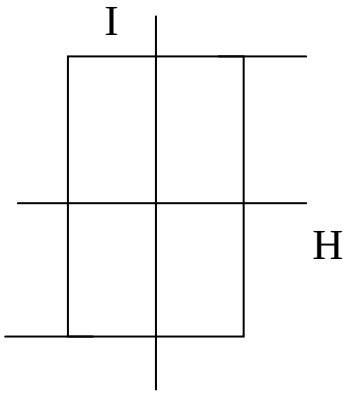
4.2 Hard magnetic materials

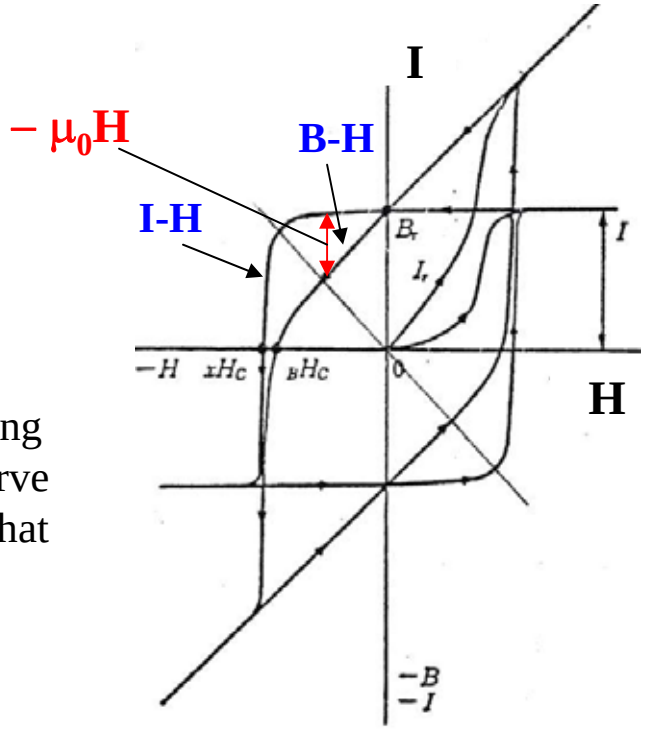
Permanent magnets are used to produce strong fields without applying a current to coil. Therefore, they should exhibit a strong net magnetization, and is stable in the presence of external fields, which requires high coercivity.

In hard magnetic materials uniaxial magnetic anisotropy is necessary and the following magnetic properties are required:

1) High coercivity
2) Large magnetization
3) Rectangular hysteresis loop



Ideal hysteresis loop



B-H and I-H loops

Two hysteresis loops, I-H and B-H loops.

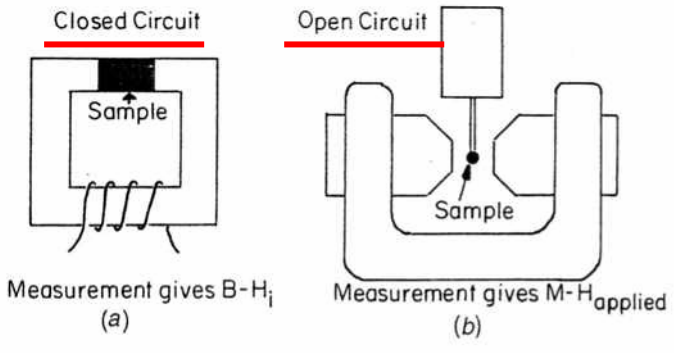
I-H loop is useful for physical understanding of the magnetic properties. While, B-H curve is effective for practical use. It is noticed that $_BH_c < {}_IH_c$.

$$B = \mu_0 H + I$$

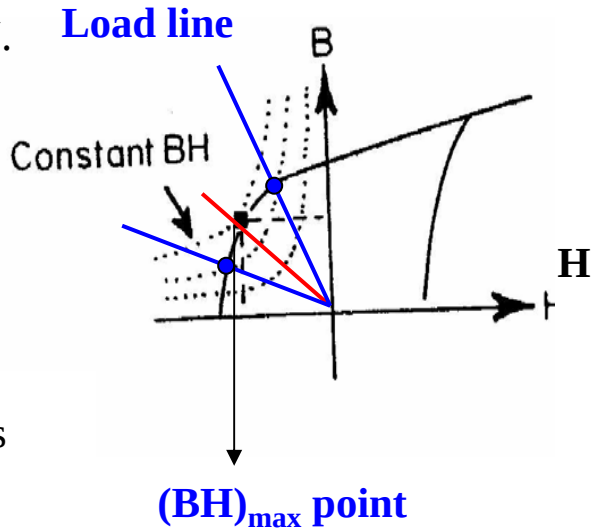
Maximum energy products $(BH)_{max}$

Load lines

The form of the hysteresis loop is very sensitive to sample shape due to the **demagnetization factor**. When permanent magnets are used in open circuit, their technical properties are strong functions of the magnet shape.Thus, it is important to distinguish between intrinsic or extrinsic.



The magnets are practically used at the the point on **the second-quadrant branch**. The load line has a slope given by –(1-N)/N, where N is the demagnetization factor. This line intersects the B – H curve at the point, which indicates the remanence actually achieved in a given shape having average demagnetization factor N.

