Magnetic Materials - II

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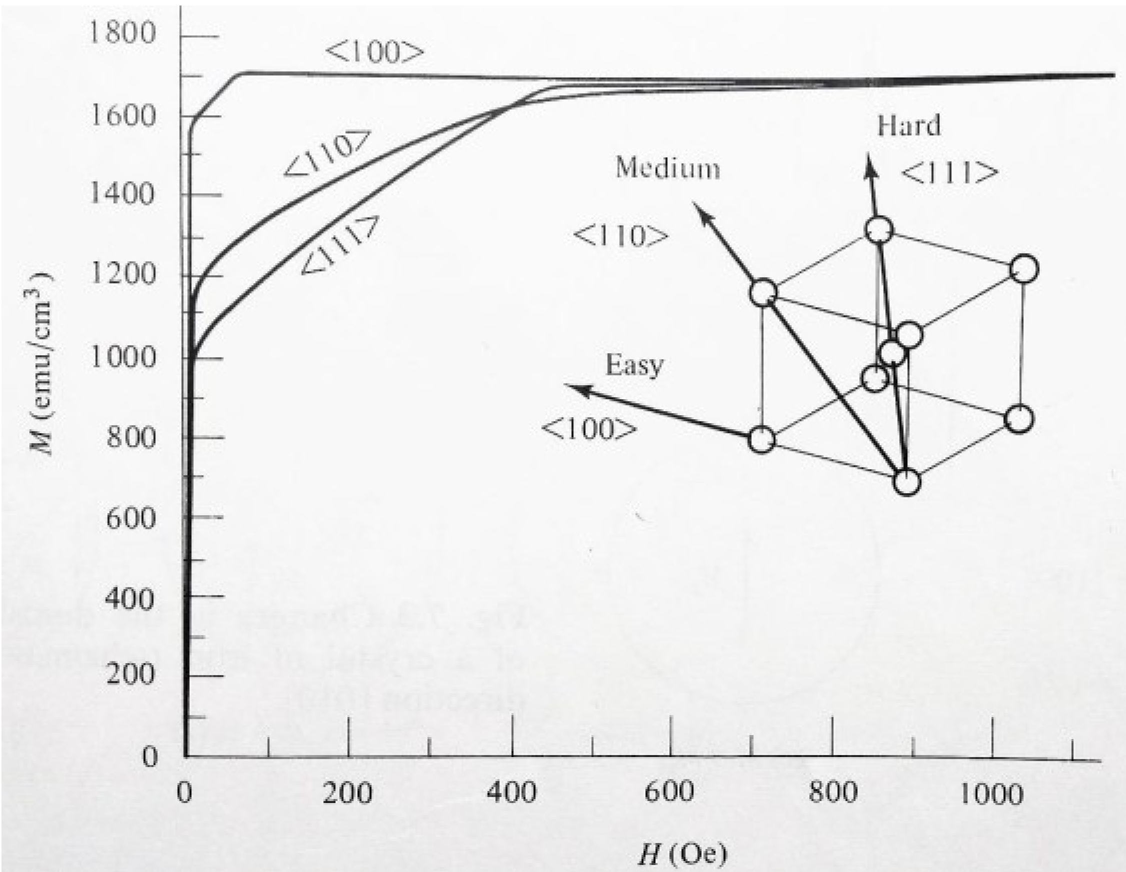
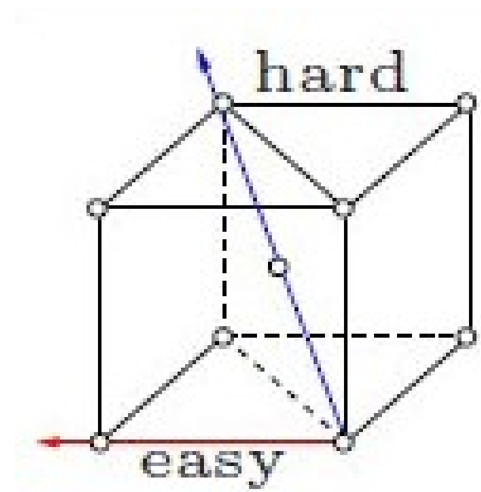
Magnetic Anisotropy

- In single crystal material of ferromagnetic material the magnetic property depends on the direction of measurement
- Thus, they exhibit some preferred direction of magnetization
- Even in absence of external filed, the spontaneous magnetization takes up a specific direction (with respect to crystal axis)

