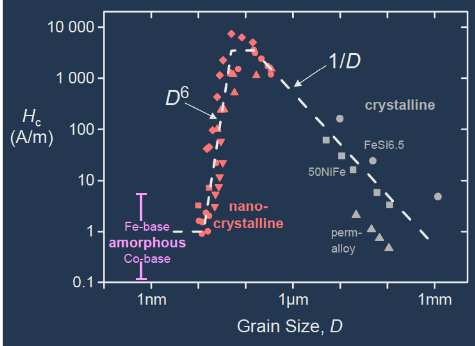
Application Oriented Development of Amorphous and Nanocrystalline Soft Magnetic Materials

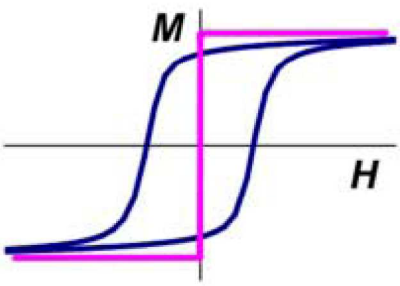


Giselher Herzer

Rapid Solidification Technology
VACUUMSCHMELZE GmbH & Co. KG, D-63450 Hanau, Germany

VACUUMSCHMELZE: all around the ~~best~~ of magnetism

most expensive



Materials
Soft to hard magnetic
($H_c \approx$ 1 mOe to 40 kOe)

Soft magnetic materials
amorphous & nanocrystalline alloys
FeNi, CoFe alloys

Semi-hard magnets
H_c ~ 10 - 1000 Oe

Hard magnets
RE Magnets (CoSm, NdFeB)

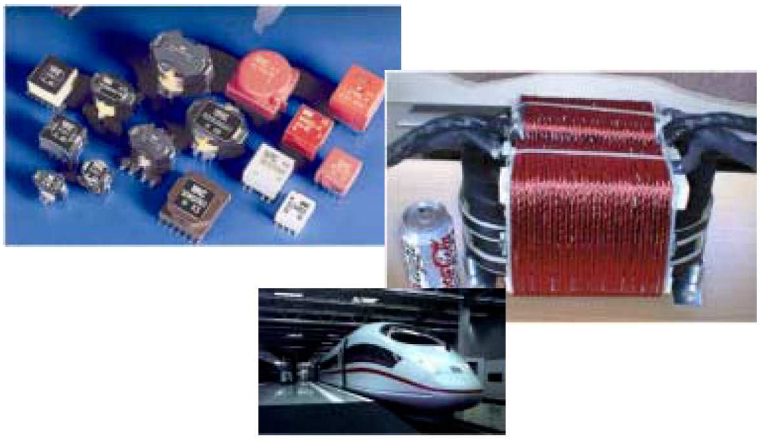
Products
The Materials itself +
Magnetic cores & parts
Components & Systems

Applications of Amorphous and Nanocrystalline Alloys

•Magnetic Cores

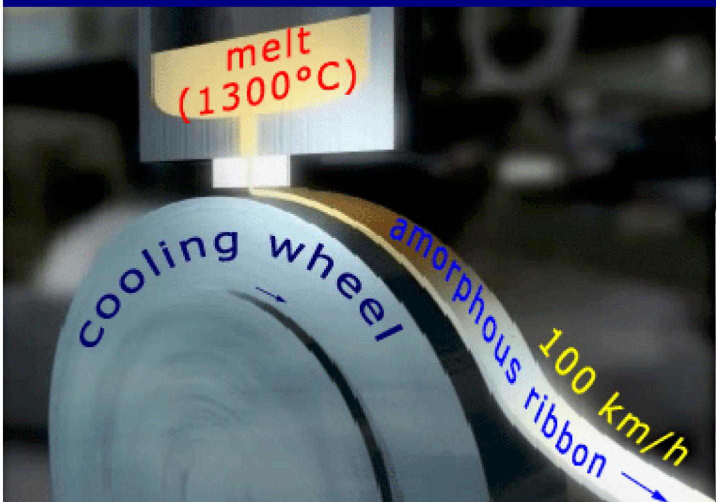
•Sensors

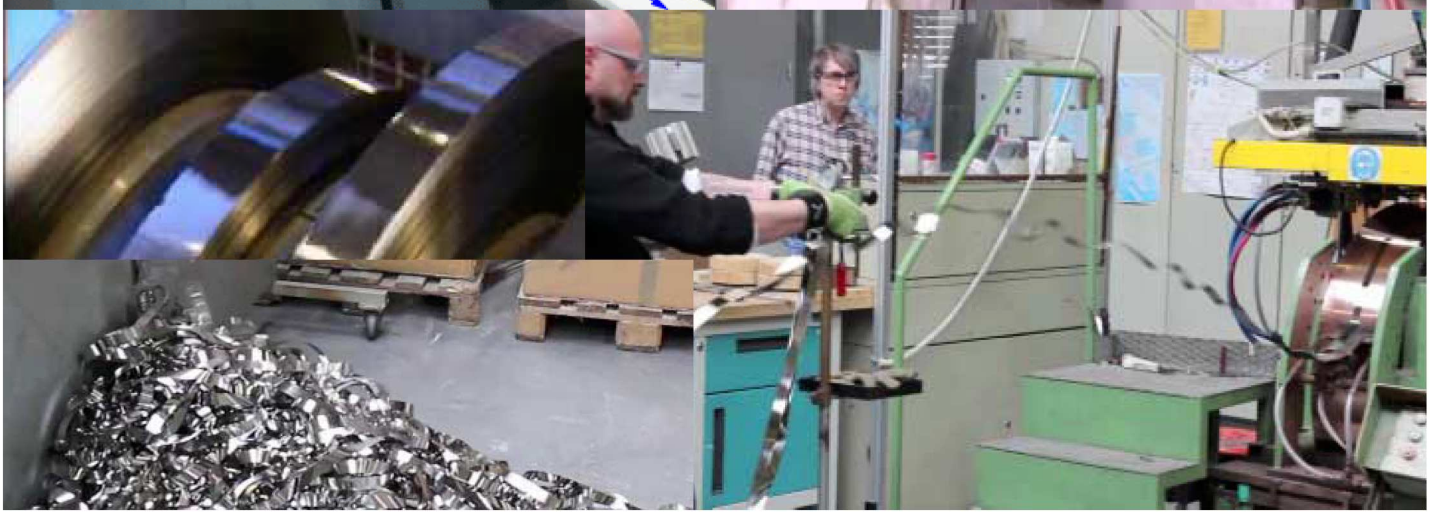
•Inductive Components



•Flexible Antenna

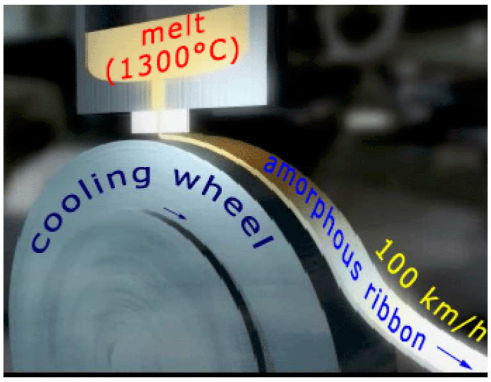
Rapid Solidification

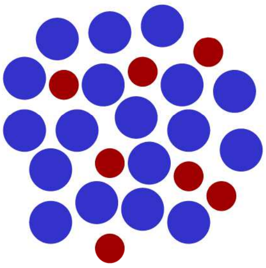




Amorphous and Nanocrystalline Alloys

rapid solidification (10^6K/s)





Amorphous structure
→ no long range order

Typical Composition

$T_{70\text{-}85}M_{15\text{-}30}$ (at%)

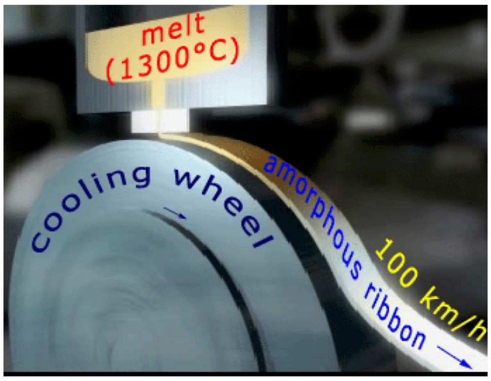
T = **Fe, Co, Ni ...**
M= **Si, B, C, Nb, Mo ...**

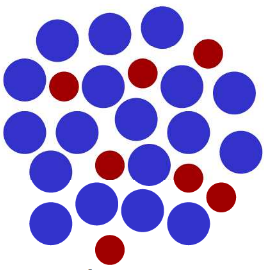
Properties

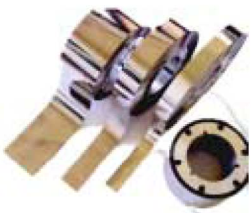
- thin ribbon (*d* ~ 20 μm)
- high electrical resisitivity
- mechanically hard
- **magnetically soft**

Amorphous and Nanocrystalline Alloys

rapid solidification (10^6K/s)

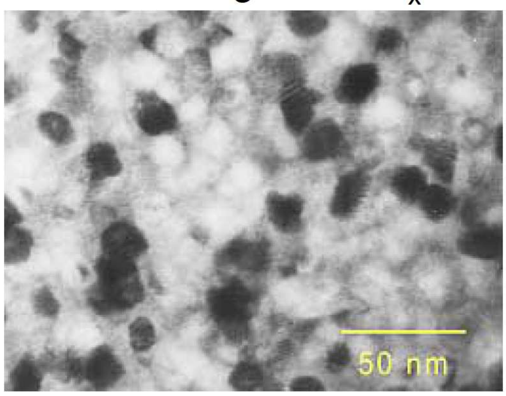






Amorphous structure
→ no long range order

Annealing above T_x

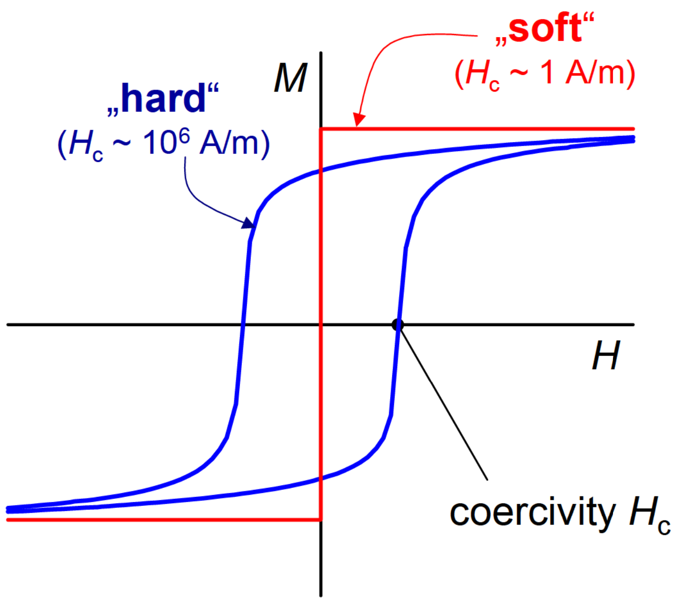


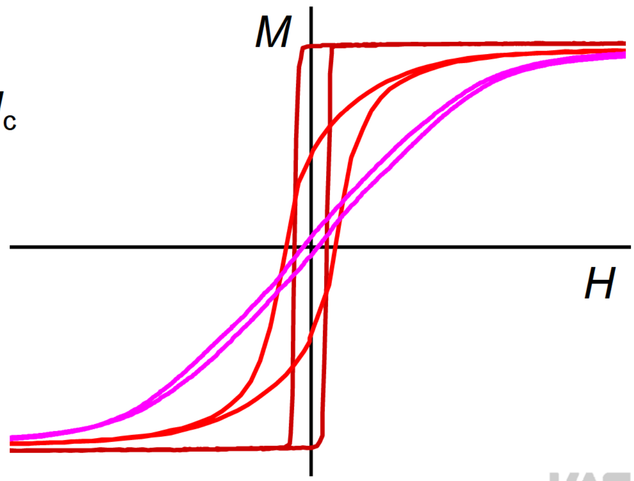
nanocrystalline state
for special compositions like:

- $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$
  (Yoshizawa & Yamauchi, 1988)
- $Fe_{86}(Cu_1)Zr_7B_6$
- $Fe_{84}Nb_7B_9$
  (Suzuki et al., 1990, 1991)

Large scale production as:
- FINEMET® (Hitachi)
- VITROPERM® (Vacuumschmelze)