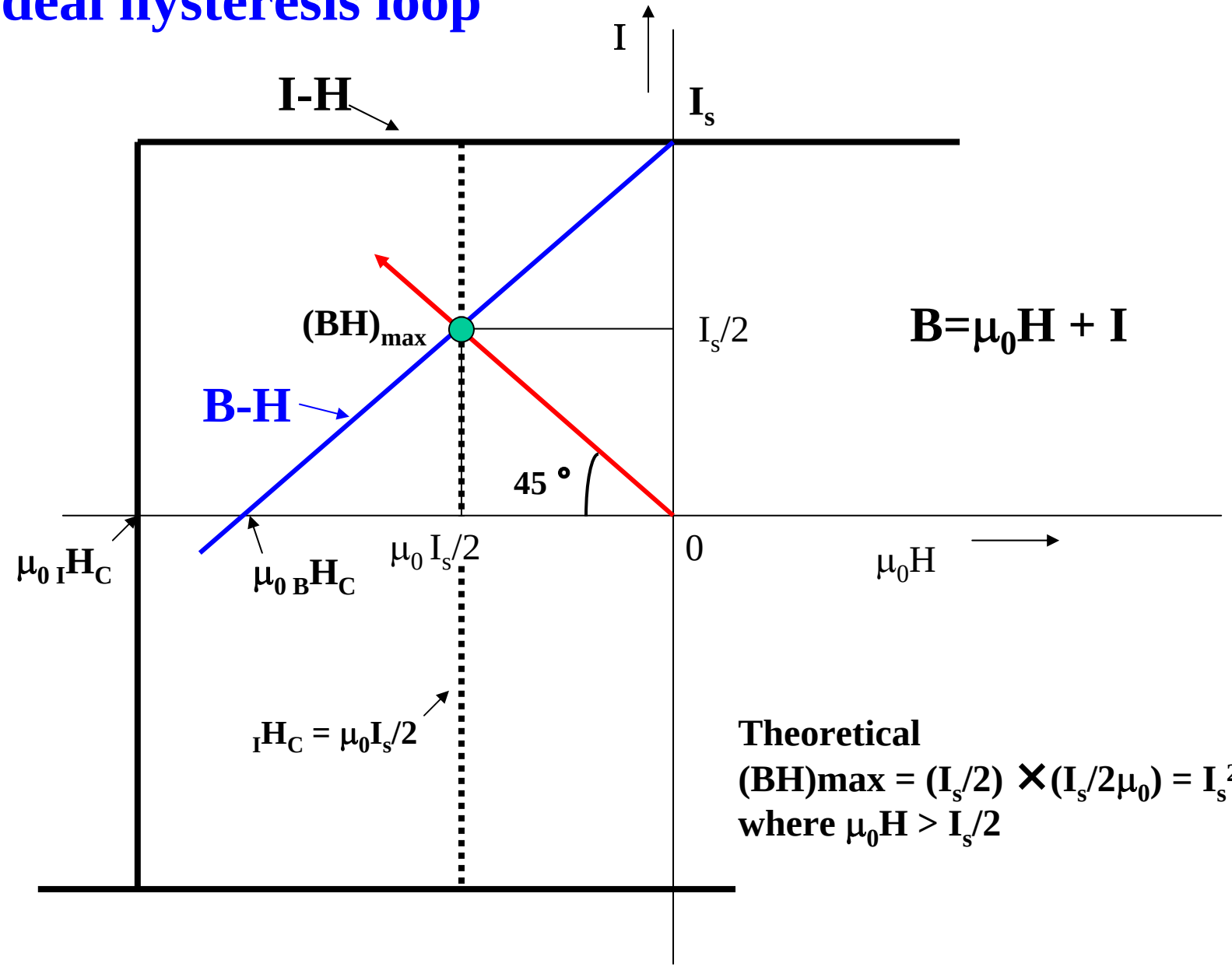


Maximum energy point

The maximum energy density of a permanent magnet $(BH)_{max}$ is determined by the point on the second-quadrant branch of the B-H loop, which gives the largest area for an enclosed rectangle.The location of $(BH)_{max}$ is the point at which the material characteristics of a magnet are most efficiently used.

Theoretical $(BH)_{max}$ is given by $(I_s^{\,2}/4\mu_0)$ on the condition of $_IH_C > I_s/2$.

