

August 2, 2006

3. Ferromagnetic materials

3.1 Soft magnetic materials

3.2 Hard magnetic materials

3.3 Magnetic recording materials

3.1 Soft magnetic materials

Soft magnetic materials have high permeability and low coercivity.

$$\mu = (B / H)$$

$$B = \mu_0 H + I$$

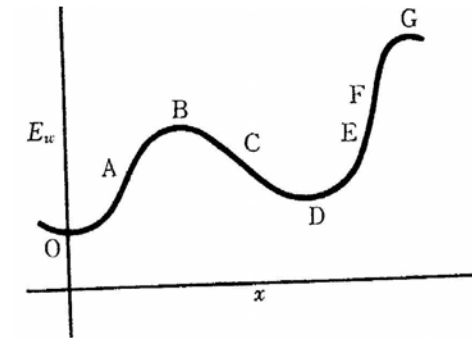
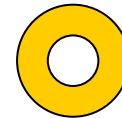
$$\mu = \mu_0 + H / I = \mu_0 + \chi = \mu_0 (1 + \bar{\chi})$$

For obtaining soft magnetic properties

- a) Materials with low magnetic anisotropy, low magnetostriction and high saturation magnetization

$$H_c = 2K_u / I_s \quad K_u = K_{crys} - \frac{3}{2} \lambda_s \sigma \quad \chi \propto I_s^2 / \alpha$$

- b) Annealing for reducing defects in a material, which makes domain wall move easily.
c) Ring shape for reducing magnetic shape anisotropy.



Soft magnetic materials

1. Fe-Si alloys: 3%Si-Fe, 6.5% Si-Fe ($\lambda_s \sim 0$)
2. Perm alloy: $K_1 \sim 0$, $\lambda_s \sim 0$ for 78%Ni-Fe, 4%Mo-79%Ni-Fe = Supermalloy, enhanced permeability
3. Sendust: Fe-Al- Si: 10%Si-5%Al-Fe, $\lambda_s \sim 0$
4. Spinel ferrites such as $Mn_{0.5}Zn_{0.5}Fe_2O_4$, $Ni_{0.3}Zn_{0.7}Fe_2O_4$: high frequency applications
5. YIG: Microwave applications
6. Amorphous alloys
7. Nanocrystals

1. 3%Si-Fe alloy

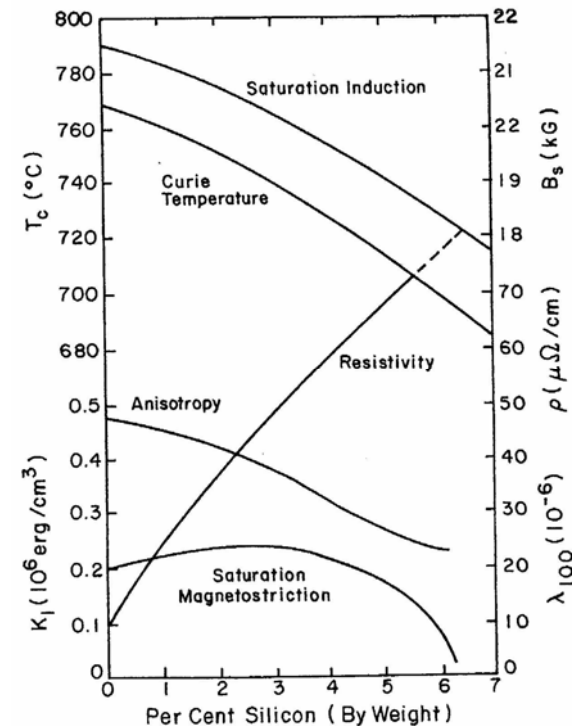
This material is for power and distribution transformers, which are used under the AC with a lower frequency. The energy loss in these transformers generally consists of magnetic core loss and coil loss due to joule heating in the copper coils.

Core loss = classical eddy current loss + eddy current loss due to domain wall movement
+ acoustic loss due to magnetostrictive deformation of the core under changing flux.

→ **For reducing core loss**, decreasing lamination thickness, increasing resistivity, decreasing domain size and decreasing magnetostriction are effective.