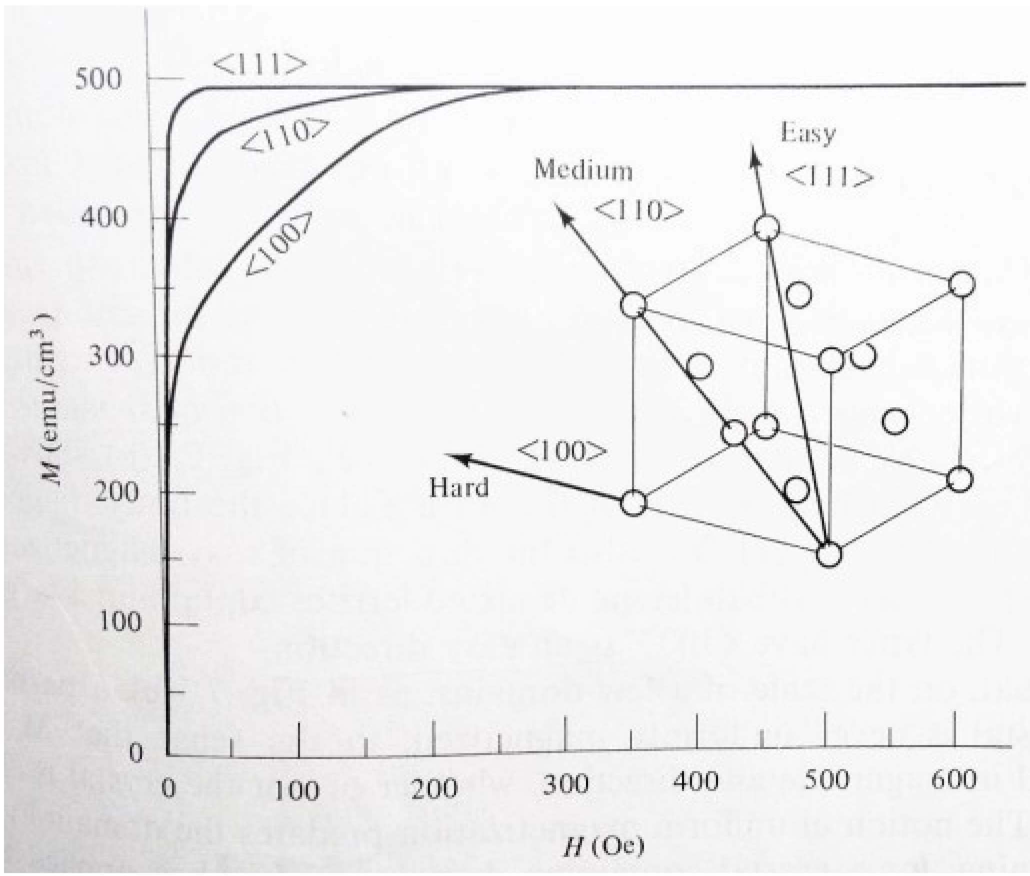
- For iron there are total six equivalent preferred easy direction of magnetization
- For bcc Fe the highest density of atoms is in the <111> direction, and consequently <111> is the hard axis. In contrast, the atom density is lowest in <100> directions and consequently <100> is the easy axis.

- Magnetization curves show that the saturation magnetization in <100> direction requires significantly lower field than in the <111> direction.
- Easy axis is the direction inside a crystal, along which small applied magnetic field is sufficient to reach the saturation magnetization.
- Hard axis is the direction inside a crystal, along which large applied magnetic field is needed to reach the saturation magnetization.

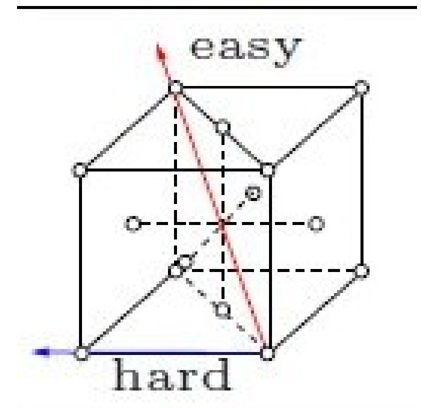




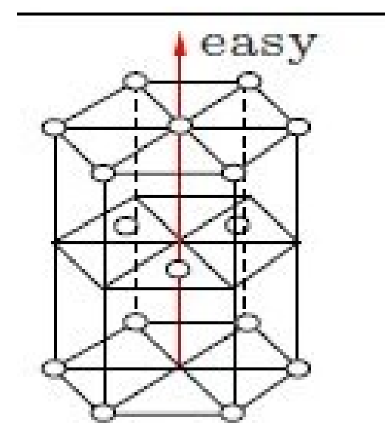
Iron: BCC crystal



Ni: FCC crystal



Ni: FCC crystal



Co: HCP

- The energy of magnetisation is given by the area of M vs H loop or $\int H(dM)$
- The energy is least when a crystal is magnetized in the easy direction
- Excess energy is required if the specimen is magnetized in hard direction
- This energy is called Anisotropic Energy

- In polycrystalline material various crystals are oriented more or less at random
- Thus the magnetic properties are not very different in different directions
- The materials need to be subjected to specific treatments such as cold rolling to create anisotropy