Ideal hysteresis loop



$B=\mu_0 H + I$

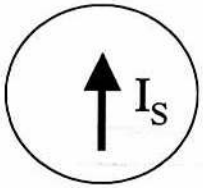
Theoretical

(BH)max = $(I_s/2) \times (I_s/2\mu_0) = I_s^2/4\mu_0$

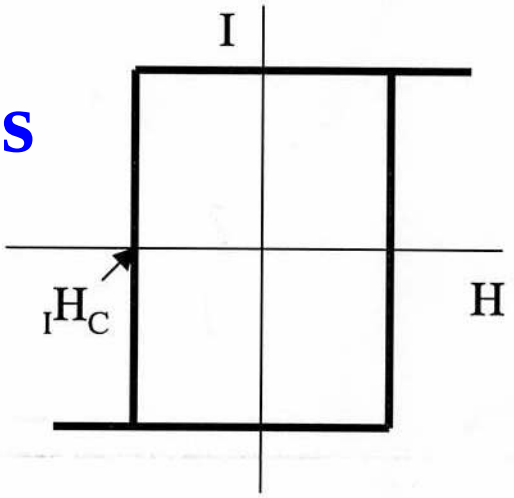
where $\mu_0 H > I_s/2$

Coercivity and hysteresis loops

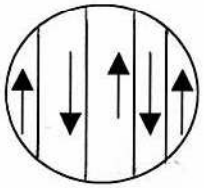
Single domain structure



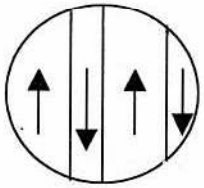
$$_IH_C = 2K_u/I_s$$



Multi-domain structure

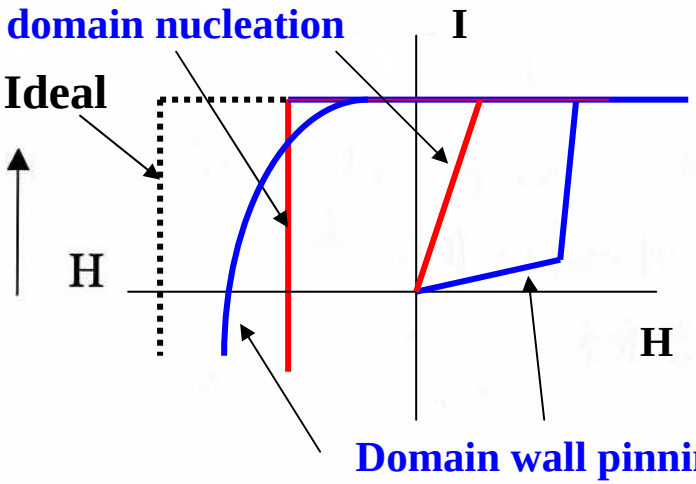


H=0

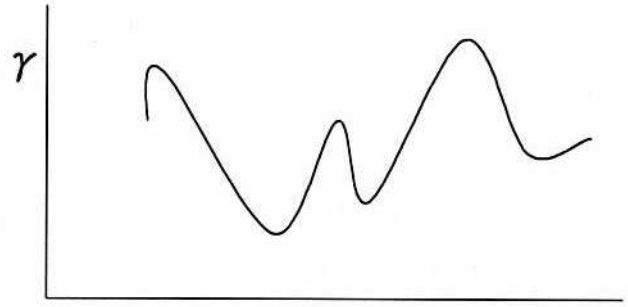


H≠0

Reversed domain nucleation

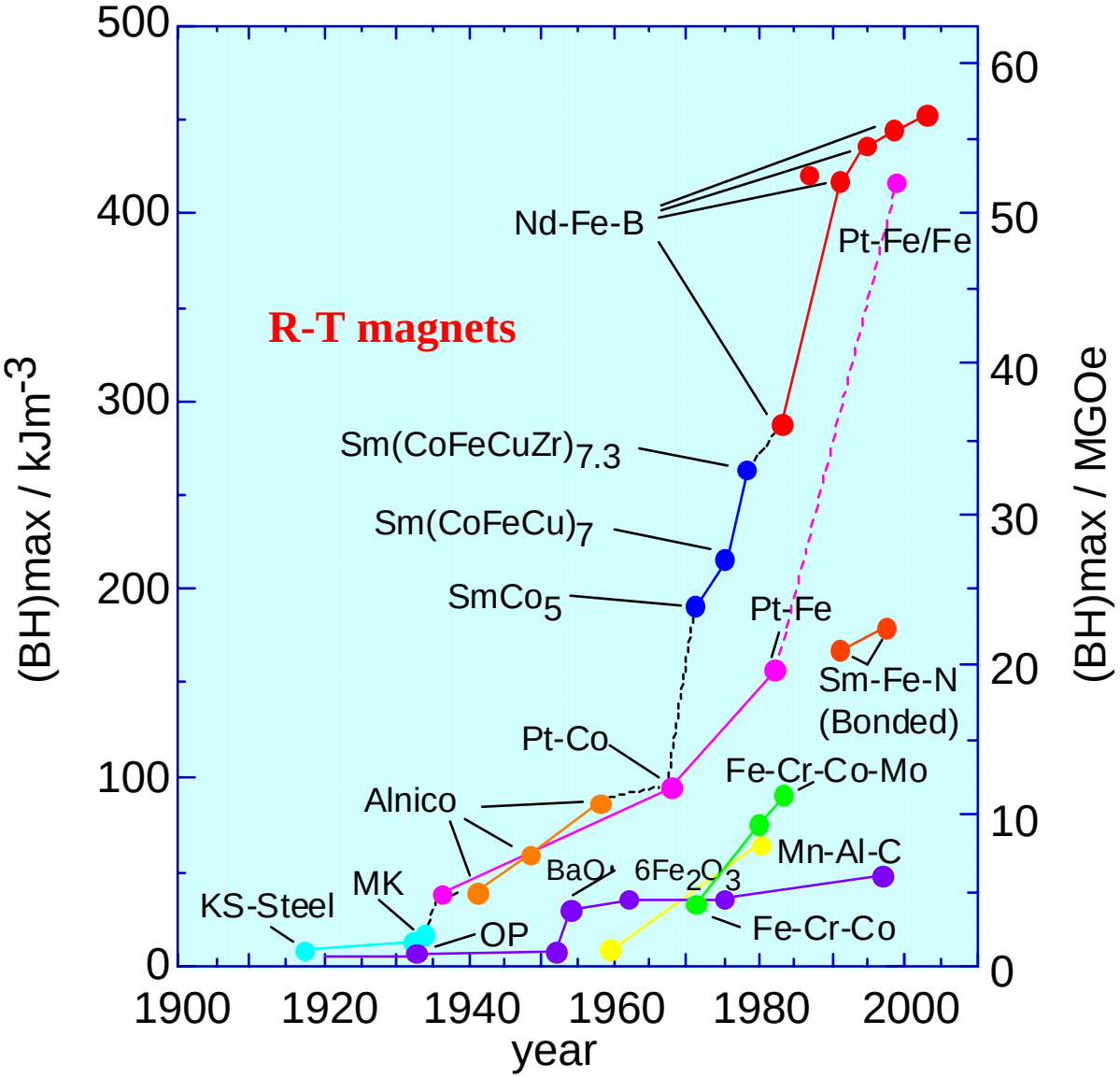


Domain wall pinning



$$_IH_C = (d\gamma/dx)_{max}/2I_s$$

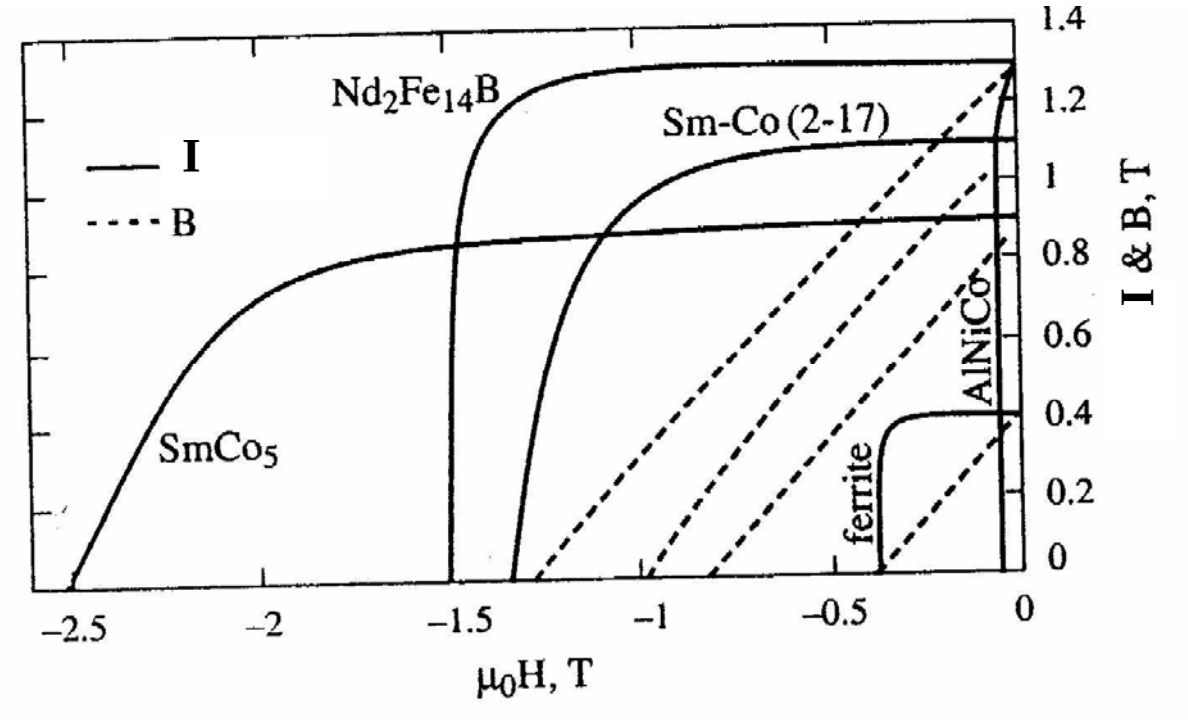
Permanent magnet development



World record

$(BH)_{max}$=460kJm^{-3}
(57.6MGOe)
for NdFeB magnets

Magnetic hysteresis curves for typical permanent magnets



All of the magnets are not formed by a single pahse but **multi-phases**, which is mainly due to the controlling of the grain size and/or enhancing the domain wall pinning.