Magnetic Materials

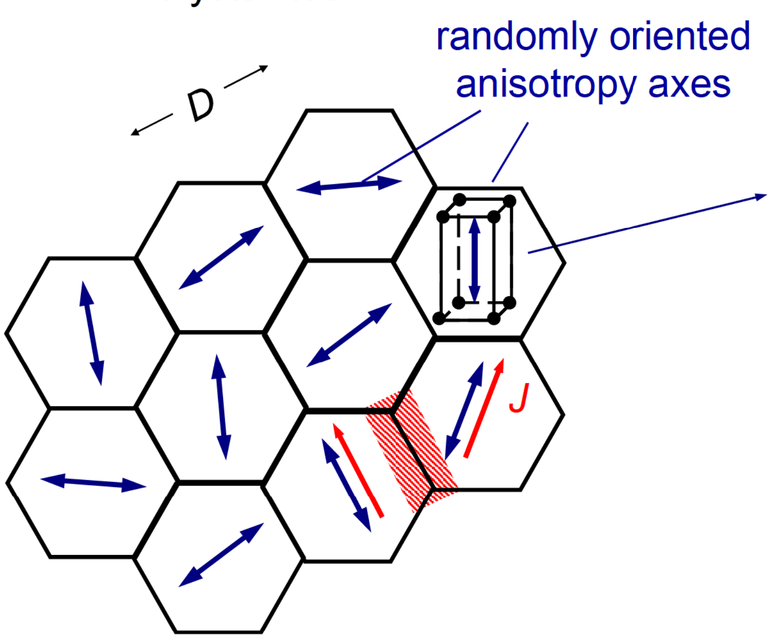




Microstructure and Magnetism

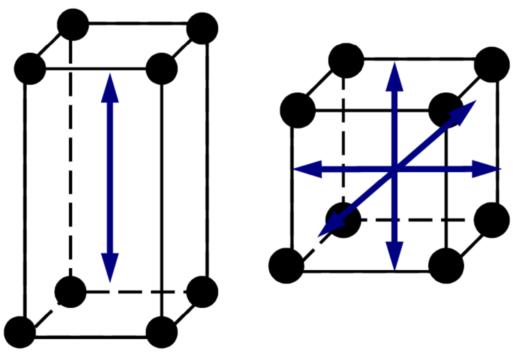
<u>microstructure</u>

randomly oriented crystallites



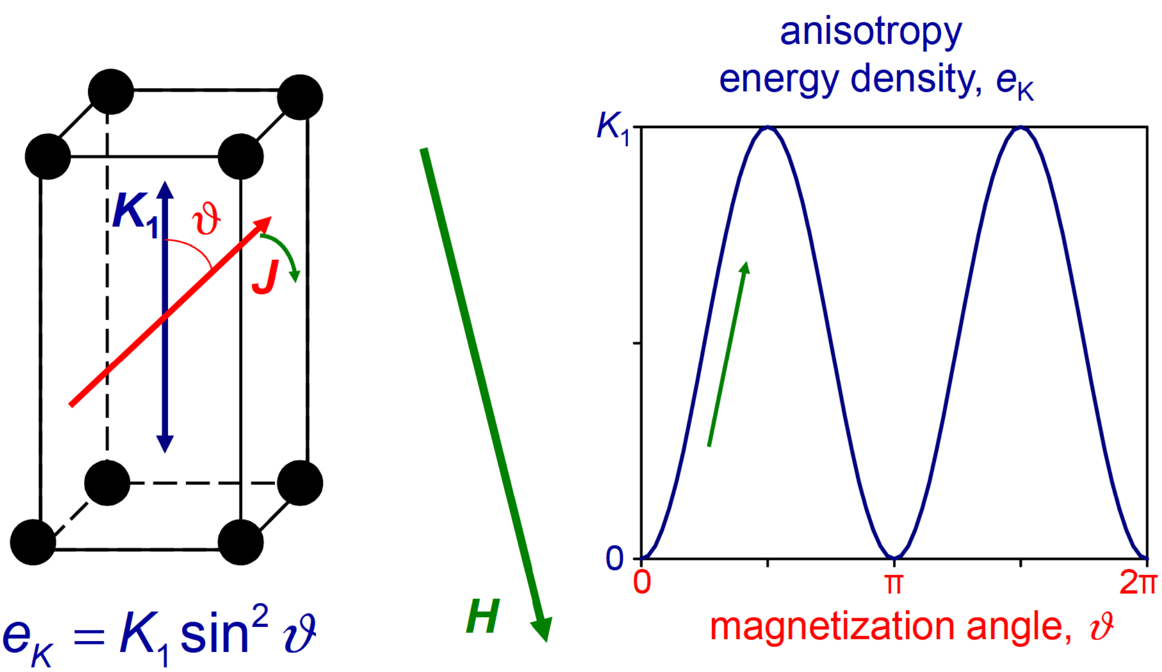
<u>atomic structure</u>

uniaxial | cubic



magneto-crystalline anisotropy energy K_1

Magnetic Anisotropy



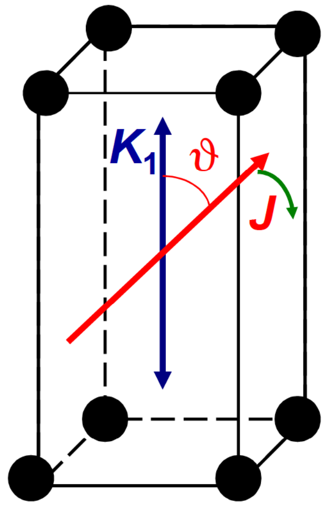
$$e_K = K_1 \sin^2 \vartheta$$

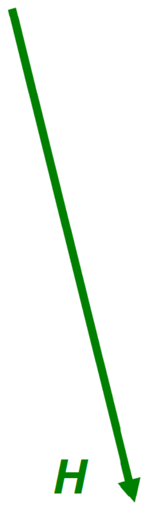
Coercivity $\quad H_c \propto K_1$

Permeability $\quad \mu \propto 1/K_1 \propto 1/H_c$

Magnetic Anisotropy and Structure

<u>atomic structure</u>



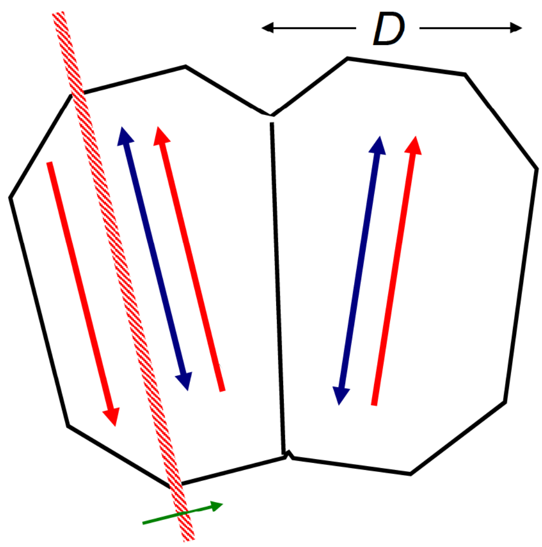


$$e_K = K_1 \sin^2 \vartheta$$

Coercivity $\quad H_c \propto K_1$

Permeability $\quad \mu \propto 1/K_1 \propto 1/H_c$

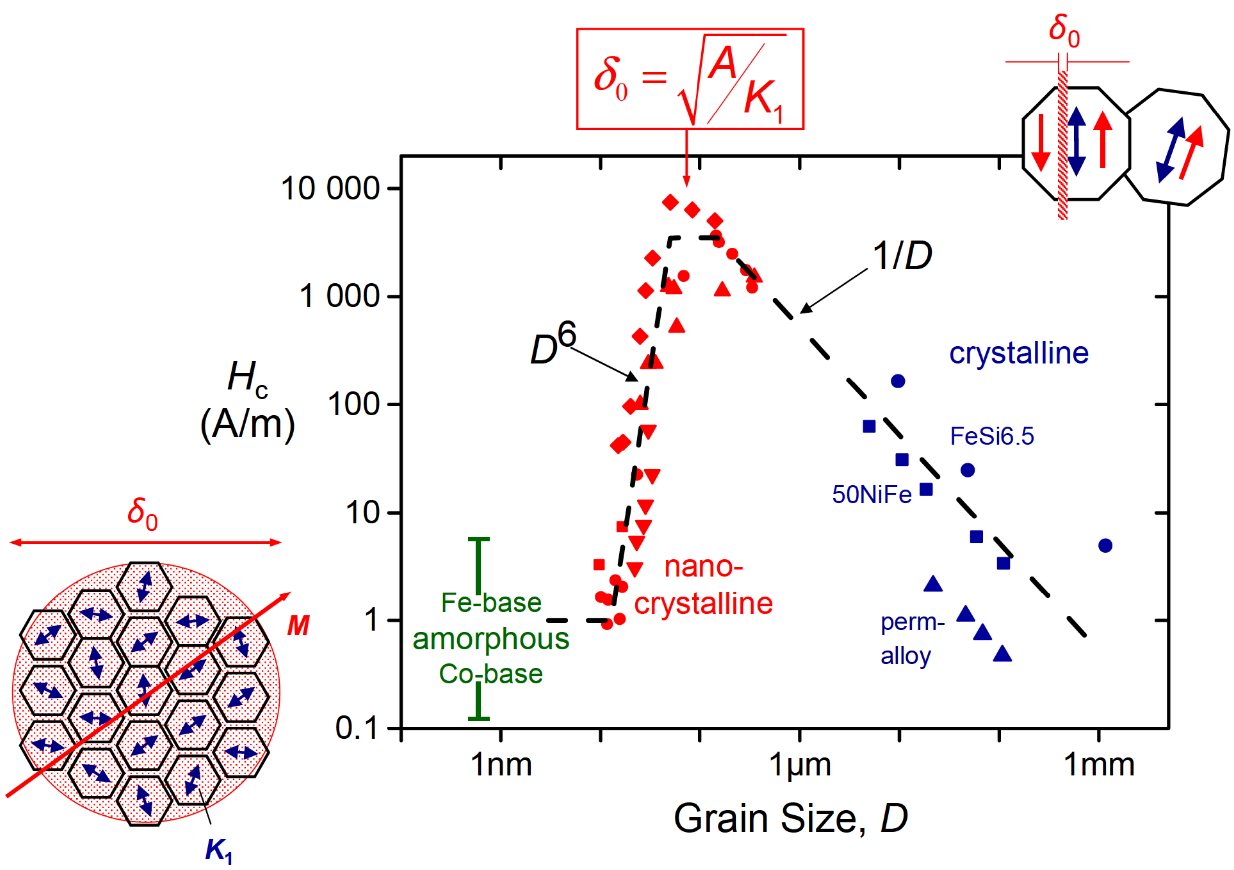
<u>micro-structure</u>



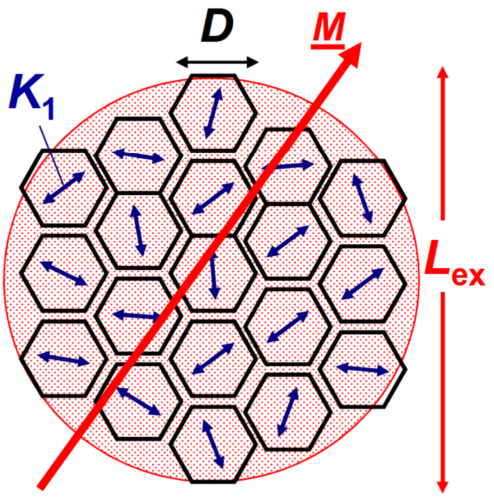
$$H_c \propto \sqrt{K_1}/D$$

$$\mu \propto 1/H_c$$

Magnetism and Microstructure



The Random Anisotropy Model



•average anisotropy constant

$$\langle K_1 \rangle = K_1 / \sqrt{N} \qquad (1)$$

•number N of coupled grains

$$N = \left(L_{ex} / D \right)^3 \qquad (2)$$

•exchange length (renormalized)

$$L_{ex} = \varphi_0 \sqrt{A / \langle K_1 \rangle} \qquad (3)$$

Combination of Eqs. (1) - (3) $\Rightarrow$

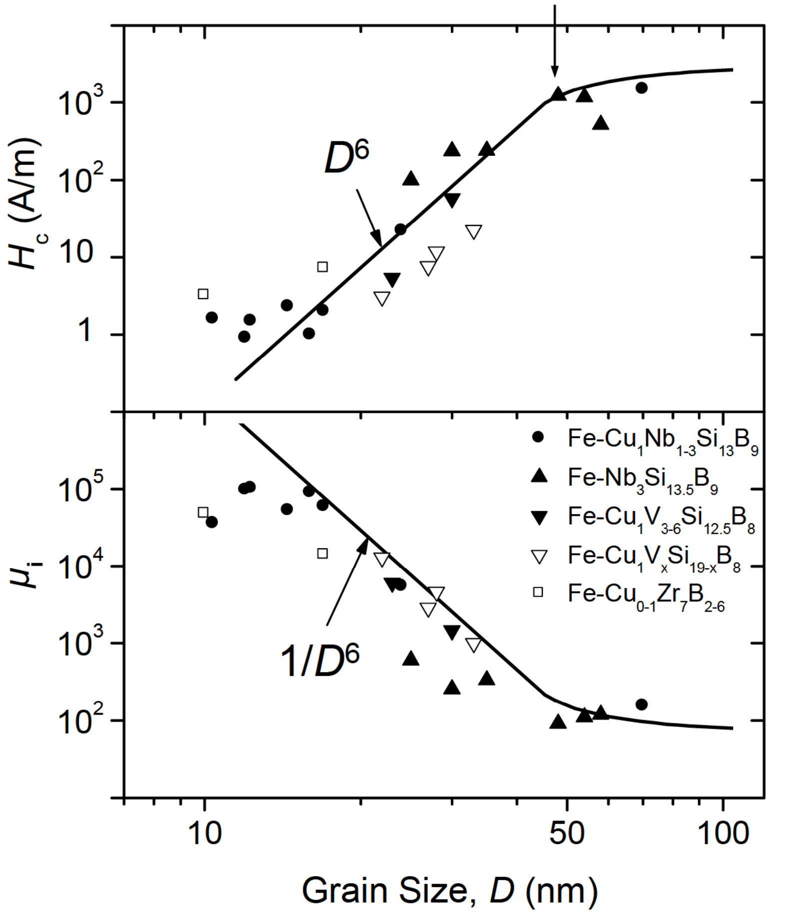
$$\langle K_1 \rangle = K_1 \left(D / L_0 \right)^6$$

$$L_0 = \varphi_0 \sqrt{A / K_1}$$

basic exchange length

Coercivity and Permeability

$N_{ex} = 1$ for $D = L_0/x^{1/6}$ with $x \approx 0.75 \Rightarrow L_0 \approx 43$nm



•average anisotropy constant

$$\langle K_1 \rangle = K_1 \cdot v_{cr}{}^2 \left(D/L_0\right)^6$$

$$L_0 = \varphi_0 \sqrt{A/K_1}$$

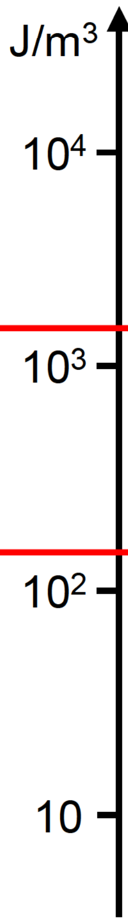
•coercivity and permeability

$$H_c = p_c \frac{\langle K_1 \rangle}{J_s}$$

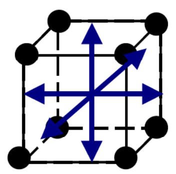
$$\mu_i = p_\mu \frac{J_s^2}{\mu_0 \langle K_1 \rangle}$$

fit with p_c=0.16, p_μ =1.3

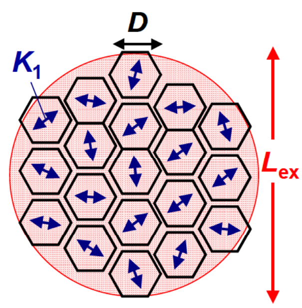
Magnetic Anisotropies



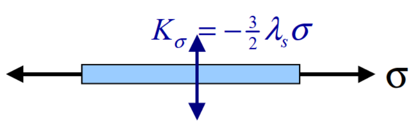
magneto-crystalline



$$\langle K \rangle = \frac{K_1}{\sqrt{N}}$$



magneto-elastic

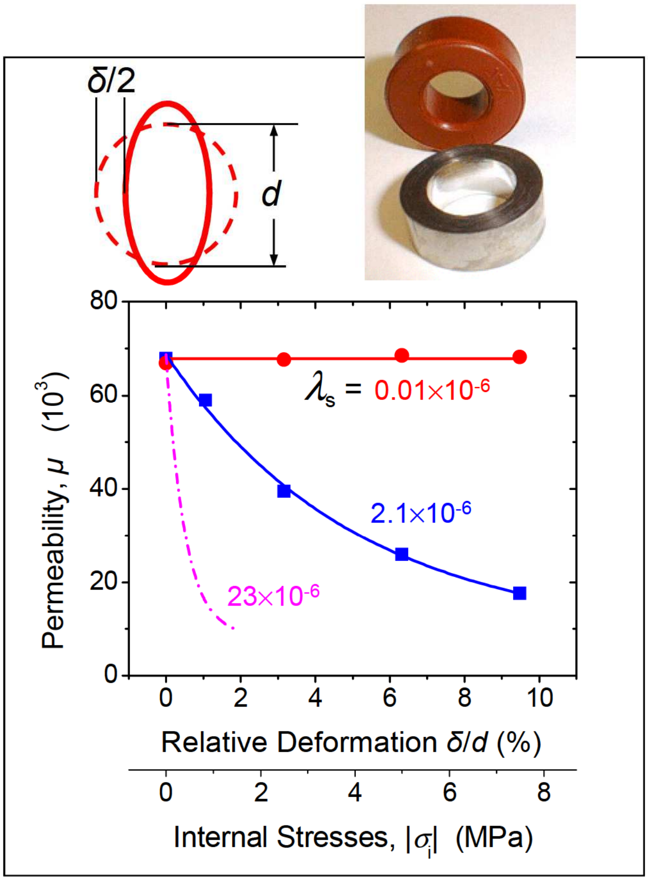


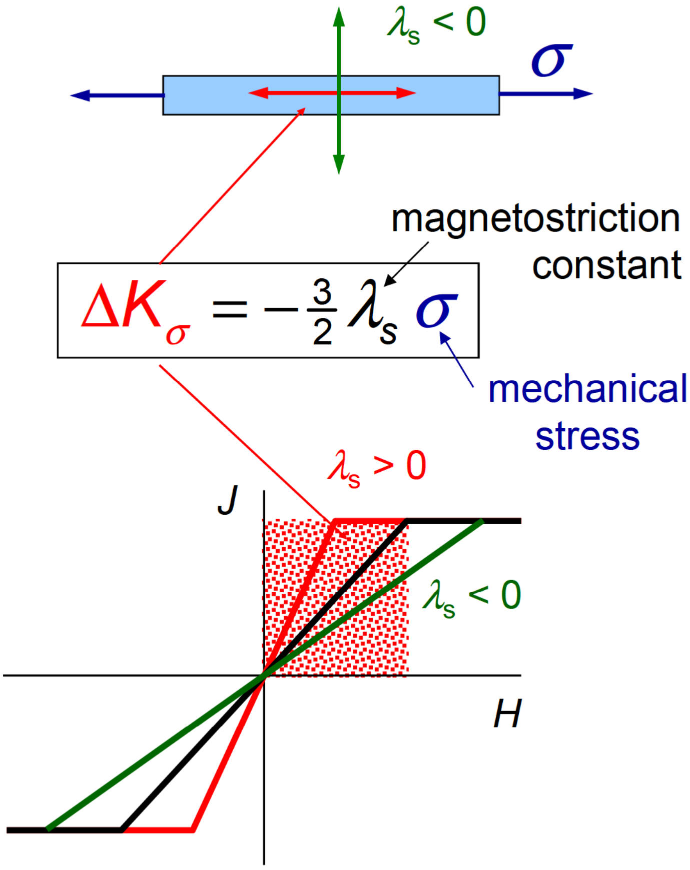
$\lambda_s \approx 0$ for amorphous Co-base
nanocrystalline Fe-base