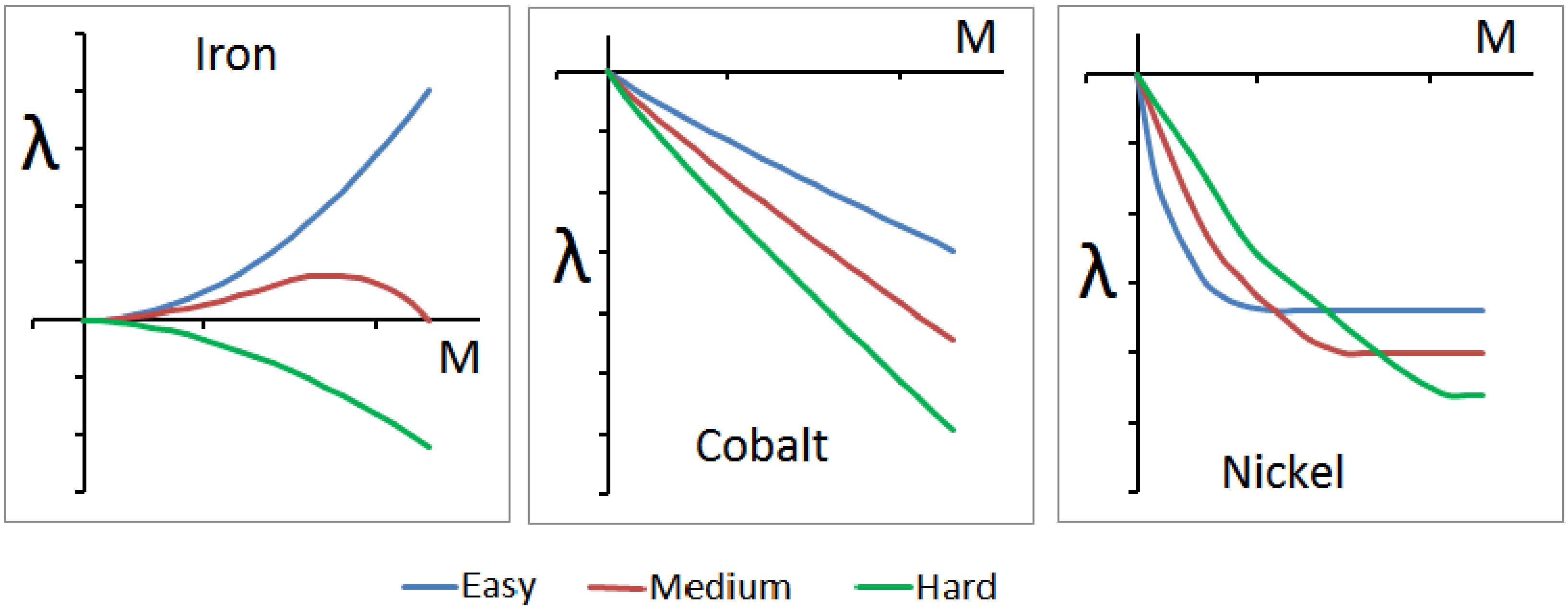
- This creates some regularity in the ditrsibution of orientation making materials property anisotropic
- This is beneficial as in each M vs H cycle excess energy I.e. anisotropic energy is lost when magnetized in non-easy directions

- In bulk materials there are mainly three methods by which uniaxial anisotropy can be induced:
  - Cold working: Particularly cold rolling
  - Magnetic annealing: heat treatment
  - Magnetic quenching: material is cooled in presence of a magnetic filed
- The anisotropic energy is responsible for change in dimension of the specimen

Magnetostriction

- When a material is magnetized some changes in physical dimension occurs. This phenomenon is known as magnetostriction
- There are three types of magnetostrictions:
  - Longitudinal: change in length in the direction of magnetization
  - Transverse: change in dimension perpendicular to the direction of magnetization
  - Volume: change in volume on magnetization

- The main concern remains with the Joule Effect of change in length in the direction of magnetization
- We define: Joule magnetostriction, $\lambda = \Delta\ell/\ell$
- As can be checked from figures, iron, cobalt, nickel crystals contract when magnetized in either of the three directions
- But, iron expands when magnetized in easy direction.



- Typical characteristics for ferromagnetic materials
- λ has the order of 10^{-6} (do not take into account the scale markings)

- Physically Magnetostriction can be explained as:
  - When a material is magnetized, the atoms experience rearrangement, such that magnetocrystalline anisotropy is kept minimum. This rearrangement of atoms result in slight changes in the dimension of the crystal.

