Soft Magnetic Materials

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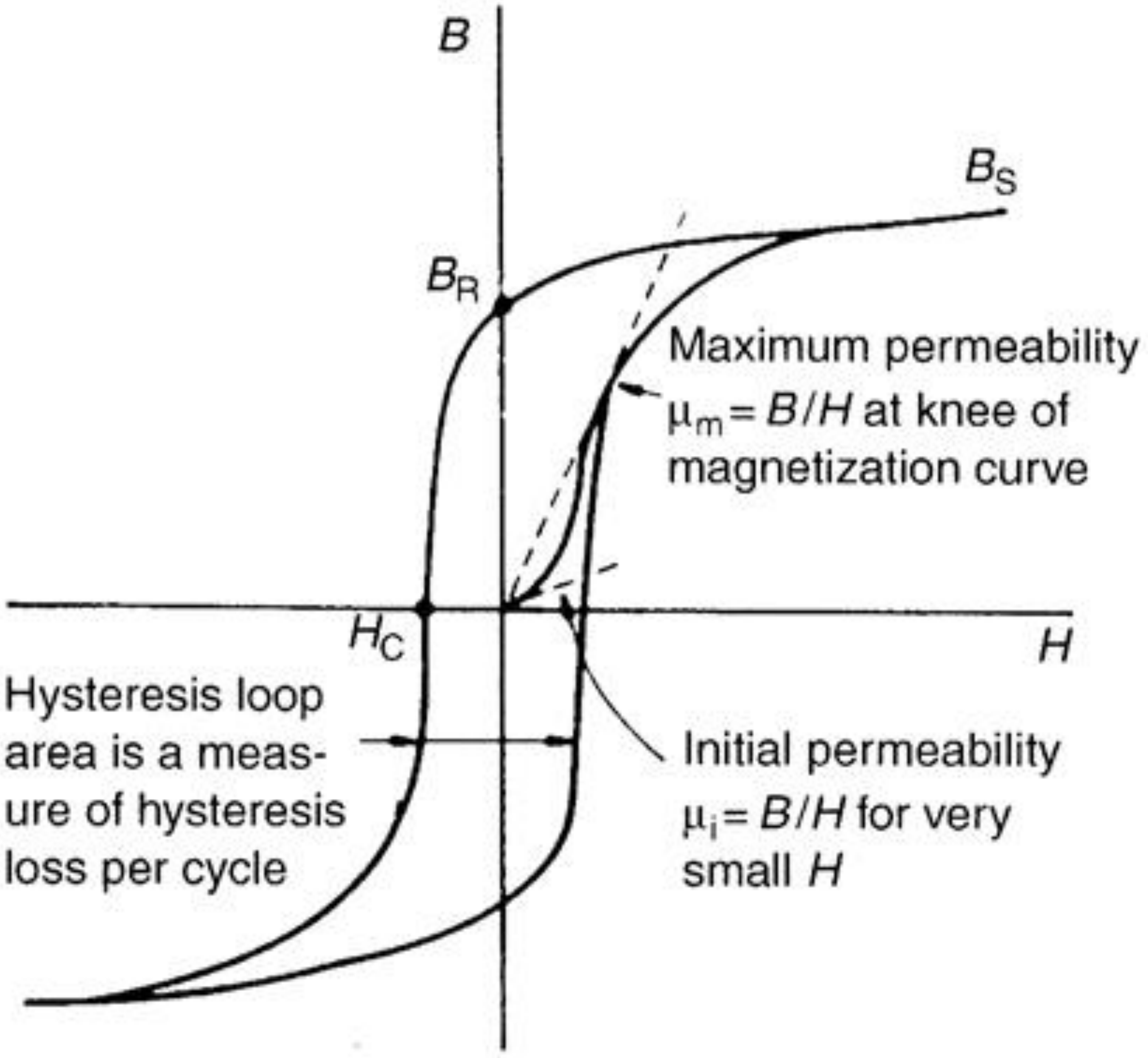
Definitions:

Remanent Induction (B_r): the value of induction which residue, once the material is magnetized and then the magnetizing field is decreased to zero.

Coercive Force or Coercivity (H_c): the amount of negative magnetic field which is essential to decrease the remanent induction to zero - a structure-sensitive magnetic property.

Permeability (μ): the most important parameter for soft magnetic materials since it indicates how much magnetic induction is generated by the material in a given magnetic field.

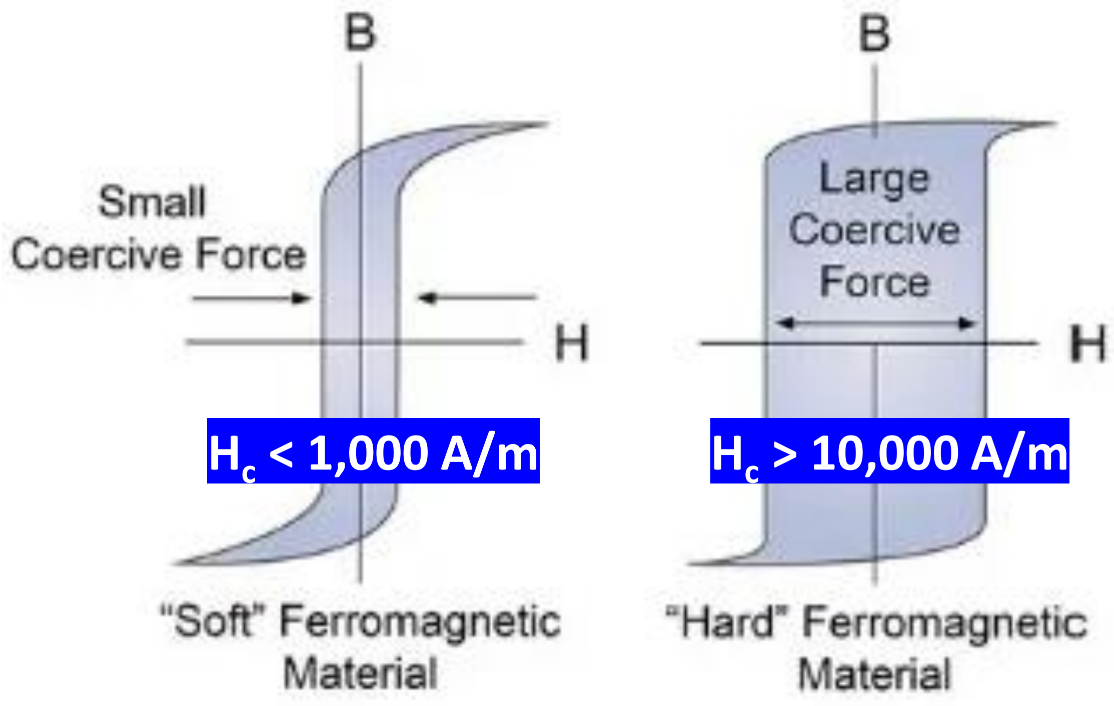
The total area of the hysteresis loop: the energy which is dissipated when a material of unit volume is magnetized during a cycle of operation.



What are soft magnetic materials?

Magnetic materials are mainly classified (based on the magnitude of coercive force) into two:

- *hard magnetic materials and*
- *soft magnetic materials.*



$H_c < 1{,}000$ A/m

$H_c > 10{,}000$ A/m

Properties desirable in a soft magnetic material:

- **large μ_i and μ_{max}**
- **small H_c,**
- **small W_h,**
- **large M_s** *(utmost quantity of magnetic field that a material can generate).*

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

$$\mu_i \propto \frac{J_s^2 D}{\sqrt{A \langle K \rangle}}$$

$$J_s = \mu_0 M_s$$

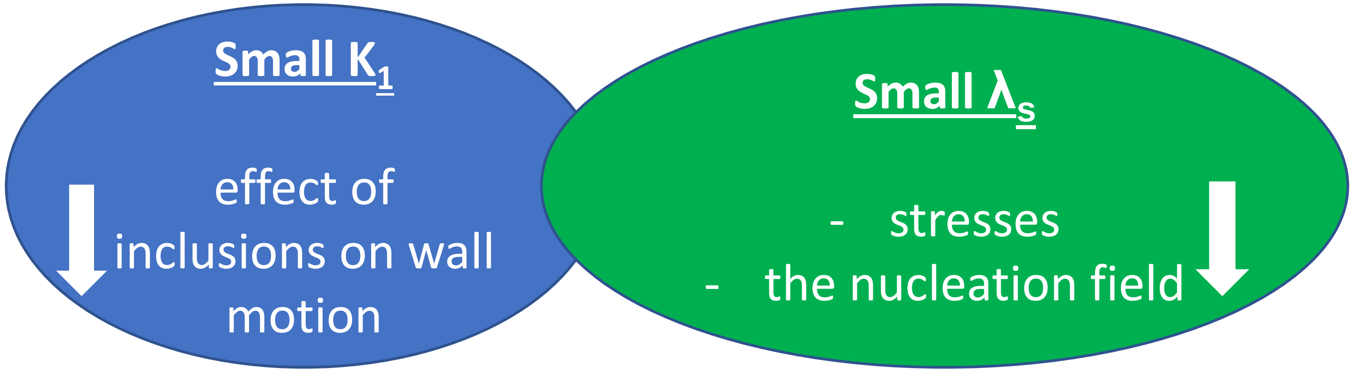
$$\mu = \frac{B}{H}; B = \mu_0 (H + M)$$

$$\chi = \frac{M}{H}$$

$$\mu_r = \frac{\mu}{\mu_0}, with\ \mu_0 = 4\pi \times 10^{-7} H/m$$

1) For large M_s we need metals or alloys with a large atomic moment, such as Fe or Fe-Co alloy.

2) The other properties are improved by increasing the freedom of motion of the domain walls, i.e. by reducing or removing the inclusions, cavities, grain boundaries and internal stresses:
  - annealing
  - cold-rolling
  - magnetic annealing



3) Coercivity can be altered by subjecting the specimen to different thermal and mechanical treatments, in a way that for example saturation magnetization cannot.

4) Initial permeability and coercivity have a reciprocal relationship, so that materials with high coercivity necessarily have low initial permeability and vice versa.

Magnetic (Iron) Losses

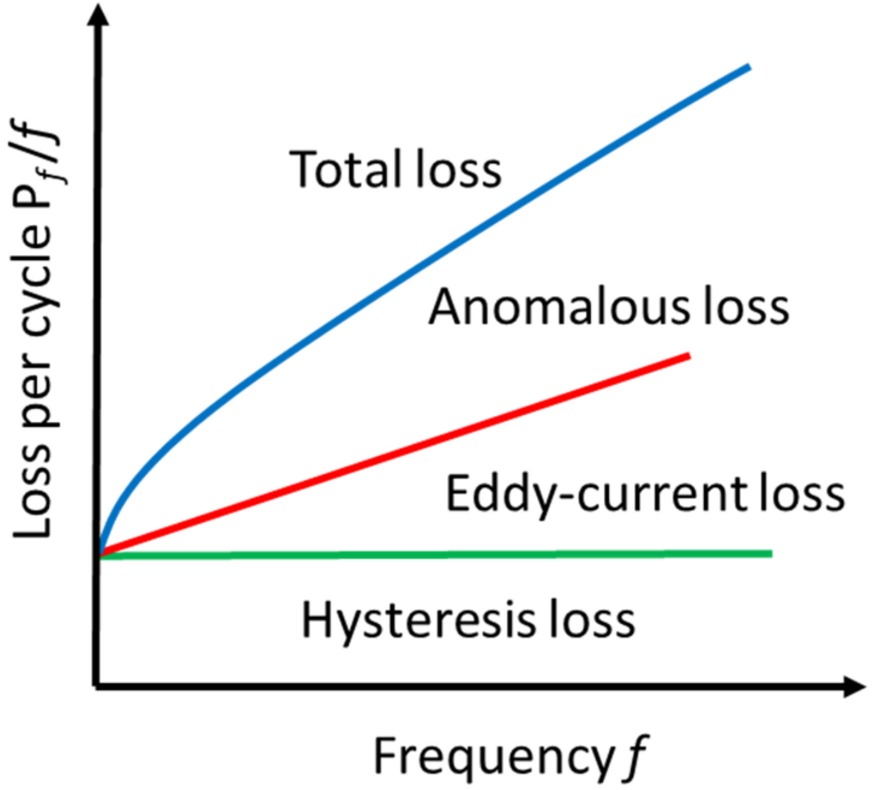
The energy loss can originate from 3 different sources:

1. hysteresis loss (W_h), which is related to the area contained within the hysteresis loop;

2. eddy current loss (W_{ec}), which is related to the generation of electric currents in the magnetic material and the associated resistive losses;

3. anomalous loss (W_a), which is related to the movement of domain walls within the material.

$$W_{tot} = W_h + W_{ec} + W_a$$



Magnetic (Iron) Losses

$$W_h = \eta \cdot B_{max}^n \cdot f \cdot V \; ; n = 1.5 \div 2.5$$

Hysteresis losses can be reduced by the reduction of the intrinsic coercivity, with a consequent reduction in the area contained within the hysteresis loop.

$$W_{ec} = k_e \cdot B_{max}^2 \cdot f^2 \cdot t^2 \cdot V$$

Eddy current losses can be reduced by decreasing the electrical conductivity of the material and by laminating the material, which has an influence on overall conductivity and is important because of skin effects at higher frequency.

Finally, the anomalous losses can be reduced by having a completely homogeneous material, within which there will be no hindrance to the motion of domain walls.

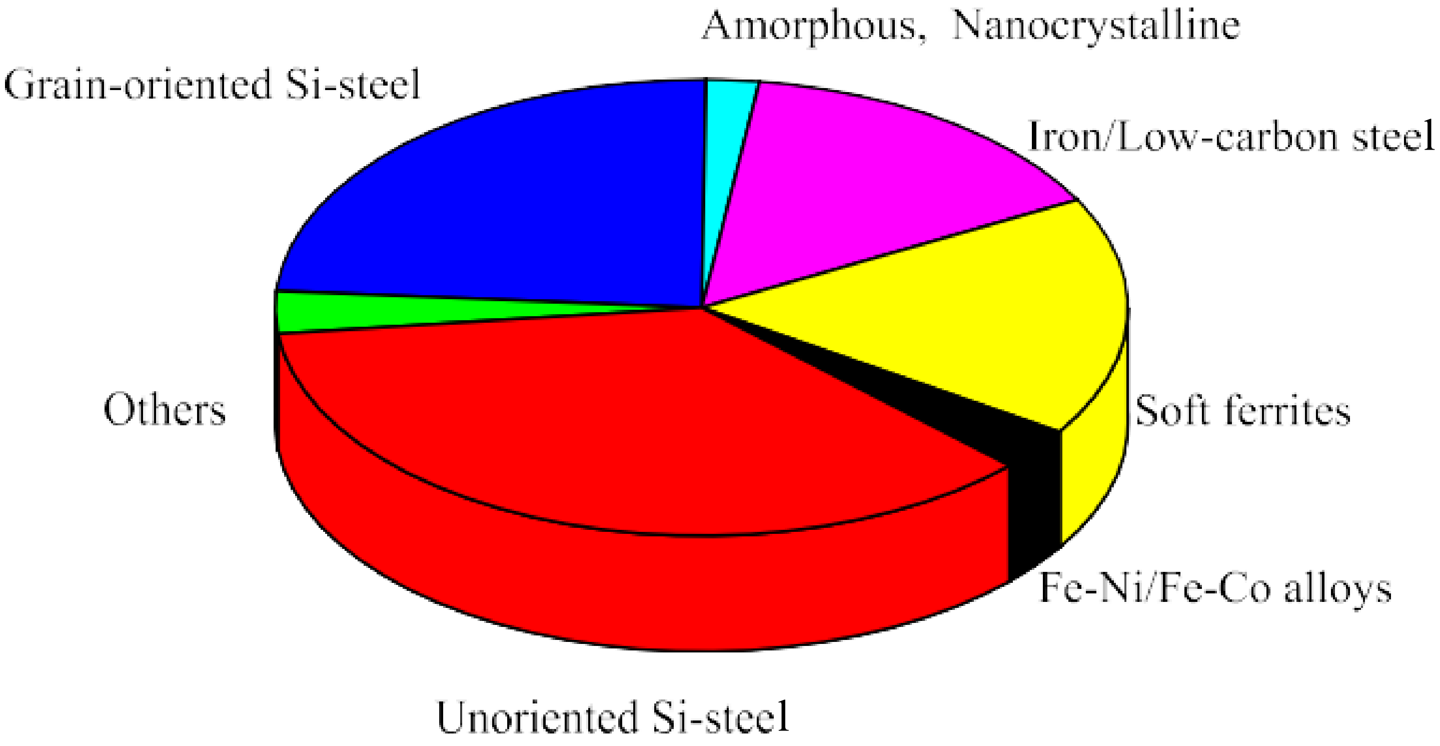
$$\delta = \sqrt{\frac{\rho}{\pi \mu_r \mu_0 f}}$$

For electrical steel:
δ = 0.36 mm @ 50 Hz
δ = 3.6 μm @ 500 kHz

Whenever metals are exposed to an a.c. magnetic field, the induced eddy currents limit the depth of penetration of the flux.

Global market for soft magnetic materials

Soft magnetic materials comprise about one-third of the total magnetic materials market.



The pie represents about 10 B$ per year.

After A. Inoue & F.L. Kong, "Soft Magnetic Materials", Elsevier, 2020.

Soft magnetic materials

1) **Fe** (contains a very small C content)
   - Pro: can be refined to get the utmost permeability (μ_{max} ~ 1.4×10^{-6}) and less coercive force.
   - Con: (i) it produces eddy current losses when subjected to a very high flux density, due to low resistivity; (ii) is extremely soft (mechanically).

It is used in low frequency applications such as components for electrical instruments and cores in electromagnets.

2) **Fe-Si Alloys** (are the most commonly used soft magnetic materials) (<6% Si; most common 3÷4% Si)
   - Pros: the addition of Si increases the permeability, reduces the eddy current losses due to the increase in resistivity, reduces the crystalline anisotropy, magnetostriction and hysteresis losses;

They are used in electrical rotating machines, electromagnets, electrical machines and transformers.

3) **Ni-Fe Alloys**

- Pros: high initial magnetic permeability; low hysteresis and eddy current losses.

They are used in communication equipment such as audio transformers, recording heads and magnetic modulators because of high initial permeability in feeble fields.

4) **Grain oriented sheet steel**

Used to make transformer cores.

5) **Mu-metal**

Used in miniature transformers meant for circuit applications.

6) **Ceramic magnets (soft ferrites)**

Used for making memory devices for microwave devices and computer. Ferrite-cored inductors are used extensively in frequency-selective circuits / resonant frequency. Used in antennae for radio receivers.