annealing induced

- *stress annealing*
- *magnetic field annealing*

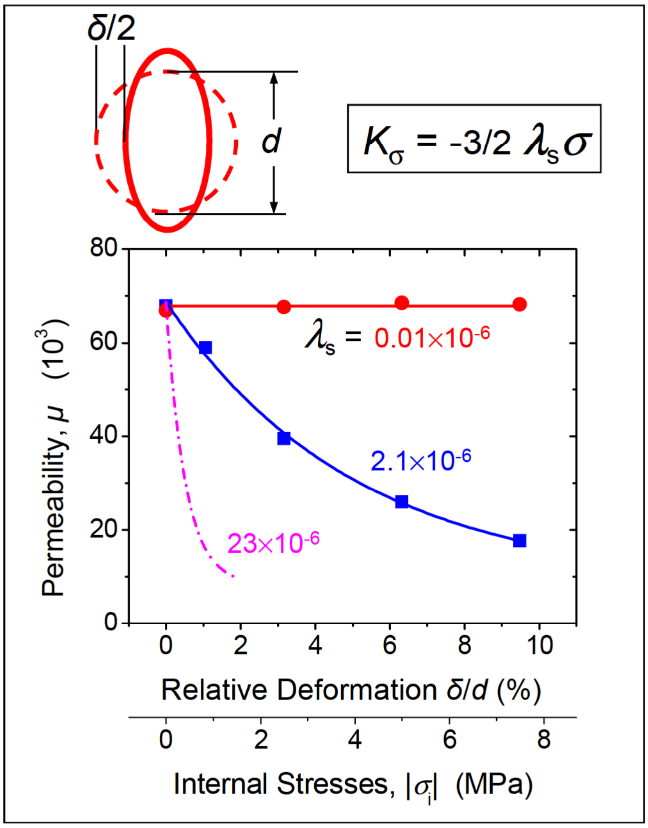
Magnetoelastic Anisotropy





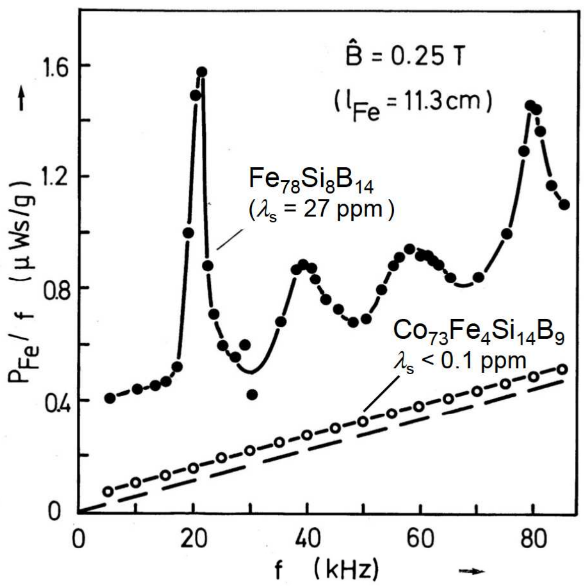
$$\Delta K_\sigma = -\tfrac{3}{2}\lambda_s \sigma$$

Effects of Magnetostriction λ_s



$$K_\sigma = -3/2\ \lambda_s \sigma$$

$$f_r = \frac{n}{2l_{Fe}}\sqrt{\frac{E}{\rho}}$$



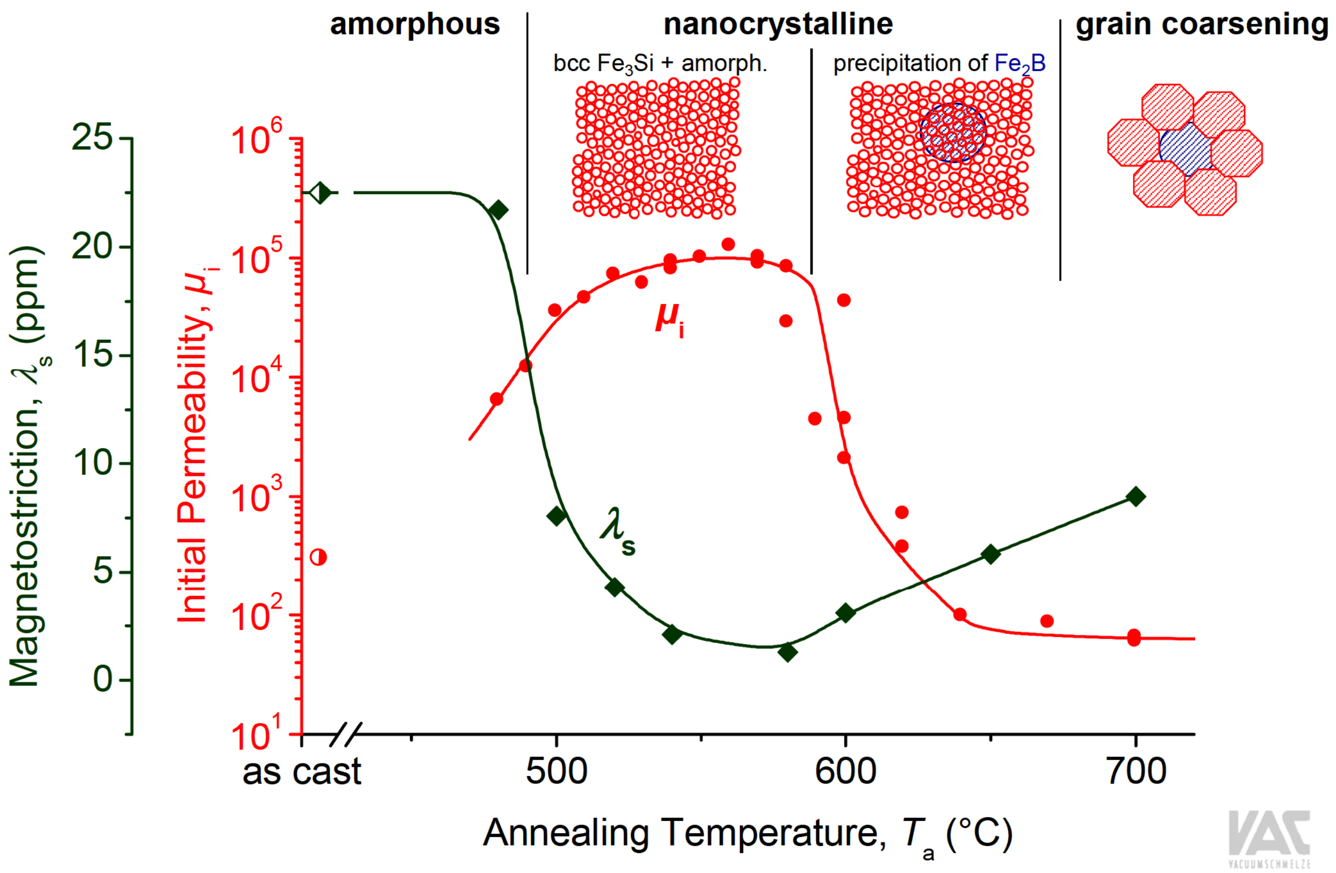
Alloy Systems

Composition		λ_s (ppm)	J_s (T)	H_c (A/m)
Co-$(FeMn)_4(SiB)_{20-27}$	am.	~ 0*	0.5 - 1.0	0.3
Fe-$(SiB)_{16-24}$	am.	~ 30	1.4 - 1.7	3
Fe-$Cu_1Nb_3Si_{15-16}B_{6-8}$	nano	~ 0*	1.24	0.3

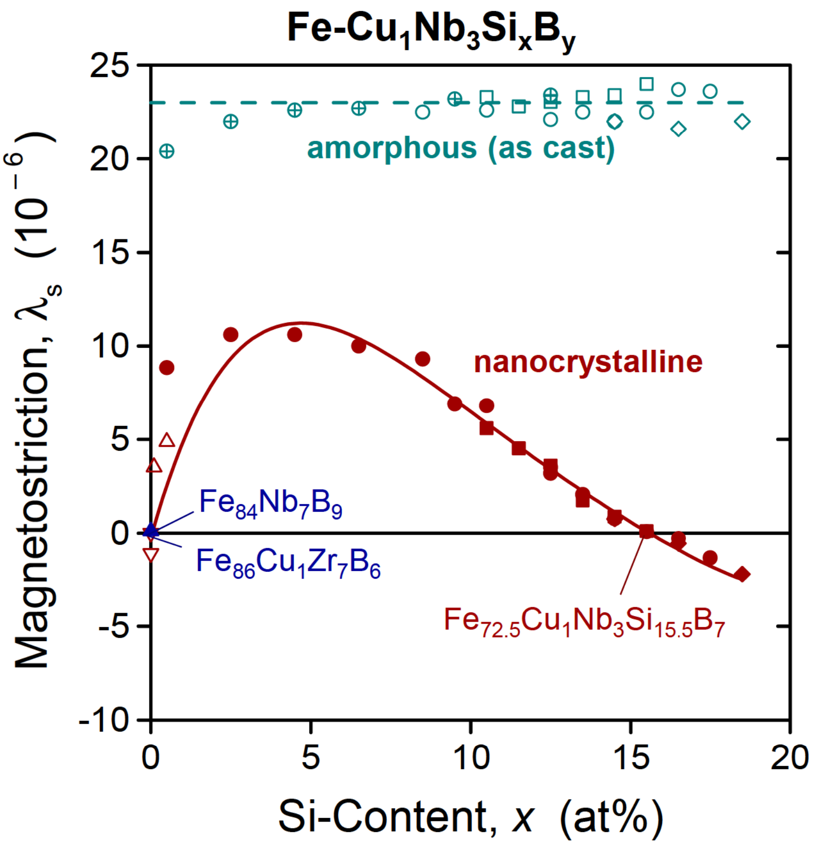
*$|\lambda_s| < 0.2$ ppm

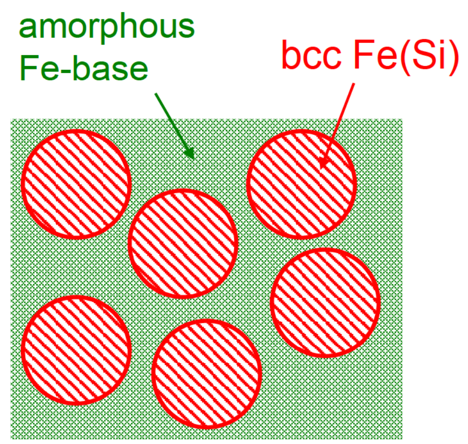
Nanocrystalline Alloys

$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (annealed 1h at T_a)

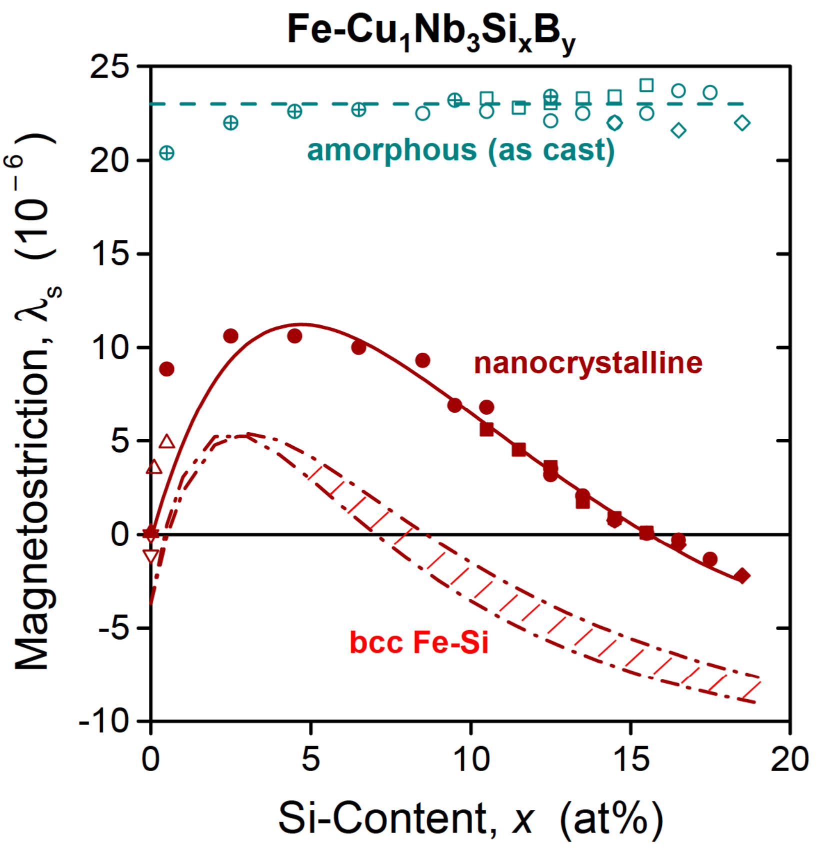


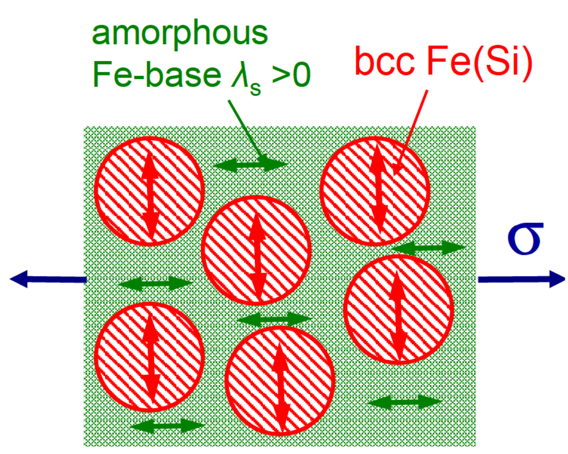
Saturation Magnetostriction λ_s in Nanocrystalline Alloys