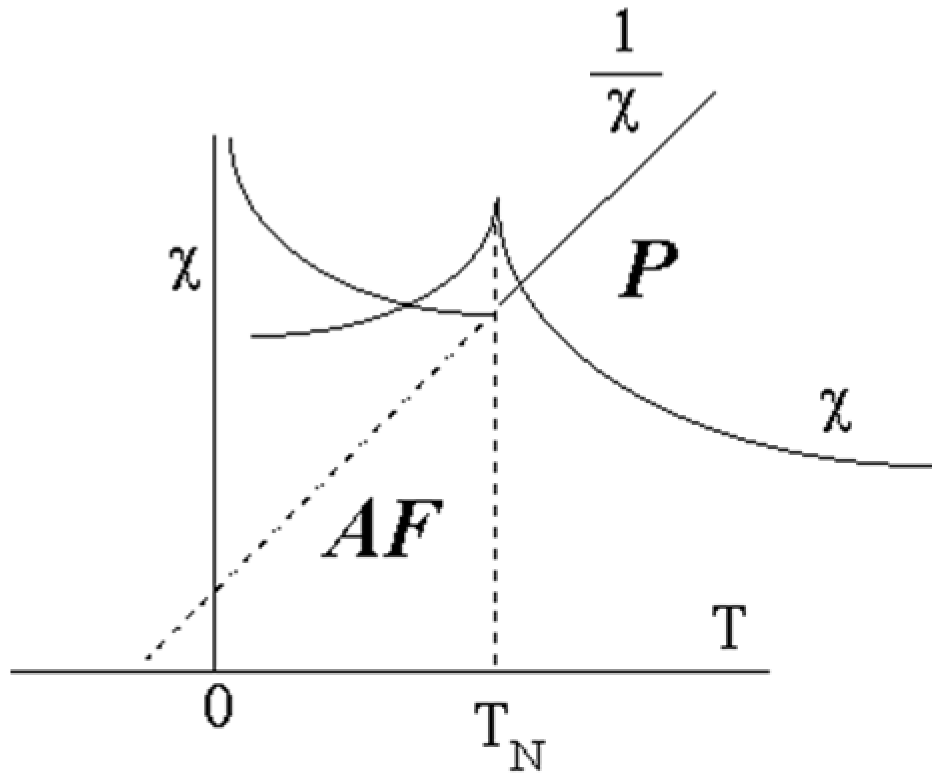
- A converse of magnetostriction effect, the ***Villari effect*** is also observed in magnetic materials.
  - Due to this effect longitudinal deformation leads to a change in permeability in the direction of applied strain

Antiferromagnetism

- When neighboring magnetic moments are aligned antiparallel, the material behaves as antiferromagnetic
- The net magnetic moment of the specimen is similar to ferrimagnetic material or zero even in the presence of applied field below Neel temperature, because the antiparallel ordering of atomic magnets is rigidly maintained.

- As temperature **decreases**, susceptibility **increases**, but at a critical temperature T_N called Neel Temperature, it goes through a maximum.
- If the temperature is further lowered, χ starts decreasing
- The material shows paramagnetism above T_N, denoted by **P** state and antiferromagnetic below it, denoted by **AF**

- The theory of antiferromagnetism was developed by French scientist **Louis Néel**, using Weiss molecular field concept.



- Some antiferromagnetic materials have Néel temperatures at, or even several hundred degrees above, room temperature, but usually these temperatures lies far below room temperature.
- The Néel temperature for manganese oxide (MnO), for example, is 122 K (−151° C)
- Although the net magnetization should be zero at a temperature of absolute zero, the effect of **spin canting** often causes a small net magnetization to develop,

- Theory of antiferromagnetism is helpful in understanding the theory of ferrimagnetism, which is of practical importance to us.
- Variation of susceptibility with temperature of an antiferromagnetic material above the critical temperature is given by:

$$\chi_m = \frac{C}{T-(-\theta)}$$

- The material obeys Curie-Weiss Law derived for ferromagnetic material but with negative value of θ.
- Here the molecular field acts to disalign the magnetic moments
- Below T_N, the tendency of dipole moments to align antiparallel is strong enough to act even in the absence of an external filed as thermal energy is quite low.

Ferrimagnetism

- In ferrimagnetic materials the magnetic moment of adjacent dipoles are aligned opposite, but, the moments are not equal so that there is a net magnetic moment
- Thus the material exhibit a net magnetic moment, although, it is less than that in ferromagnetic materials
- This moment disappears above Curie temperature, Tc, analogous to Neel temperature

- Similar to other cases, thermal energy randomizes the individual magnetic moments above Curie temperature and the material becomes paramagnetic
- Ferromagnetic material has the diadvantage of lower Electrical resistivity (low resistivity not always a boon!!)

… ferrites ..

- This restricts their application as core material in high frequency AC application
- As this causes high eddy current losses
- Ferrites have useful magnetic properties (not as good as ferromagnetics) with DC resistances many order higher
- Ferrites can be used at higher frequencies even upto microwave in transformer core for certain range of power

- Ferrites are in general complex oxides of various metals
- Many of the useful ferries are isomorphic (of similar chemical notational structure) with formulae MO, Fe_2O_3
  - M is the replacement metal
  - Usable replacement metals are bivalent such as Mn, Co, Ni, Cu, Mg, Fe++ etc

- The properties of final ferrite depend on the mature of replacement metals
- For many applications mixed ferrites, in which replacement are more than one, have more desirable property
- Magnetite or loadstone was actually a ferrite
- Ferrites depending upon coercivity are classified into hard and soft ferrites

- In general ferrites are with
  - Very high resistivity, of the order of $10^5 \Omega$-cm
  - Low dielectric loss
  - High permeability (but much less than ferromagnetic materials)
  - Saturation magnetization is appreciable, but noticably lower than ferromagnetic materials
  - Curie temperature from 100˚C to several hundreds
  - Mechanically hard, brittle and difficult to machine