7) **Amorphous/nanocrystalline materials**

Used for pulsed power transformers, in magnetic sensors, magnetostrictive transducers, communication equipment, switches, other engineering and medical applications.

Material	Remarks	Composition	μ_i	μ_{max}	H_c (A/m)	B_s @ 300K (T)
Iron	Commercial	99 Fe	200	6,000	7.2	2.16
Iron	Pure	99.9 Fe	25,000	350,000	0.08	2.16
Fe-Si		96Fe-4Si	1,200	6,500	40	1.95
Fe-Si	GO (Hypersil)	97Fe-3Si	9,000	40,000	12	2.01
50 Permalloy	Hypernik	50Ni-50Fe		100,000	4	1.6
78 Permalloy		78Ni-22Fe	4,000	100,000	4	1.05
Mumetal		75Ni-18Fe-5Cu-2Cr	20,000	100,000	4	0.75
Supermalloy		79Ni-15Fe-5Mo-0.5Mn	90,000	10^6	0.32	0.80
Permendur		50Fe-50Co	500	6,000	16	2.46
Fe-Co-V		49Fe-49Co-2V		100,000	16	2.30
Perminvar	Annealed in magnetic field	43Ni-34Fe-23Co		400,000	2.4	1.50
Fe-Si-Al	Sendust in powder	85Fe-9.5Si-5.5Al	35,000	120,000	0.16	1,20

Application of Soft Magnetic Materials

Applications of soft ferromagnetic materials are almost exclusively associated with electrical circuits in which the magnetic material is used to amplify the flux generated by the electric currents.

For DC applications: *high permeability is required*.

For AC applications: *small energy loss is required.*

Low coercivity

Important applications of soft magnetic materials include:

1) inductors and inductive components, low- and high-frequency transformers;
2) AC machines, motors and generators;
3) converters;
4) flexible electromagnetic shielding;
5) magnetic lenses for particle beams and magnetic amplifiers;
6) high-frequency inductors and absorbers;
7) magnetocaloric materials;
8) magnetic and magnetomechanical sensors.

Application of Soft Magnetic Materials

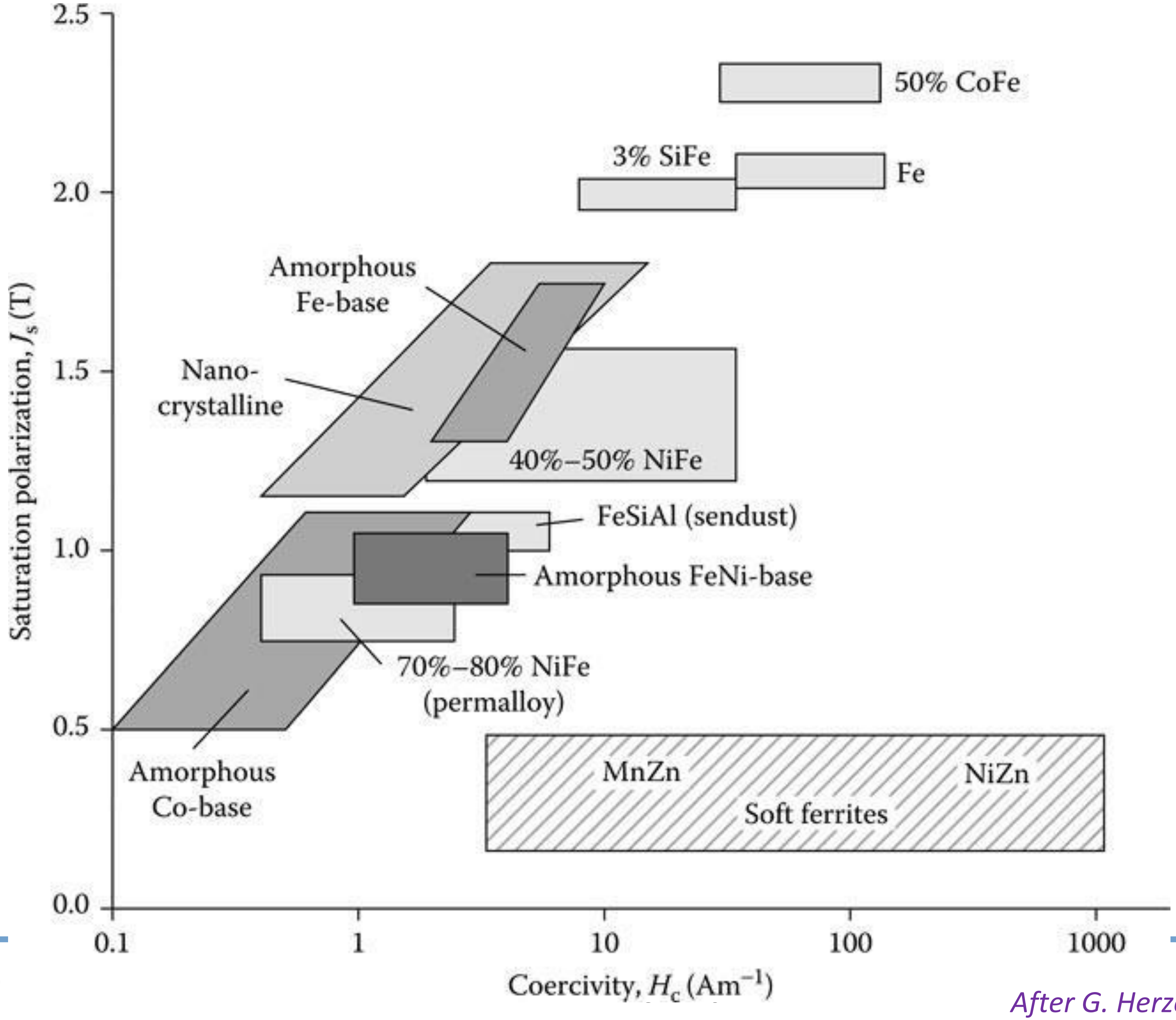
Electromagnets	Transformers
- the core material should have **high permeability** (to enable high B_s to be achieved) and **low coercivity** (the induction can easily be reversed); - **soft iron is used almost exclusively** ($H_c \approx 80$ A/m (1 Oe); $M_s = 1.7 \times 10^6$ A/m); - are used in the laboratory for generating high magnetic fields (max. 2 T for Fe without any special configuration, 2.5 T with small air gaps; max. 3 T for 49Fe-49Co-2V alloy); - electromagnets cannot generate magnetic inductions above 3 T, because the iron cannot contribute much additional field; - therefore, for higher field strengths, either water-cooled iron-free magnets (known as Bitter magnets) or superconducting magnets are used.	- operate under AC conditions and therefore, although **high permeability** of the core material is desirable, it is also necessary to **reduce the eddy current losses** by employing as **low** a **conductivity material** as possible; - the material **used exclusively** for transformer cores is **grain-oriented silicon-iron**. This contains about 3%–4% wt. Si (to reduce conductivity). The material is usually hot-rolled, then cold-worked twice, followed by annealing to improve the grain orientation and increase permeability along the rolling direction; - one of the most important parameters for transformer steels is the total core loss at a frequency of 50 or 60 Hz. Losses decrease with increasing Si content, but the material also becomes more brittle.

Application of Soft Magnetic Materials

Core Losses of Soft Magnetic Materials	
Material	**Core Loss at 1.5 T and 60 Hz (W/kg)**
Low-carbon steel	2.8
Nonoriented silicon-iron	0.9
Grain-oriented silicon-iron	0.3
80 Permalloy ($Ni_{80}Fe_{20}$)	0.2[a]
Metglas	0.2–0.3[b]

[a] $B_m = 1.1$ T
[b] $B_m = 1.4$ T, since loss increases rapidly above this.
The sheets thicknesses are equal to or less than the skin depth δ in the materials, which at 60 Hz is typically $\delta = 0.3 \div 0.7$ mm.

Amorphous metals have been developed for use in electromagnetic devices.
These alloys, such as Metglas, have found applications in some smaller, lower-power devices, but have not been successful in replacing Fe-Si in transformers, except in some cases where distribution transformers have been required in locations where fuel costs are high.
Large-scale adoption of these materials as transformer cores depends not so much on performance as cost, both for the materials themselves and the fabrication costs in producing the transformers.



After G. Herzer, Acta Mater. 61 (2013) 718

Iron and low-Carbon Steels (Soft Iron)

Iron and low-Carbon Steels (Soft Iron)

- Soft iron is used as a core material for DC electromagnets such as laboratory electromagnets for which it remains the best material.
- The prime concern is to obtain either high magnetic flux densities and/or very uniform magnetic flux densities.
- Iron with low levels of impurities such as C (0.05%) and N has H_c ~ 80 A/m (1 Oe) and $\mu_{r,max}$ ~ 10,000.
- By annealing in H_2, the impurities can be removed, and this results in a reduction in H_c to 4 A/m (0.05 Oe) and an increase in $\mu_{r,max}$ to about 100,000.
- The highest μ_r obtained for pure Fe is 1.5×10^6; however, this material is too expensive for many applications.

Magnetic Properties of Various High-Purity Forms of Iron

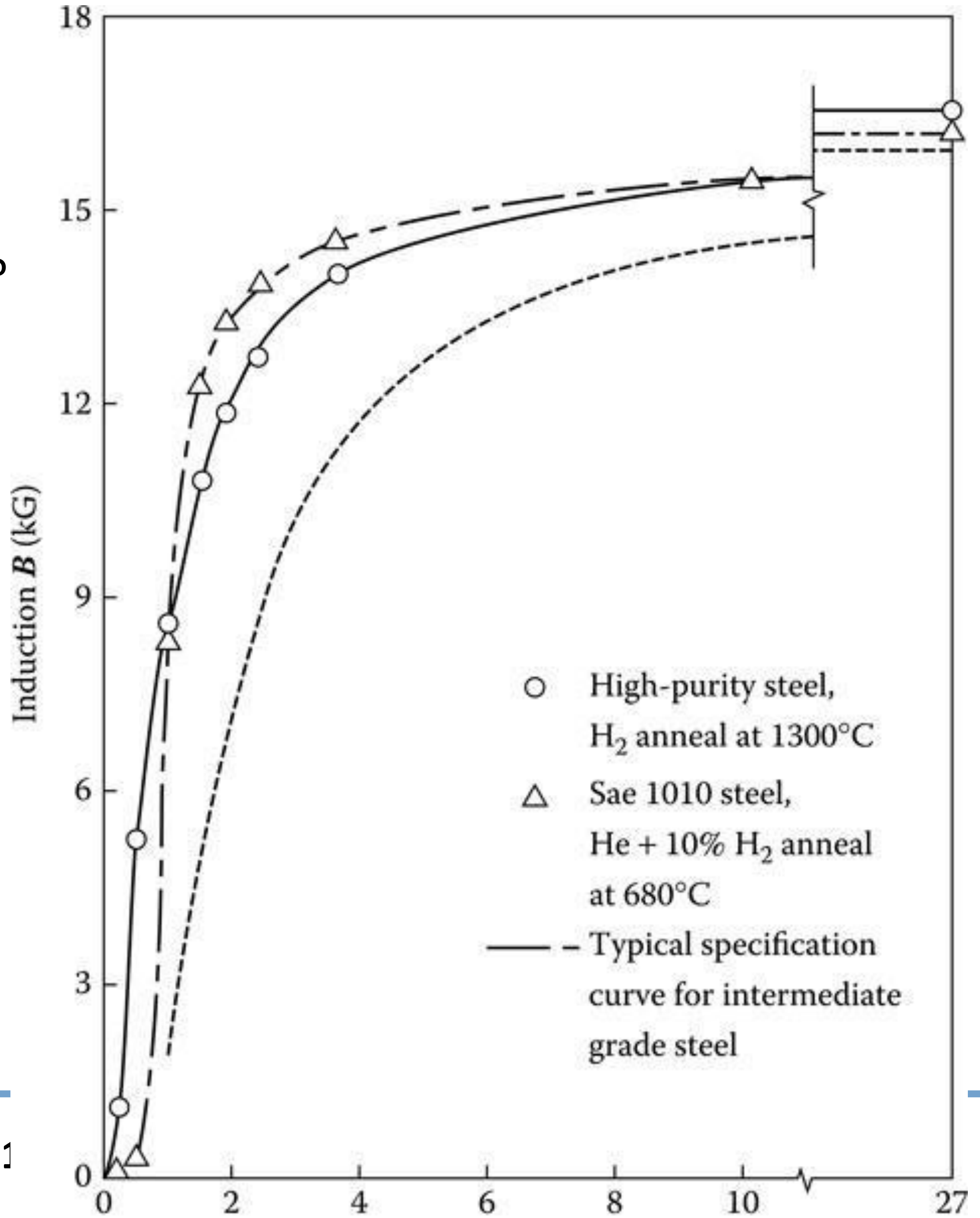
	B_s (T)	H_c (A/m)	μ_r at 80 A/m	μ_r at 800 A/m	$\mu_{r,max}$
Cast magnetic ingot iron	2.15	68	3500	1500	–
Magnetic ingot iron (2 mm sheet)	2.15	89	1800	1575	–
Electromagnet iron (2 mm sheet)	2.15	81.6	2750	1575	–
Ingot iron (vacuum melted)	–	24.8	–	–	21,000
Electrolytic iron (annealed)	–	18.4	–	–	41,500
Electrolytic iron (vacuum melted and annealed)	–	7.2	–	–	61,000
Puron (H_2 treated)	2.16	4.0	–	–	100,000

Iron and low-Carbon Steels (Soft Iron)

- In most applications, ultra-high-purity iron is unnecessary.
- For electromagnets, the principal question that arises is:

What field is necessary to produce an induction of 1.0 or 1.5 T?

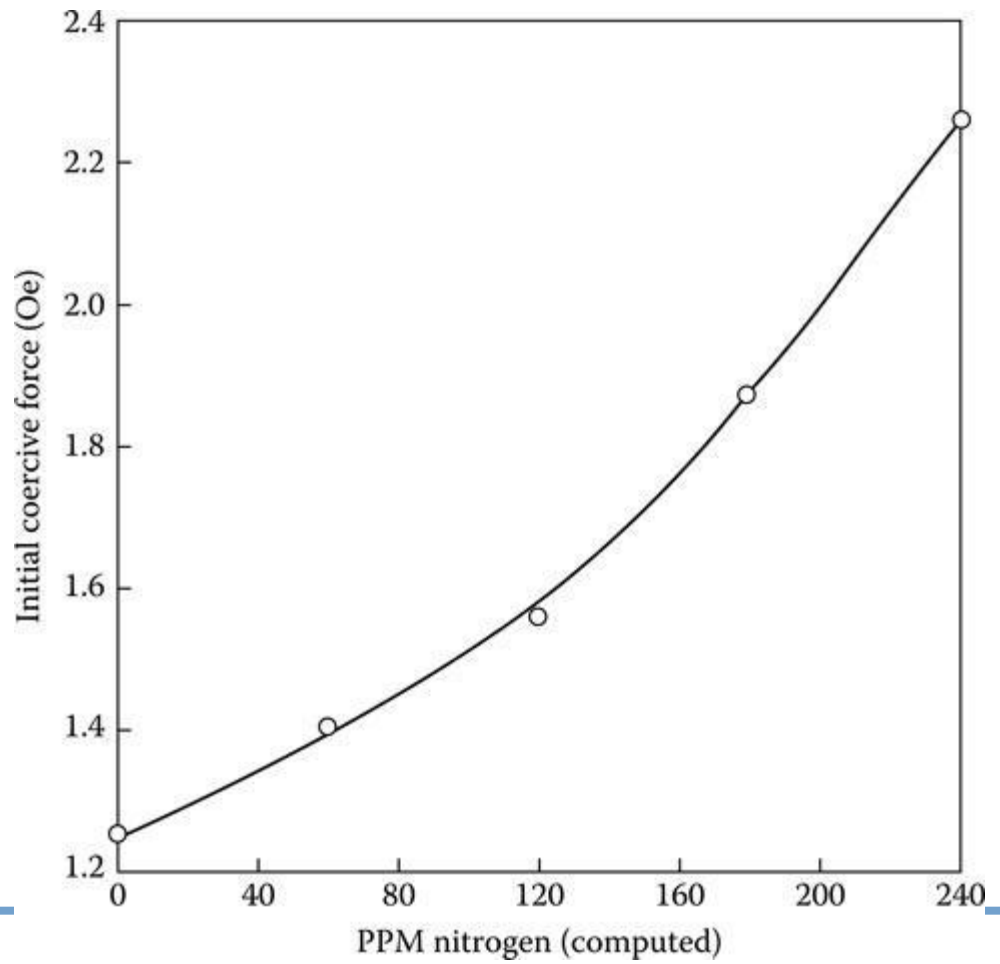
For the commercial soft iron the values are typically 200 and 700 A/m, respectively.

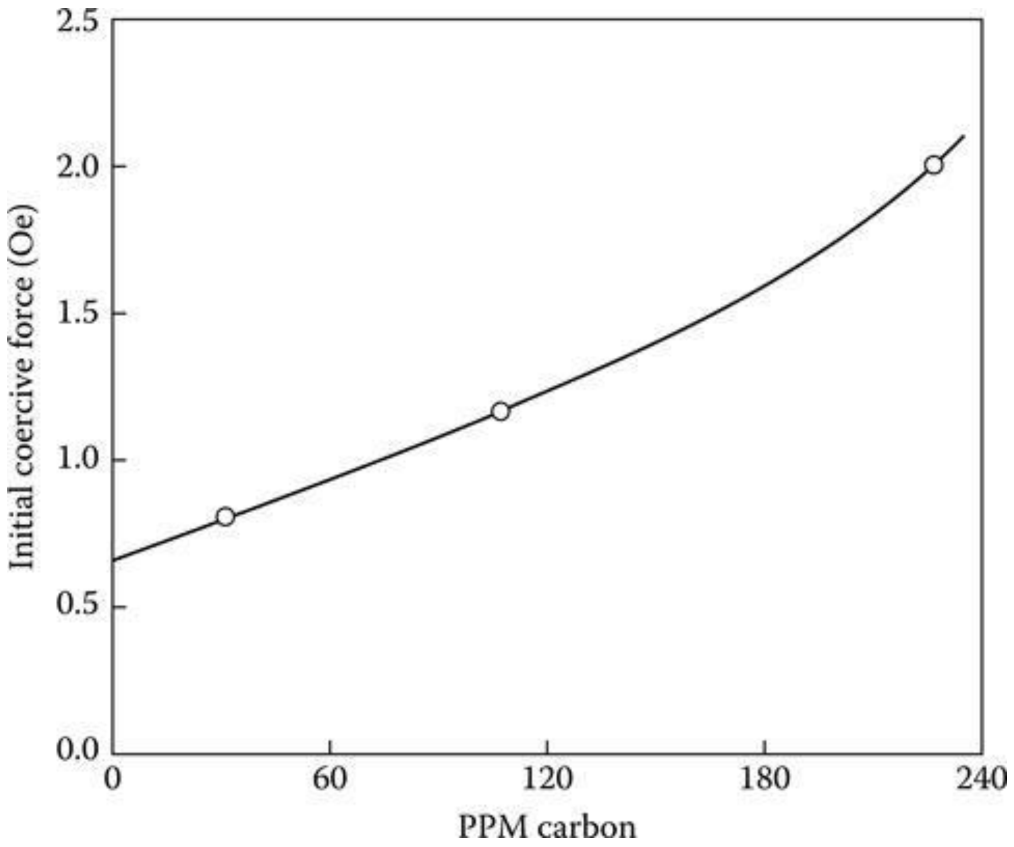


Initial magnetization curves for two high-purity steels, after annealing in a reducing atmosphere of hydrogen, and a typical intermediate-grade steel. (Data from J.H. Swisher et al., Trans. A.S.M. 62 (1969) 257; J.H. Swisher and E.O. Fuchs, J. Iron. Steel. Inst., August 1970, 777).