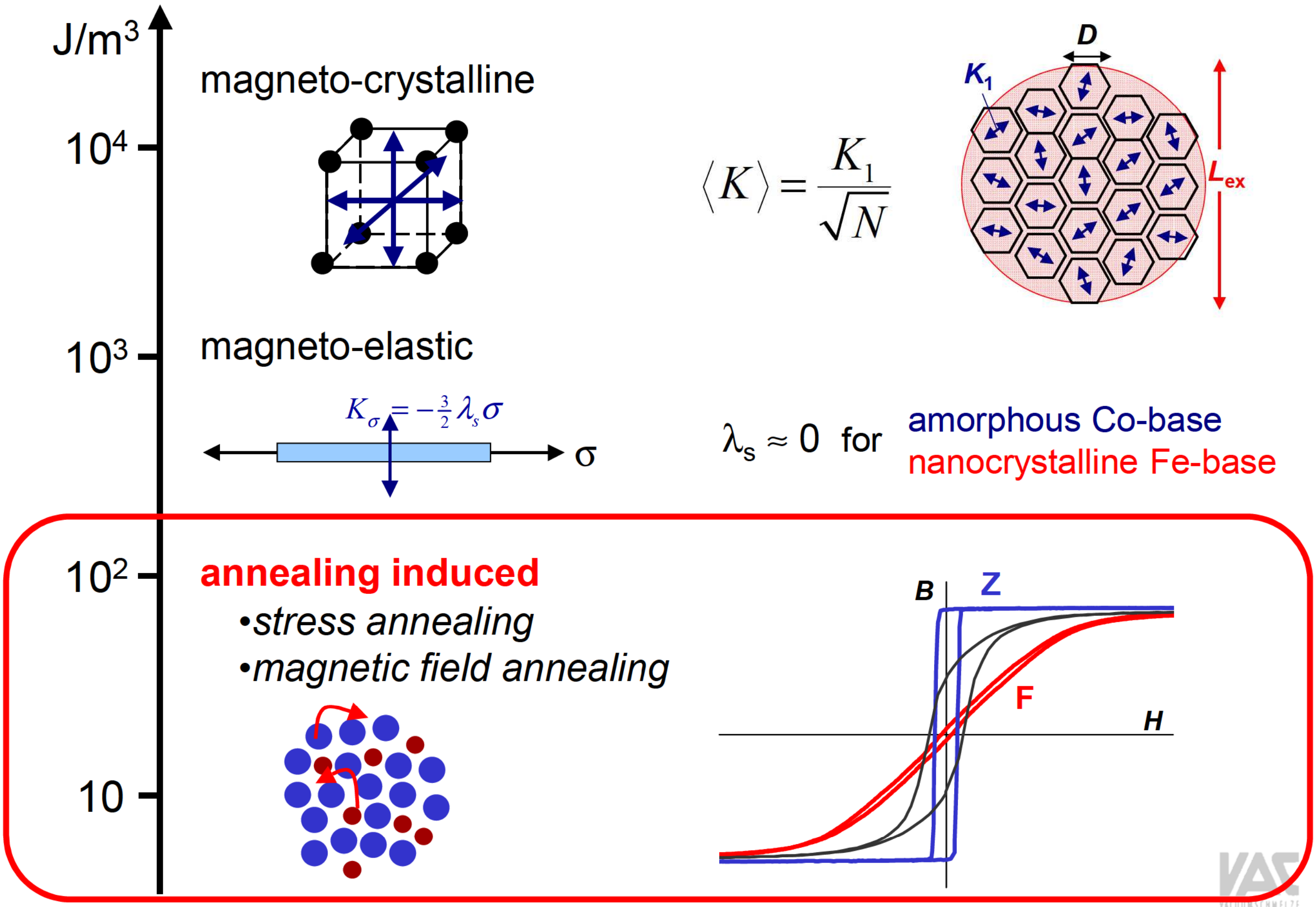
Saturation Magnetostriction λ_s in Nanocrystalline Alloys