Soft and Hard Magnetic Materials

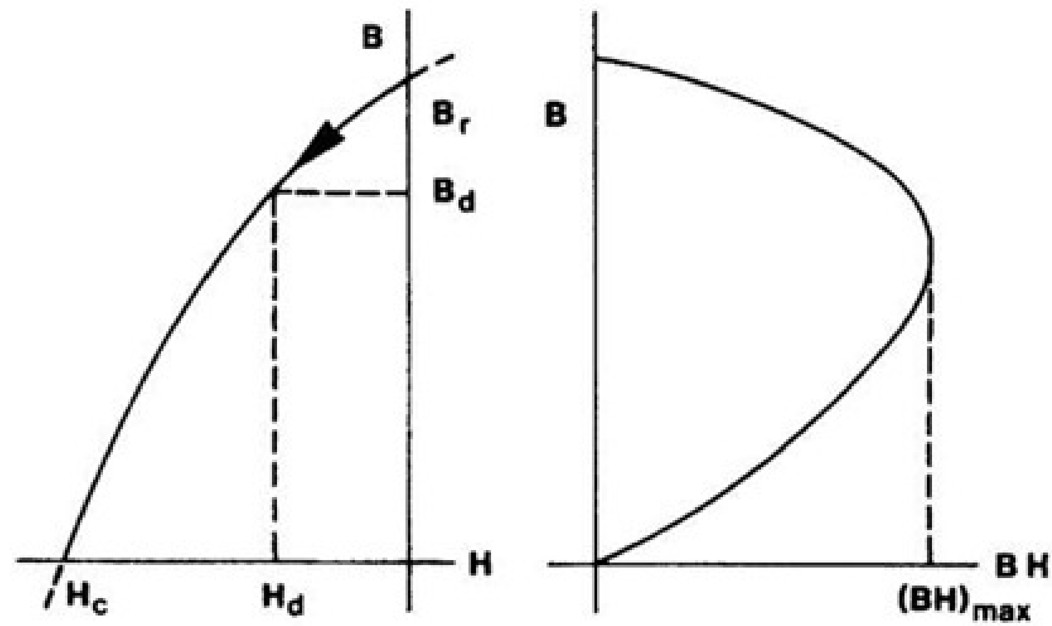
- Application wise magnetic materials are classified into soft and hard magnetic materials
- They are classified depending upon the ease with which the direction of magnetization can be altered by an applied magnetic field
- The shape of hysteresis loop plays an important role in this classification

- Soft magnetic materials are easy to magnetize and easy to demagnetize
- This enables them to reverse magnetization rapidly on application of an alternating field
- Thus, the area within the hysteresis loop for these materials should be as small as possible

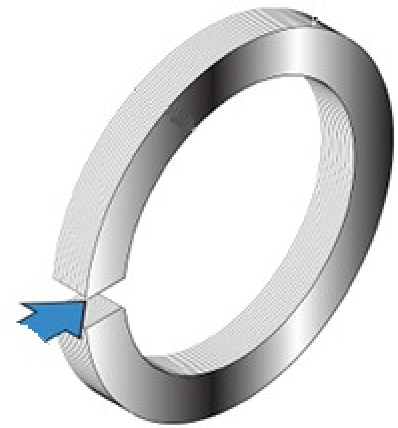
- Hard magnetic materials are hard to magnetize and hard to demagnetize
- High value of residual flux density and coercive force characterise these materials
- They are suitable to produce permanent magnets
- High residual flux produces high induction field and high coercive force prevents the magnetization being influenced by external field

- This combined requirement of high residual flux (Bm) and high coercive force (Hc) is usually addressed by a single quantity, the maximum BH product or (BH)max which is used to as a convenient figure of merit for the strength of a permanent magnetic material.
- (BH)max is derived from the demagnetization portion or second quadrant of B-H curve

- As it is derived from hysteresis curve, the BH product is also called energy product or energy density.



- Permanent magnets are designed to produce the highest possible field across the airgap



- Let it be required to produce a flux Ø in the airgap. The airgap reluctance is $\mathscr{R}_a$. ℓ_m = length of the magnetic material. A_m is the cross section of the magnetic material