Comparison of Physical Properties of Pure Iron with Those of 3% SiFe

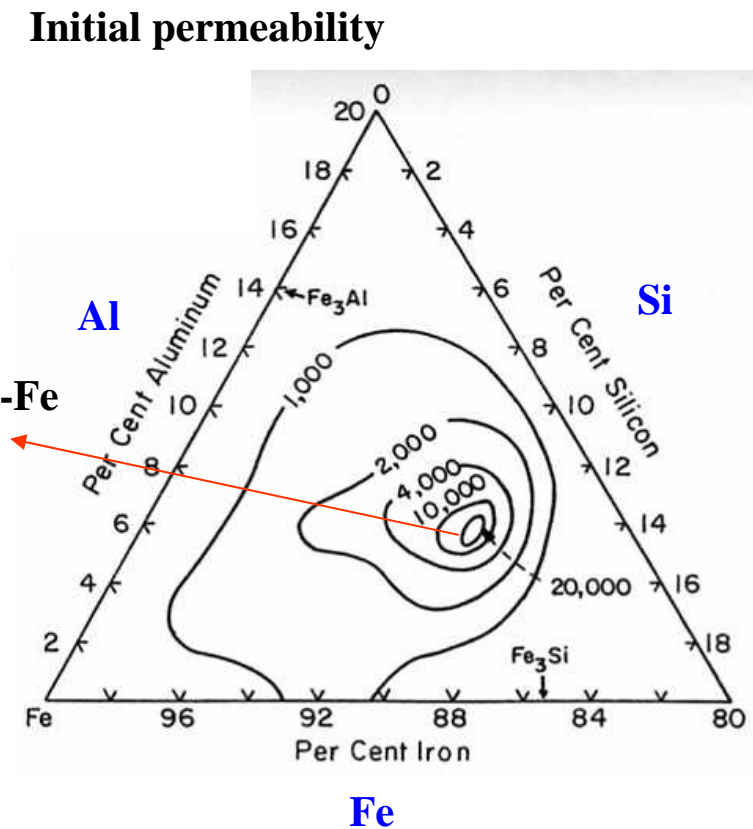
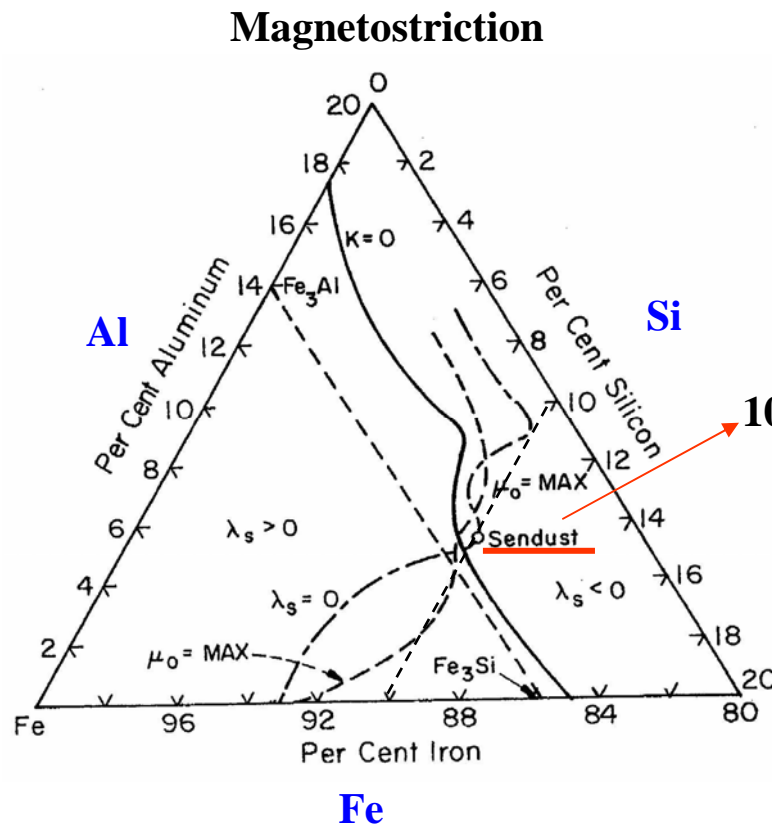
Property	BCC Fe	3% SiFe
$4\pi M_s$ (kG)	22	20
ρ_m (g/cm ³)	7.87	7.65
ρ_e ($\mu\Omega$ cm)	10.1	48
a_0 (Å)	2.866	2.857
T_c (°C)	771	745
K_1 (10^5 erg/cm ³)	5	3.6
λ_{100} (10^{-6})	25	23
λ_{111} (10^{-6})	-20	-4



2. Sendust

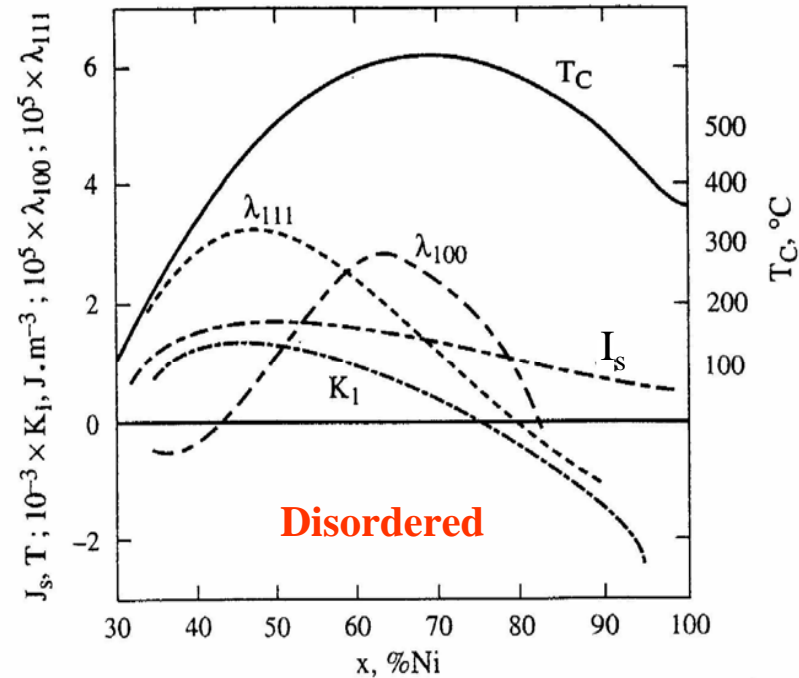
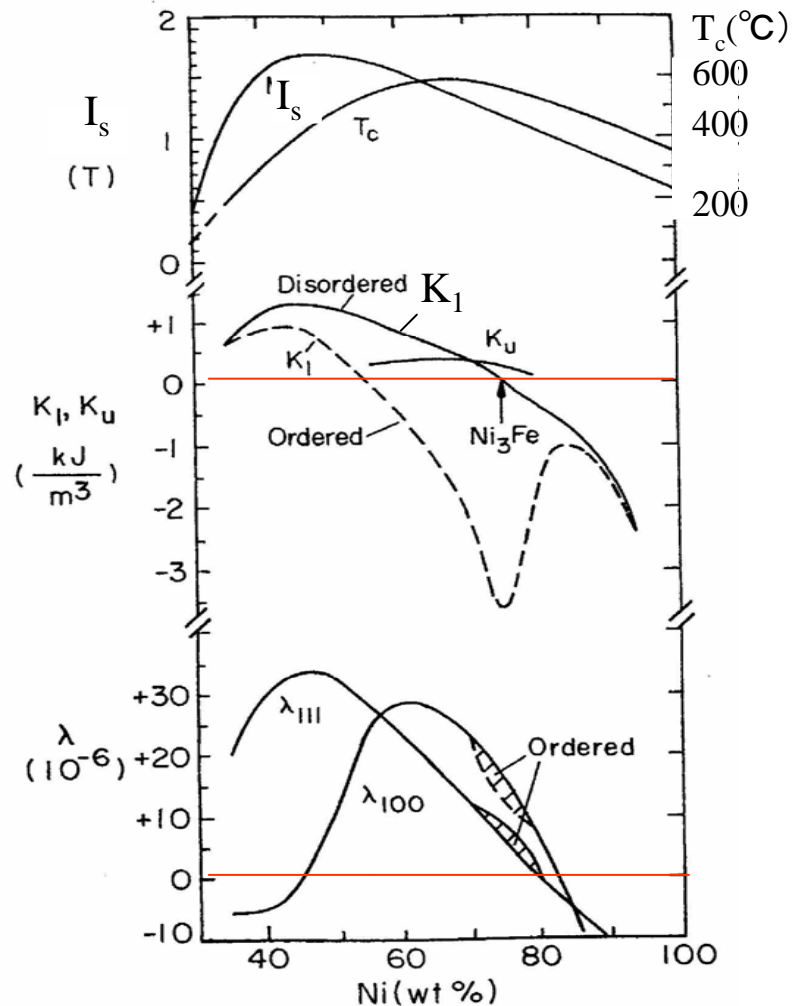
Sendust was named by its discoverers at Tohoku University in Sendai to reflect the fact that it is very brittle, and thus the material has to be made and used in **powder or dust form**.