Magnetic properties for various permanent magnet alloys

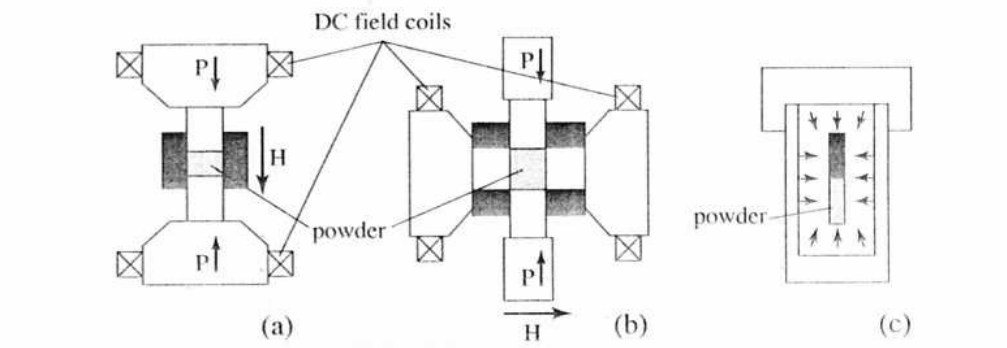
Material	Saturation magnetization I_S (T)	Anisotropy energy K_u (J/m^3)	Anisotropy field H_K (A/m)	Curie temperature T_C (℃)	$(BH)_{max}$* (kJ/m^3)	Single domain size r_c (μm)
$SmCo_5$	1.1	1.5×10^7	2.3×10^7	725	240	1.7
Sm_2Co_{17}	1.28	3.2×10^6	5.6×10^6	926	326	0.6
$Nd_2Fe_{14}B$	1.6	4.3×10^6	5.3×10^6	320	510	0.3
Ba-Ferrite	0.48	3.3×10^5	1.1×10^5	450	39	

*Theory: $(I_s^2/4\mu_0)$

$r_c = 9\gamma\mu_0/2I_s^2$

Magnet fabrication processes

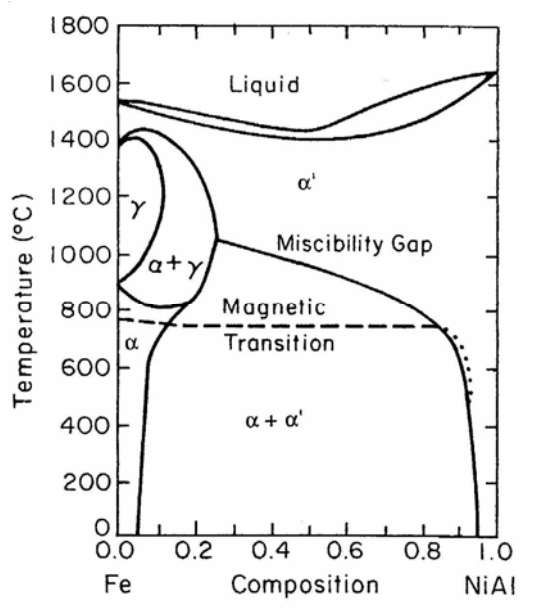
	Sintered Ferrite	Sintered NdFeB	Sintered $SmCo_5$	SmCo 2-17	AlNiCo
Principal phase	$BaO\text{-}6Fe_2O_3$ $SrO\text{-}6Fe_2O_3$	$Nd_2Fe_{14}B$	$SmCo_5$	$Sm_2(CoFe)_{17}$	FeCo
Anisotropy	----------	magnetocrystalline	----------		shape
Reduction into grains	----------	by milling	----------	by thermal phase segregation +milling	by thermal phase segregation
Inter-granular phase	$BaO\text{-}nFe_2O_3$ $SrO\text{-}nFe_2O_3$	Nd rich eutectic	Sm eutectic	$Sm(CoCu)_5$	NiAl
Orientation of grains	----------	by compression under field	----------		by heat treatment under field
Densification	----------	during sintering	----------		during melting or sintering
Nature of generic process used	----------	Powder metallurgy	----------		casting or powder metallurgy



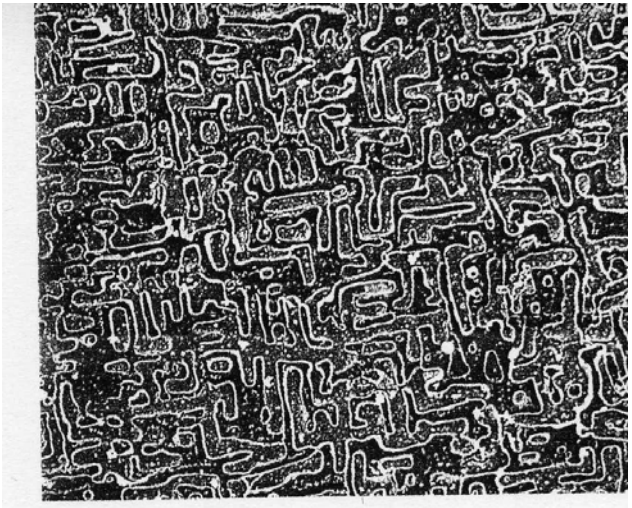
Sintering magnets
Casting magnets
Bonded magnets