$$mmf = \varphi R_a = H_m l_m$$

$$\Rightarrow l_m = \frac{\varphi R_a}{H_m}$$

$$B_m = \frac{\varphi}{A_m} \Rightarrow A_m = \frac{\varphi}{B_m}$$

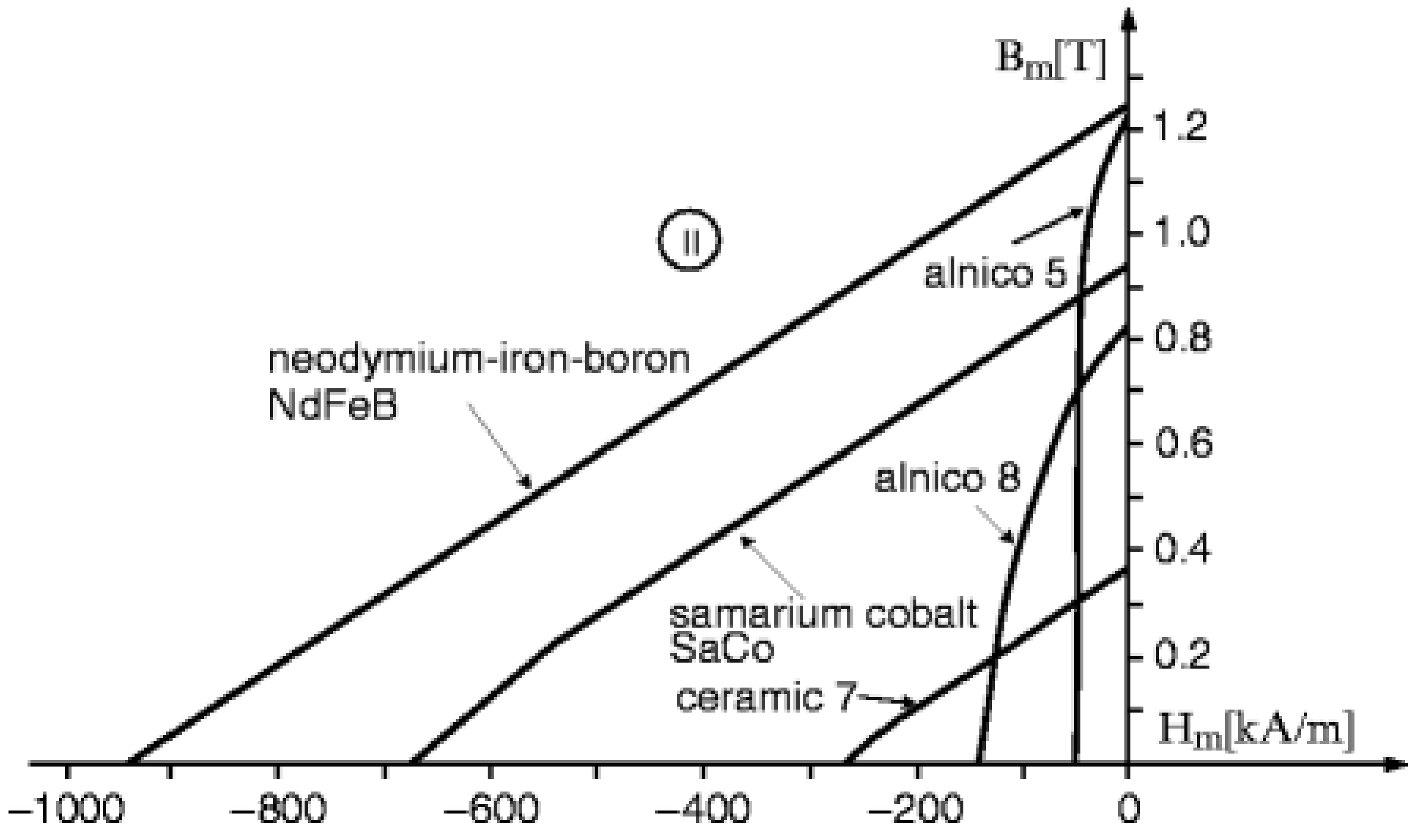
$$Volume, V_m = A_m l_m = \frac{R_a \varphi^2}{(B_m H_m)}$$

- Here we considered linear magentisation without any leakage
- It shows that volume of the magnetic material required will