Sendust has zero magnetostriction.



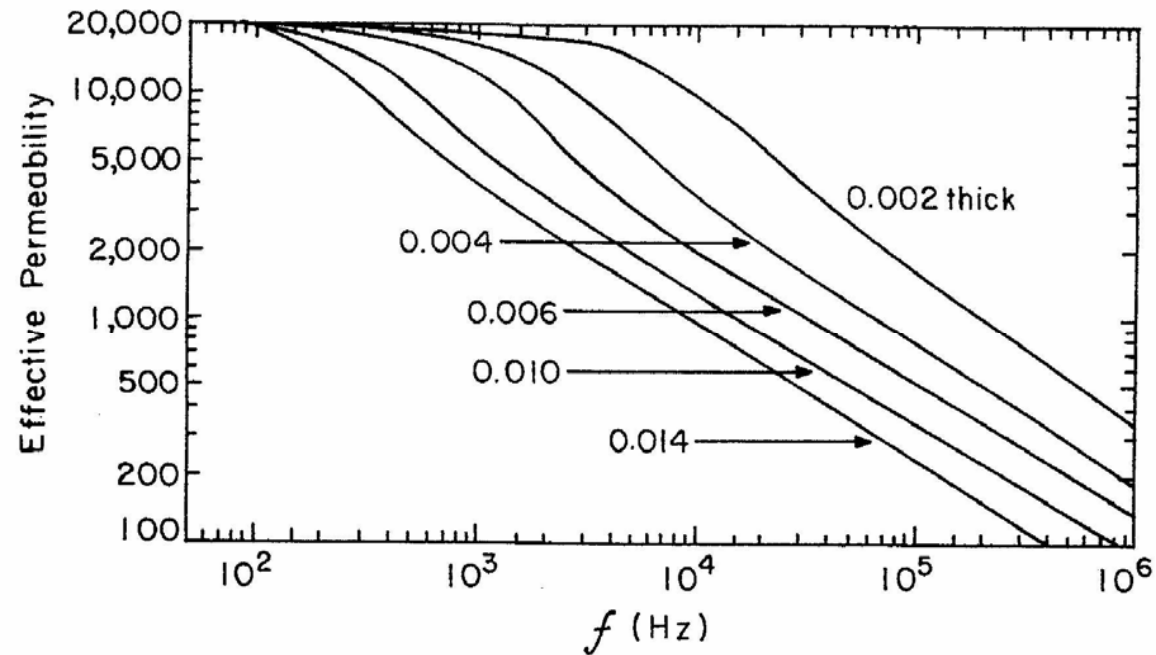
3. Permalloys

Magnetic iron-nickel alloys are generally called permalloys. Especially **78% Ni permalloy** has low magnetocrystalline anisotropy and magnetostriction.



Mo addition suppresses formation of the ordered structure, which leads to the large permeability due to slow cooling after annealing. This alloy is called **supermalloy**.

4%Mo-79% Fe Permalloy sheet (inches)



4. Spinel Ferrites

The electrons in oxides are localized around atoms, and the electronic states in oxides are more atomic like than metals. Thus, the electrons in oxides can be described by the same quantum numbers that apply to isolated atoms. **Spinel ferrites are the typical oxide ferromagnets.**

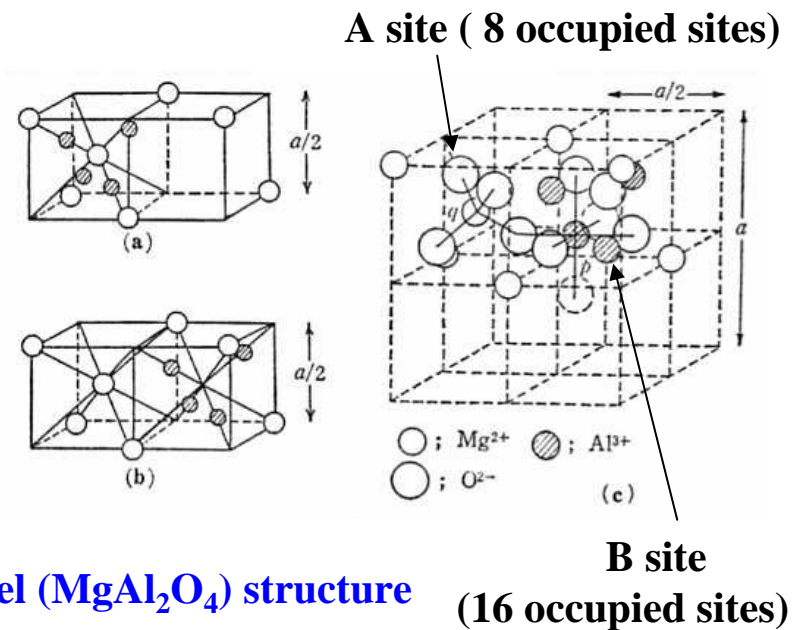
Spinel ferrites: MFe_2O_4 , $M = Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}$

There are two distinct types of sites for transition metal ions occupancy, **tetrahedral (A) sites** and **octahedral (B) sites**.