Iron and low-Carbon Steels (Soft Iron)

- Any form of mechanical deformation will result in a deterioration of the magnetic properties of soft iron for electromagnet applications.





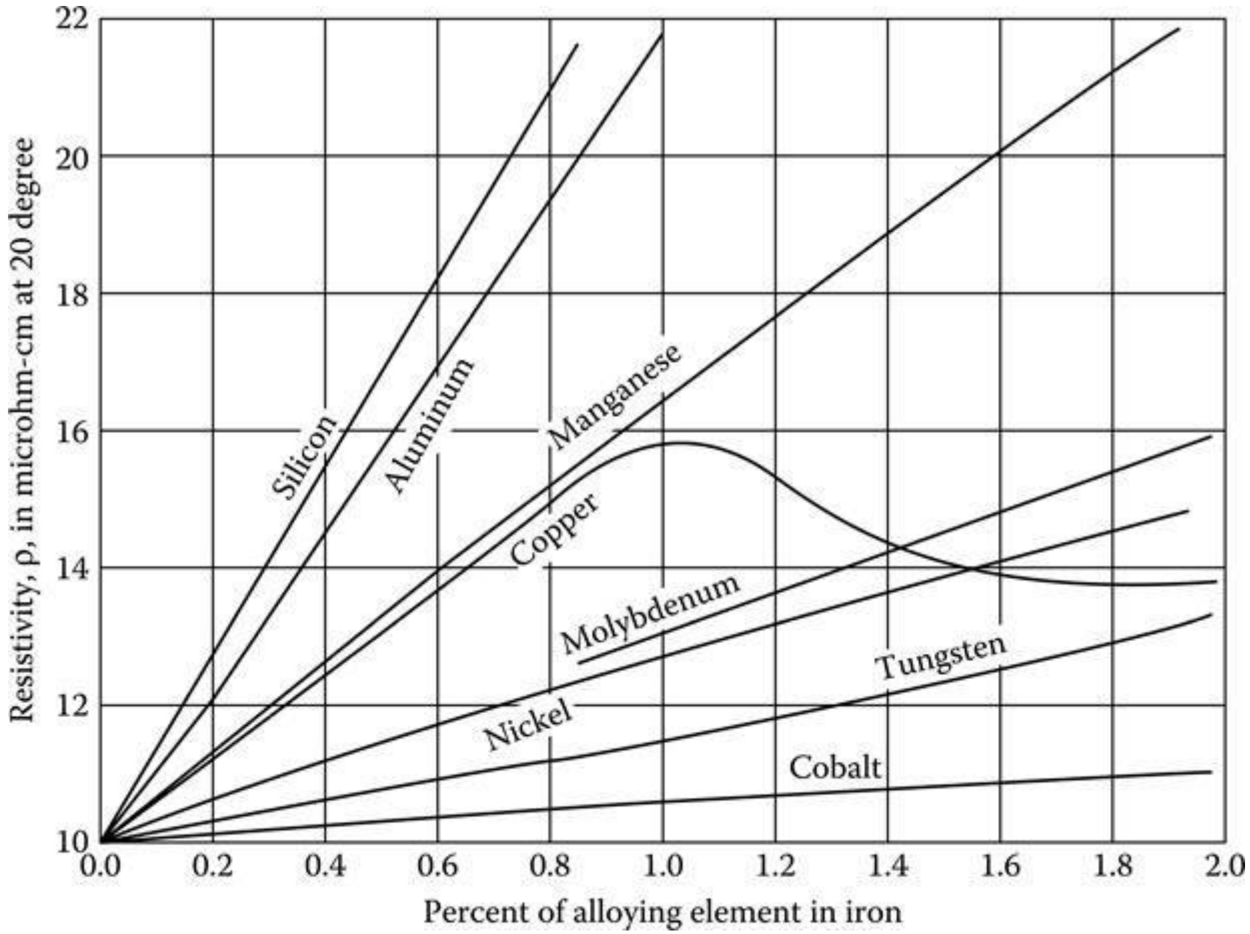
- The internal stresses produced by cold working can be removed by annealing at temperatures between 725°C and 900°C, provided the material does not suffer oxidation during annealing, which would also result in impaired magnetic properties.
- The usual procedure is to anneal in a hydrogen atmosphere, which has the additional advantage of removing some of the impurities.

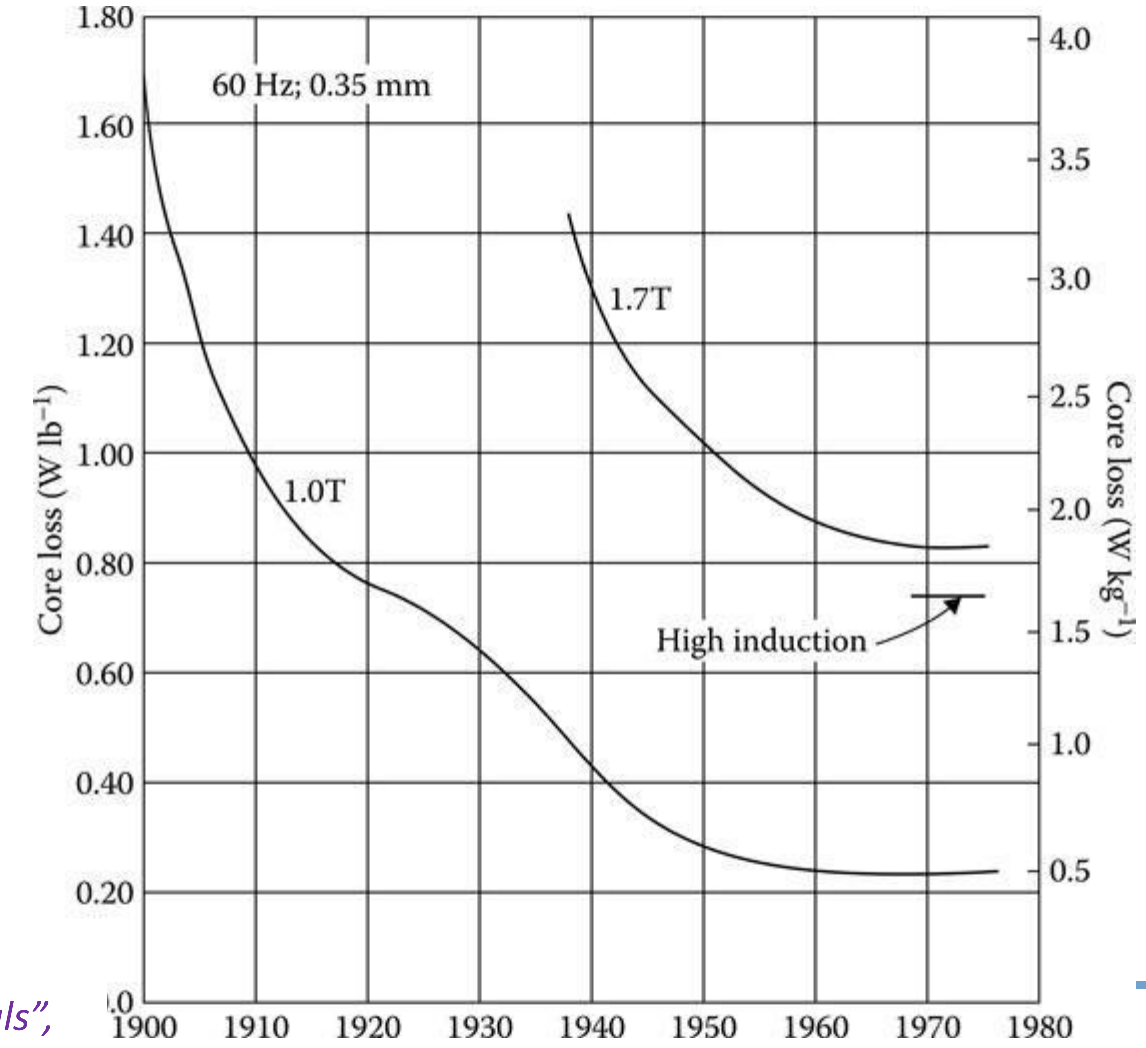
Iron-Silicon Alloys
(Electrical Steels or Silicon Steels)

Iron-Silicon Alloys (Electrical Steels or Silicon Steels)

Q: How to improve the properties of iron and make it more suitable for electrical power conversion at low frequencies?

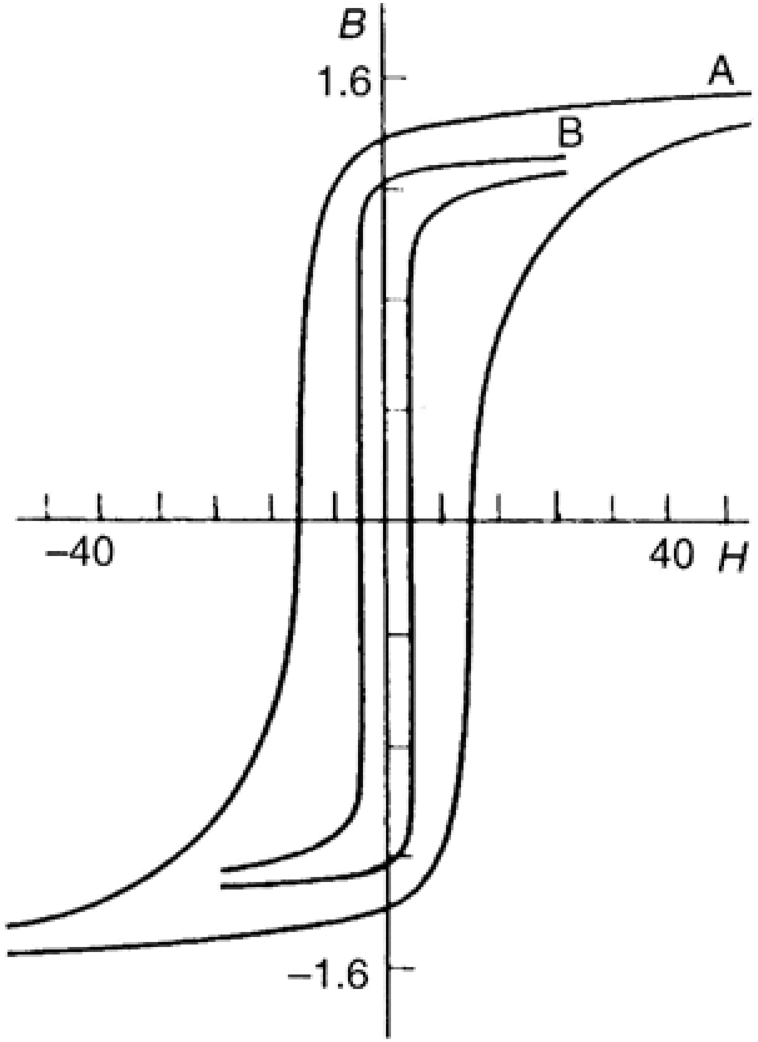
A: By increasing the resistivity we will reduce the eddy current losses. This is achieved by alloying Si with Fe.





After D. Jiles, "Introduction to Magnetism and Magnetic Materials", 3rd Edition, Taylor & Francis, 2015.

Iron-Silicon Alloys (Electrical Steels or Silicon Steels)



Hysteresis loop of:
(A) pure Fe and
(B) a grain-oriented alloy consisting of 97% Fe and 3% Si.

B and H are given in units of T and A/m.

ATTENTION!

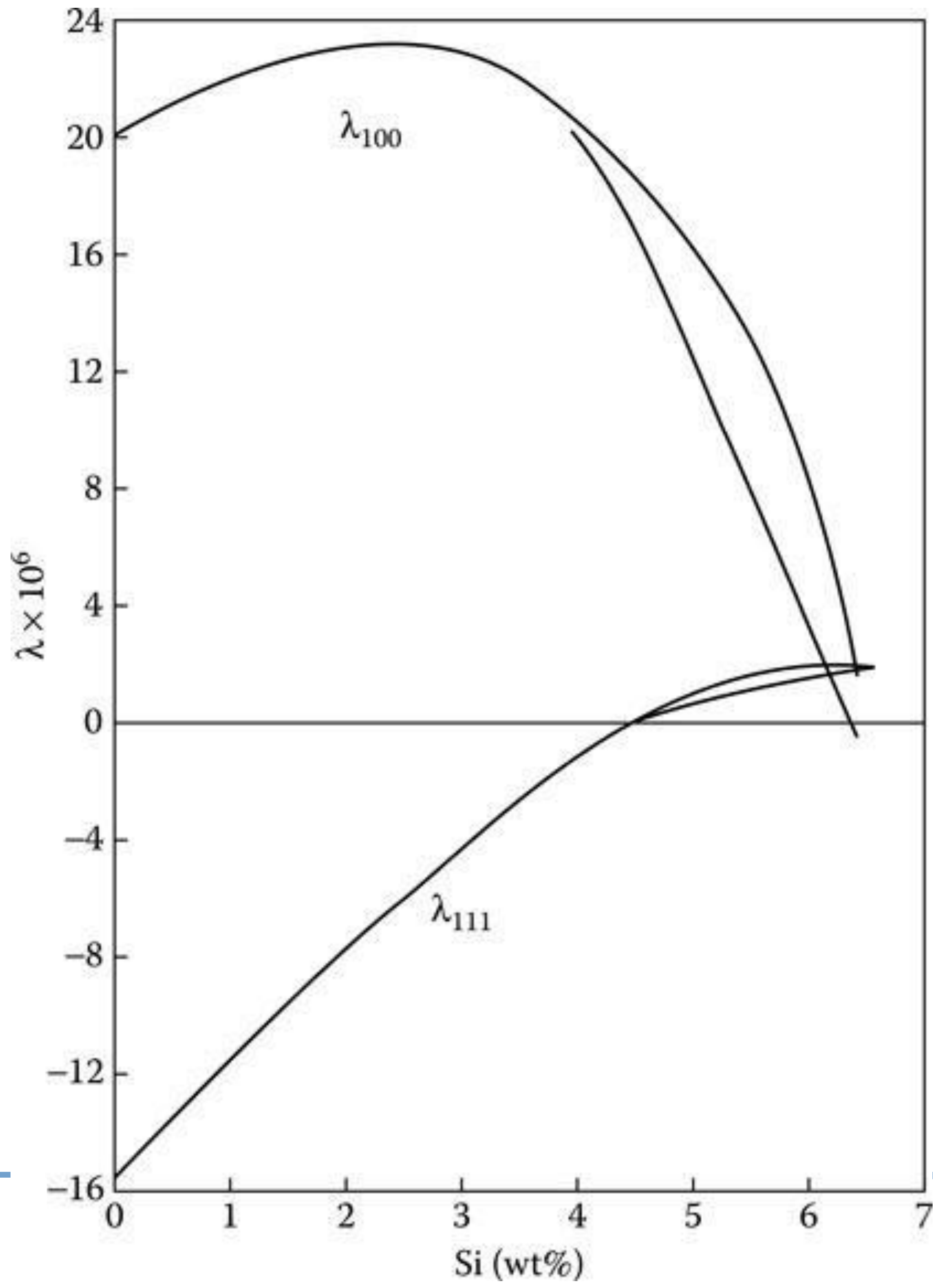
- Fe-Si becomes brittle when the Si content is high (> 4 wt.%; in special conditions can increase to 6.5 wt.%).
- Si reduces B_s.

IMPORTANT!

- *for high-power applications, silicon-iron is widely used;*
- *non-oriented silicon-iron is the material of choice in motors and generators;*
- *grain-oriented silicon-iron is used for transformers.*

Iron-Silicon Alloys (Electrical Steels or Silicon Steels)

- The magnetic properties of Fe-Si are dependent on the microstructure and texture.
- Depending on the type of rolling and heat treatment silicon iron can be produced in a non-oriented form or a grain-oriented form.



Dependence of the magnetostriction coefficients λ_{100} and λ_{111} of Fe-Si on Si content. The lower curves in the range of 4%–7% Si are for slowly cooled samples.