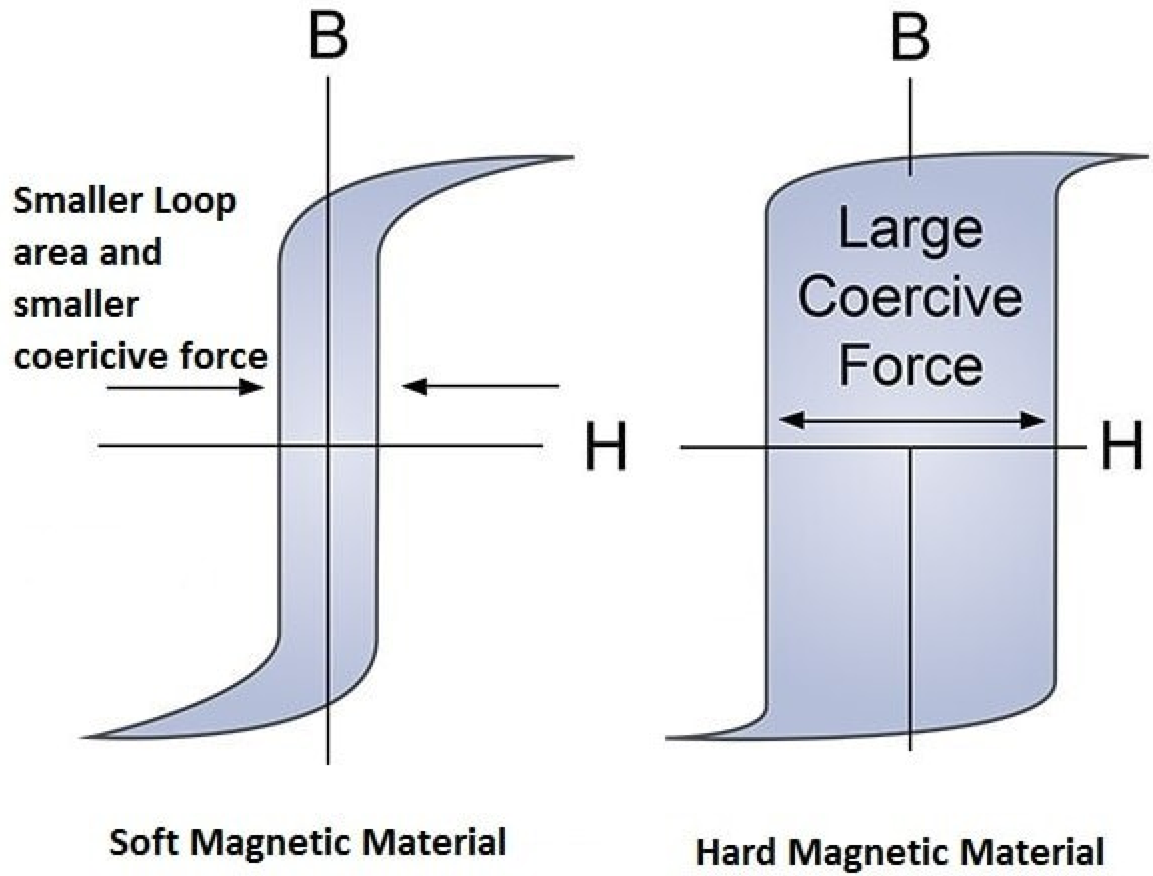
be minimum if BH product is maximum

- Moreover, if retentivity is low magnet will be large in cross section
- If coercivity is low magnet will be longer in length
- Hard magnetic materials, example:
  - Carbon steel, Tungsten steel, chromium steel etc
  - Alnico: Al, Ni, Co, Fe and a bit of Cu, Ti

- Rare earth materials:
  - Samarium Cobalt, $SmCo_5$ → (BH)max ≈ 5-6 times of Alnico, Coercivity ≈ 5 times of Alnico
  - Neodymium Iron Boron, NdFeB → highest BHmax reported till now, but cost is very high
- Ferrite magnets
  - Based largely on Barium Ferrite BaO, $6Fe_2O_3$
  - Strontium Ferrite, SrO, $6Fe_2O_3$
  - Due to their moderate cost, they are widespread
  - BHmax much lower than rare earth



Typical comparison of Permanent Magnetic Materials


B
Smaller Loop area and smaller coericive force
H
B
Large Coercive Force
H
Soft Magnetic Material
Hard Magnetic Material

- Hard magnetic materials usually have/should have:
  - High permeability
  - High coercive force
  - Appreciable remnant flux density
  - High Curie temperature
  - Low cost

- Soft magnetic materials are required to have high permeability, high saturation flux, low core loss, low coercivity
- Practically it is impossible to maximise al these in a single material, as magnetic properties are affected by chemical composition, mechanical and thermal treatment
- Thus, the requirement of high permeability and low core loss are conflicting

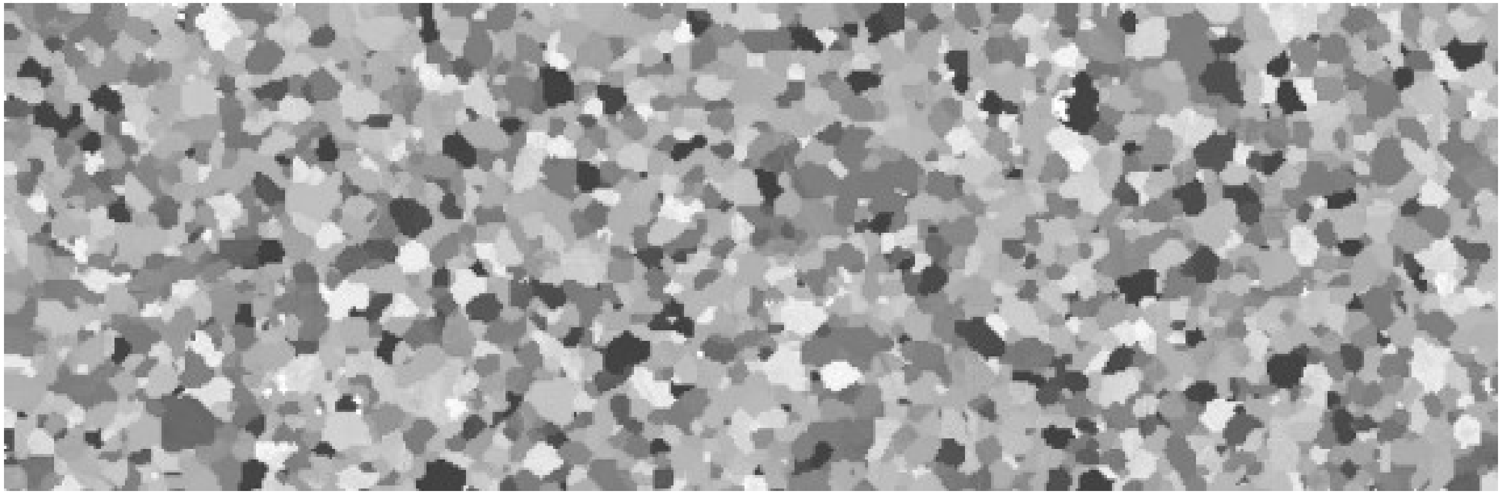
- Ordinary soft iron (not a good soft iron practically) contains impurities, which adversely affects its characteristics
- Presence of Carbon causes magnetic aging and raises the coercive force and hysteresis loss
- Impurities can be removed by annealing for several hours in the presence of hydrogen