	A site (Tetrahedral)	B site (Octahedral)
Normal spinel	M^{2+}	$Fe^{3+} \quad Fe^{3+}$
Inverse spinel	Fe^{3+}	$M^{2+} \quad Fe^{3+}$

Normal spinel: $M = Zn$

Inverse spinel: $M = Mn, Fe, Co, Ni, Cu$

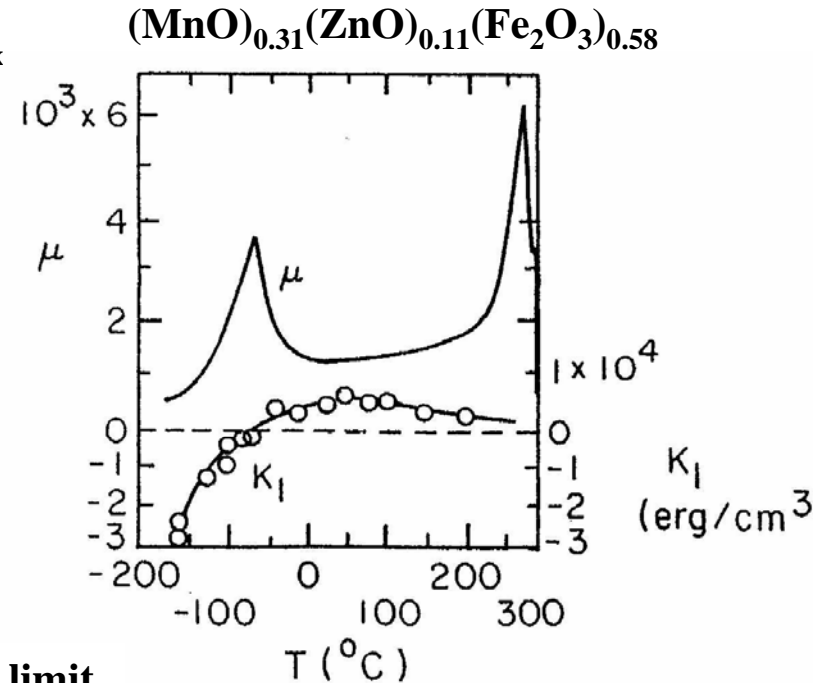
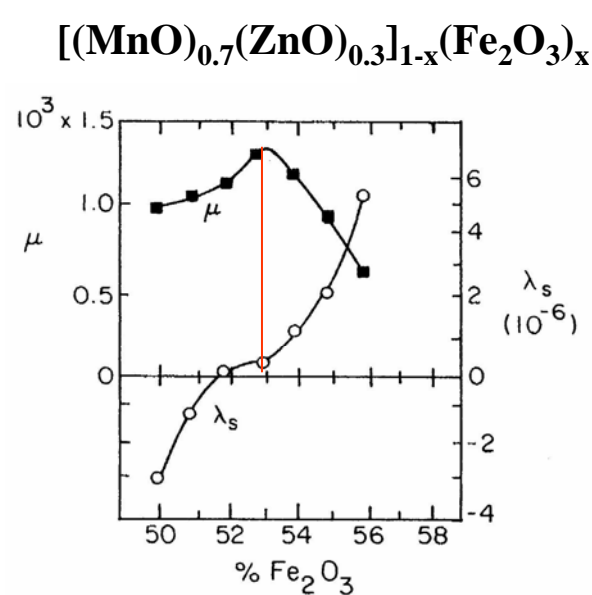


Magnetic properties of spinel ferrites

1) Mn-Zn ferrites



Mn-Zn ferrites have soft magnetic properties and relatively low resistivity of the order of Ωcm .



2) Ni-Zn ferrites $(\text{Ni-Zn})\text{Fe}_2\text{O}_4$

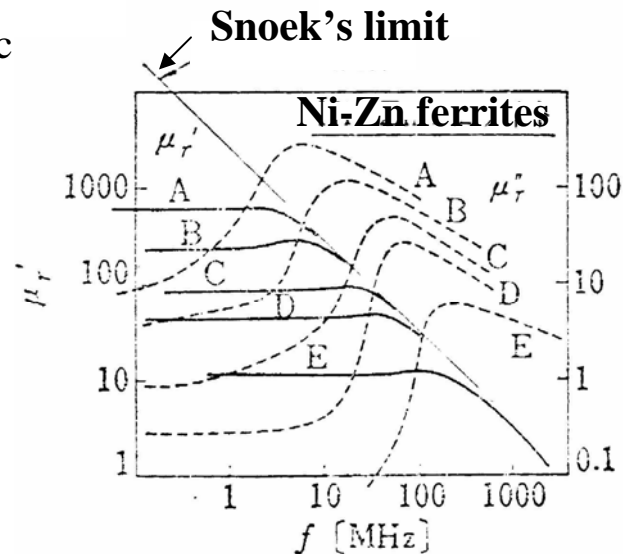
Ni-Zn ferrites have soft magnetic properties and a high resistivity of the order of $10^3 \Omega\text{cm}$.

Snoek's limit

$$f_r(\mu_i - 1) = \frac{\gamma I_s}{3\pi\mu_0}$$

f_r : resonance frequency.