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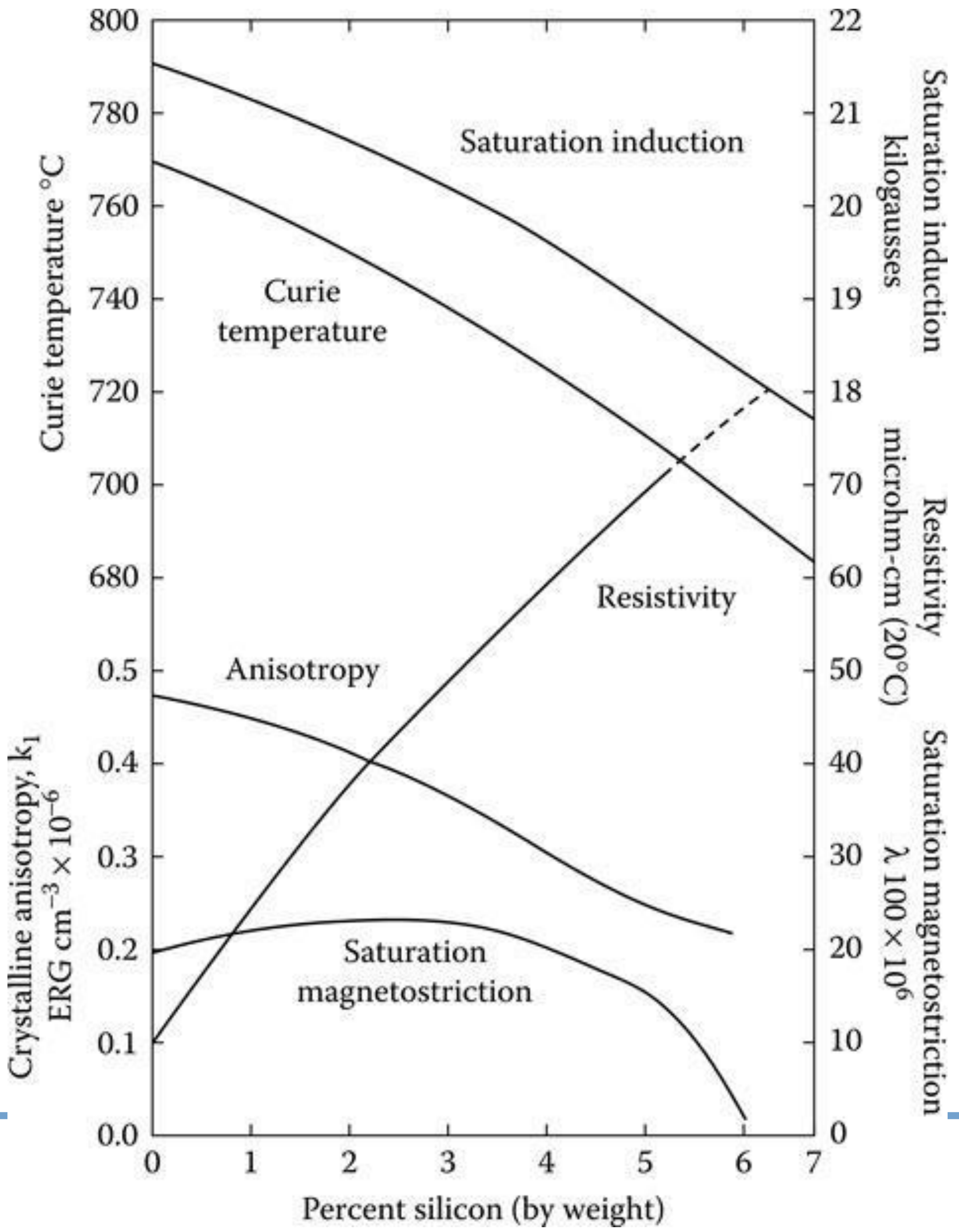

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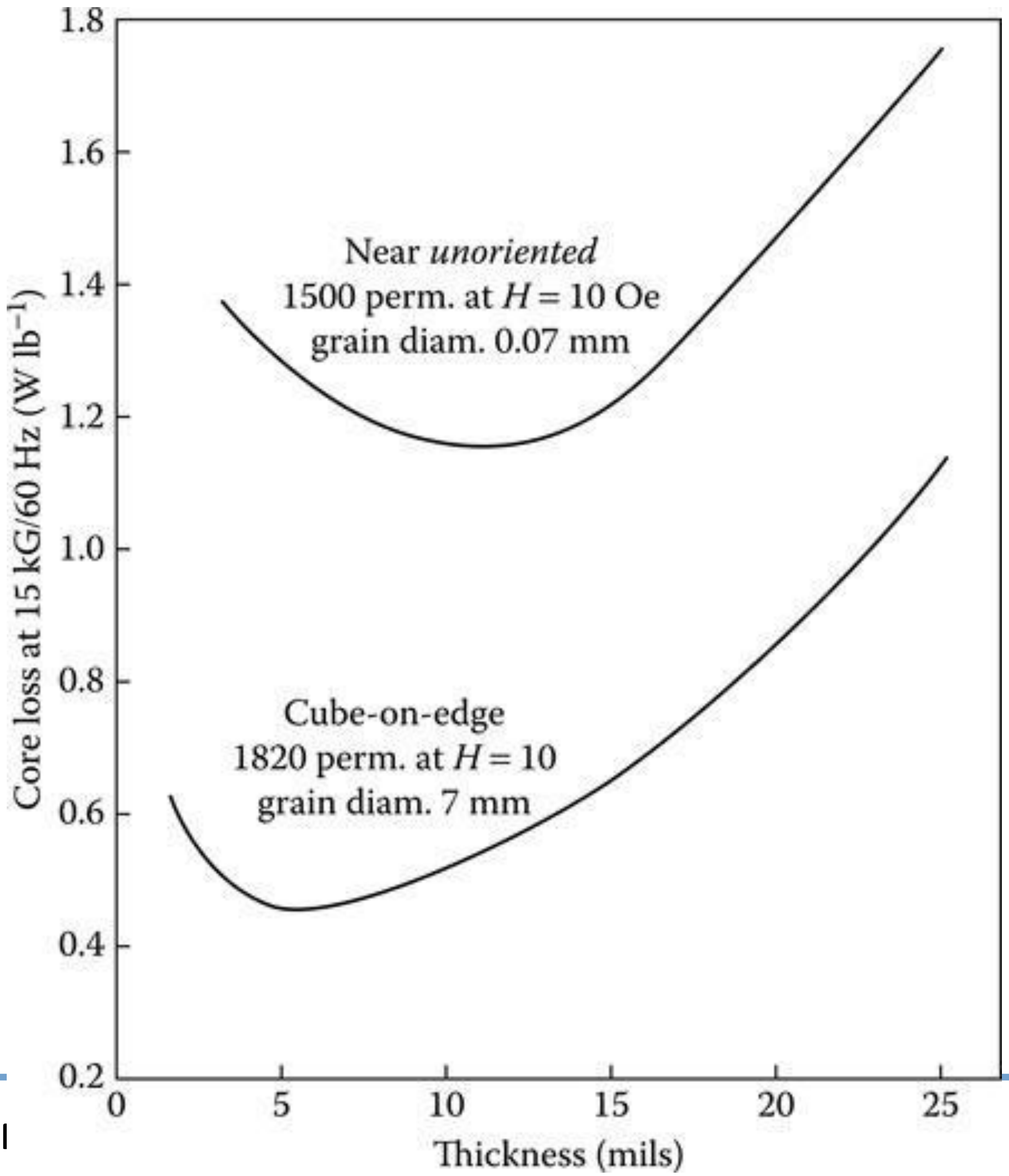
Iron-Silicon Alloys (Electrical Steels or Silicon Steels)

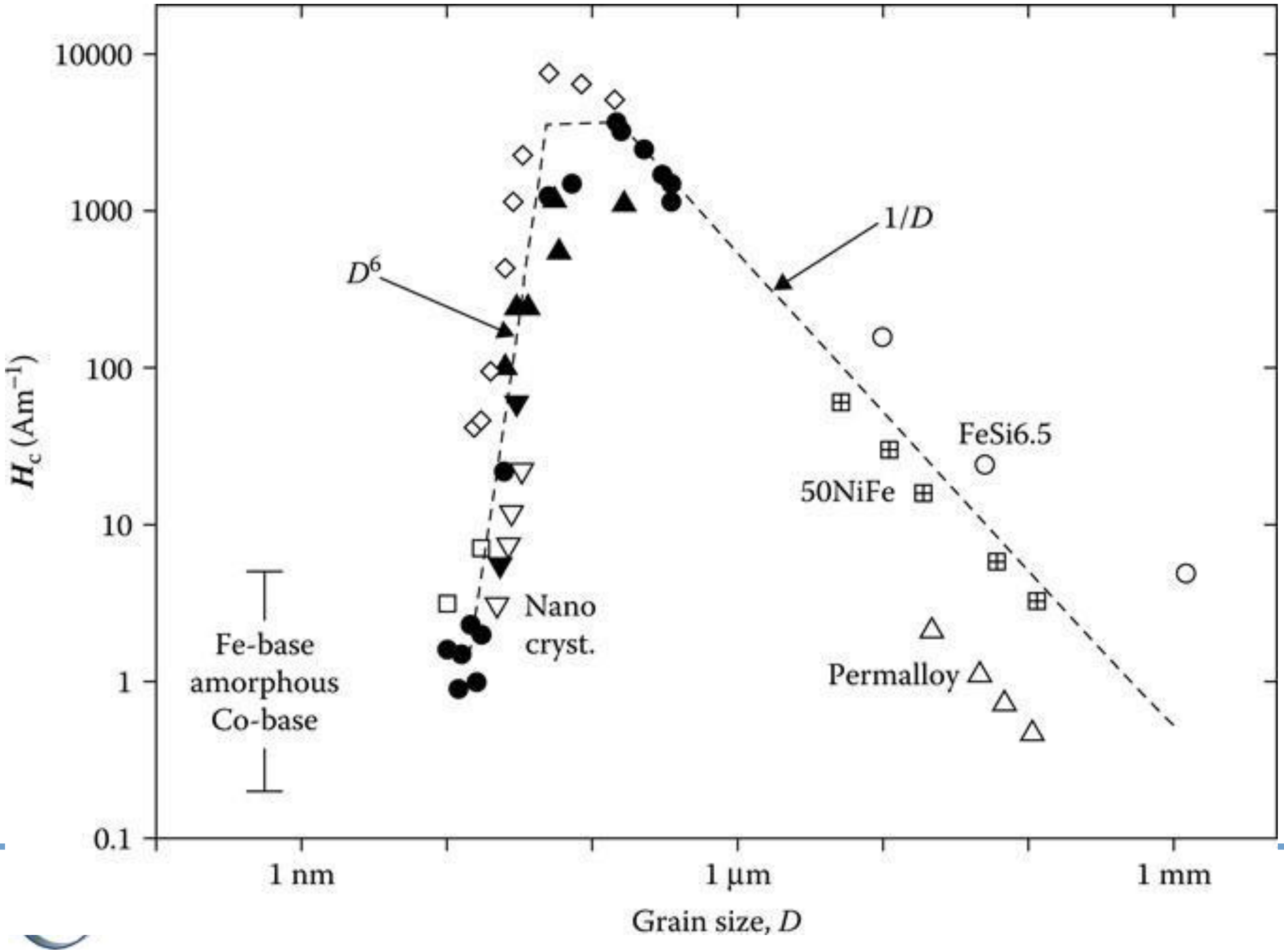
- It is also beneficial to laminate the cores in such a way that the laminations run parallel to the magnetic field direction → to reduce the eddy current losses, by only allowing the eddy currents to exist in a narrow layer of material.
- The coating of laminations with an insulating material also improves the eddy current losses by preventing current passing from one layer to the next.
- The thickness of the laminations for optimum performance is comparable with the skin depth at 50 or 60 Hz, which is typically 0.3–0.7 mm.



Dependence of core loss on sheet thickness in 3.15% silicon-iron (f = 60 Hz).

Iron-Silicon Alloys (Electrical Steels or Silicon Steels)

- By optimizing the rolling and heat treatments, can control better the grain size and domain structures.



Variation of coercivity H_c with grain diameter D for various soft magnetic materials:

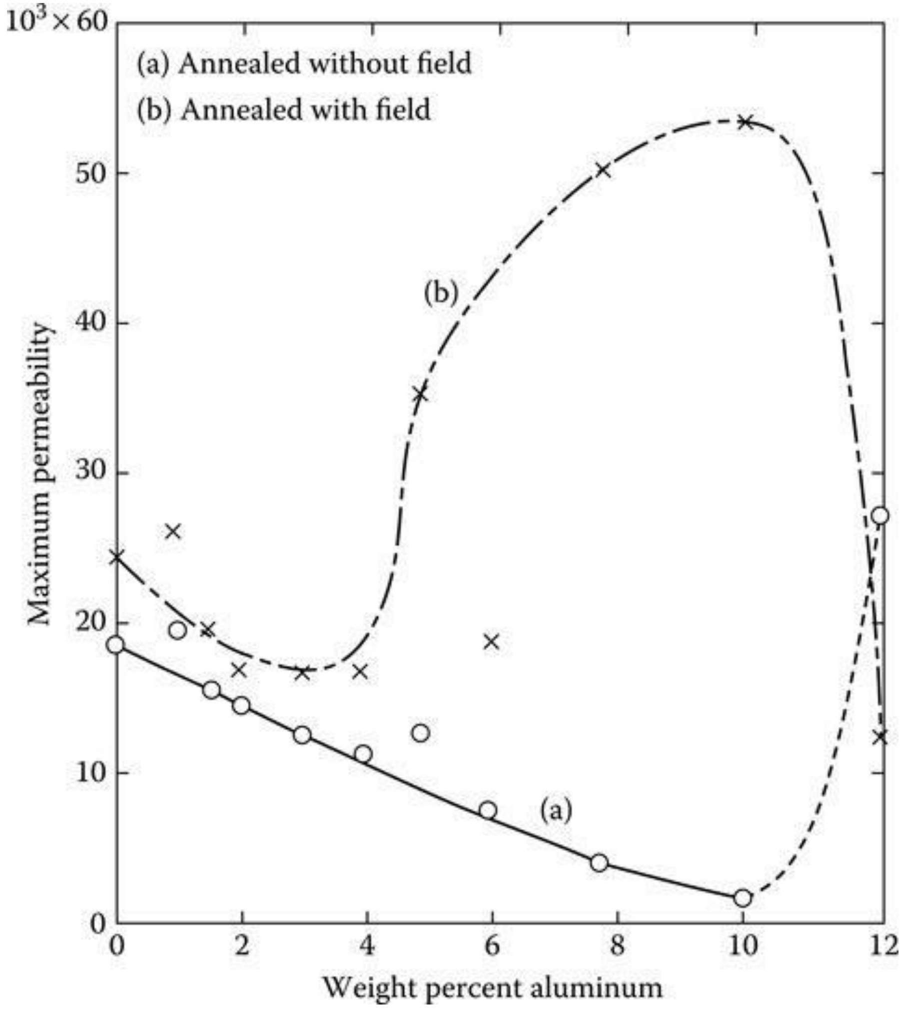
- *Fe-Nb-Si-B (solid triangles),*
- *Fe-Cu-Nb-Si-B (solid circles),*
- *Fe-Cu-V-Si-B (solid nablas and open down triangles),*
- *Fe-Zr-B (open squares),*
- *Fe-Co-Zr (open diamonds),*
- *NiFe alloys (+ center squares and open triangles), and*
- *Fe-6.5 wt% Si (open circles).*

After G. Herzer, Acta Mater. 61 (2013) 718

Iron-Aluminium Alloys

Iron-Aluminum Alloys

- The properties of Fe-Al are very similar to those of Fe-Si, but since Al is more expensive than Si, these alloys are unlikely to replace silicon-iron in applications where they both compete.
- Alloys of up to 17% Al are FM, but at higher Al contents they become PM.
- Often, Al is used as an addition in Fe-Si, because it promotes grain growth, which can lead to lower losses.
- Furthermore, the addition of Al produces higher resistivity with less danger from brittleness.
- Therefore, ternary alloys of Fe, Si, and Al are used in electrical steels for special applications.
- **Sendust is a magnetic metal powder with the composition: Fe85-Si9-Al6.** The powder is sintered into cores to manufacture inductors. **Sendust cores have high magnetic permeability (up to 140,000), low loss, low coercivity (5 A/m) good temperature stability, saturation flux density up to 1 T, zero magnetostriction and zero magnetocrystalline anisotropy.**

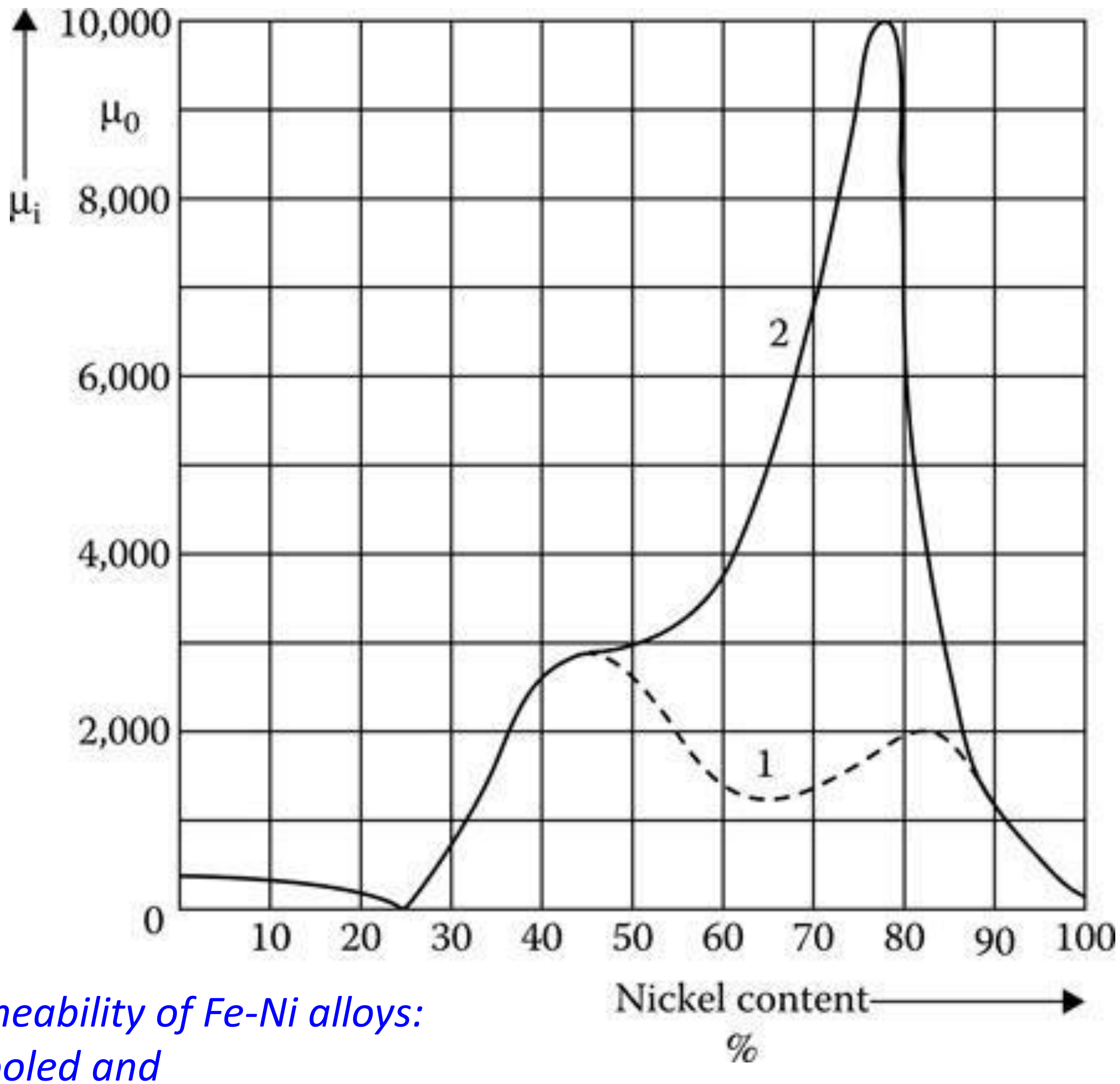


Maximum permeability of Fe-Al alloys as a function of Al content after two different types of annealing. H_{ann} = 136 A/m; t = 0.35 mm; laminated samples.