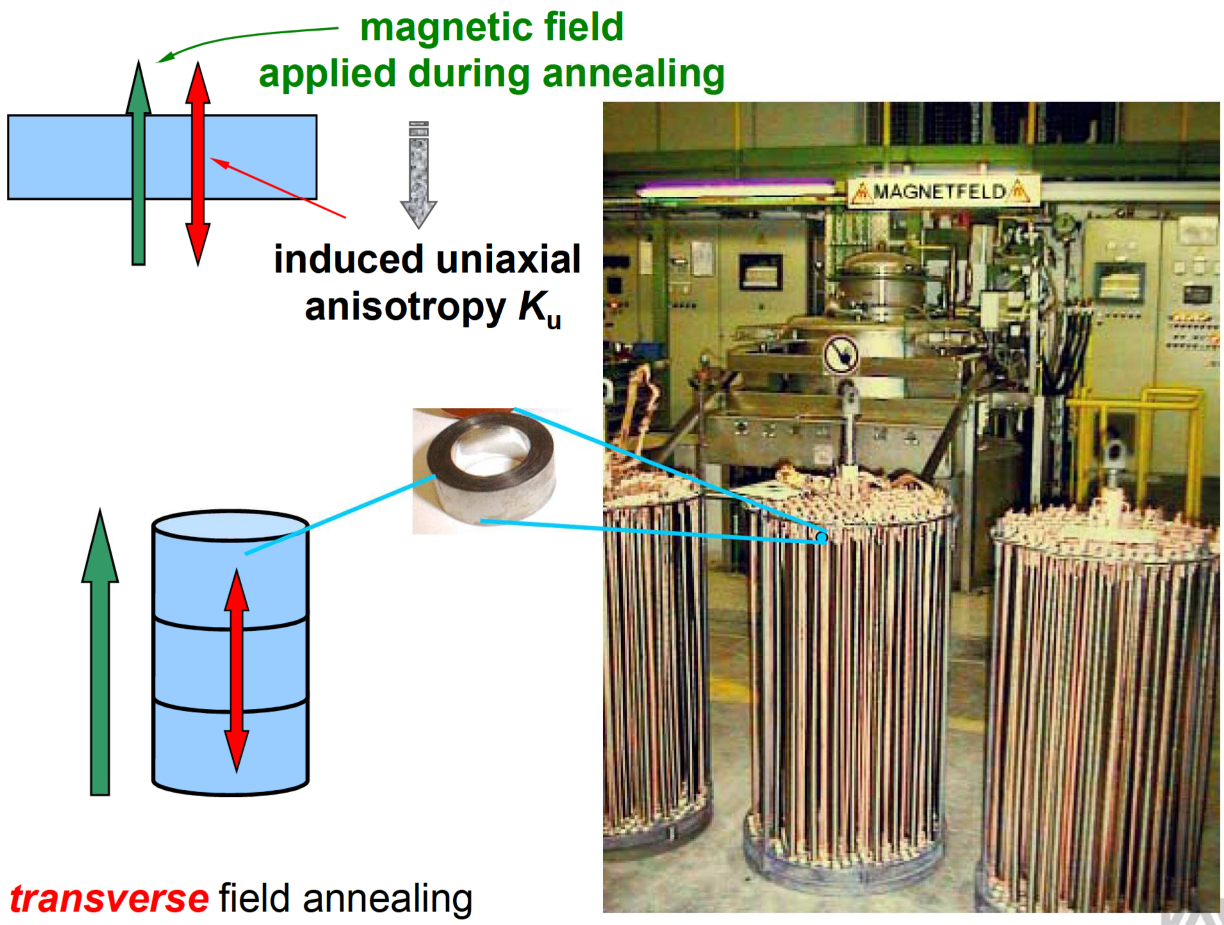


$$\lambda_s = v_{cr}\lambda_s^{(cr)} + (1 - v_{cr})\,\lambda_s^{(am)}$$

Magnetic Anisotropies

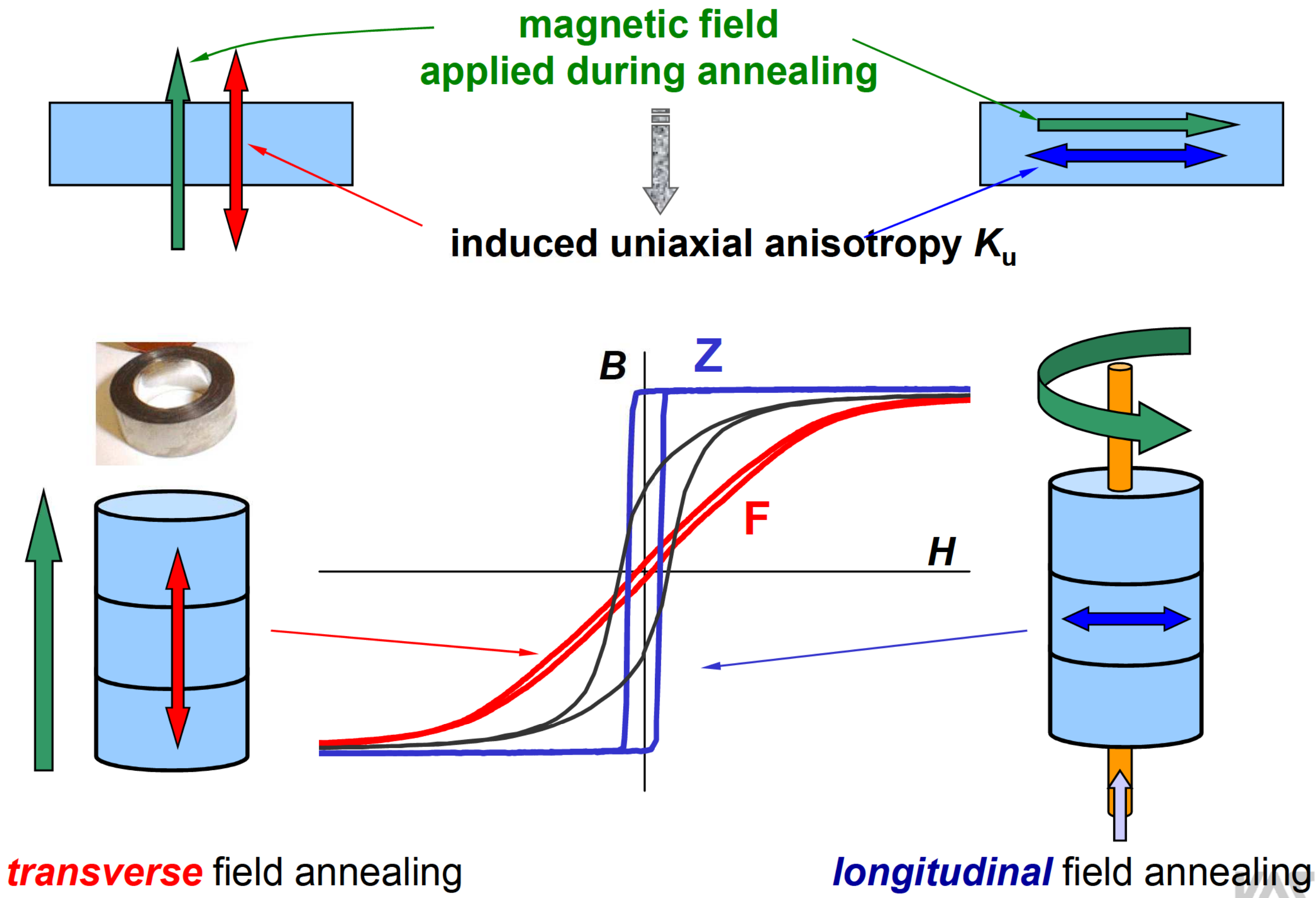


Magnetic Field Annealing

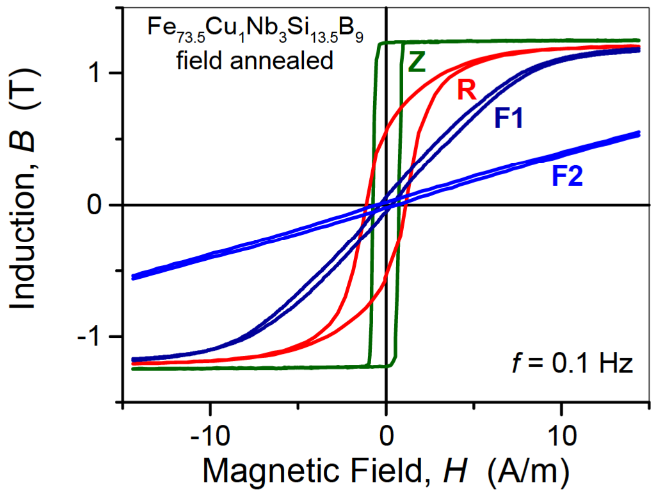


transverse field annealing

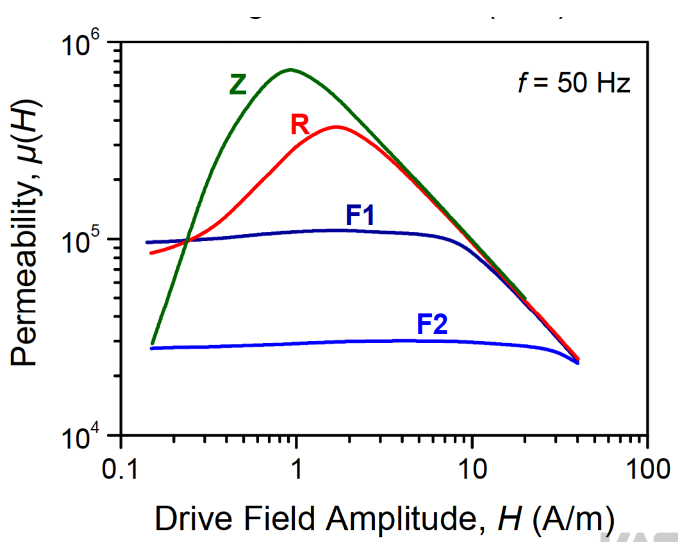
Magnetic Field Annealing



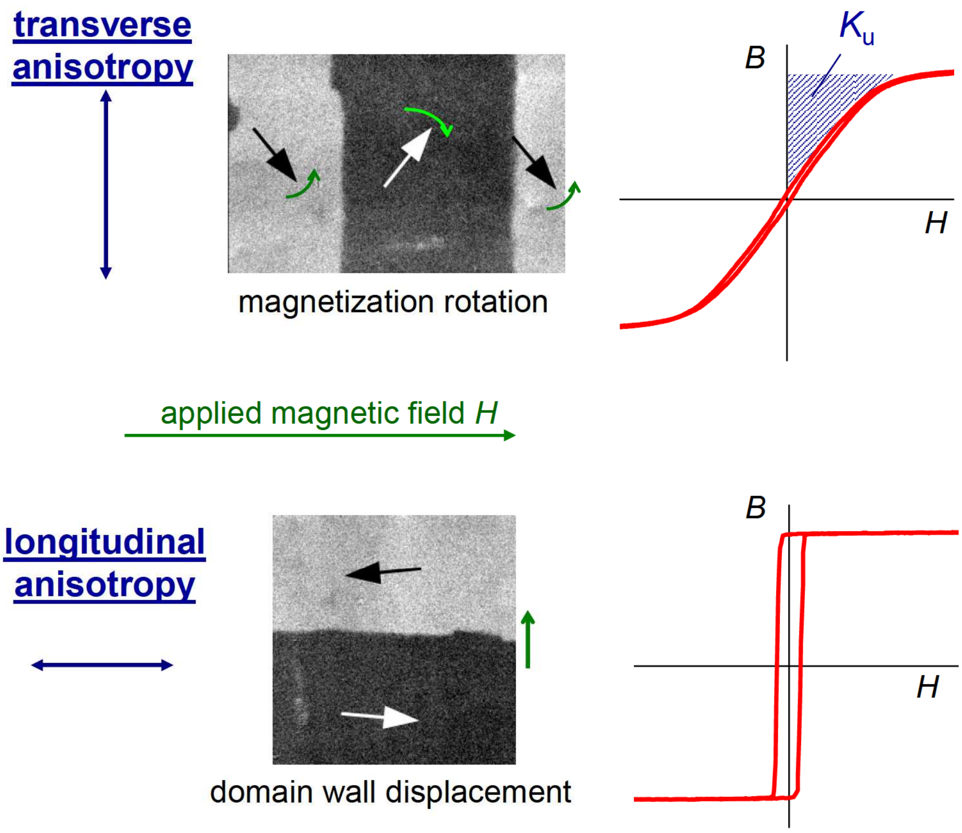
Typical BH Loops



	K_u (J/m^3)	μ
F1	6	100 000
F2	20	30 000



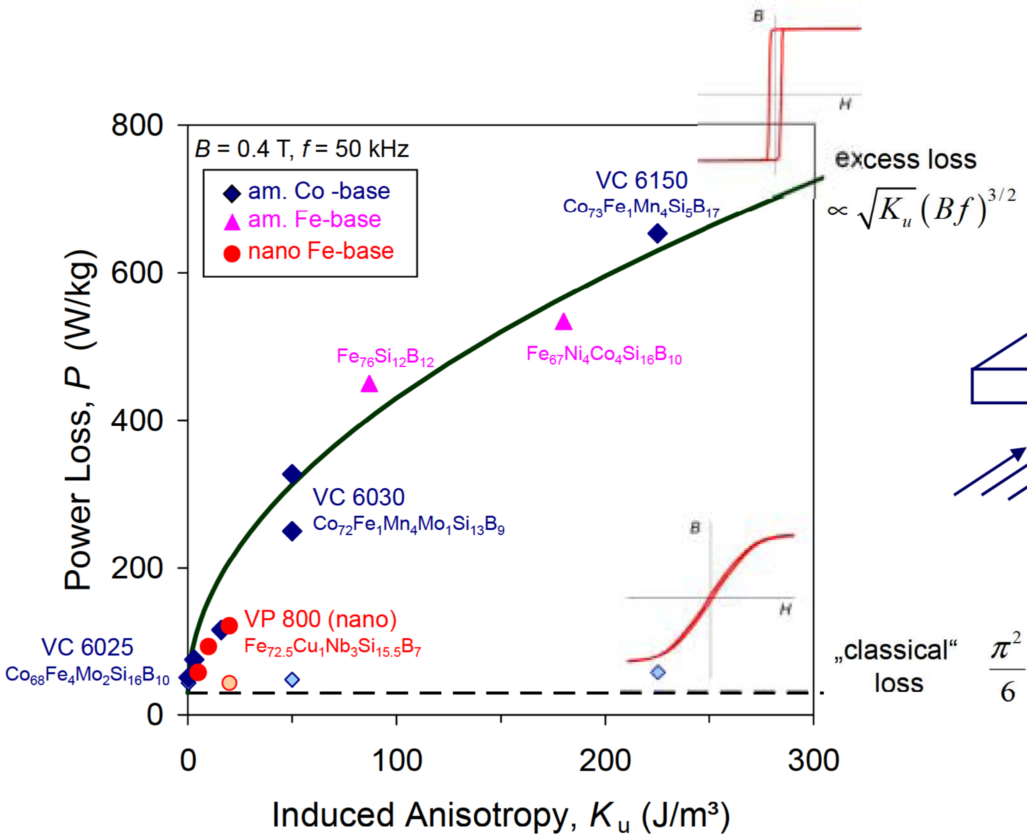
Magnetization processes



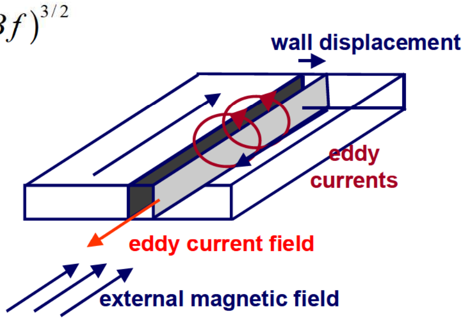
$$\mu = \frac{J_s^2}{2\mu_0 K_u}$$

$$\Delta P_{Fe} \propto \sqrt{K_u} \cdot \left(f\hat{B}\right)^{3/2}$$

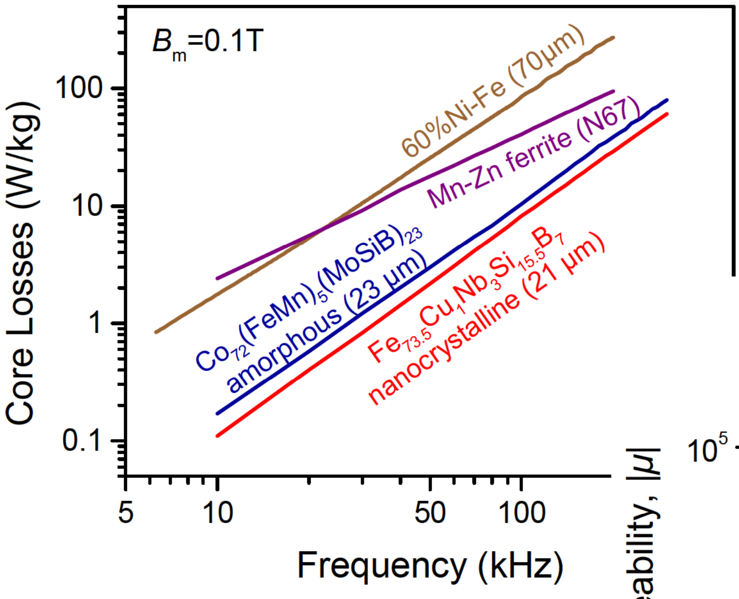
Anisotropy and Eddy Current Loss

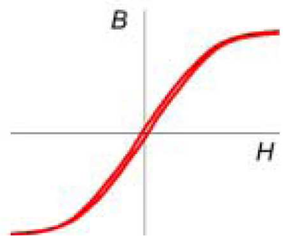


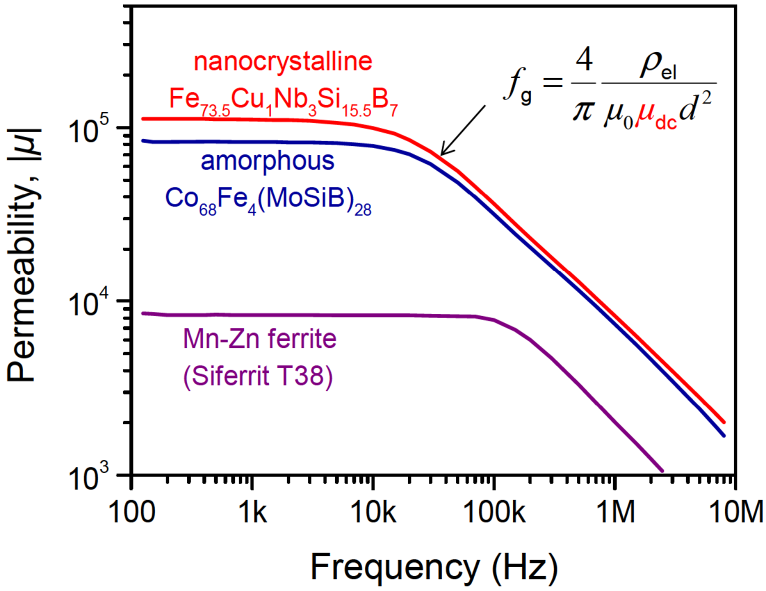
$$\frac{\pi^2}{6}\frac{d^2}{\rho_{el}}(Bf)^2$$



High frequency properties (F-loop)

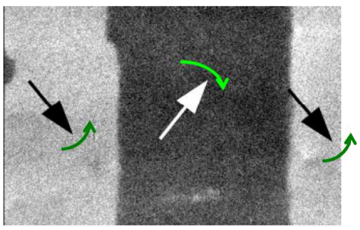




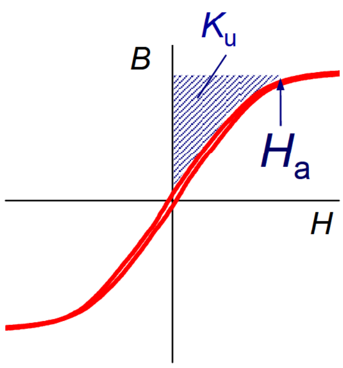


Magnetization processes

transverse anisotropy

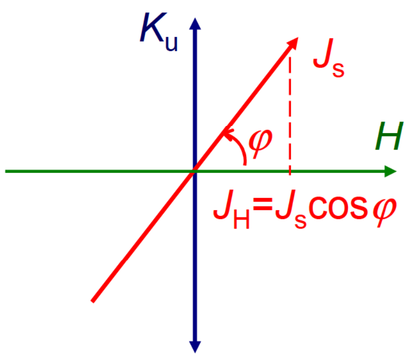


magnetization rotation



$$\mu = \frac{J_s^2}{2\mu_0 K_u}$$

applied magnetic field *H*



$$e = K_u \cos^2\varphi - HJ_s \cos\varphi$$

anisotropy energy   Zeeman energy

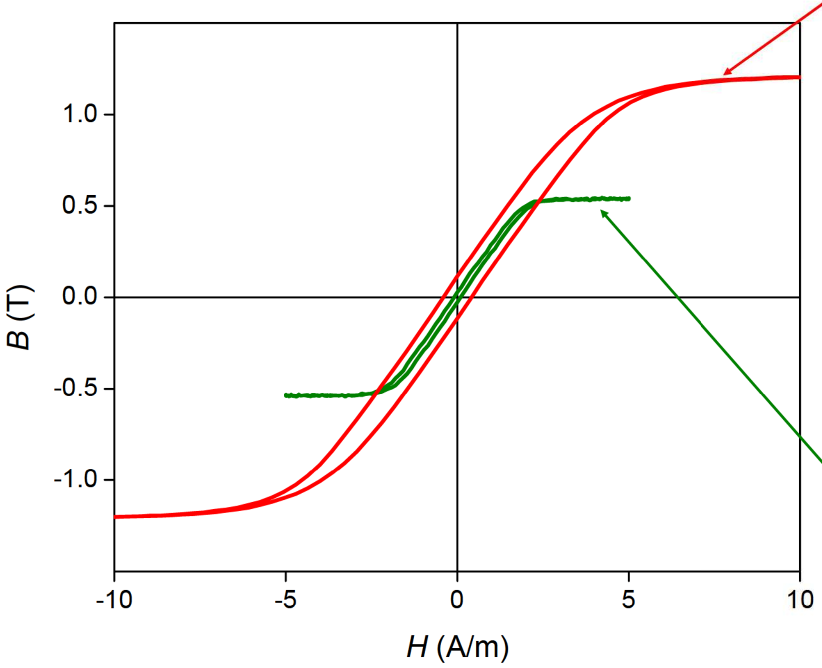
$$\frac{de}{d\varphi} = 0 \Rightarrow$$

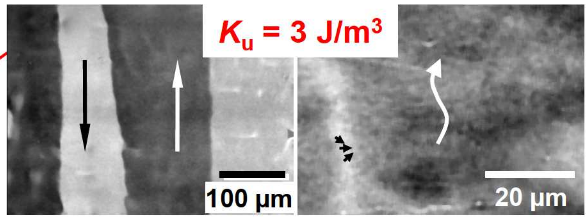
$$J_H = J_s \begin{cases} -1 & H < -H_a \\ H/H_a \quad \text{for} & |H| < H_a \\ 1 & H > H_a \end{cases}$$

Interplay of Uniform and Random Anisotropy

Kerr sensitivity

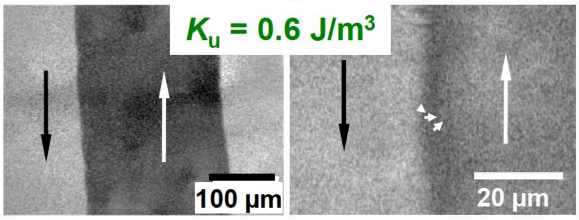
nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$





μ_i = 200 000

amorphous $Co_{68}Fe_4Mo_2Si_{16}B_{10}$



S. Flohrer, R. Schäfer, Ch. Polak, G.Herzer, *Acta Materialia* **53** (2005) 2937

Interplay of Uniform and Random Anisotropy

Kerr sensitivity

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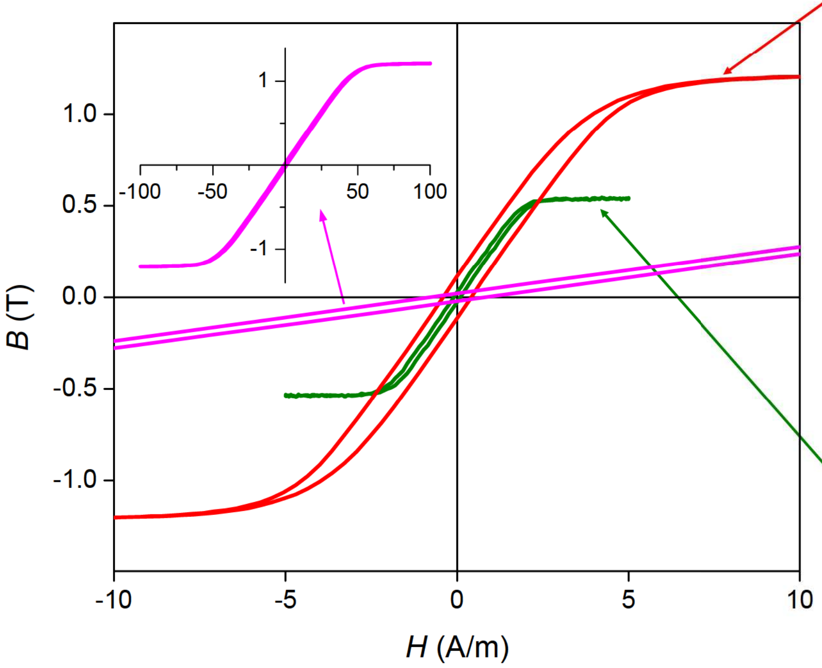
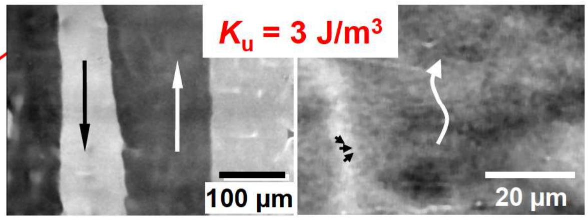
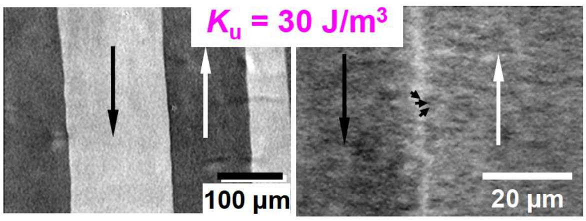
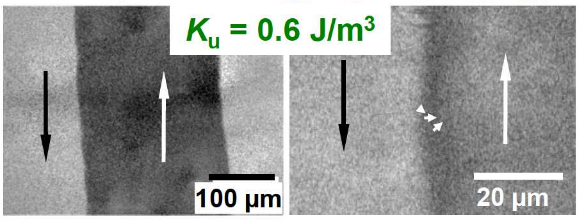






amorphous $Co_{68}Fe_4Mo_2Si_{16}B_{10}$



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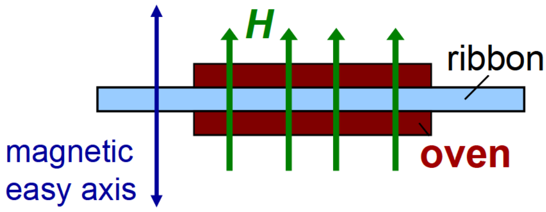
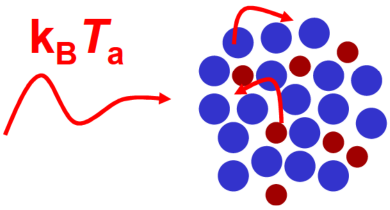
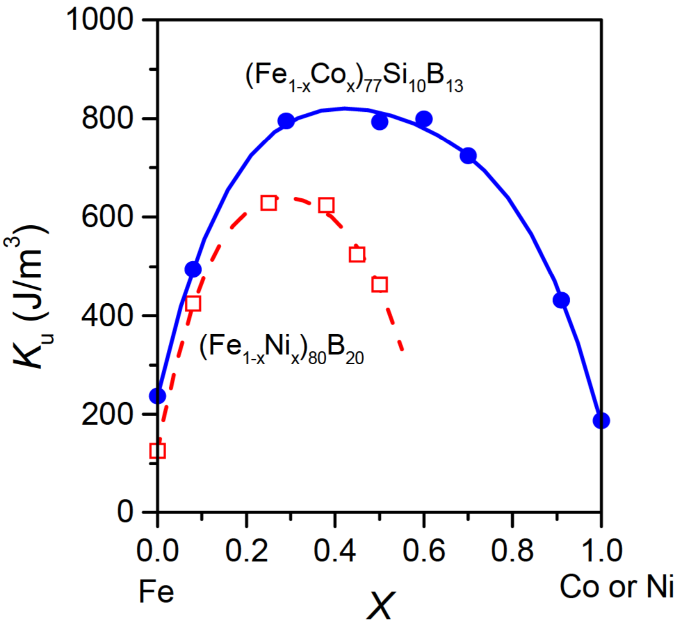
Magnetic Field Induced Anisotropy K_u



thermally activated change of (chemical) short range order

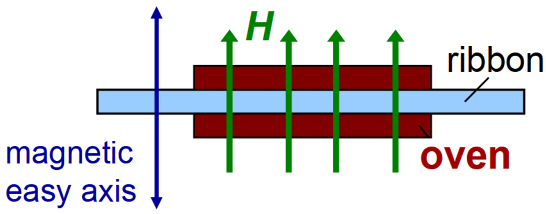


driving force: spin orbit interaction

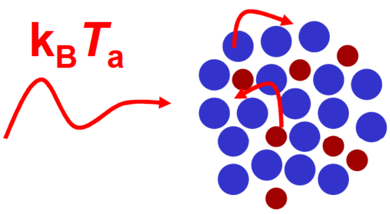


after H.Fujimori (1983)
in *Amorphous Metallic Alloys* (ed. F.E. Luborsky)