γ : gyro magnetic ratio



Natural resonance

Higher μ leads to resonance at lower frequency.

5. Amorphous alloys

Amorphous alloys are fabricated by **melt quenching** and **vapor deposition** etc., which are metastable and thus transformed into crystalline states by the heating. In order to obtain amorphous alloys, high-rate cooling of over 10^6 °C/s is required in general.

1. Material systems

T-M (T = Transition metal, M = Metalloid) : M = B, P, C, Si , Melt quenching, thin films

T-T: Co-Zr, Co-Nb etc., mainly thin films

R-T (R = Rare earth): Gd-Co, Fe-Tb etc., mainly thin films

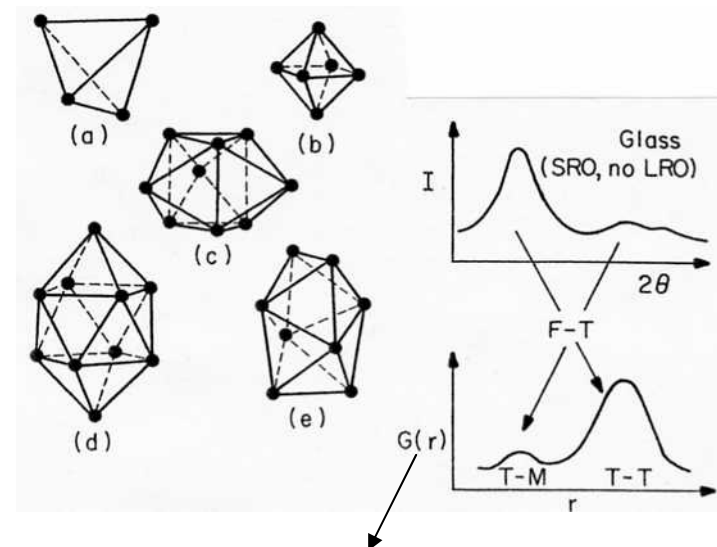
2. Atomic structure

The local atomic arrangement in amorphous alloys is not completely random, but the short-range order exists, which is likely similar to that of **Bernal polyhedra** (a) and (b) constructed of transition metal atoms and having metalloid atoms at their centers.

The short range order of amorphous alloys generally results in X-ray diffraction patterns similar to that in the figure right, upper. Fourier transformation of such data leads to **radial distribution functions** or **pair correlation functions** indicating T-T pairs and T-M pairs but no M-M nearest neighbors.

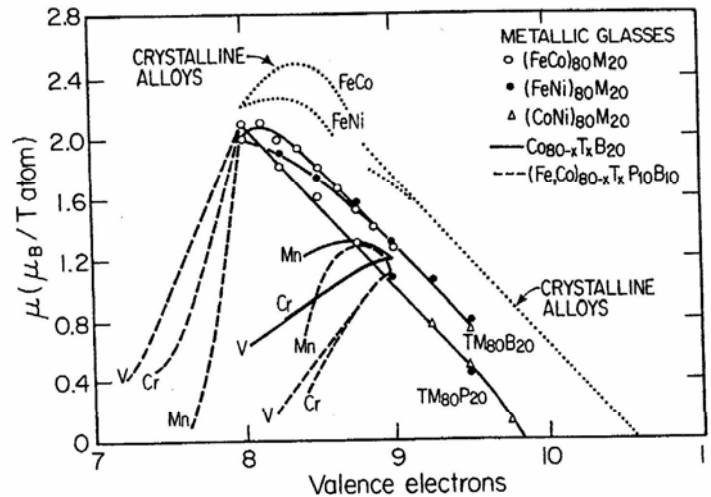
Correlation numbers for amorphous alloys are usually close to **12**, as in close packed crystals.

Structure of Bernal polyhedra



Pair correlation functions

3. Magnetic moment



$$\delta^2 = \frac{\langle (\sum_j \Delta J_{ij})^2 \rangle}{(\sum_j \langle J_{ij} \rangle)^2} \quad x = \mu H / k_B T$$

4. Exchange fluctuations

Fluctuations in short-range order in amorphous alloys cause the strength of the exchange interaction to vary spatially.

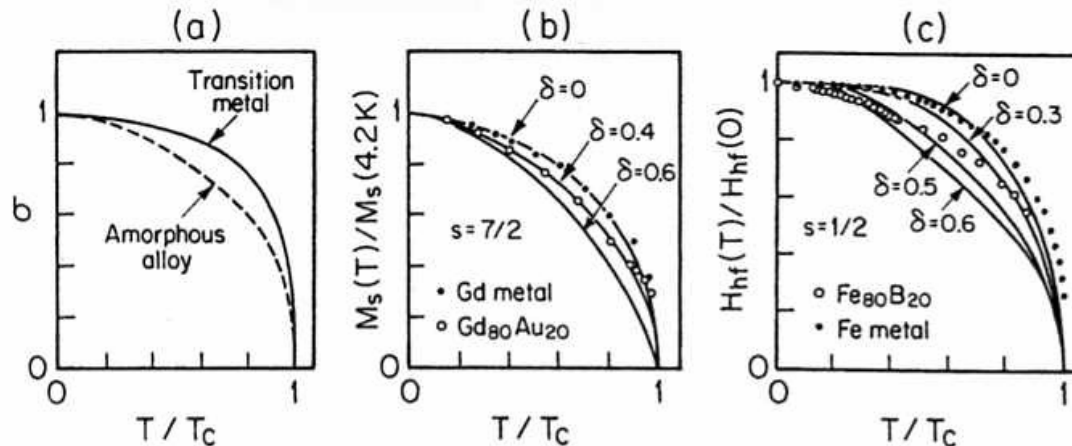
$$J_{ij} = \langle J_{ij} \rangle + \Delta J_i$$

This exchange fluctuation leads to local variations in the saturation moment.