Nickel-Iron Alloys

Nickel-iron Alloys (Permalloy)

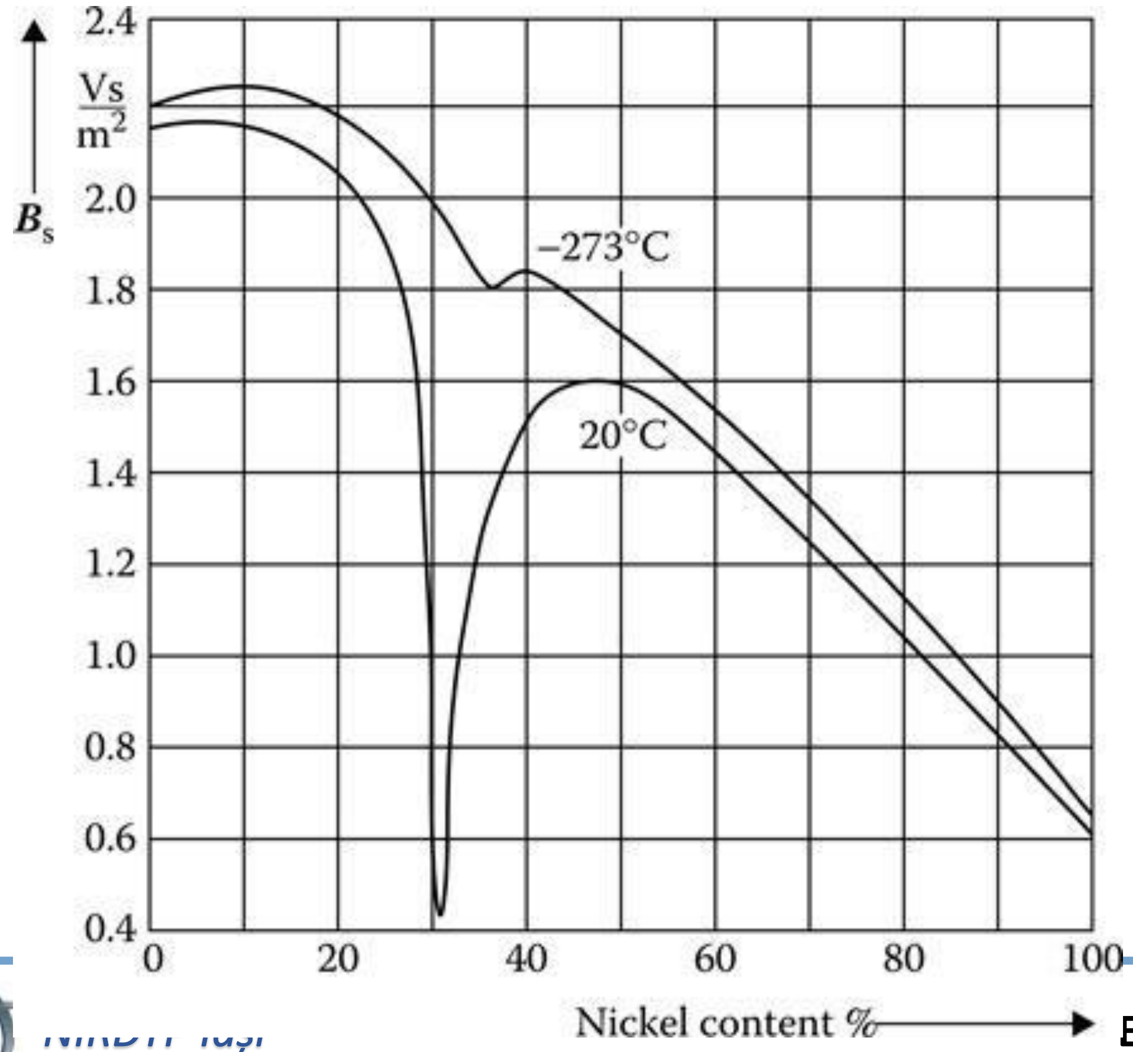
- These alloys are the most versatile of all soft magnetic materials for electromagnetic applications.
- These alloys are used in inductance coils and transformers, particularly power supply transformers.
- They are used at audio frequencies as transformer cores and also for higher frequency applications.
- They are also used in magnetic shielding because of their very high permeability.
- 3 groups of these alloys are commonly encountered: with Ni contents close to 80%, 50%, or in the range of 30%–40%.
- The permeability is highest for the alloys close to 80% Ni.

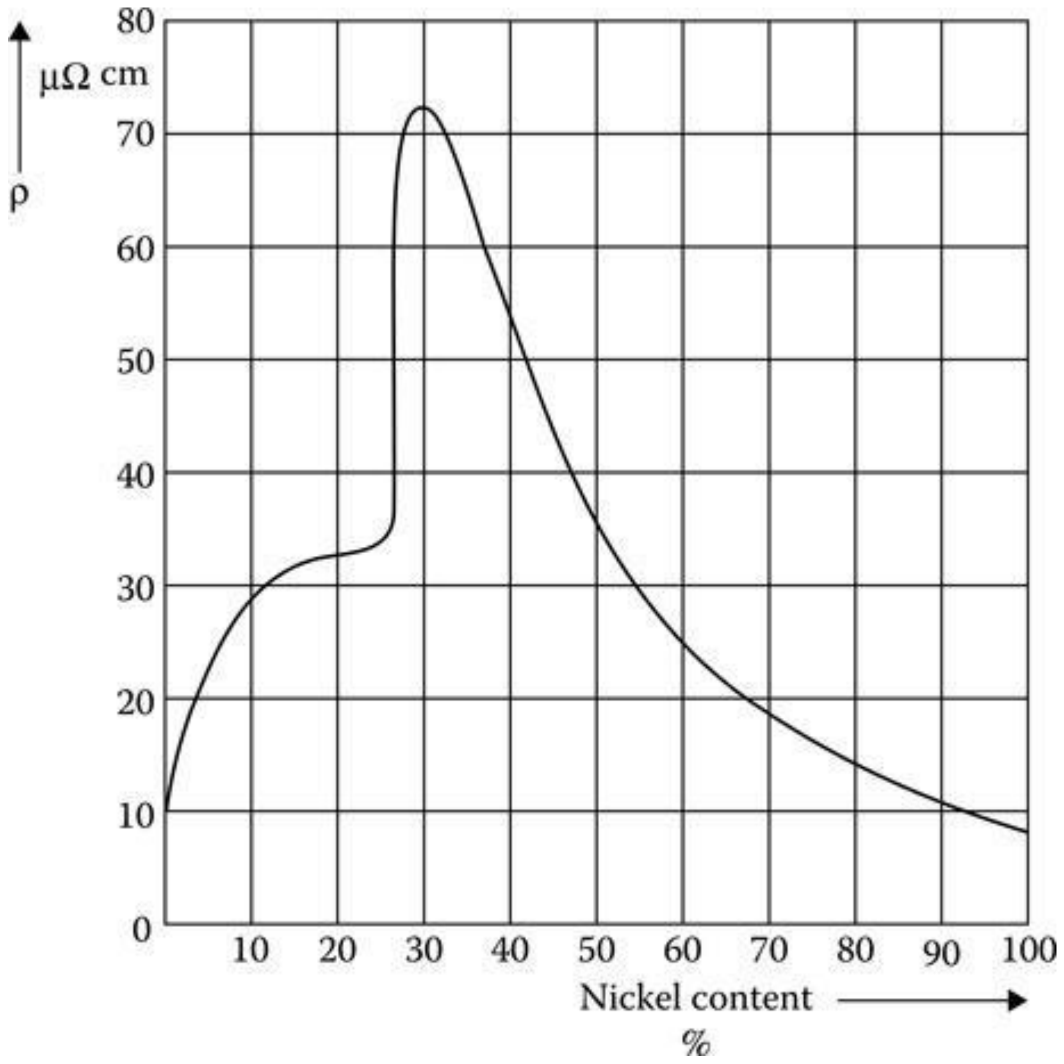


Initial permeability of Fe-Ni alloys:
1 = slow cooled and
2 = normal permalloy treatment.

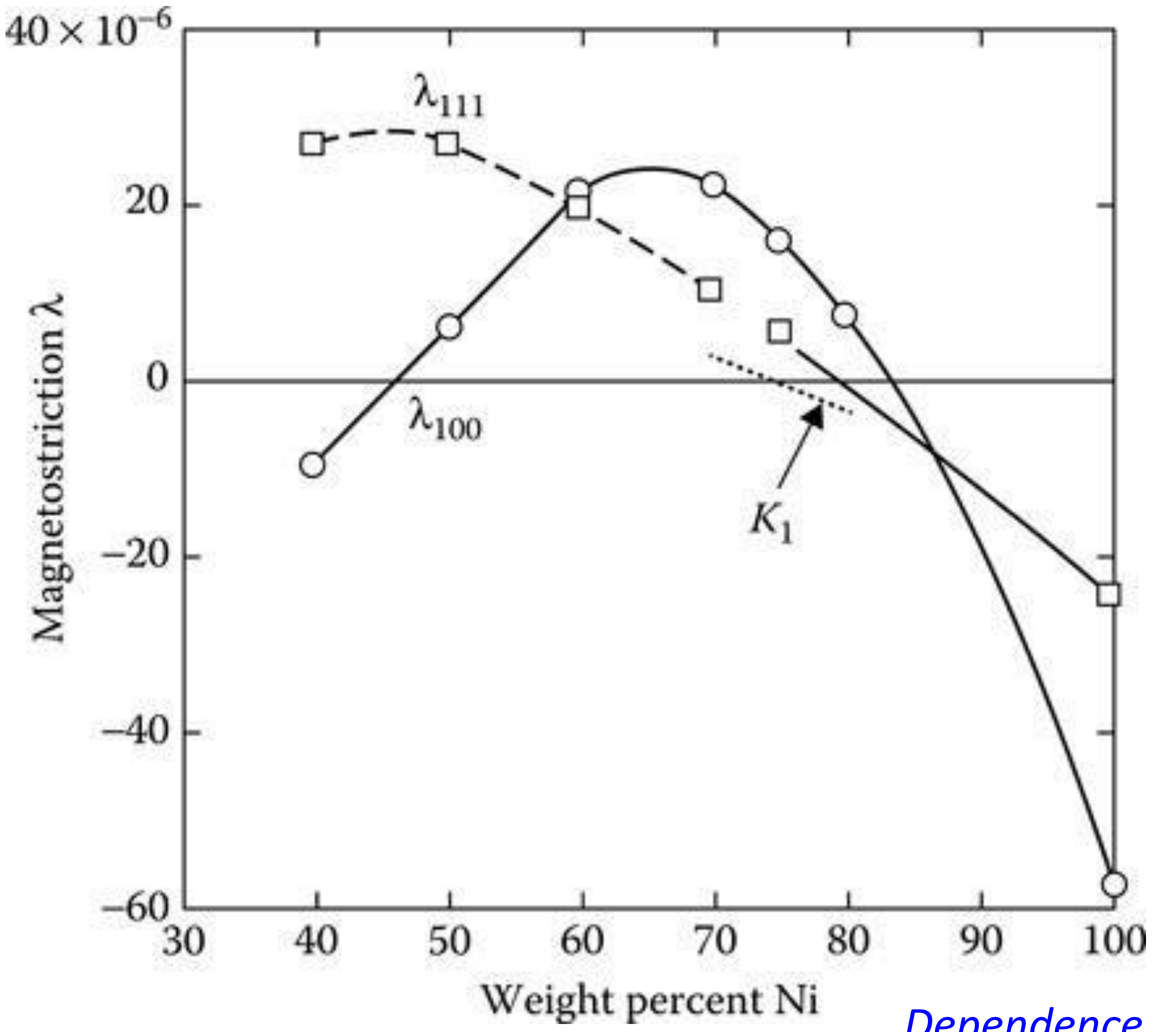
Nickel-iron Alloys (Permalloy)

- The saturation magnetization is highest in the vicinity of 50% Ni.
- The electrical resistivity is highest in the 30% Ni range.





Nickel-iron Alloys (Permalloy)

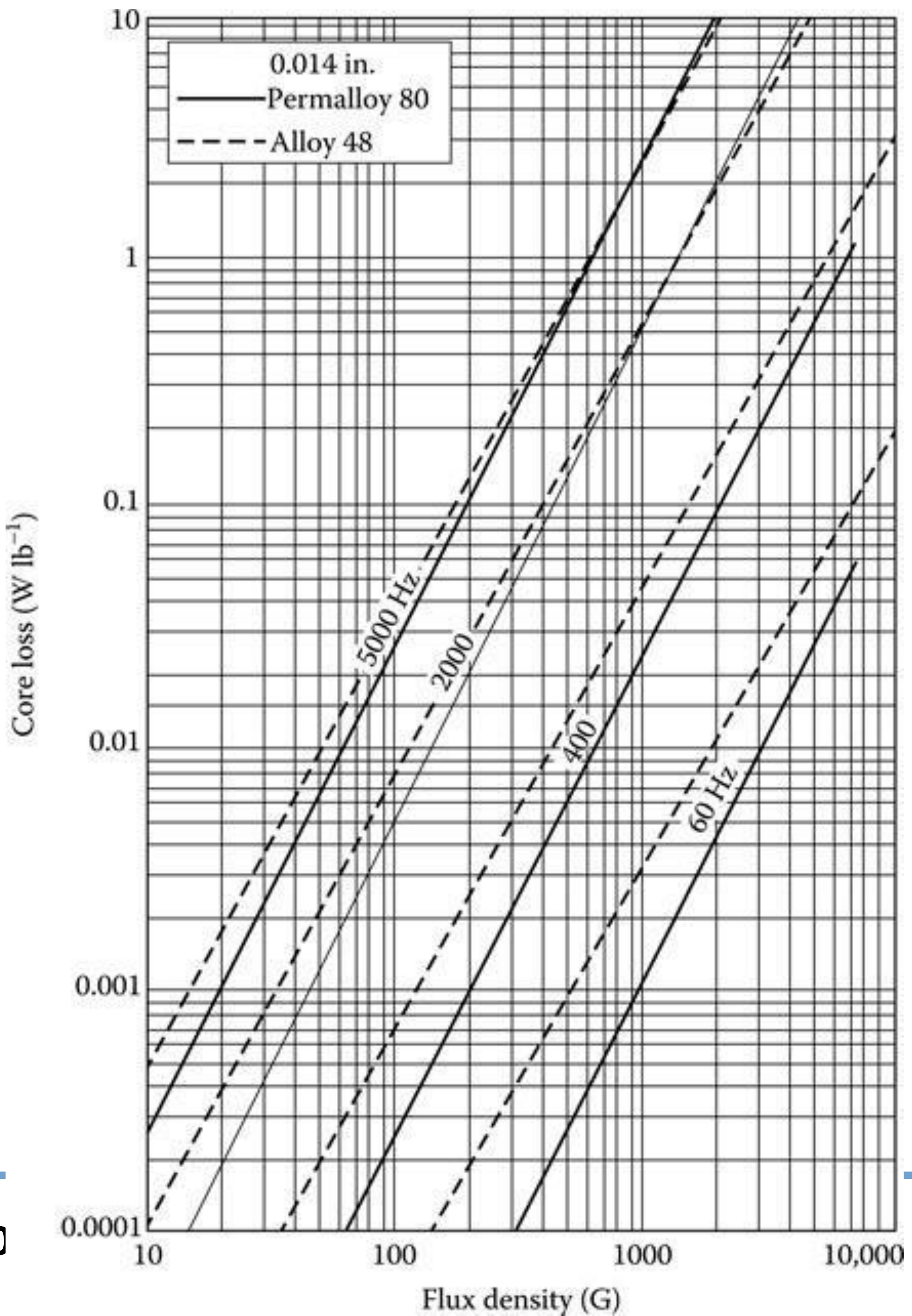


- Fe-Ni alloys can be made with low, or even zero magnetostriction.
- Cold working by rolling gives rise to high permeability perpendicular to the field as in Isoperm Fe50–Ni50.
- Invar (Fe64-Ni36) alloy has zero thermal expansion.
- High-quality transformers are often made of permalloy. Relative permeabilities of up to 100,000 are attainable with coercivities in the range of 0.16–800 A/m (0.002–10 Oe) and these can be adjusted with precision by suitable processing of the material.

Dependence of magnetostriction coefficients λ_{100} and λ_{111} with Ni content in Fe-Ni alloys.

Nickel-iron Alloys (Permalloy)

- This alloy system is also used in some magnetic memory devices and amplifiers.
- For high-frequency applications of up to 100 kHz, the alloy can be used in the form of powdered cores in which each particle is electrically insulated from others and therefore the bulk conductivity of the material is low.



Core losses against peak magnetic induction and frequency for 0.35 mm thick laminations of two commercial nickel-iron alloys: permalloy 80 and alloy 48.

Soft Ferrites

Soft Ferrites

- For high-frequency applications, the conductivity of metals limits their use and so we turn to magnetic insulators. These materials must have the usual properties associated with soft ferromagnets: high μ_r, low H_c, and high M_s (B_s).

- Ferrites are ceramic magnetic solids, which first appeared commercially in 1945. They are ferrimagnetic rather than ferromagnetic, but on the bulk scale, they behave in much the same way as ferromagnets with the presence of domains, a saturation magnetization, a Curie temperature and hysteresis in their B-H characteristics.

- There are two most commonly used soft ferrites:
  (1) Manganese zinc ferrite [$Mn_xZn_{1-x}Fe_2O_4$] - have higher permeability and saturation induction than nickel zinc ferrites and therefore are more suitable for lower frequency applications (up to 1 MHz).
  (2) Nickel zinc ferrite [$Ni_xZn_{1-x}Fe_2O_4$] - exhibit higher resistivity than manganese zinc ferrites and are therefore more suitable for higher frequencies.

- The cubic or soft ferrites all have the general chemical formula $MOFe_2O_3$, where M = Ni, Fe, Mn, Mg, Zn.
- The most familiar of these is Fe_3O_4.
- The ferrite $CoO{\cdot}Fe_2O_3$ although of the same general type is nevertheless a hard ferrite rather than a soft ferrite.
- Yttrium-iron garnet (YIG) is another best-known example of ferrite.

