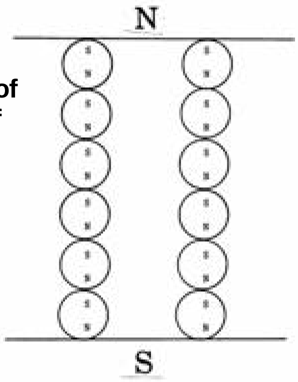


Magnetorheology

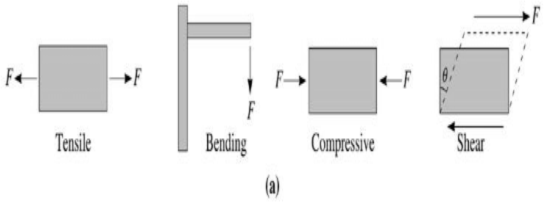
Phenomenon in which the rheological behavior changes with the magnetic field

Magnetorheological (MR) fluid

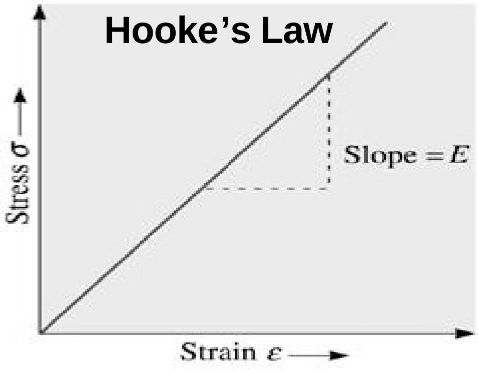
A dispersion of fine magnetic particles in a liquid medium



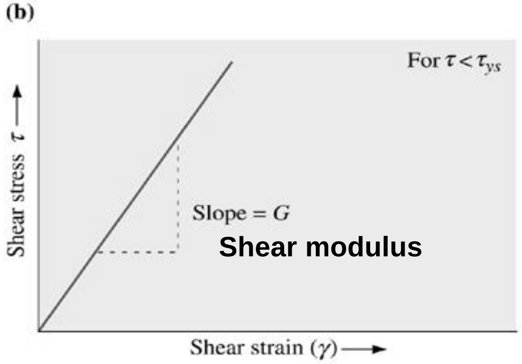
Formation of columns of magnetic particles under a magnetic field



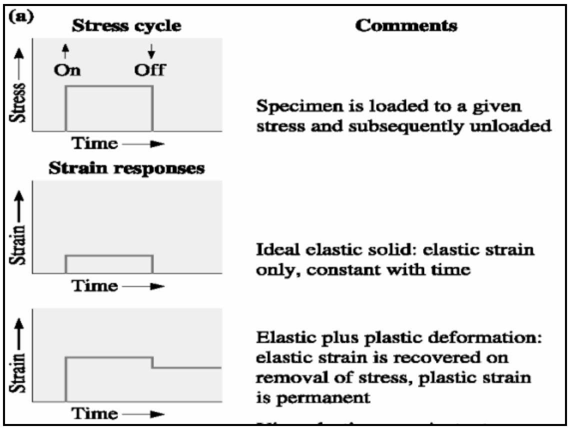
Hooke’s Law



(b) Elastic material



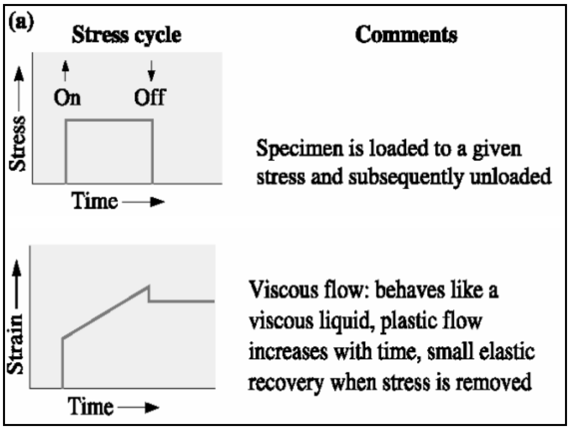
Shear modulus



Specimen is loaded to a given stress and subsequently unloaded

Ideal elastic solid: elastic strain only, constant with time

Elastic plus plastic deformation: elastic strain is recovered on removal of stress, plastic strain is permanent

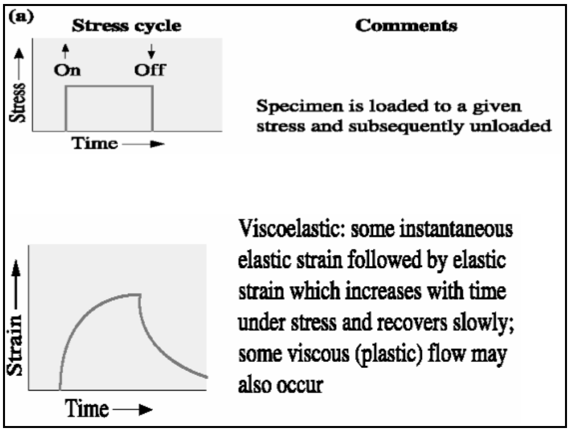


Specimen is loaded to a given stress and subsequently unloaded

Viscous flow: behaves like a viscous liquid, plastic flow increases with time, small elastic recovery when stress is removed

Viscous material

A material in which the strain develops over a period of time and the material does not go to its original shape after the stress is removed.