The Brillouin function is then suppressed:

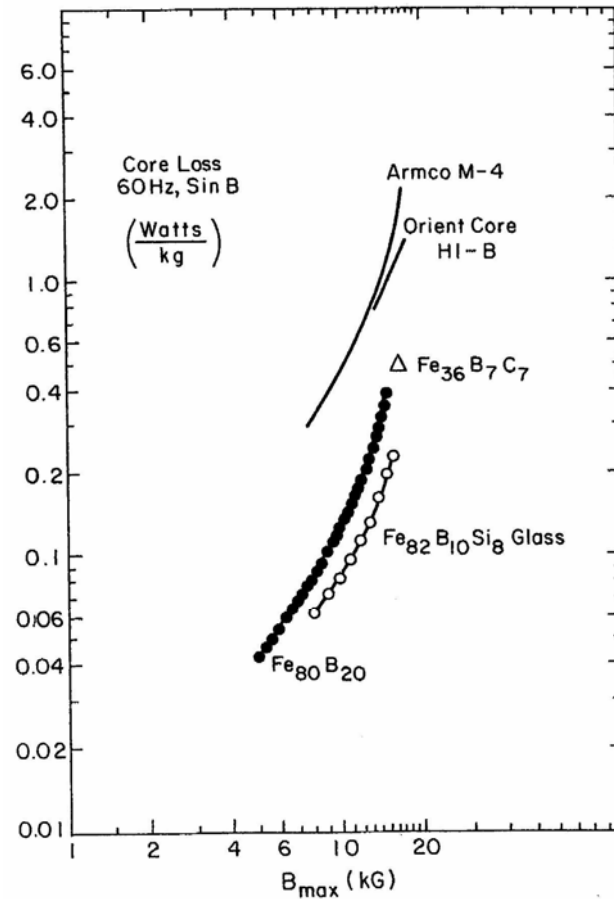
$$I(T) / I(0) = \frac{1}{2} \{ B_s[x(1+\delta)] + B_s[x(1-\delta)] \}$$

δ is the root-mean square exchange fluctuation.



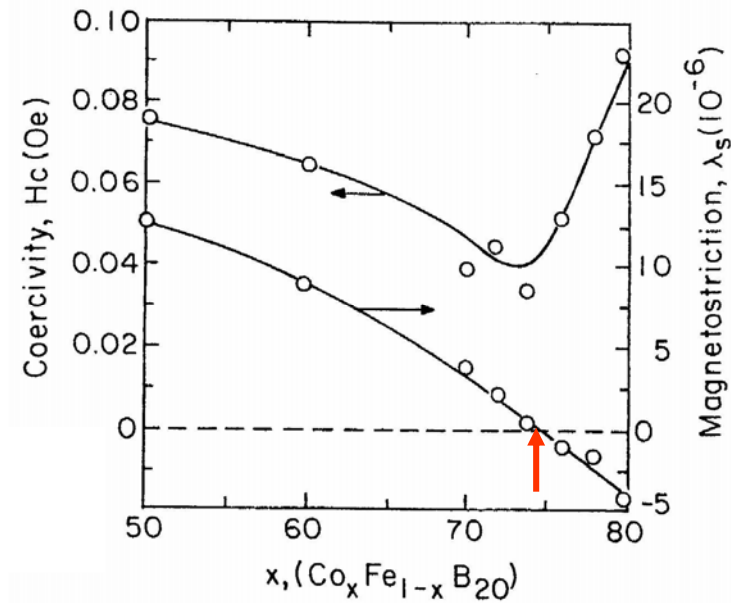
Reduced magnetization for Amorphous alloys are interpreted in terms of the above model.

5. High induction amorphous alloys Fe-based



Applications: Power transformer

6. Low magnetostriction Co-based amorphous alloys



High frequency applications

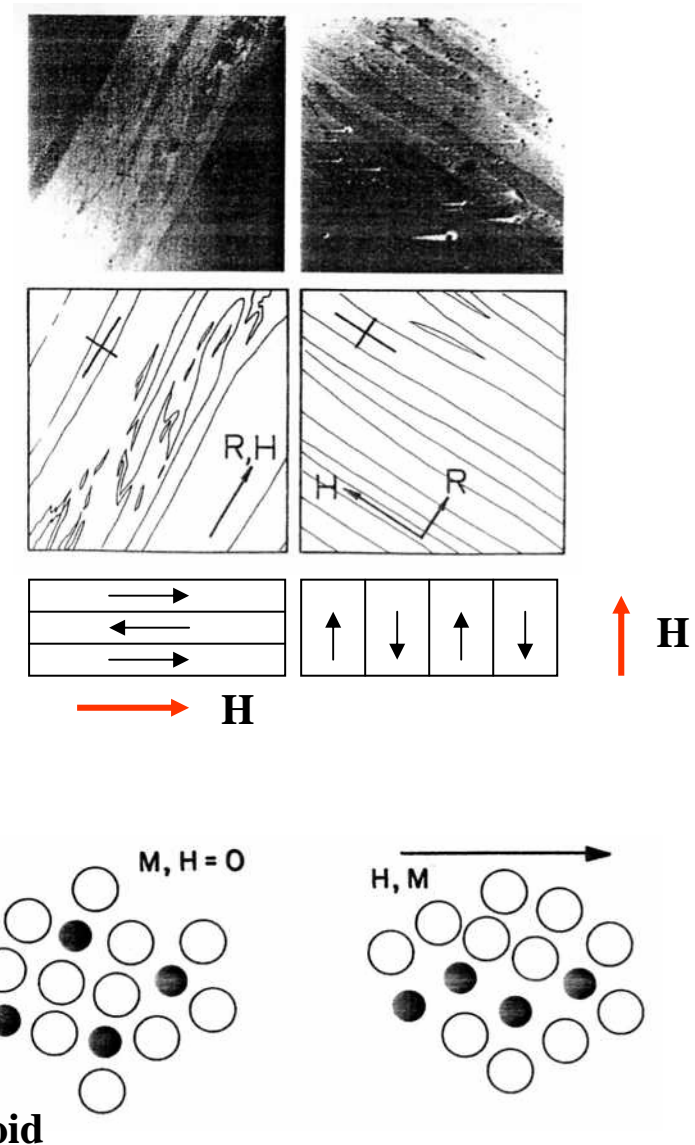
Switching power supply
Noise suppressor

Induced Anisotropy

It is possible to alter the technical properties of amorphous alloys by **field annealing**, which changes magnetic domain structures as shown in the figure. The atomic mechanism behind field-induced anisotropy is essentially that the local atomic order is biased by field annealing to have a small degree of **directional order**.