Soft Ferrites

- Soft ferrites can be further classified into the non-microwave ferrites for frequencies from audio up to 500 MHz and microwave ferrites for frequencies from 500 MHz to 500 GHz.
- Microwave ferrites, such as YIG, are used as waveguides for electromagnetic radiation and in phase shifters.
- Soft ferrites are also used in frequency selective circuits in electronic equipment, for example, in phone signal transmitters and receivers.
- Another area where ferrites find wide application is in antennae for radio receivers. Almost all radio receivers using amplitude modulation of signals have ferrite rod antennae.
- Other applications include waveguides and wave shaping, for example, in pulse-compression systems.

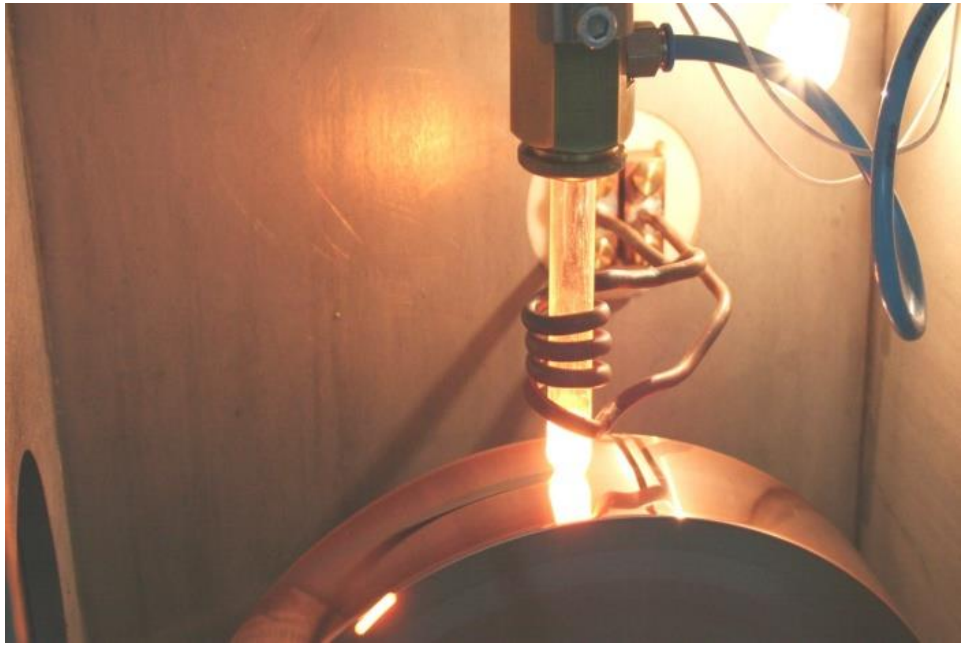
- The permeability of these soft ferrites does not change much with frequency up to a critical frequency, but then decays rapidly with increasing frequency.
- The critical frequency of these materials varies between 1 and 100 MHz.
- The saturation magnetization of ferrites is typically 0.5 T, which is low compared with Fe and Co alloys.

- For very high-frequency applications, beyond 100 MHz, there are other materials such as some of the hexagonal ferrites, which have properties that make them suitable for use at these frequencies. These materials have their magnetic moments confined by anisotropy to the hexagonal base plane.

Magnetic Amorphous Alloys

Amorphous Magnetic Ribbons (Metallic Glasses)

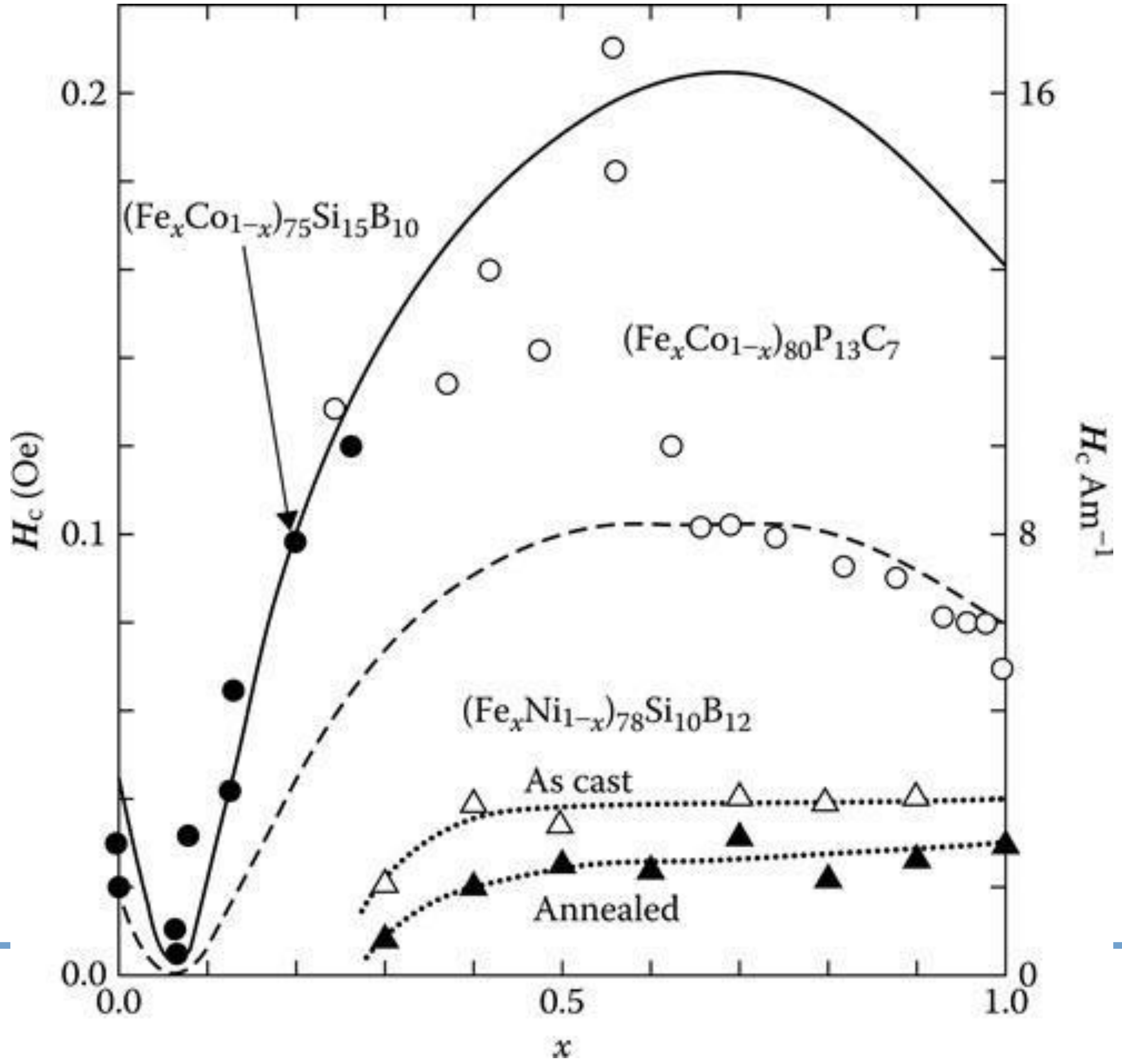
- The main interest in amorphous soft magnetic materials arises from the low coercivities, which are an order of magnitude smaller than Fe-Si, while the permeabilities are about an order of magnitude greater.
- Core losses are also very low.
- Such properties are a distinct advantage for soft magnetic material application; however, certain disadvantages also emerge.



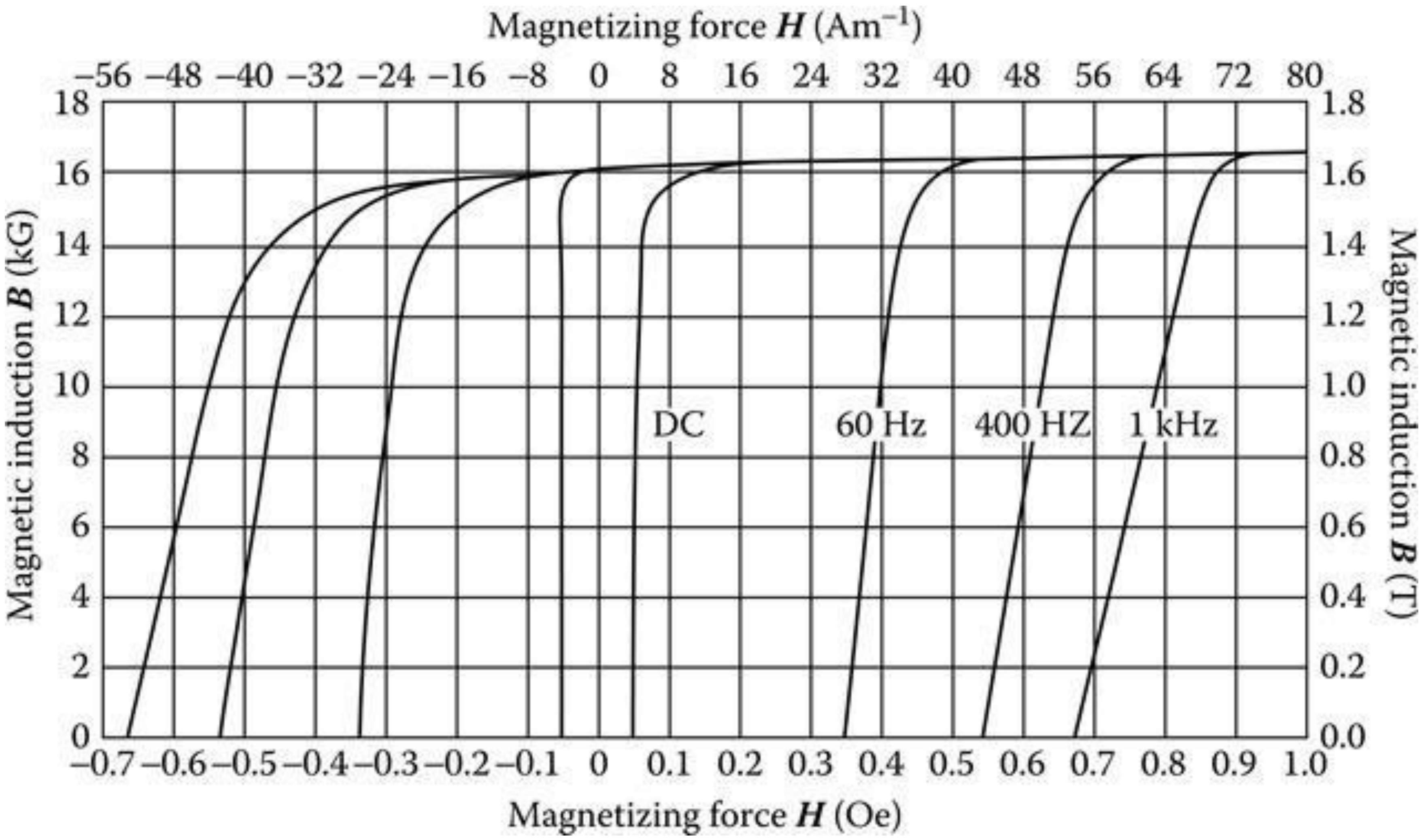
Rapidly quenching equipment for amorphous and nanocrystalline ribbons preparation.

Power transformers
DC-DC converters
AC-DC converters
EM shielding systems
Antitheft systems

Amorphous Magnetic Ribbons (Metallic Glasses)

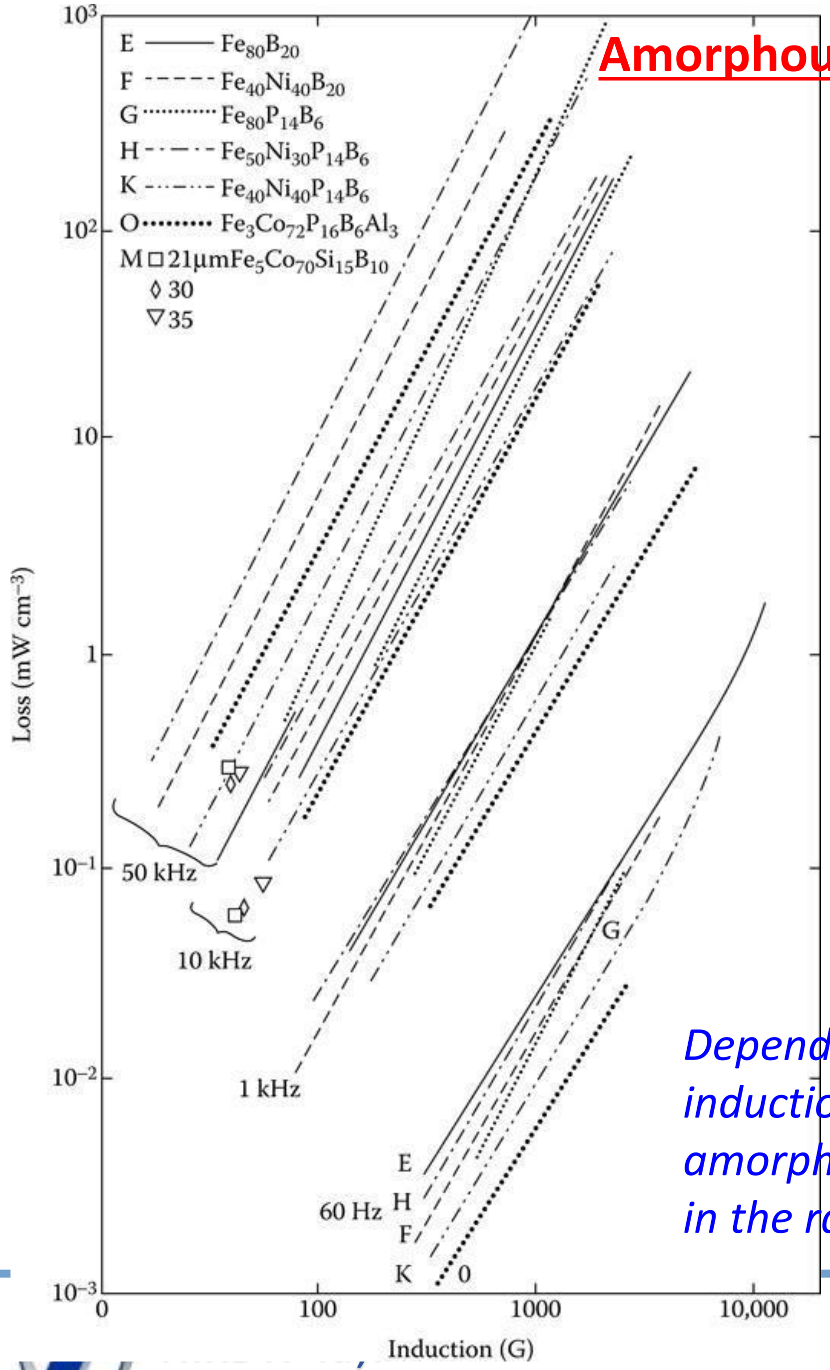


Amorphous Magnetic Ribbons (Metallic Glasses)

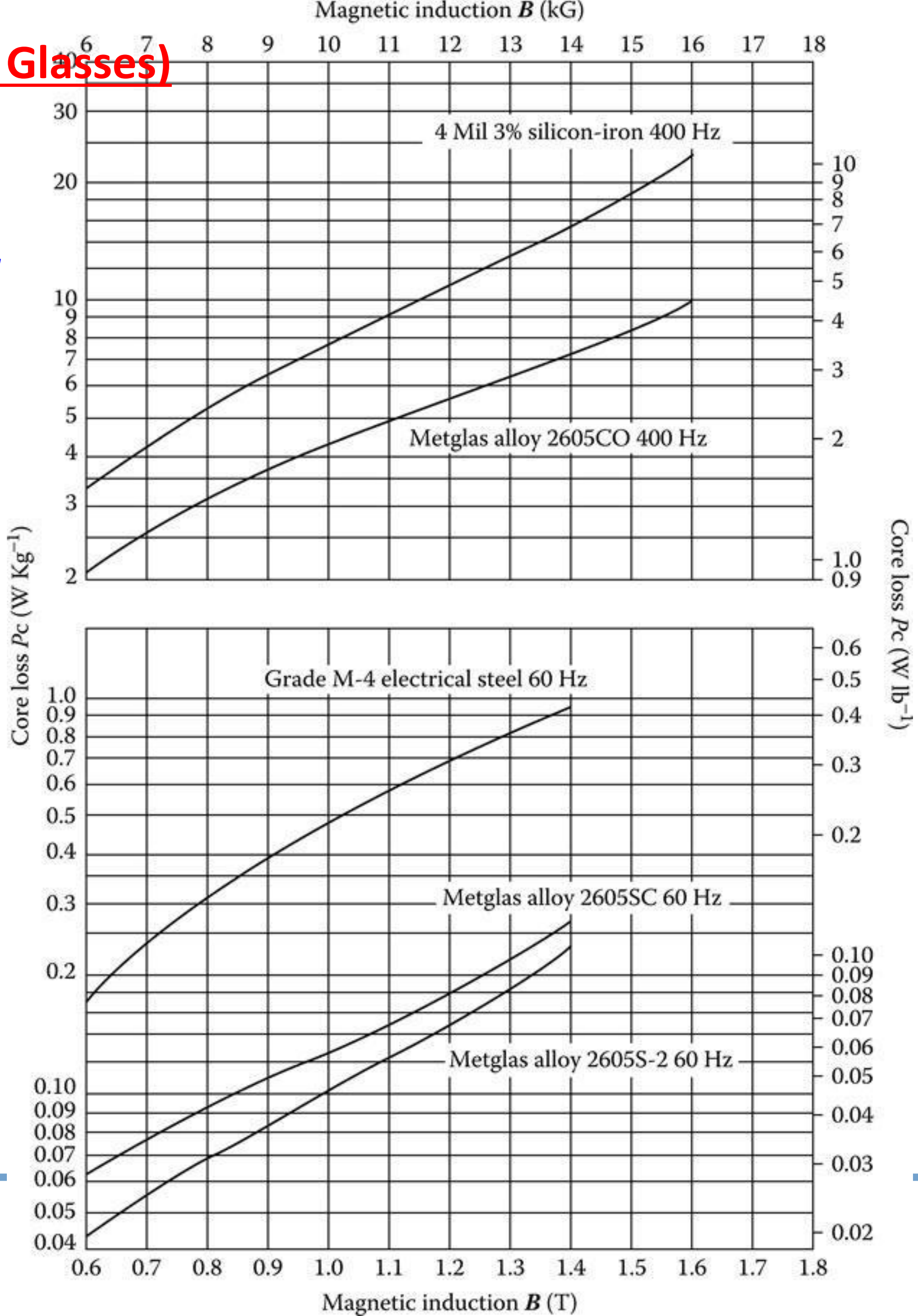


Upper two quadrants of the hysteresis loop of Metglas 2605CO ($Fe_{80}B_{20}$) at different frequencies.