Various magnets

1. Alnico : Single domain, Shape anisotropy, good thermal stability

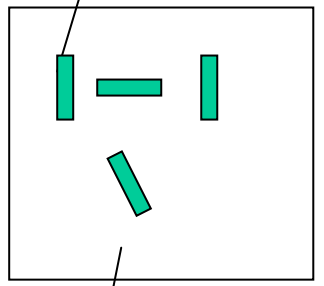


Spinodal decomposition
Fe_2NiAl

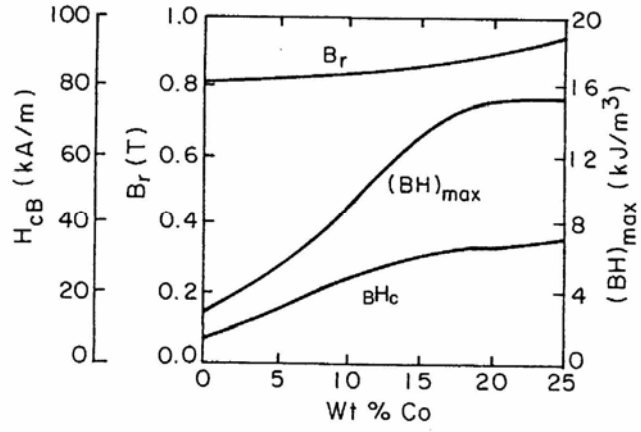


850℃× 2h then quenching

Fe-rich α phase



NiAl-rich α' phase



$Fe_xCo_{1-x}NiAl$

Coercivity by shape anisotropy

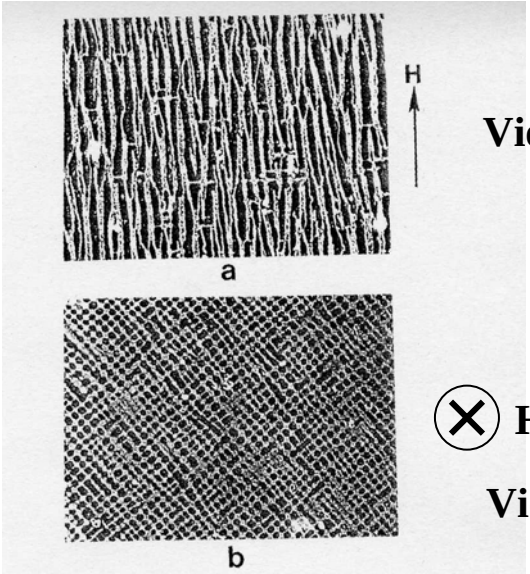
$$H_c \propto \Delta I (N_2 - N_1)$$

$$\Delta I = I_\alpha - I_{\alpha'}$$

N: demagnetization factor

Anisotropic Alnico magnets

Alnico 8 DG **Orientated particles**

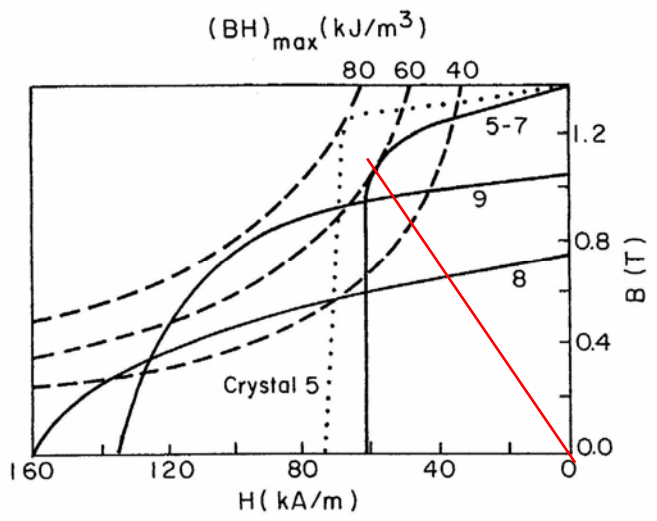


View ⊥ H

⊗ H

View // H

800℃×9h in a magnetic field



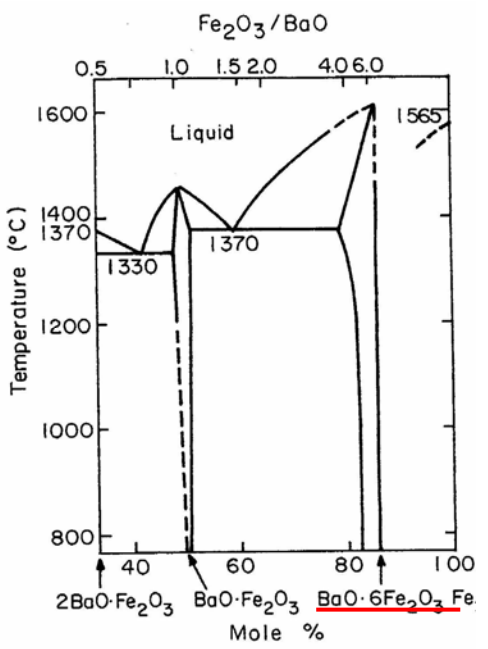
Alnico	Character	Composition (wt%) (balance Fe) Ni	Al	Co	Cu	Other	Magnetic Properties B_r (T)	${}_BH_c$ (kA/m)	$(BH)_{max}$ (kJ/m³)
5	Random grain	12–15	7.8–8.5	23–35	2–4	0–0.5 Ti 0–1 Nb	1.2–1.3	52–46	40–44
DG[a] 5	Directed grain 5	13–15	7.8–8.5	24–25	2–4	0–1 Nb	1.3–1.4	62–56	56–64
5 xtl	Single crystal	14	8	25	3		1.4	68	80
8	Random grain	14–15	7–8	37–40	3	7–8 Ti	0.74–0.78	150–170	44–48
DG 8(9)	Directed grain 8	14–16	7–8	32–36	4	0.3S	1.0–1.1	140–110	60–75

2. Hexagonal Ferrites

Single domain particle, Nucleation type

Hard ferrites are **cheap** and **light** in weight, and thus used for where energy per unit weight and cost are important conditions.

The hexagonal ferrites based on **BaO 6[Fe_2O_3]** have the **magnetoplumbite structure** as shown below, which is given the notation BaM and includes PbM and SrM. The hexagonal ferrites have a strong uniaxial anisotropy, $\mathbf{K_u = 3 \times 10^5\ J/m^3}$ with easy axis along the c axis and small magetization of **0.4 – 0.5 T**.



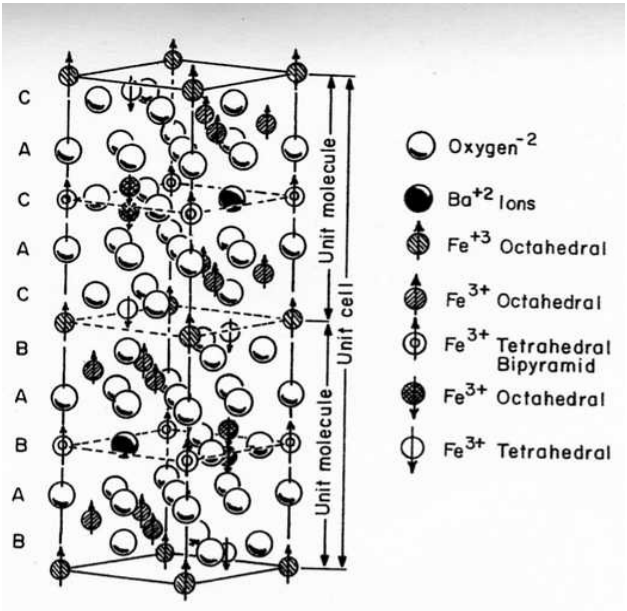
Some Fundamental Physical Properties of Ba, Sr, and Pb Hexaferrites

	Lattice Constants (nm)		Mass Density	$\mu_0 M_s$(RT)	T_c
	a	c	(g/cm^3)	(T)	(K)
BaM	0.589	2.32	5.3	0.48	740
SrM	0.587	2.31	5.11	0.48	745
PbM	0.588	2.30	5.68	0.43	725