Specimen is loaded to a given stress and subsequently unloaded

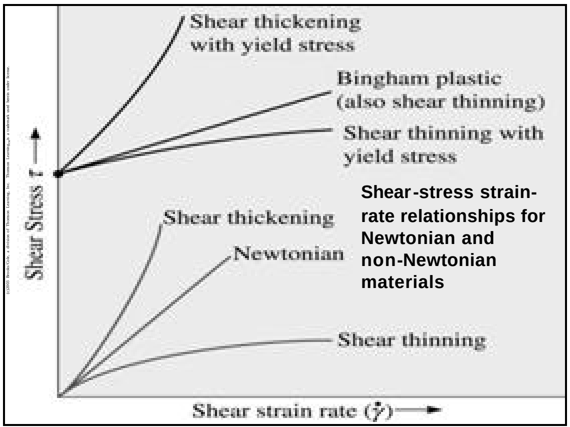
Viscoelastic: some instantaneous elastic strain followed by elastic strain which increases with time under stress and recovers slowly; some viscous (plastic) flow may also occur

Viscoelastic material

- A material in which the total strain developed has elastic and viscous components.
- Part of the total strain recovers similar to elastic strain.
- Some part of the total strain recovers over a period of time.
- Examples: polymer melts.

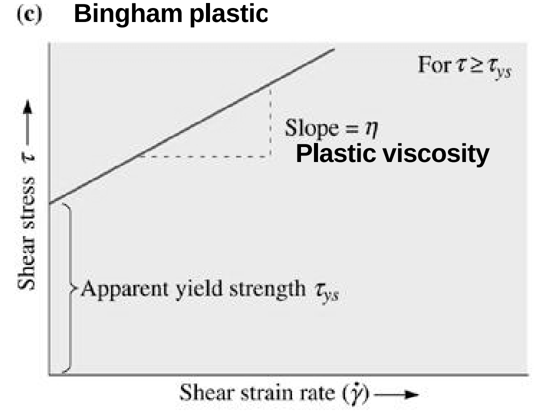
Viscosity

- Measure of resistance to flow
- Defined as the ratio of shear stress to shear strain rate
- Unit: Poise or Pa.s
- 1 Pa.s = 10 P = 1000 cP

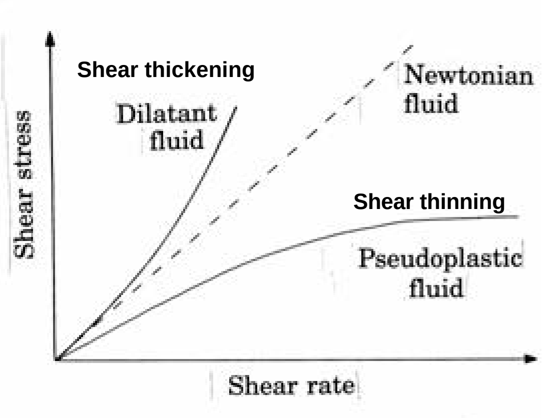


Shear-stress strain-rate relationships for Newtonian and non-Newtonian materials

Bingham plastic

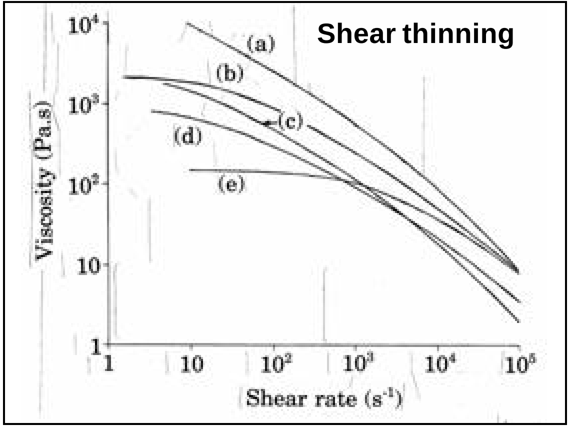


Plastic viscosity

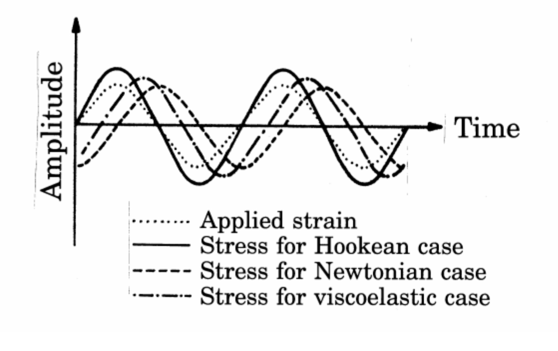


Shear thickening

Shear thinning



Shear thinning



Electrorheological (ER) fluid

Dispersion of fine dielectric particles in a liquid medium

Table 1. Typical properties of MR and ER fluids

	MR fluids	ER fluids
Maximum yield stress	50-100 kPa	2-5 kPa
Plastic viscosity	0.2-1.0 Pa.s	0.2-1.0 Pa.s
Maximum field	~ 250 kA/m	~ 4 kV/mm
Response time	ms	ms
Density	3-4 g/cm^3	1-2 g/cm^3
Operable temperature range	-50 to 150°C	+10 to 90°C
Power supply	2-25 V 1-2 A (2-50 W)	2000-5000 V 1-10 mA (2-50 W)
Stability	Not affected by most impurities	Cannot tolerate impurities