Briefly, when a magnetic material is heated below its Curie and crystalline temperatures but at a temperature high enough to allow substantial short-range atomic mobility, the thermal motion of the atoms may result in a slight biasing of the local structure toward an atomic configuration that is more stable with respect to the local direction of magnetization.

If a field is applied during the annealing process, then the local atomic rearrangements may result in a long-range correlation of a small fraction of the bond directions with the magnetization direction. **The metalloids play a role** in this process because of their high mobility and strong chemical interaction with the T metals.

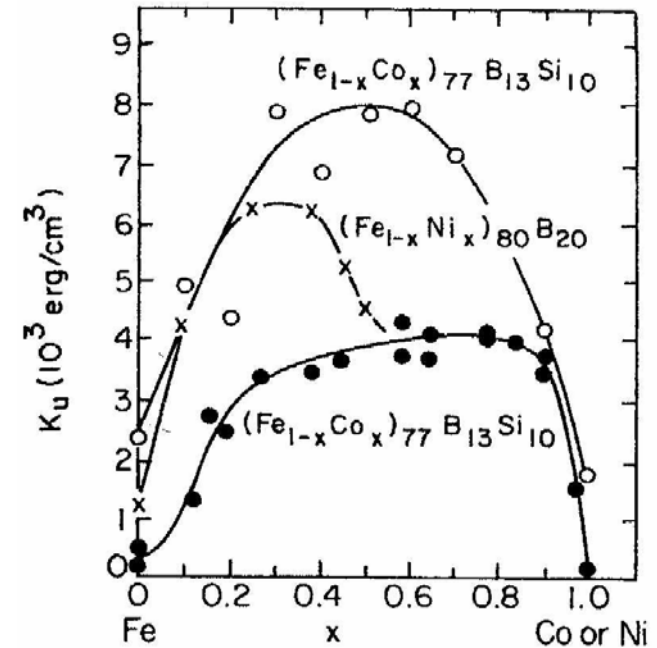
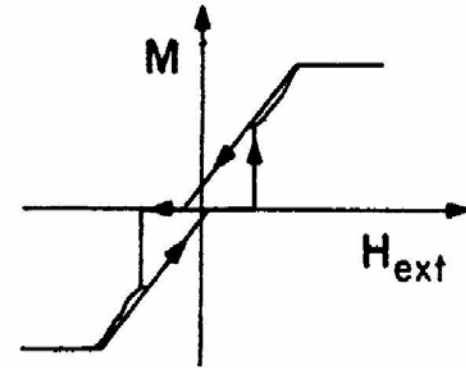


Annealing in the absence of a field also induces a local magnetic anisotropy that changes in direction as the direction of magnetization changes from domain to domain.

Further, where a domain wall exists during annealing, it will be stabilized or pinned in that position by the same mechanism as in the field annealing. Such domain wall pinning induces large coercivity and a characteristic I-H loop as shown in the right figure.

Because of the dependence of induced anisotropy on the number of pairs in an A_xB_{1-x} alloy, the strength of induced anisotropy varies as $[x(1-x)]^2$. As for the composition dependence of induced anisotropy in amorphous alloys, **K_u is grater near $x = 0.5$** as expected, while it does not vanish quadratically near $x = 0$ or 1 . It is believed that this is due to contributions to the directed-pair energy by transition metal-metalloid pairs.

Pinned-wall



(a)

6. Nanocrystals

Nanocrystalline alloys are comprised primarily of crystalline grains having at least one dimension on the order of a few nanometers. Each magnetic nanocrystallite is a single-domain particle that may or may not be exchange coupled to other nanocrystallites. **The exchange coupled materials Can provide soft magnetism.** While, isolated nanocrystals exhibit hard magnetic properties for Some materials with high magnetocrystalline anisotropy .

Soft magnetic nanocrystalline alloys

Processing:

- 1) Quenching certain alloy compositions from the melt at a rate insufficient to achieve a homogeneous nanocrystalline structure. Fine-grain structure may result from the large undercooling and kinetically frustrated grain growth.
- 2) Heat-treatment an amorphous alloy precursor.

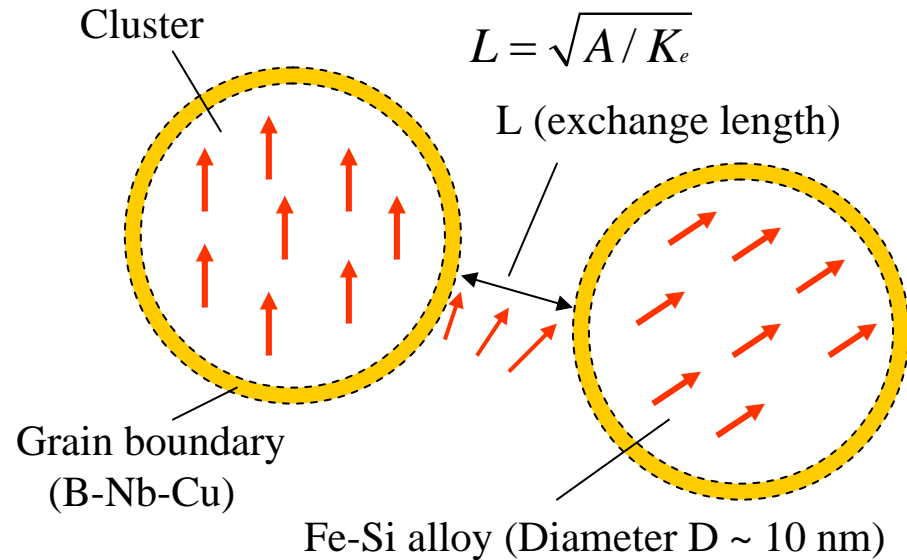
Typical materials:

Fe-Cu-Nb-Si-B: Widely studied nanocrystalline alloy, having nominal composition of $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$. The presence of Cu, insoluble in Fe, promotes massive nucleation, and Nb retards grain growth. The nanocrystalline phase in these alloys is $\alpha\text{-Fe}_3\text{Si}$, which occupies some 70-80 vol% and 10-15 nm in size. The amorphous grain boundary phase has a thickness of about 1 nm.