Magnetic Properties of Isotropic and Anisotropic BaM

Grade	$(BH)_{max}$ (kJ/m^3)	B_r (T)	$_BH_c$ (kA/m)	$_iH_c$ (kA/m)	$\Delta M_s/M_s\Delta T$ (%/K)	$\Delta_iH_c/_iH_c\Delta T$ (%/K)	Mass Densit (g/cm^3
Isotropic	6.5–9	0.19–0.22	125–145	210–270	−0.2	0.2–0.5	4.6–5.(
Anisotropic	20–30	0.32–0.4	125–250	130–340	"	"	"

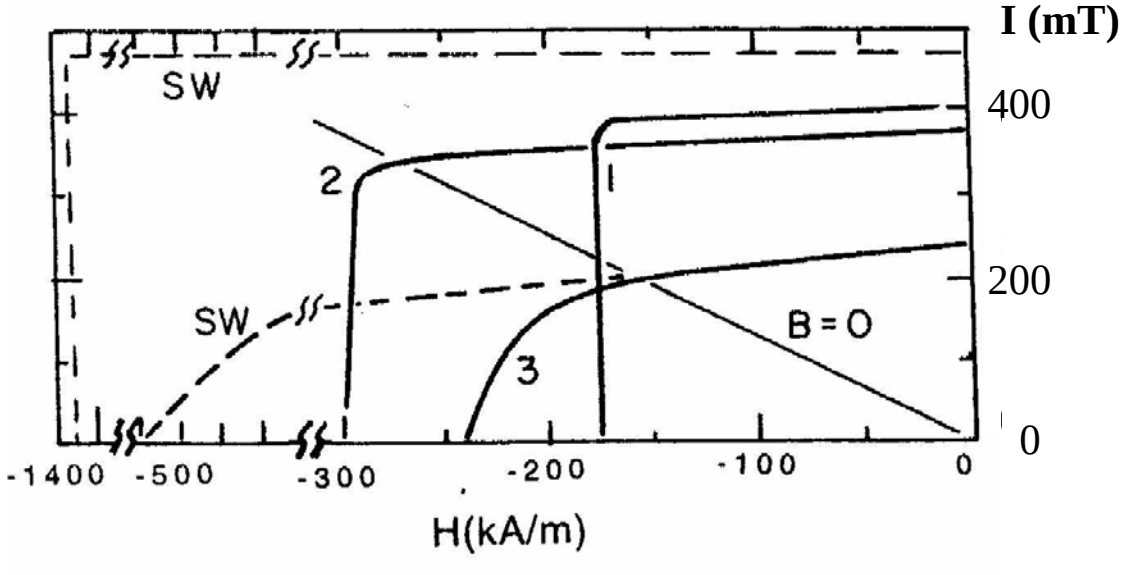
Source: After Stäblein (1982).



Magnetoplumbite structure

The coercivity of the hexagonal ferrites is limitted by **nucleation**; once a domain wall exists in a particle, it moves with ease through the particle under an applied field. However, wall motion does not appear to propagate from grain to grain. Thus, the coercivity of hexagonal ferrites can be described by the **mechanism of single-domain particle magnetization** with the magnetocrystalline anisotropy.

Commercial ferrite magnets



SW: Stoner-Wohlfarth model

$K_1 = 3.46 \times 10^5$ J/m^3

1.2: Anisotropic magnets

3: Isotropic magnet

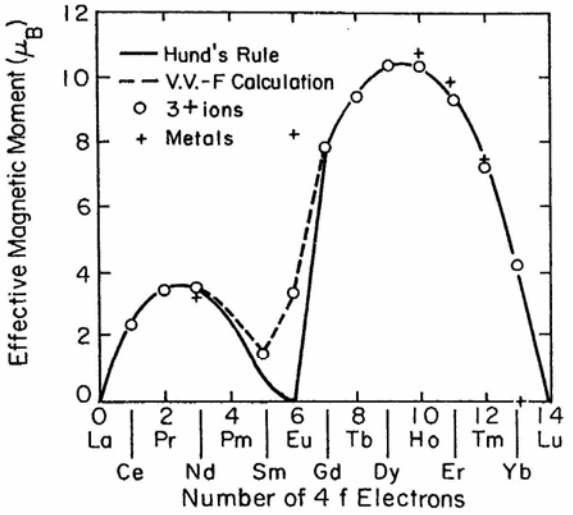
3. R-T magnets

Magnetic properties of R-T intermetallics

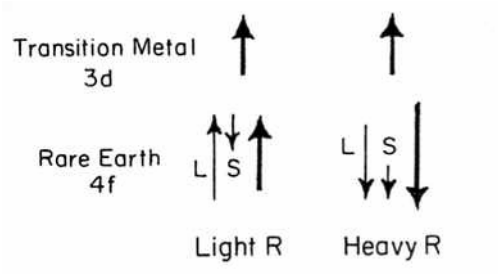
Effective magnetic moments of rare earth metals are given by $\mu_{eff} = g\mu_B\sqrt{J(J+1)}$

For less than half **J = L –S**

For more than half **J = L + S**

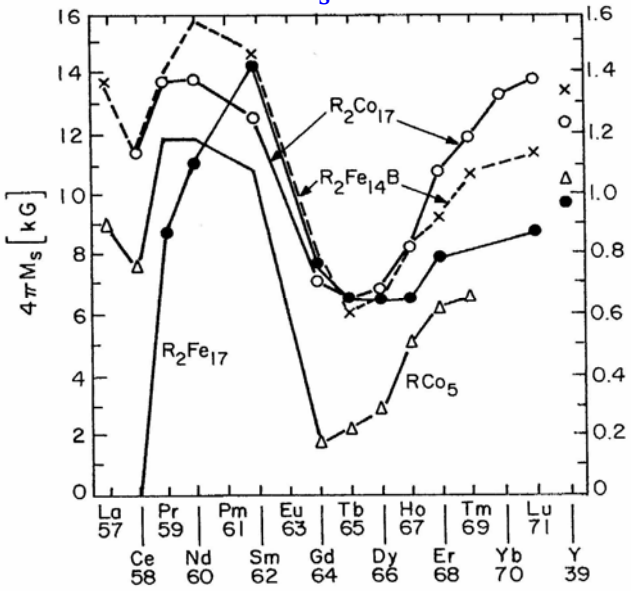


Exchange coupling of R and T atoms

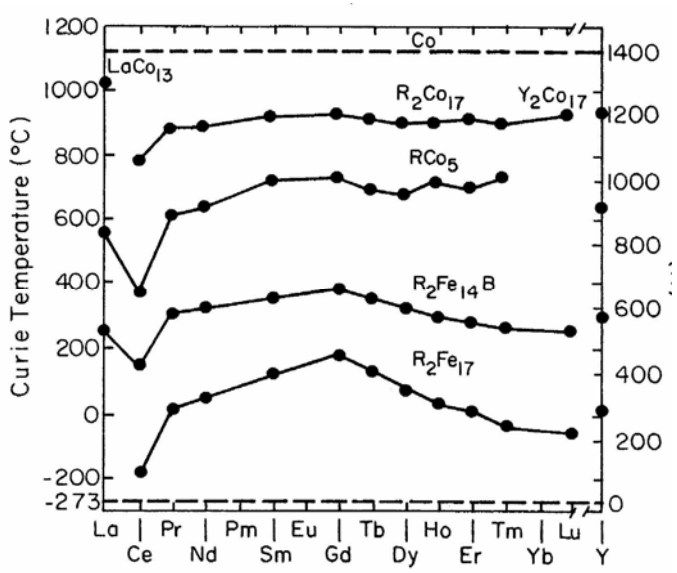


Antiferromagnetic coupling between T and R spins.