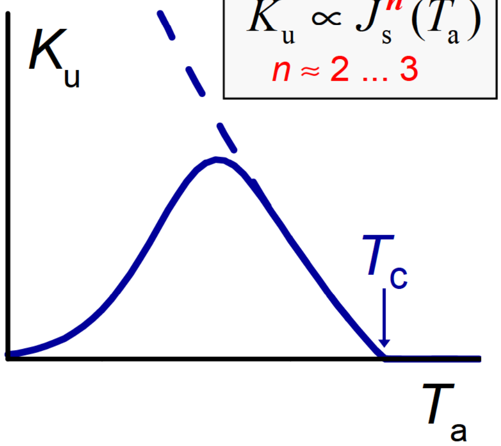
Magnetic Field Induced Anisotropy K_u



thermally activated change of (chemical) short range order

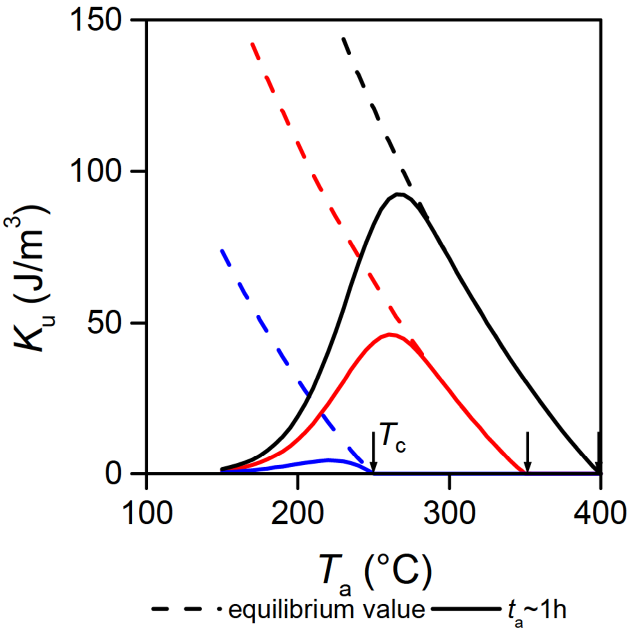


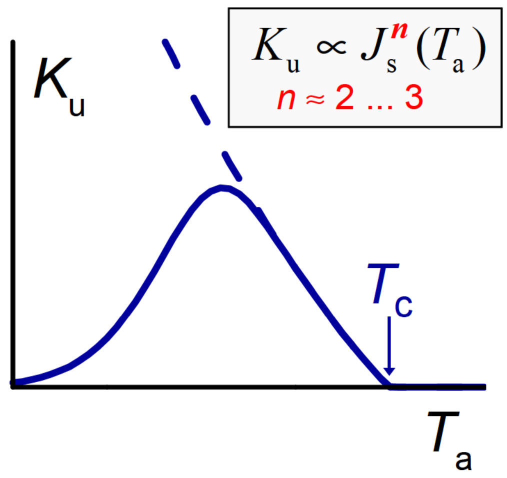
driving force: spin orbit interaction



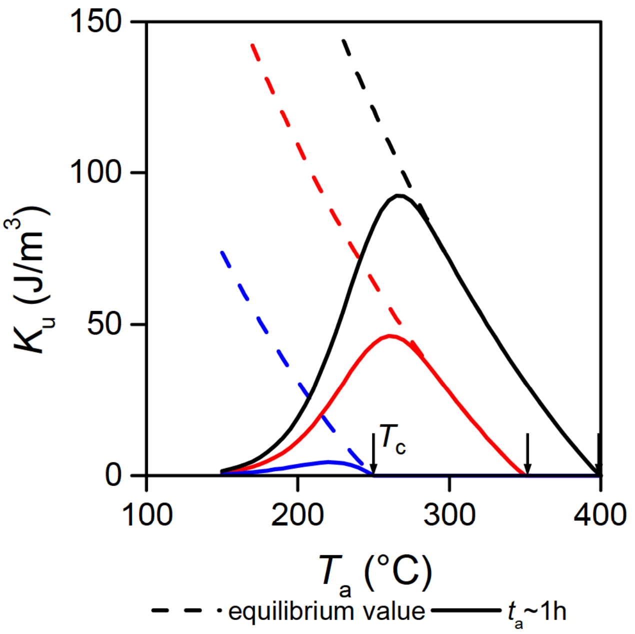
$$K_u \propto J_s^n(T_a)$$
$n \approx 2 \ldots 3$

Magnetic Field Induced Anisotropy K_u

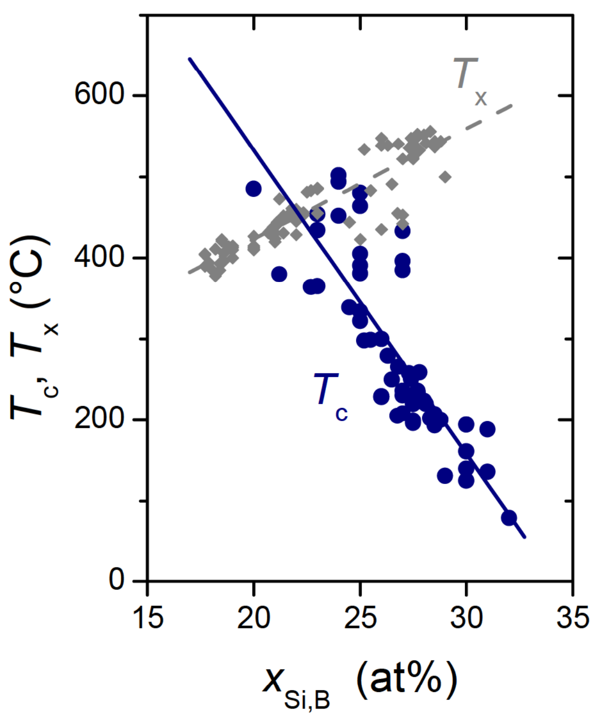




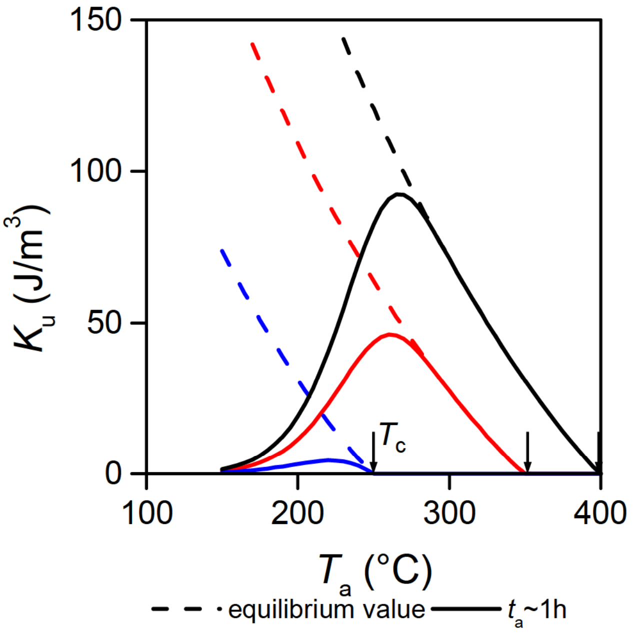
Magnetic Field Induced Anisotropy K_u

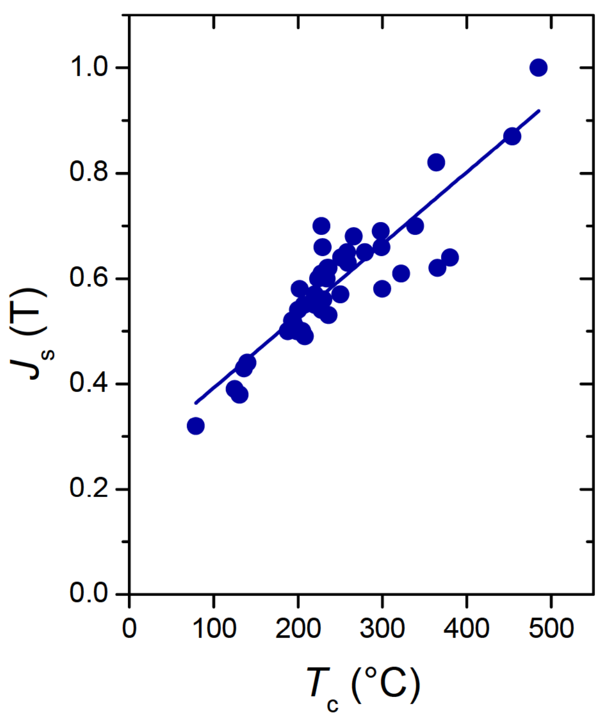


$Co_{bal}(Fe,Mn)_{\sim 5}(Si,B)_x$



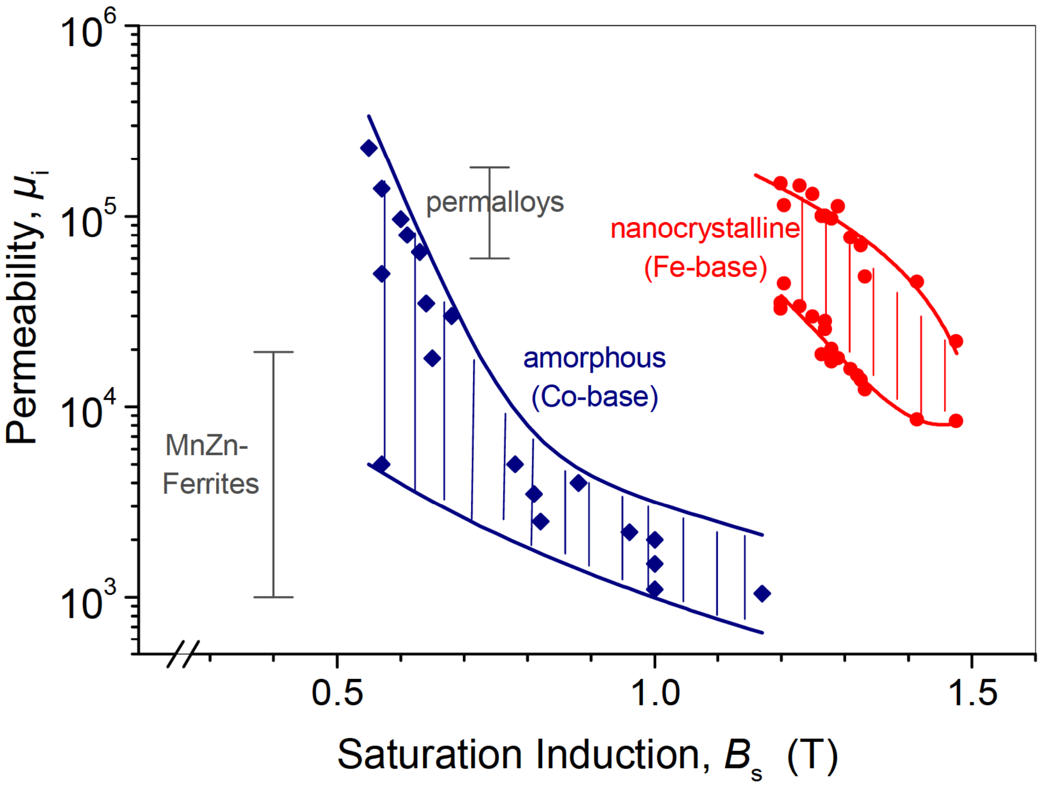
Magnetic Field Induced Anisotropy K_u



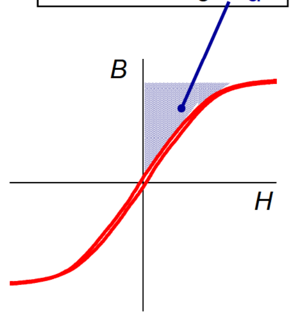


VAC VACUUMSCHMELZE

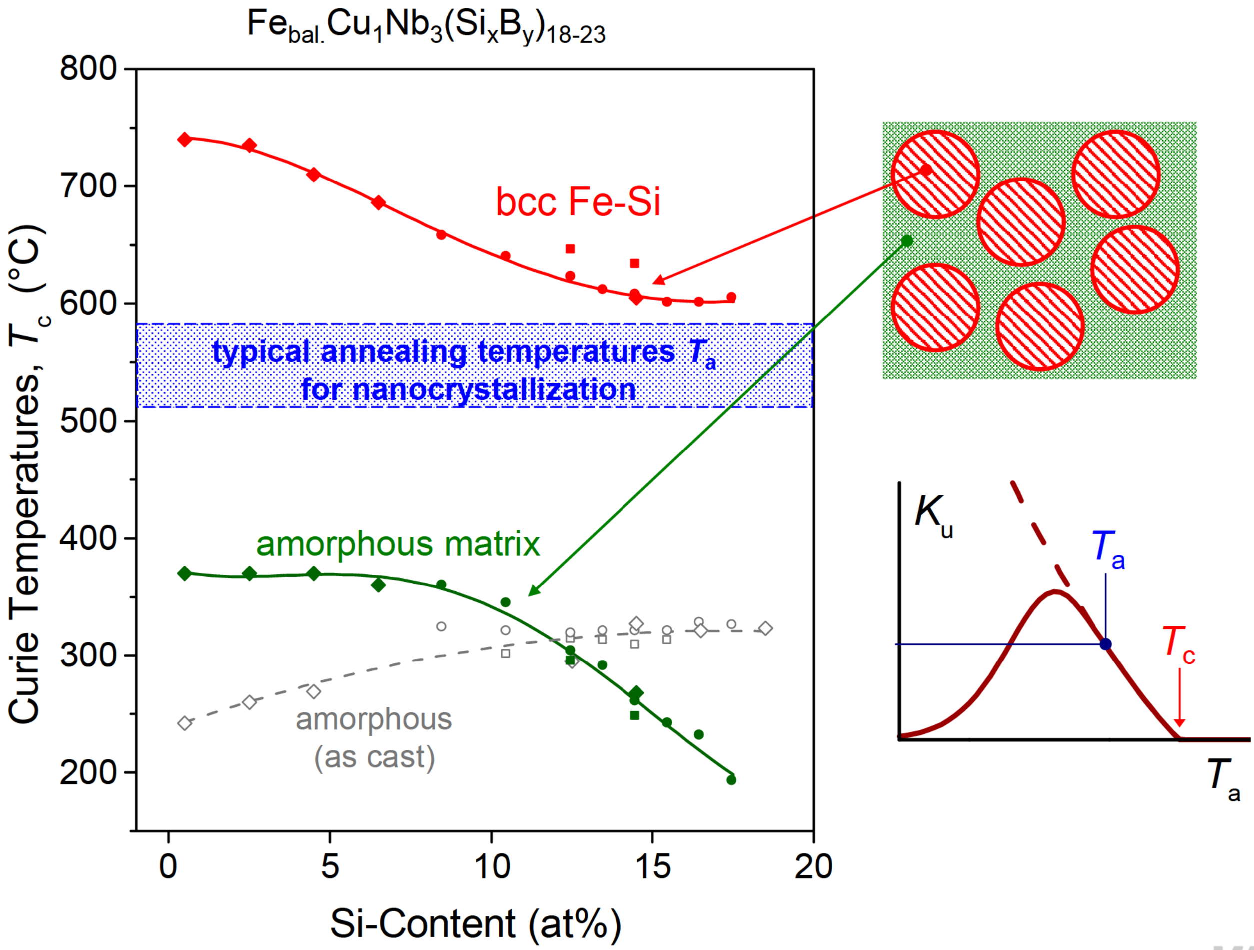
Typical permeabilities after transverse field annealing