Amorphous Magnetic Ribbons (Metallic Glasses)



Dependence of core loss on magnetic induction and frequency for various amorphous alloys. All sample thicknesses in the range of 25–50 µm.

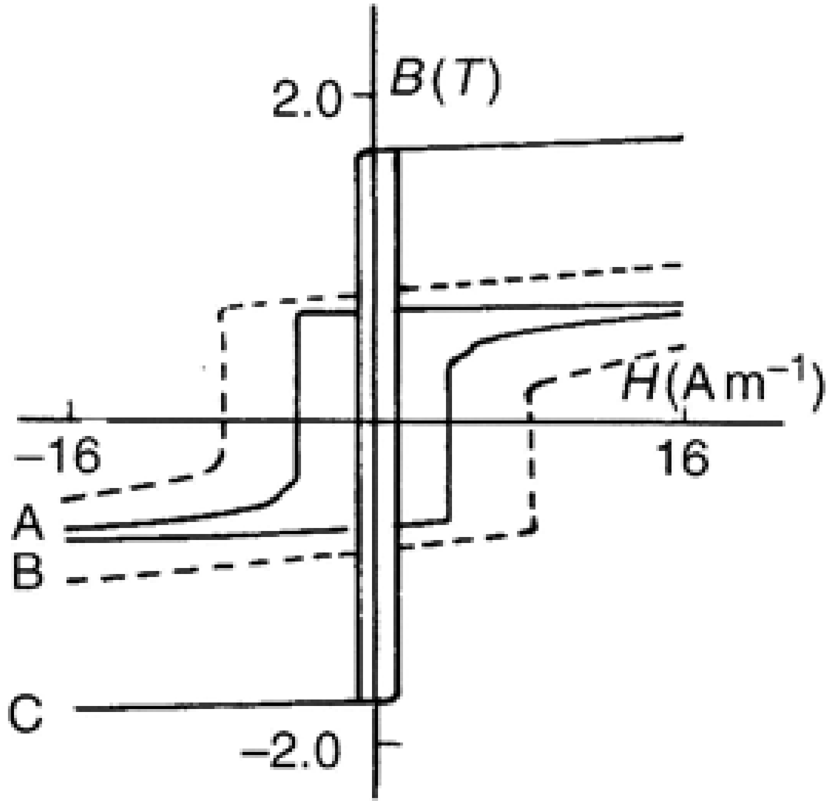


Comparison of core losses for different soft magnetic materials as a function of peak magnetic induction.

https://metglas.com/

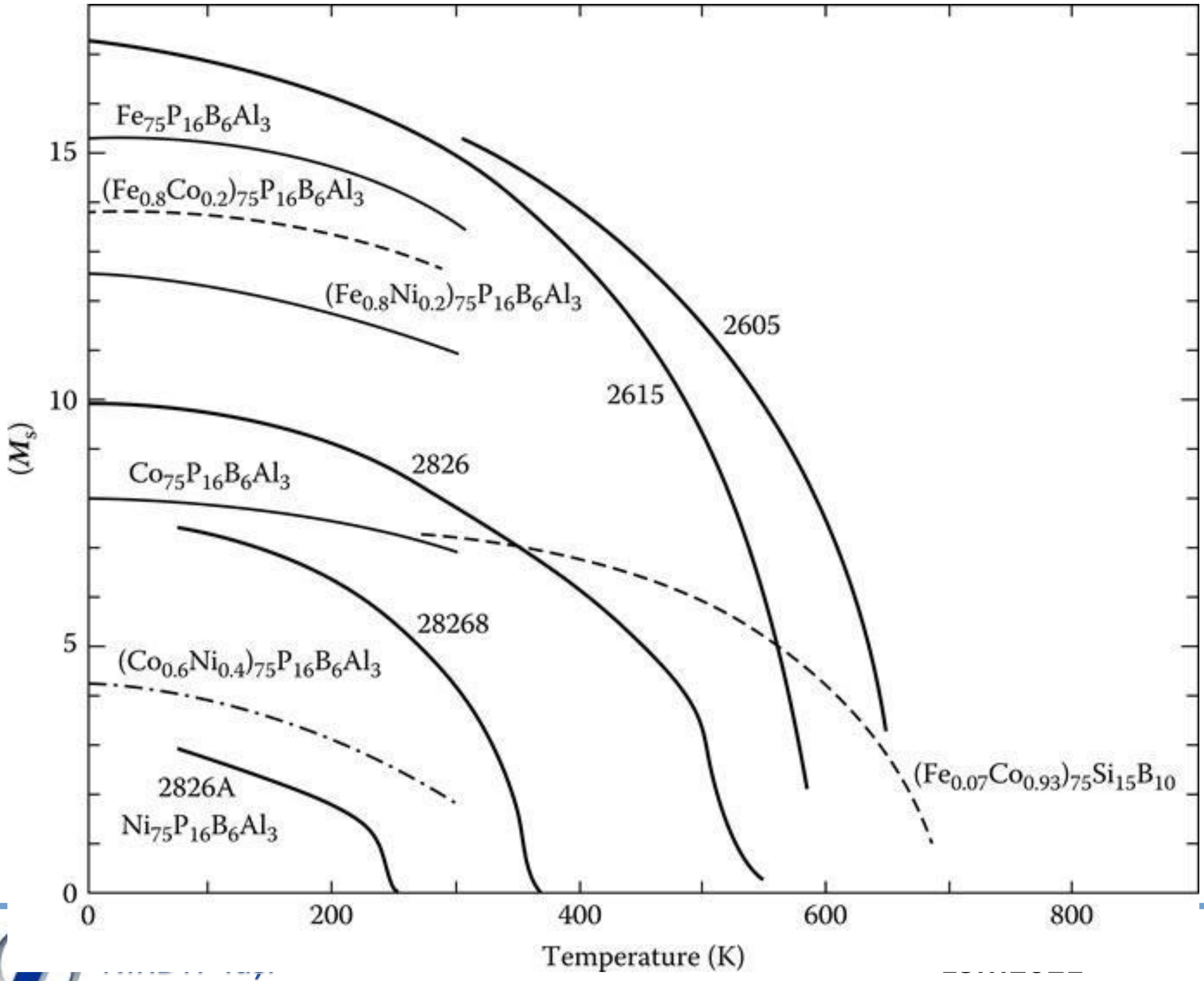
Amorphous Magnetic Ribbons (Metallic Glasses)

- One of the disadvantages of these materials is the low B_s, which limits their use in heavy current engineering when compared, for example, with Fe-Si steels.
- Second, at higher flux densities, their core losses begin to increase rapidly.
- There is a better market for these alloys in low power, low current applications, and specialized small-device applications in which transformers are needed with only moderate flux densities, where the amorphous alloys can compete successfully with Py.
- These amorphous alloys are being produced in large quantities and have found uses in pulsed power transformers, in magnetic sensors, in magnetostrictive transducers, and in communication equipment.
- One of the advantages of amorphous alloys is their high electrical resistivity, which leads to low eddy-current losses up to very high frequencies.



Hysteresis loops for an amorphous $Fe_{72}Co_8Si_5B_{15}$ alloy treated in different ways: A - as-prepared; B - annealed without applied field; C - field-annealed. From H. Fujimori et al., JAP 52 (1981) 1893.

Amorphous Magnetic Ribbons (Metallic Glasses)



Temperature dependence of the saturation magnetic induction for different amorphous alloys.

Allied Chemical Metglas alloys are as follows:

2605 is $Fe_{80}B_{20}$;

2615 is $Fe_{80}P_{16}C_3B$;

2826 is $Fe_{40}Ni_{40}P_{14}B_6$;

2826A is $Fe_{32}Ni_{36}Cr_{14}P_{12}B_6$;

2826B is $Fe_{29}Ni_{49}P_{14}B_6Si_2$.

Amorphous Magnetic Ribbons (Metallic Glasses)

Magnetic Properties of Amorphous Alloys under DC Conditions							
Alloy	Shape	As-Cast			Annealed		
		H_c (A/m)	M_r/M_s	μ_{max} (10^3)	H_c (A/m)	M_r/M_s	μ_{max} (10^3)
Metglas 2605 ($Fe_{80}B_{20}$)	Toroid	6.4	0.51	100	3.2	0.77	300
Metglas 2826 ($Fe_{40}Ni_{40}P_{14}B_6$)	Toroid	4.8	0.45	58	1.6	0.71	275
Metglas 2826 ($Fe_{29}Ni_{44}P_{14}B_6Si_2$)	Toroid	4.6	0.54	46	0.88	0.70	310
$Fe_{4.7}Co_{70.3}Si_{15}B_{10}$	Strip	1.04	0.36	190	0.48	0.63	700
$(Fe_{0.8}Ni_{0.2})_{78}Si_8B_{14}$	Strip	1.44	0.41	300	0.48	0.95	2,000
Metglas 2615 ($Fe_{80}P_{16}C_3B$)	Toroid	4.96	0.40	96	4.0	0.42	130

Amorphous Magnetic Ribbons (Metallic Glasses)

Properties of commercially available soft magnetic amorphous alloys								
Trade name	Composition	M_s (T)	H_c (A/m)	T_c (^{0}C)	T_x (^{0}C)	ρ (μΩ·m)	λ_s (10^{-6})	H_v
Fe-based amorphous alloys								
2605HB1M	Fe–Si–B	1.63	1.5	363	490	1.20	27	
2605SA1	Fe–Si–B	1.56	2.0	399	510	1.30	27	
2605S3A	Fe–Si–B–Cr	1.41	5.0	358	535	1.38	20	860
Co-based amorphous alloys								
2705M	Co–Fe–Ni–Si–B–Mo	0.77	1.0	365	520	1.36	<0.5	900
2714A	Co–Fe–Ni–Si–B	0.57	0.4	225	550	1.42	<0.5	960
Fe–Ni-based amorphous alloy								
2826MB	Fe–Ni–Mo–B	0.88	4.0	353	410	1.38	12	740

After H.H. Liebermann, “Rapidly Solidified Alloys: Processes, Structures, Properties, Applications”, New York: CRC Press, 1993 and Hitachi Metals website (https://www. hitachi-metals.co.jp/products/infr/en/pdf/hj-b10-b.pdf).

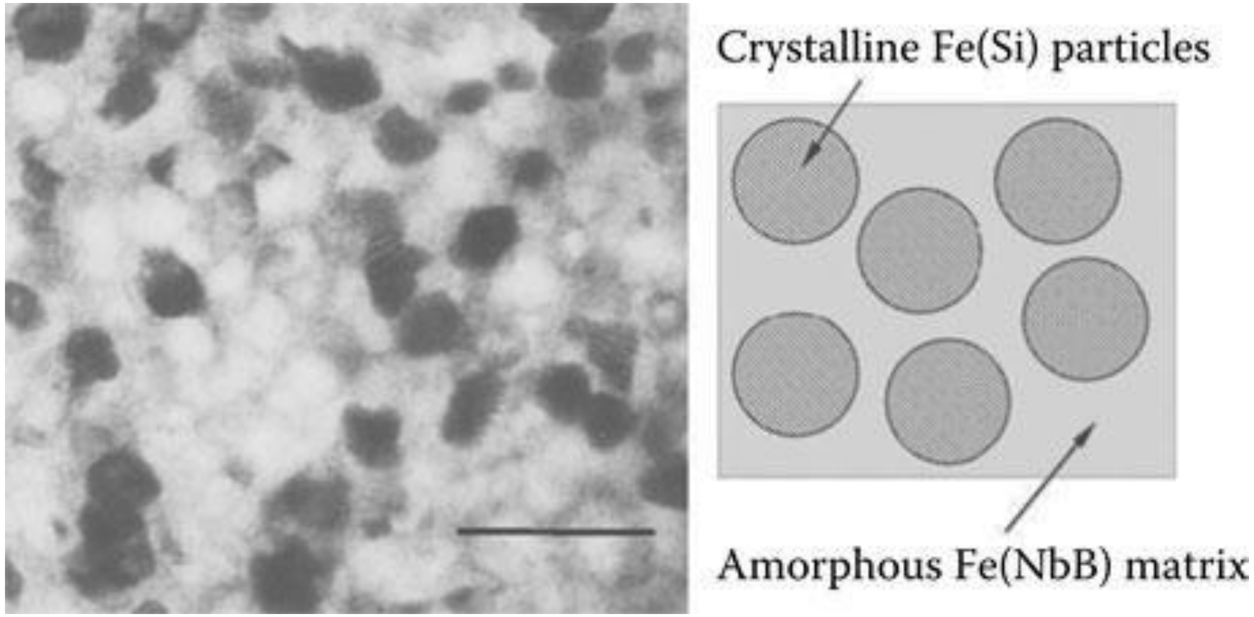
Amorphous Magnetic Ribbons (Metallic Glasses)

- One class of antitheft, or antishoplifting, system uses a short length of high-permeability ribbon or wire as the tag or target which is attached to the article to be protected.
- When an article, and the tag, are carried out through a detection gate they are subjected to an AC field in the kHz frequency range, which magnetizes the tag.
- The AC field of the tag (or sometimes the acoustic signal due to its magnetostriction) is detected and used to activate an alarm.
- If the article has been paid for, the tag is deactivated, usually by causing it to be permanently magnetized by an adjacent strip of permanent magnet material.
- Permalloys and amorphous alloys are both used to make the tags, which must be very low in cost.

Nanocrystalline Magnetic Ribbons

Nanocrystalline Magnetic Ribbons

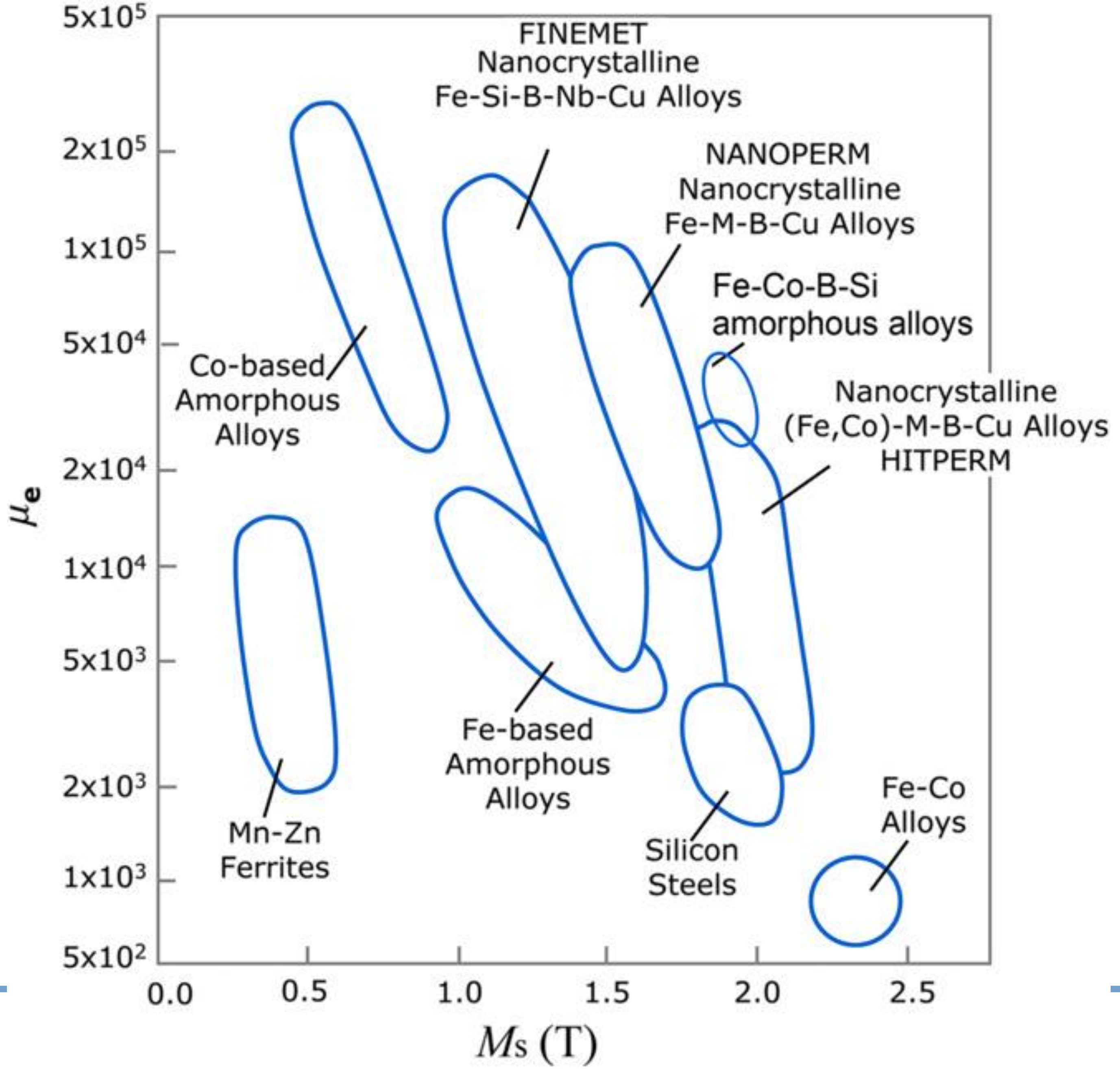
- The range of available soft magnetic materials was significantly increased by the discovery of nanocrystalline magnetic materials by Yoshizawa et al. ($Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$ or FINEMET).
- The exceptional properties of these materials, which have coercivities below 1 A/m (0.0125 Oe) and high relative permeabilities of typically 10^5 combined with relatively high saturation magnetization of 1.05×10^6 A/m (13 kG) and resistivities as high as 1.15×10^6 Ω·m, make them suitable for applications in magnetic cores for ground fault circuit interrupters, high-frequency transformers, and chokes.
- These nanostructured alloys have soft magnetic properties that are comparable to permalloys and Co-based amorphous alloys, but with a significantly higher saturation induction of 1.2 T and above.



Transmission electron micrograph of the two-phase structure of nanocrystalline FeCuNbSiB (left) and idealized schematic representation of the two-phase structure (right).