I_s



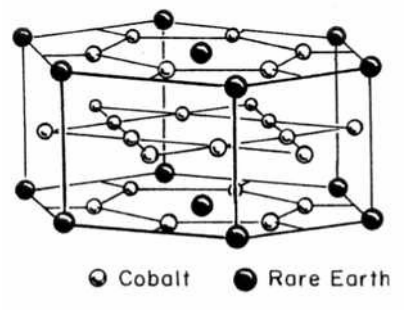
T_c



R-T compounds

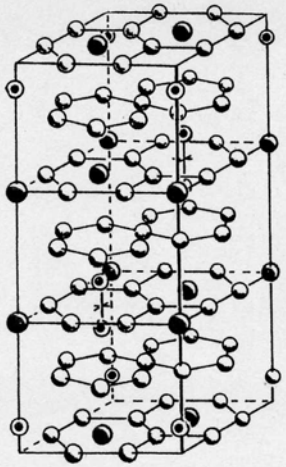
R-T compounds with high K_u and high T_c

RT_5



Hexagonal

R_2T_{17}
= 3(RT_5)
-R + 2T

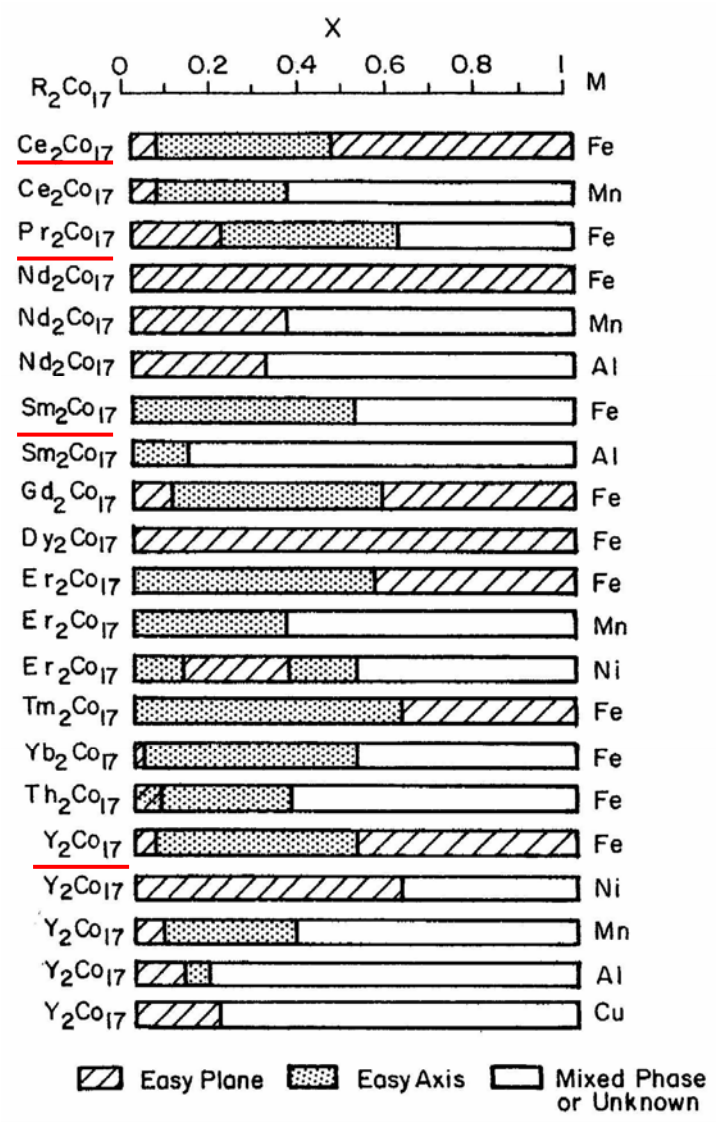


Rhombohedral

Fe dumb-bell site
In R_2Fe_{17}

Reduce T_C

R_2T_{17}



Sm-Co magnets

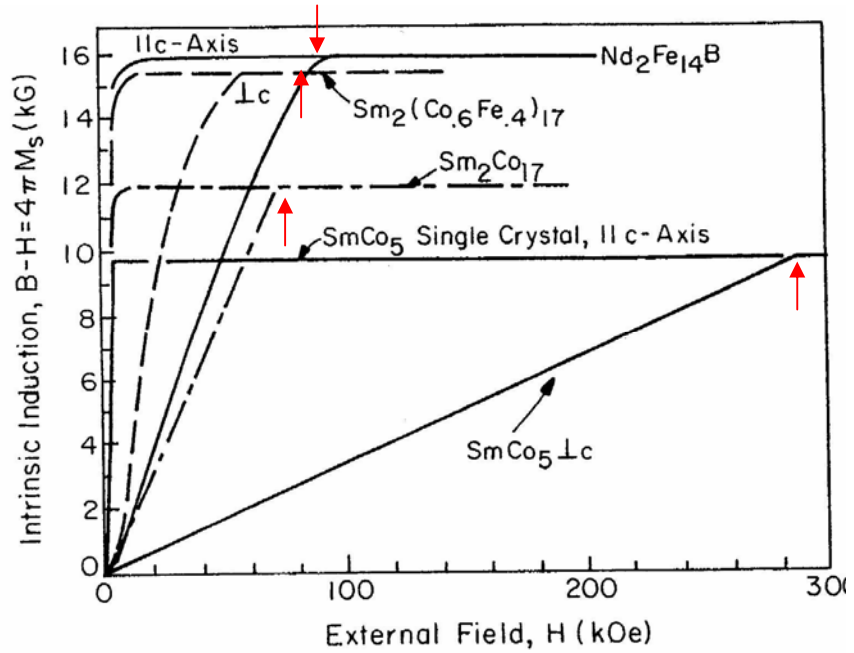
$SmCo_5$ magnets

$SmCo_5$ has a very large magnetocrystalline anisotropy of 10^7 J/m^3. This magnet exhibits nucleation type coercivity.