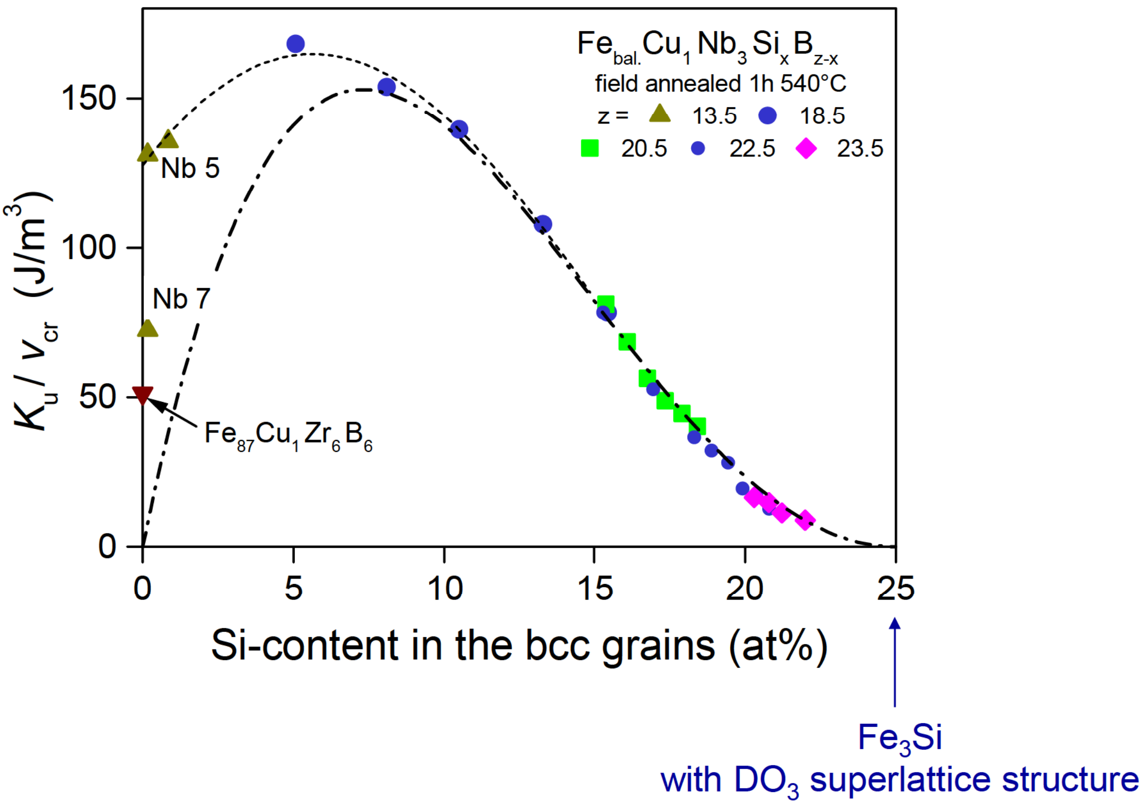
$$\mu = \frac{J_s^2}{2\mu_0 K_u}$$



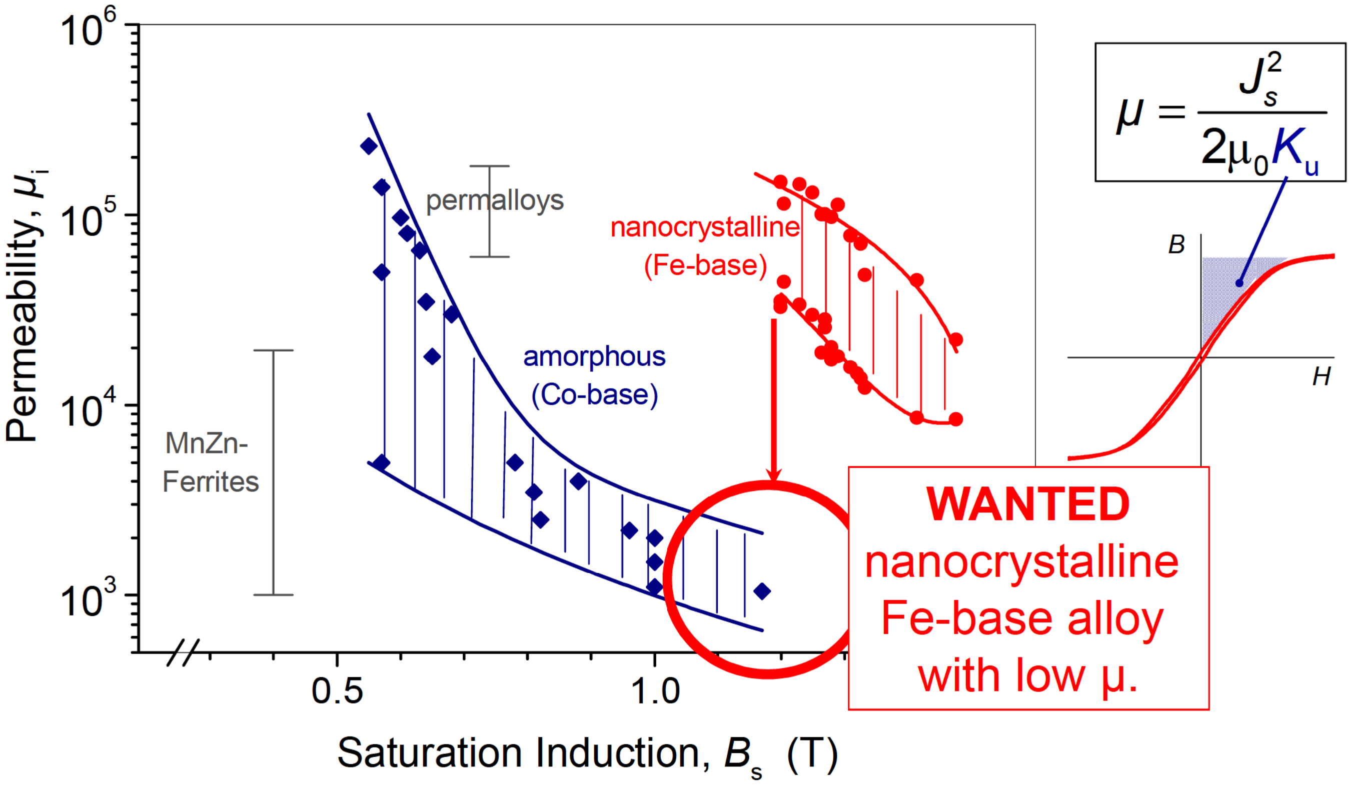
VAC VACUUMSCHMELZE



Field Induced Anisotropy in the bcc FeSi Grains



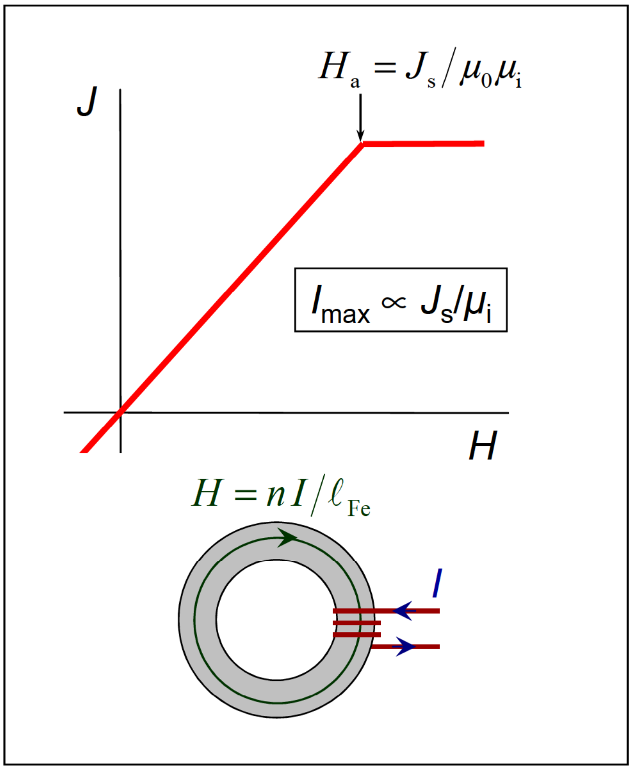
Typical permeabilities after transverse field annealing

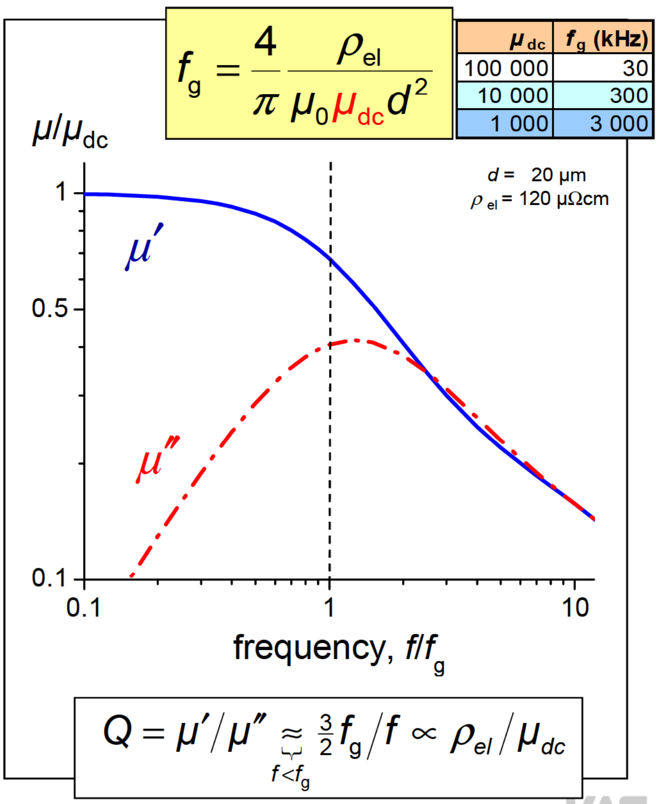


Why Low Permeabilities?