- Addition of small percentage of Silicon to soft iron improves resistivity, reduces coercive force considerably

  however, marginally reduces saturation magnetization. Normally 2-3% Silicon is added, 5% or more makes iron brittle

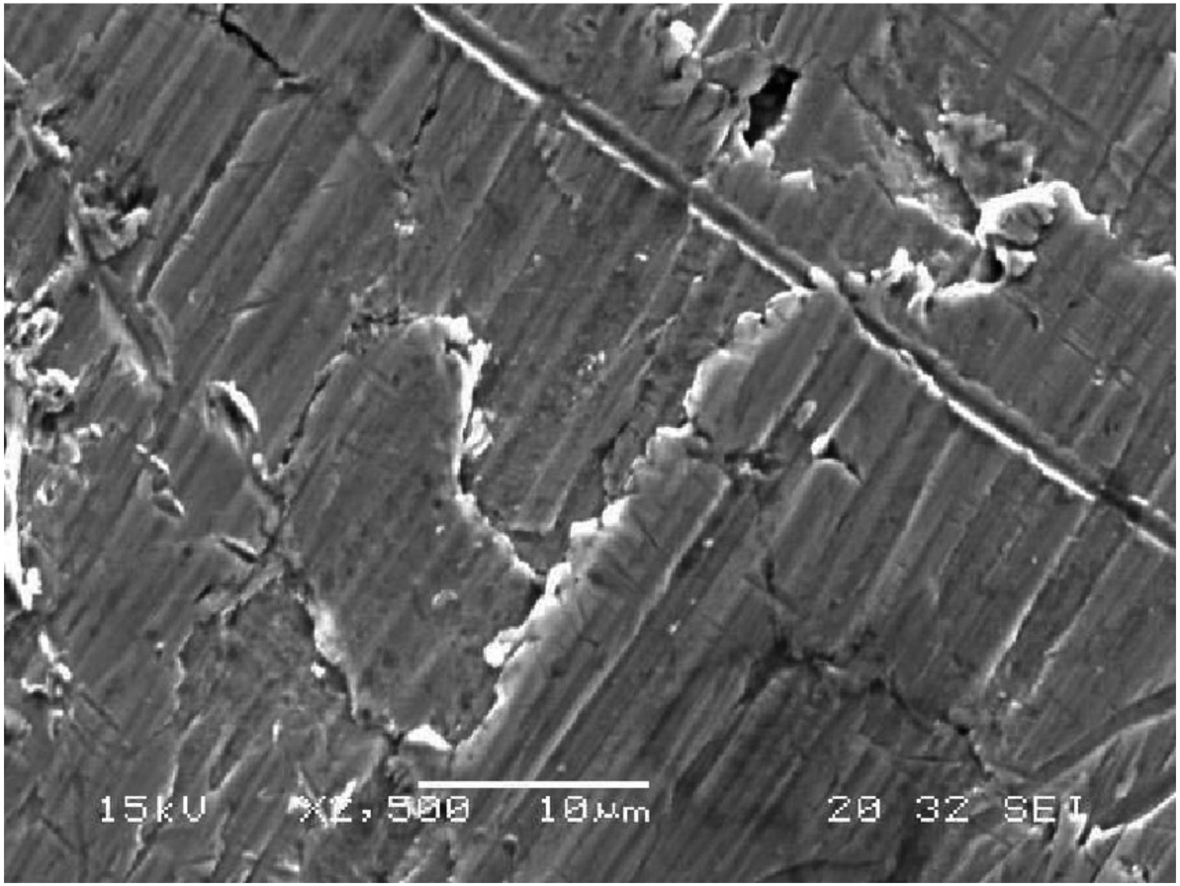
- Electrical Steels
  - Permeability of electrical steel substantially increases and hysteresis loss decreases with favorable grain orientation in the material due to magnetic anisotropy
  - Grain oriented electrical steel is produced by initially hot rolling the alloy followed by two stages of cold reduction with intervening annealing
  - During rolling the grains are elongated and their orientation altered

- Finally sheets are recrystallized, whereby some crystals grow in size at the expense of other
- Electrical steels used as lamination are mainly of two types
- (i) non-oriented
  - Non-oriented steels with 0-3% Si are isotropic
  - They are produced in strips of thickness 0.35-0.8mm and insulated



the microstructure of non-oriented electrical steel sheet
(using coloring)

- (ii) grain-oriented
  - They have almost half the core losses compared to non-oriented steels
  - Mechanically and thermally processed to align the grains in such a way so as to have their crystalline orientation such that cube faces are oriented parallel to the direction of rolling
  - Grain size is made larger in order to minimize grain boundaries
  - Flux density is almost twice that of the non-oriented



SEM of cold rolled steel showing grain structure