Liquid phase sintering

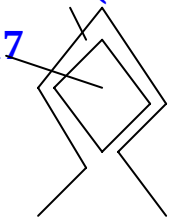
Sm_2Co_{17} type magnets

Rhombohedral 2-17 phase has a lower anisotropy than the 1-5 phase, heat treatment and inclusion of nonmagnetic atoms such as Cu and Zr to promote optimal phase segregation are generally used to achieve higher coercivity due to the **domain wall pinning** Thus, 2-17 magnets are called as **precipitation hardened magnets**.

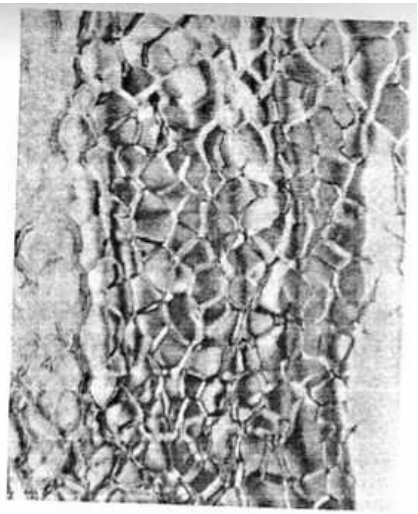


1-5 (thickness 10 nm)

2-17



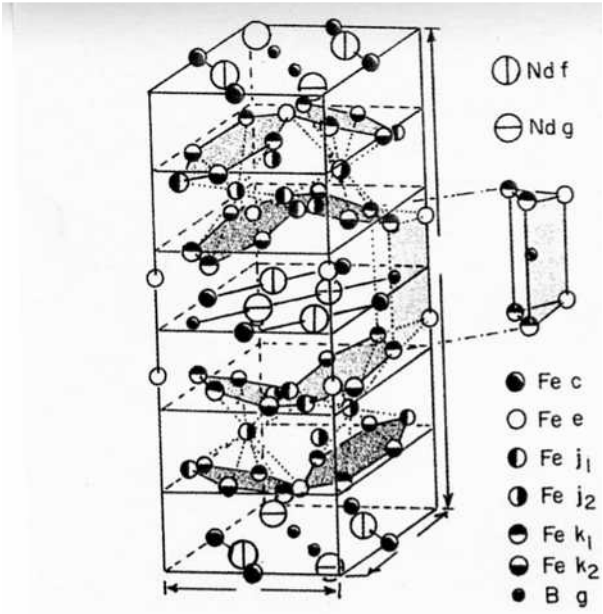
Cell structure



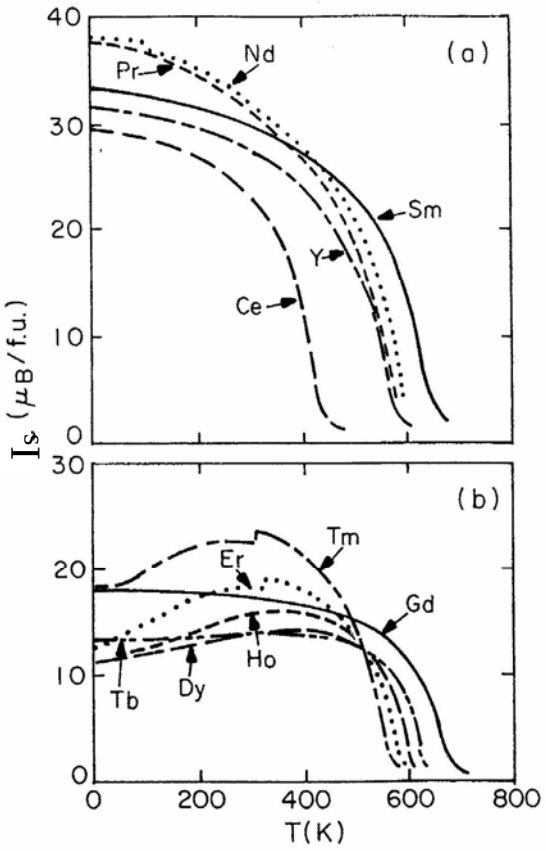
	$\mu_0 M_s$ (T)	T_C (°C)	I_s (T)	$_iH_c$ (MA/m) Isotropic	$_iH_c$ (MA/m) Aligned	$(BH)_{max}$ (MG·Oe) 2D	$(BH)_{max}$ (MG·Oe) 3D
$SmCo_5$	1.0	685–700	10	0.8–1	2.9	14–16	18–24
$Sm_2(CoFe)_{17}$	1.2–1.5	810–970	3.3	1–1.3	2.4	16–20	24–30
$Fe_{14}Nd_2B$	1.6	312	5	—	1.2–1.6	34–45	

NdFeB magnets

Crystalline structure of $R_2Fe_{14}B$



I-T curves for $R_2Fe_{14}B$



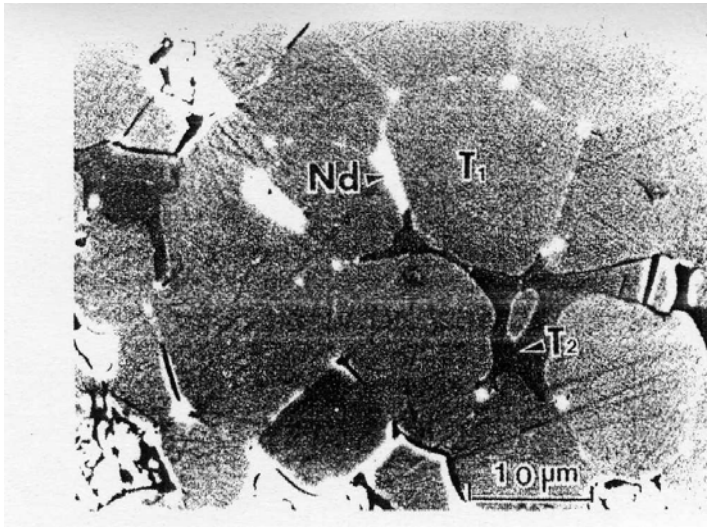
Nucleation type magnets

Magnetization reversal in **sintered** 2-14-1 magnets occurs by nucleation and growth of reversal domains. According to Kronmuller the coercivity is given by

$$iH_C = \frac{2K_u}{I_s} a_K a_\Psi - N_{eff} I$$

Here, a_K describes the micromagnetic effects of anisotropy, wall width, and inhomogeneity size; a_ψ describes the effects of grain misallignment. These two factors differ depending on whether wall motion is limited by pinning or nucleation. Experiments support **nuclation form** of this model.

Structure of sintered NdFeB magnet



T_1: $Nd_2Fe_{14}B$, T_2: $Nd_{1+\varepsilon}Fe_4B_4$

Nd: Nd-rich phase

Next lecture is on September 6th.