- current transformers
- energy storage chokes

- favourable at high frequencies

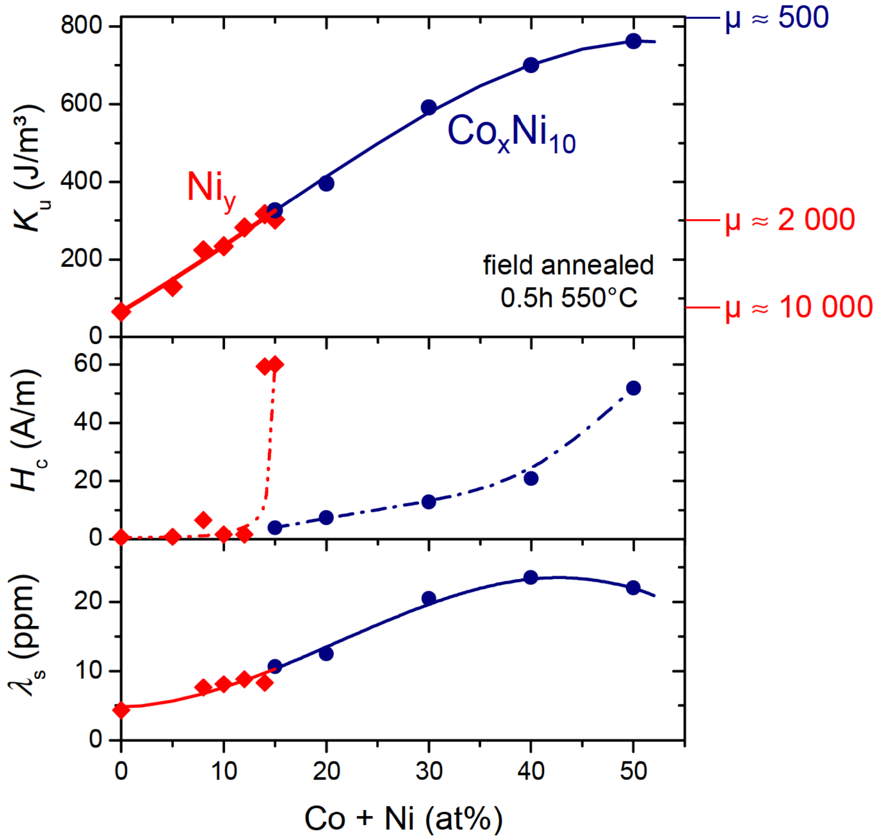




μ_{dc}	f_g (kHz)
100 000	30
10 000	300
1 000	3 000

Field Induced Anisotropy K_u in Nanocrystalline Alloys

$Fe_{bal}Co_xNi_yCu_1Nb_3Si_{12}B_8$

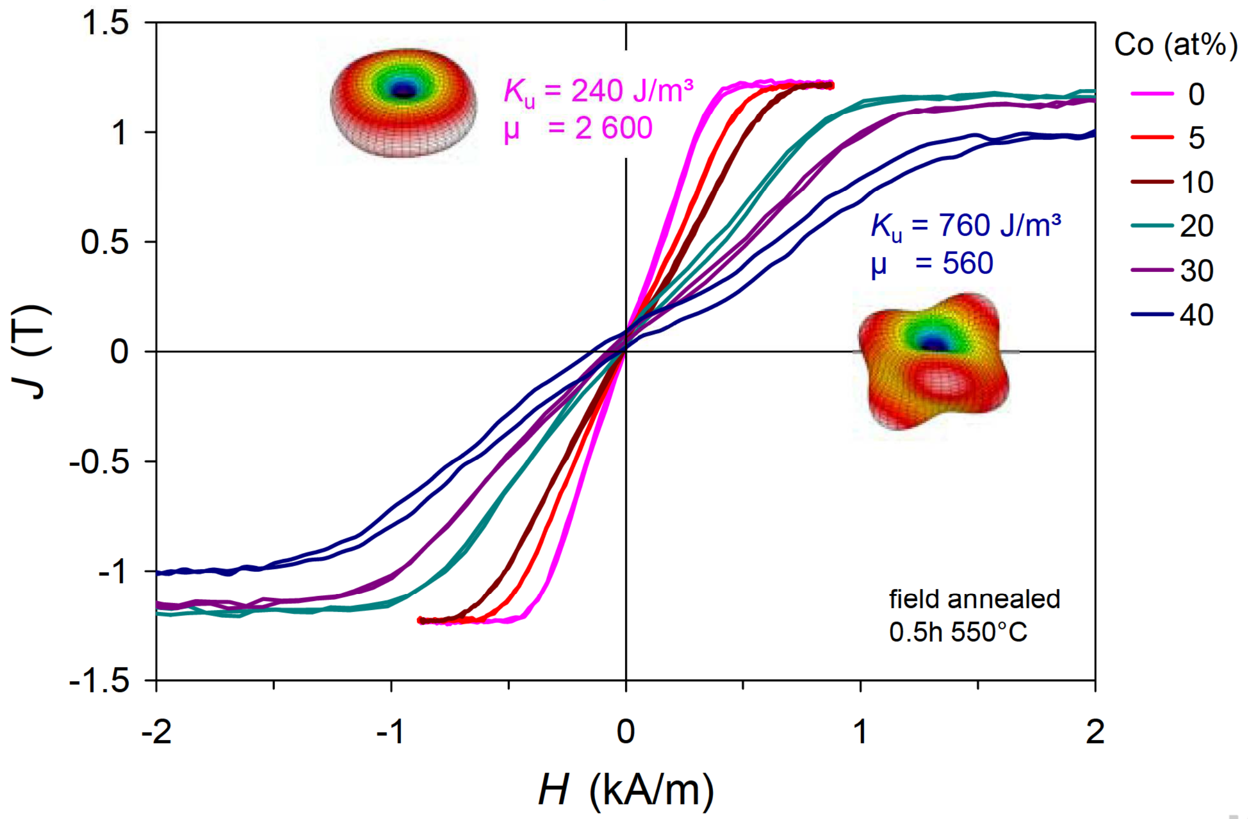


$$\mu = \frac{J_s^2}{2\mu_0 K_u}$$

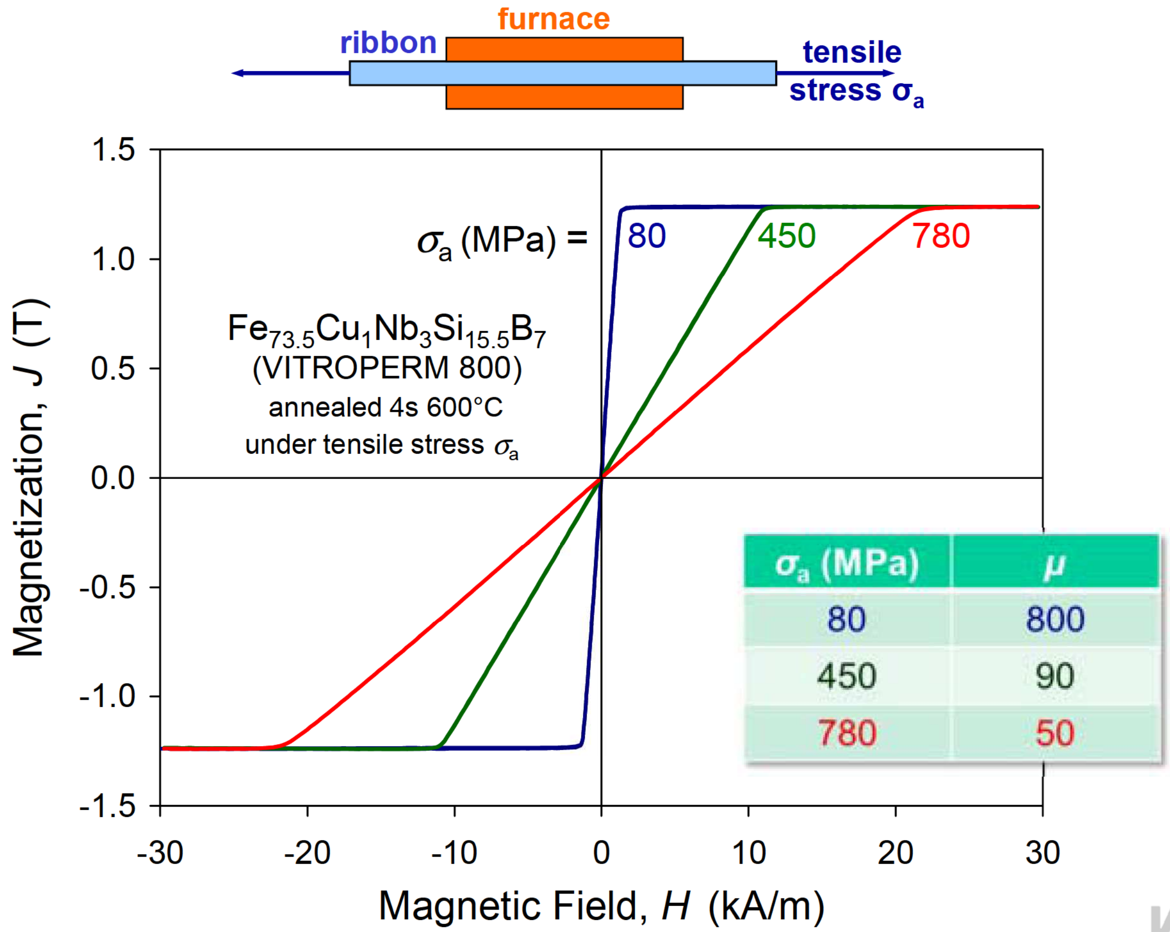
Herzer, G. and Otte, D. (2004). PCT Patent Application WO 2004/088681 A2.

Field Induced Anisotropy K_u in Nanocrystalline Alloys

$Fe_{bal}Co_xNi_yCu_1Nb_3Si_{12}B_8$



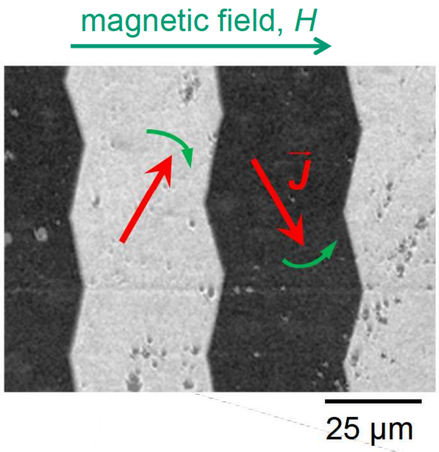
Nanocrystallisation under tensile stress

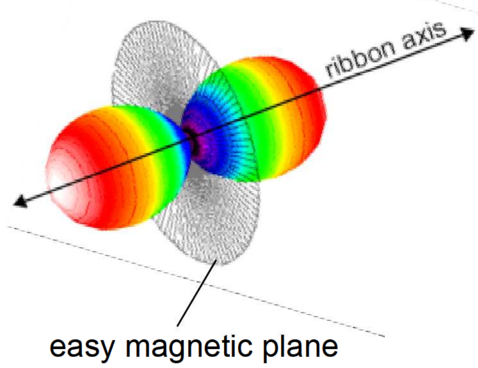


σ_a (MPa)	μ
80	800
450	90
780	50

G. Herzer, V. Budinsky, Ch. Polak, Phys. Status Solidi B 248, No. 10, 2382–2388 (2011)

Magnetisation Process

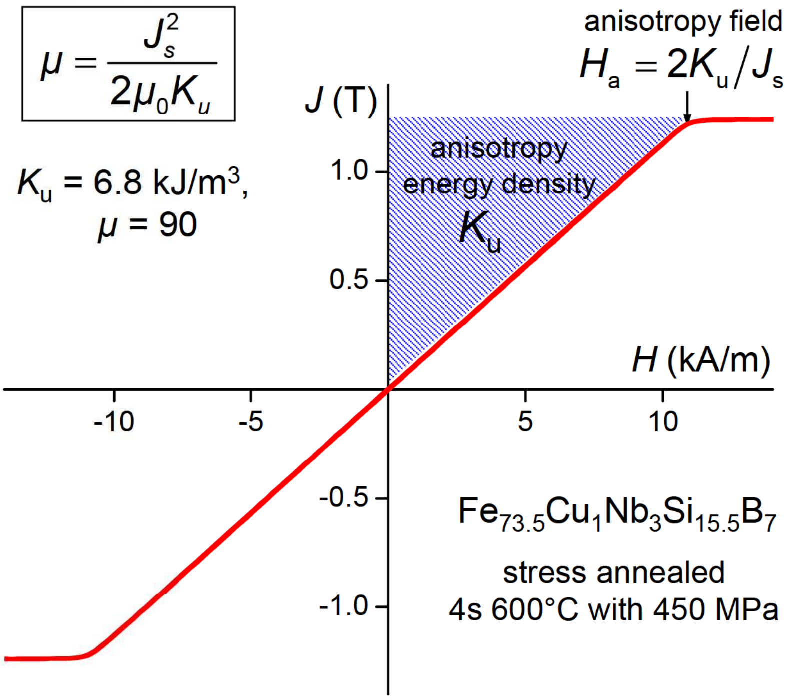




permeability

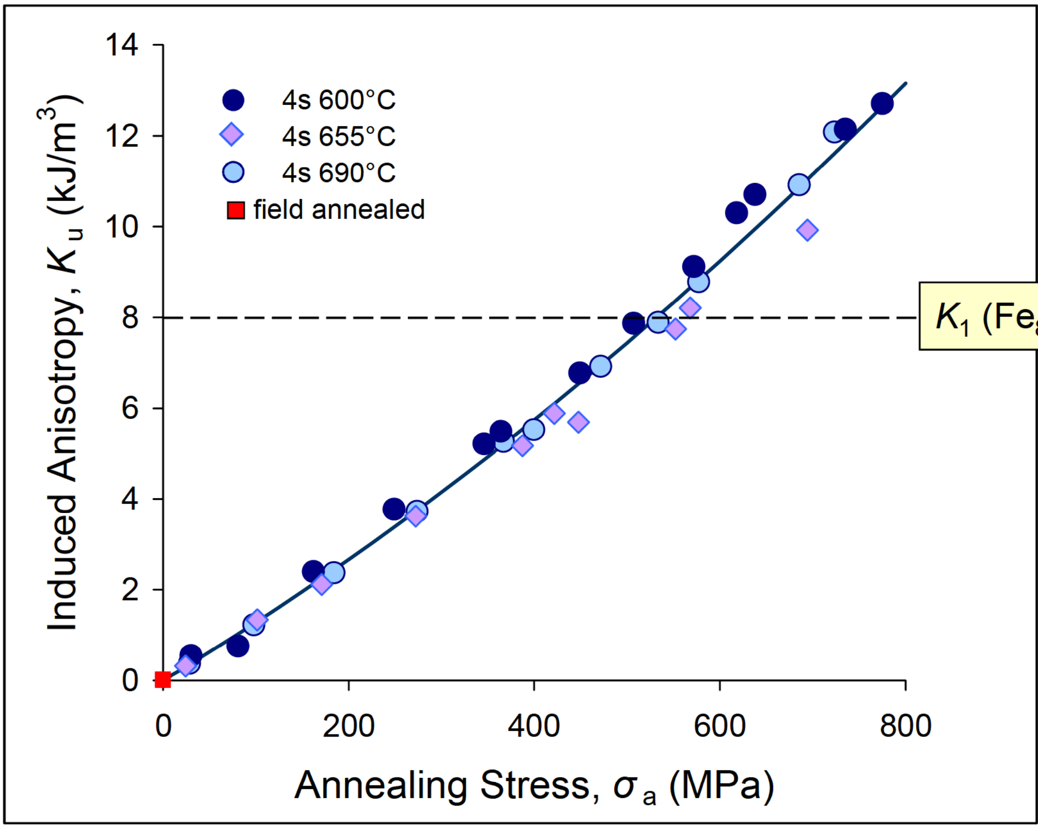
$$\mu = \frac{J_s^2}{2\mu_0 K_u}$$

K_u = 6.8 kJ/m^3,
μ = 90

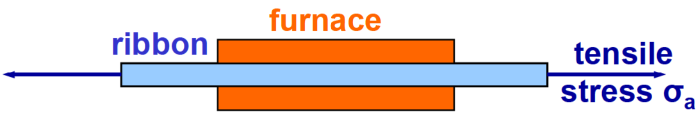


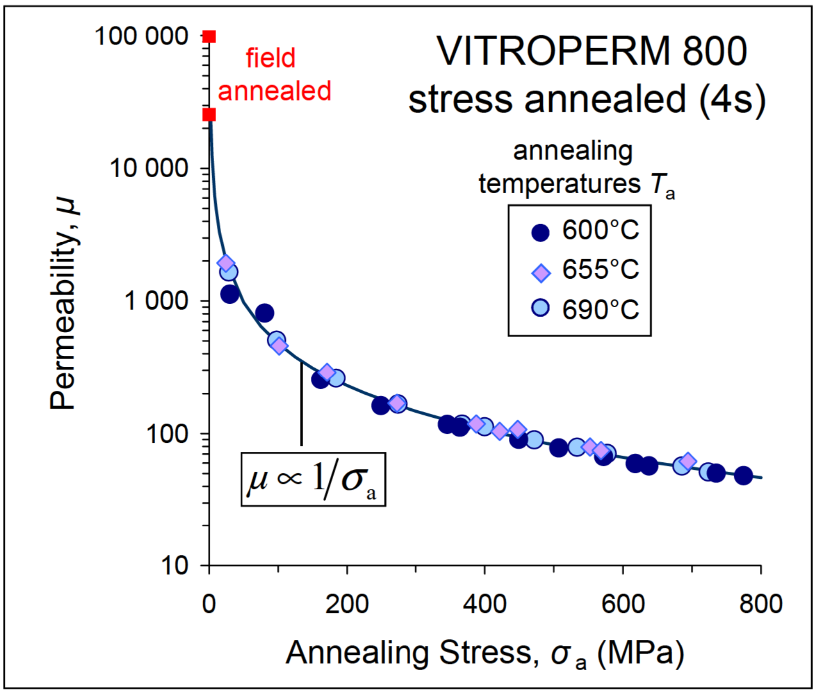
Induced Anisotropy vs. Annealing Stress

$Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$
tensile stress annealed for 4s at T_a



Tensile Stress Annealing





Conclusions: Amorphous and Nanocrystalline Materials

- Vanishing Magneto-Crystalline Anisotropy
  (independent of composition and temperature)
- Isotropically Vanishing Magnetostriction
  (λ_s < 0.2 ppm by appropriate alloying)

→ superior soft magnetic properties

- Favourable High Frequency Behaviour
  (thin ribbons ~20 µm, high resistivity ~120 µΩcm)

→ competitive to Mn-Zn ferrites

- High Versatility of Soft Magnetic Properties
  (μ_i ~ 100 - 300'000; annealing induced anisotropies)

→ large range of soft magnetic applications

Literature

- G. Herzer, *Modern soft magnets: Amorphous and nanocrystalline materials*, Acta Materialia 61 (2013) 718–734 (http://dx.doi.org/10.1016/j.actamat.2012.10.040)
- G. Herzer, *Anisotropies in soft magnetic nanocrystalline alloys*, J. of Magn. Magn. Materials 294 (2005) 99–106
- G. Herzer (1997). *Nanocrystalline soft magnetic alloys*. In Handbook of Magnetic Materials, Buschow, K.H.J. (Ed.), Elsevier Science B.V., pp. 415–462, Vol. 10.
- and many references cited therein