$H_c \sim 0.01 \text{ Oe}$, $4\pi I_s \sim 10\text{-}12 \text{ kG}$, $\mu \sim \text{order of } 10^5$, $\lambda_s \sim 3 \times 10^{-6}$ (20×10^{-6} in amorphous alloy)

Why soft magnetic properties are obtained in nanocrystals ?

Example: Fe-Si-B-Nb-Cu nano-structured material



$$K_{loc} = 8 \times 10^4 \text{ erg} / \text{cm}^3$$

$$K_e = 50 \text{ erg} / \text{cm}^3$$

Reason for soft magnetism:

- 1) Grain size is very small, which does not influence domain wall movement.
- 2) Cluster is made of a soft magnetic material with small magnetostriction.
- 3) Exchange coupling between clusters is larger than the magnetic anisotropy.

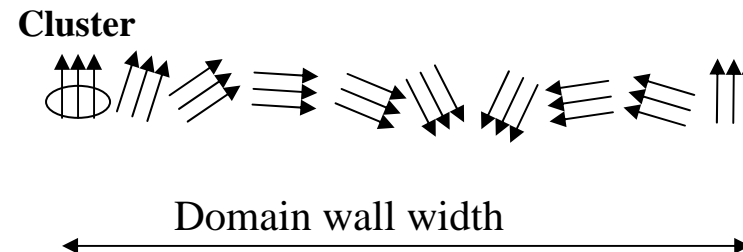
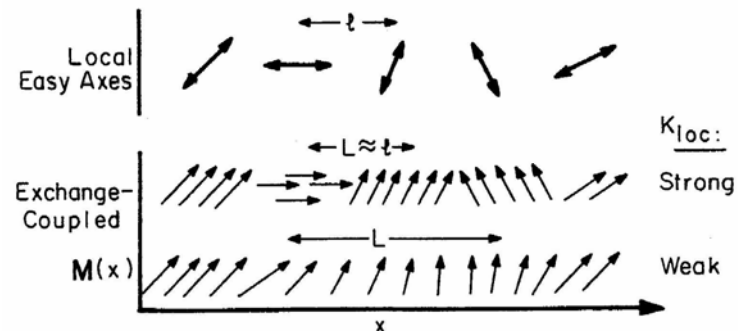
The spins in a cluster are exchange-coupled ferromagnetically, and spins between clusters are also exchange-coupled in a range of exchange coupling length L .

Effective magnetic anisotropy is given by

$$K_e = K_{loc} / \sqrt{N}$$

N : Number of atoms in a cluster

K_{loc} : Magnetocrystalline anisotropy of a cluster



Exchange length: $L = \sqrt{A / K_e}$, where A is the exchange stiffness constant.

As $N = (L / D)^3$,

we obtain
$$\left. \begin{aligned} K_e &= K_1 / \sqrt{N} = K_1 (D / L)^{3/2} \\ L &= \sqrt{A / K_e} = A^{1/2} K_1^{-1/2} D^{-3/4} L^{3/4} \end{aligned} \right\}$$

which leads to

$$\left. \begin{aligned} L &= A^2 K_1^{-2} D^{-3} \\ K_e &= K_1 (D / L)^{3/2} = K_1^4 A^{-3} D^6 \\ \underline{H_c} &= \underline{2K_e / I_s} = \underline{2K_1^4 A^{-3} D^6 / I_s} \end{aligned} \right\}$$

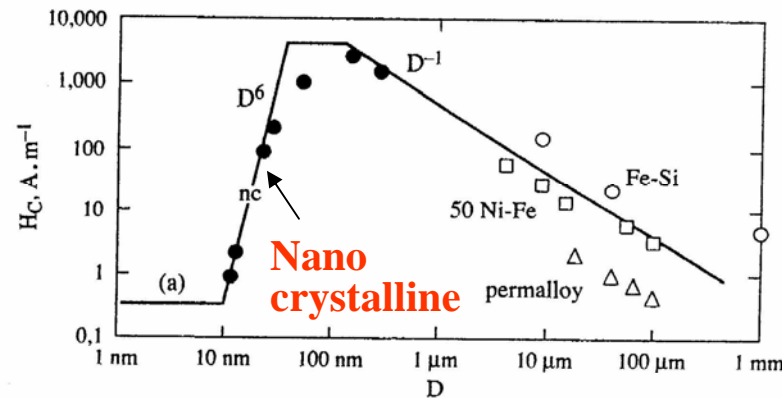


Figure 16.20 - Coercive field (H_c) as a function of the grain size (D) for different families of soft materials (after [21])

Amorphous (a), nanocrystallized (nc) and crystallized materials (Fe-Si, 50FeNi and Permalloy)

Applications of soft magnetic materials

Fe-Si alloys	Power transformer, motors, Noise filters
Permalloy	Magnetic heads (Audio), Inductors, Sensors
Sendust	Dust cores for choke coil
Soft ferrites	Magnetic heads (Video), Inductors for high frequency
Amorphous alloys	Switching regulators, Inductors, Sensors, Noise killers
Nanocrystals	Inductors