[After Y. Yoshizawa et al., J. Appl. Phys. 64 (1988) 6044]

Nanocrystalline Magnetic Ribbons

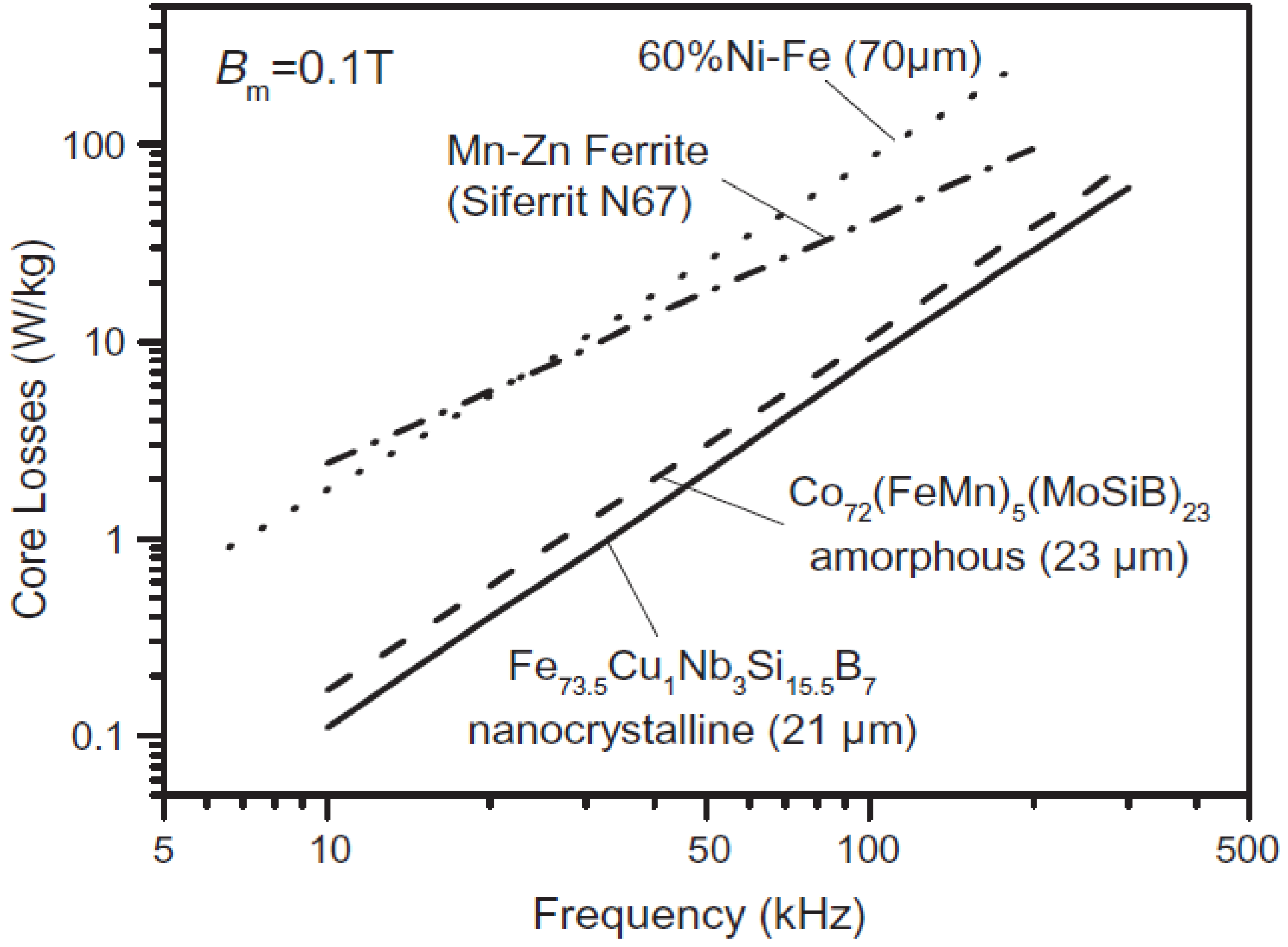


The relation between saturation magnetization M_s and μ_e at 1 kHz for soft magnetic materials.

[After M.E. McHenry, M.A. Willard, D.E. Laughlin, "Amorphous and nanocrystalline materials for applications as soft magnets", Prog. Mater. Sci. 44(4) (1999) 291]

Nanocrystalline Magnetic Ribbons

- Their favorable high frequency behavior up to frequencies of several hundred kHz has made amorphous and nanocrystalline soft magnets competitive, even with MnZn ferrites.
- The low eddy current losses of wound cores of amorphous or nanocrystalline ribbons are essentially due to (1) the thin ribbon gauge d ≈ 20 μm, inherent to the production technique, and (2) a relatively high electrical resistivity of typically ρ≈ 100÷130 μΩ·cm, related to the microstructure.

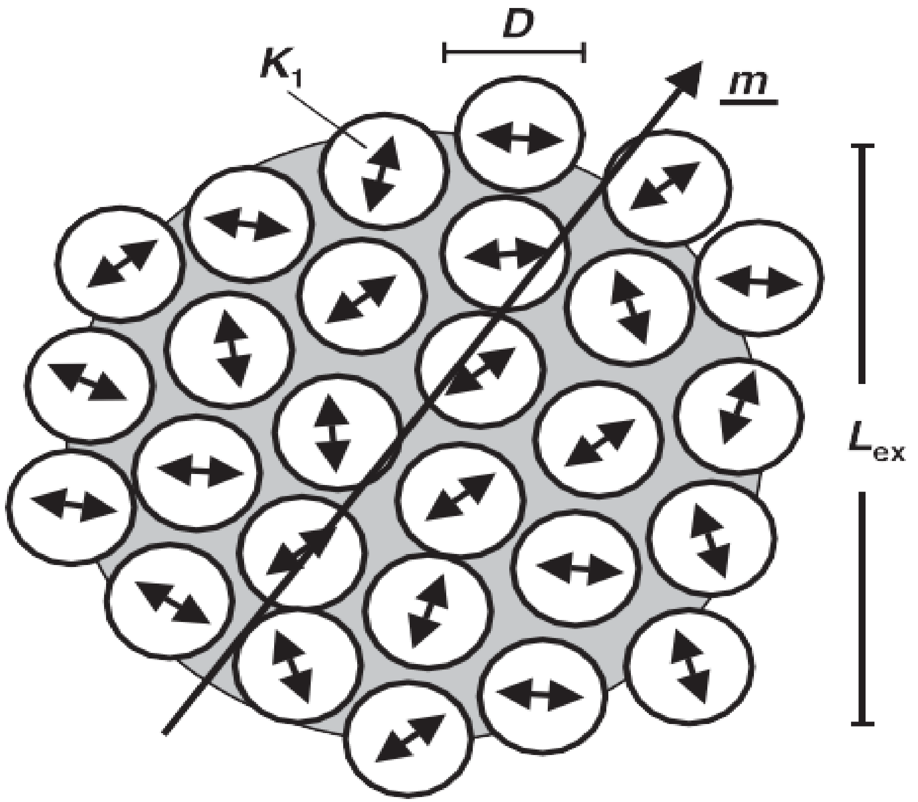


Core losses vs. frequency for soft magnetic materials used for high frequency power transformers.

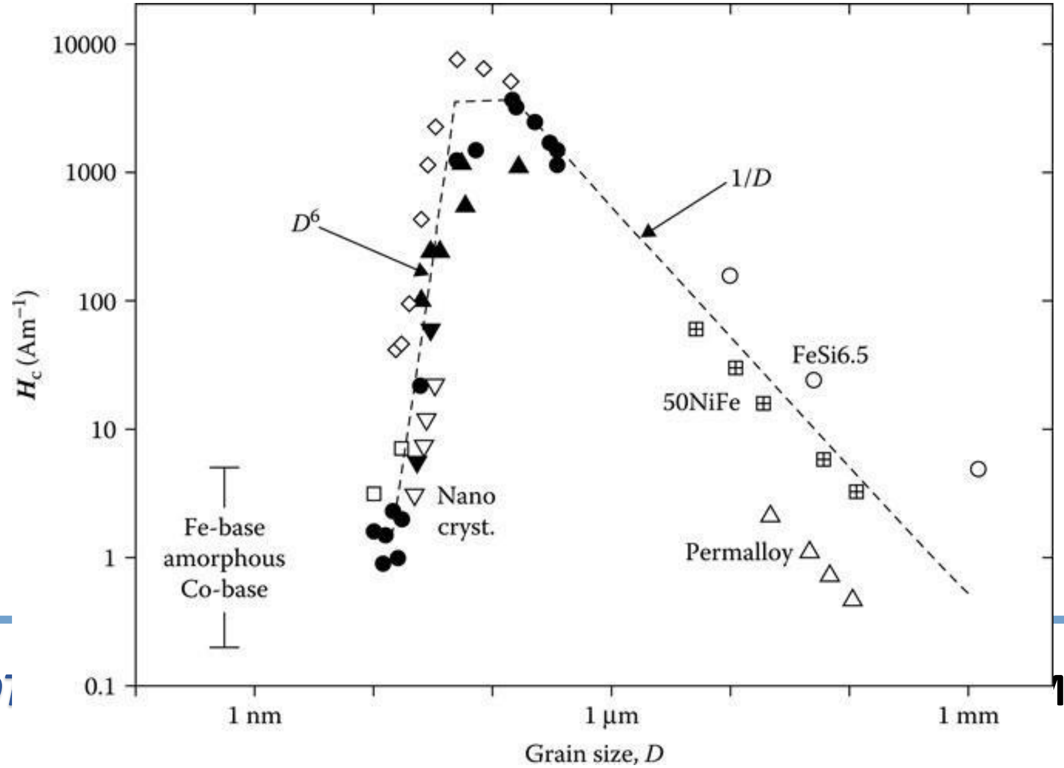
After G. Herzer, Acta Materialia 61 (2013) 718.

Nanocrystalline Magnetic Ribbons

- Owing to their small structural correlation length, amorphous and nanocrystalline materials are not only magnetically soft, but at the same time mechanically hard (a Vickers hardness of typically 800–1000 H_V) and exhibit a high yield strength of around 3000 MPa.
- This contrasts with the situation in conventional soft magnetic metals, which are known to also be mechanically soft, with yield strengths of the order of only a few hundred MPa.

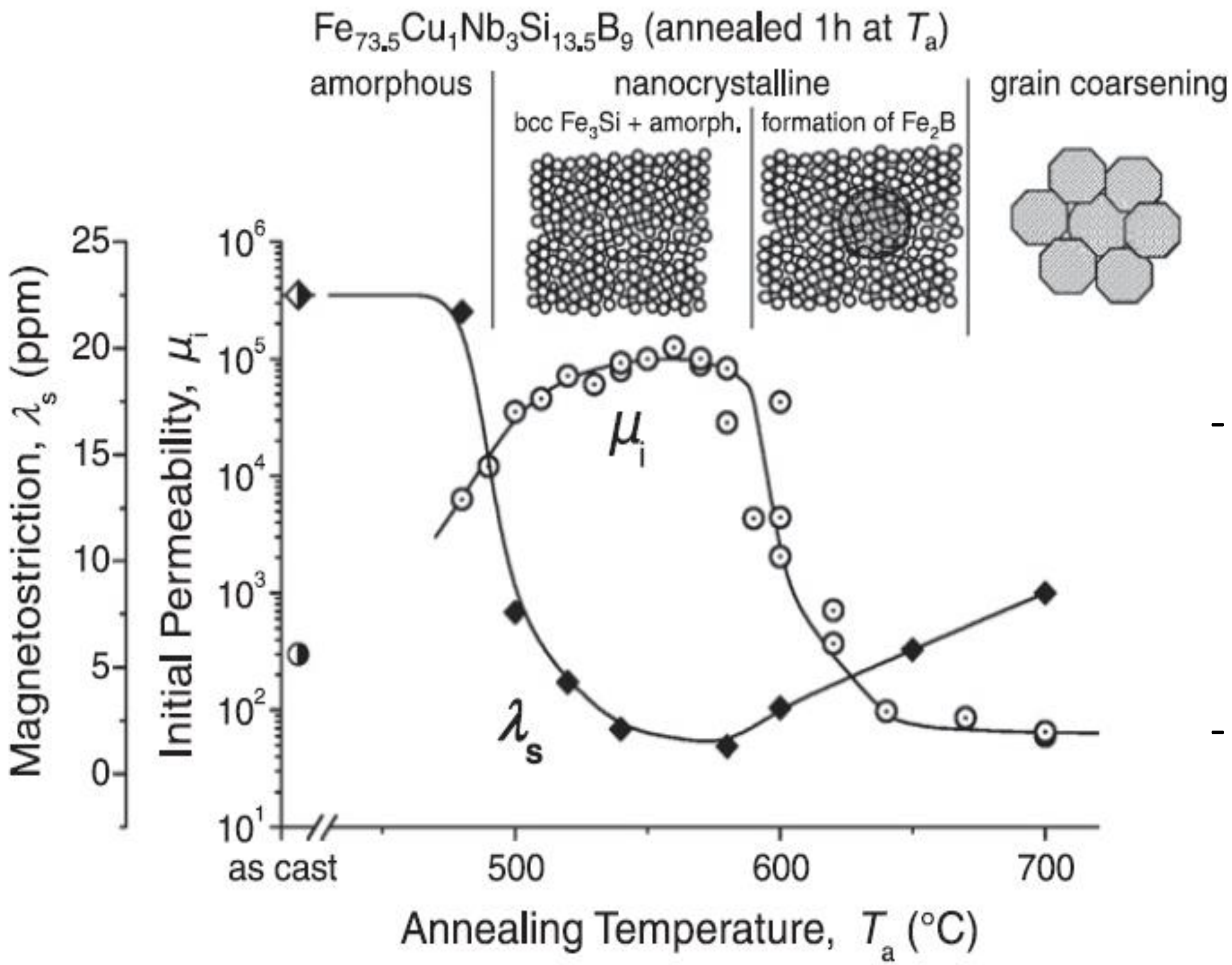


Schematic representation of the random anisotropy model for grains embedded in an ideally soft ferromagnetic matrix. The double arrows indicate the randomly fluctuating anisotropy axis, the hatched area represents the ferromagnetic correlation volume determined from the exchange length Lex within which the orientation m of the magnetization is constant.



After G. Herzer, Acta Materialia 61 (2013) 718.

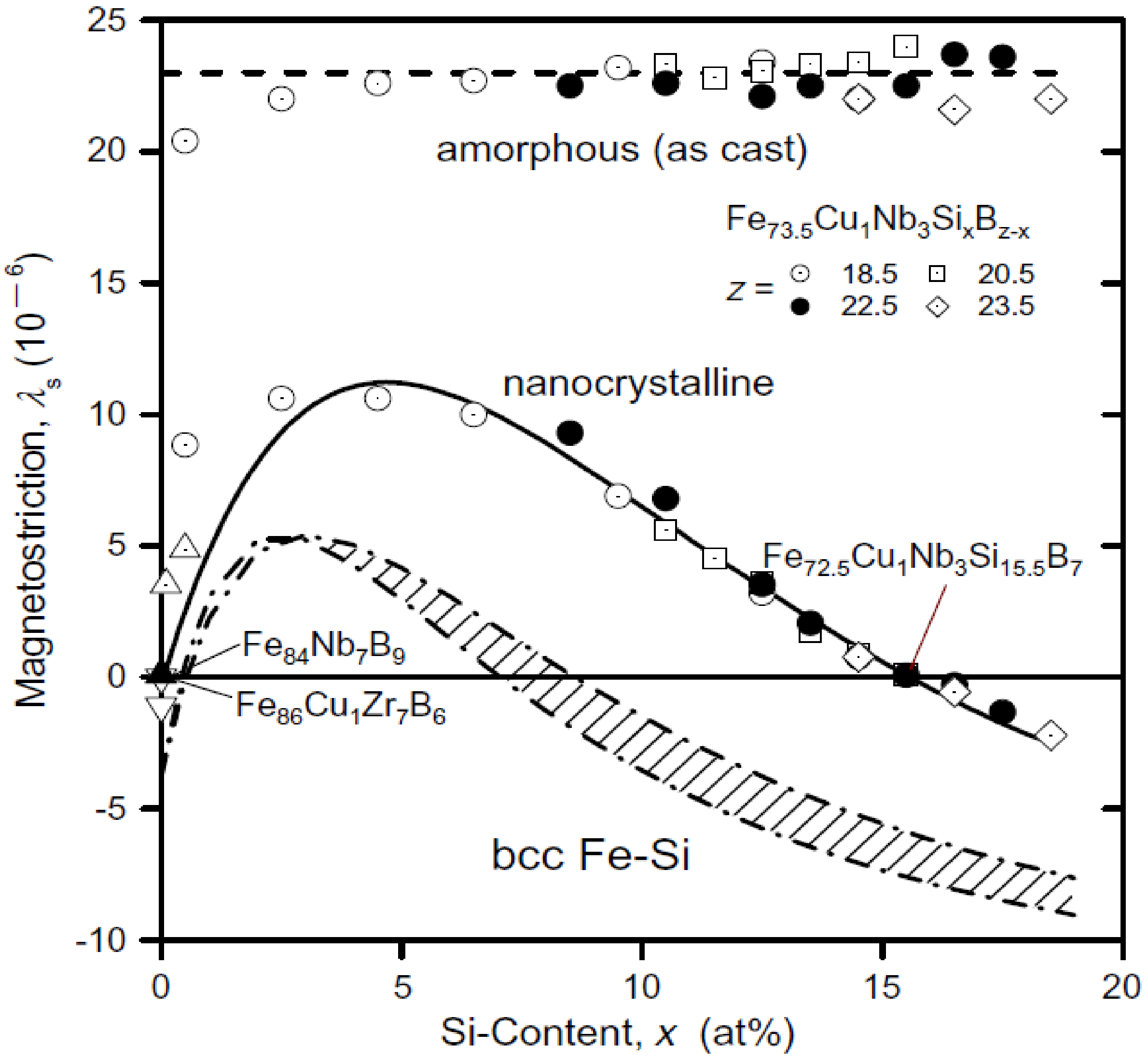
Nanocrystalline Magnetic Ribbons



Formation of the nanocrystalline state and evolution of the initial permeability (μ_i) and saturation magnetostriction (λ_s) in $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ annealed for 1 h at temperature T_a.

- Ultrafine grains of bcc Fe–Si–20 at.% with typical grain sizes of 10–12 nm embedded in a residual amorphous matrix which occupies about 20–30% of the volume and separates the crystallites at a distance of about 1–2 nm.
- These features are the basis for the excellent soft magnetic properties indicated by the high initial permeability values of about 10^5 and correspondingly low coercivity of less than 1 A/m.

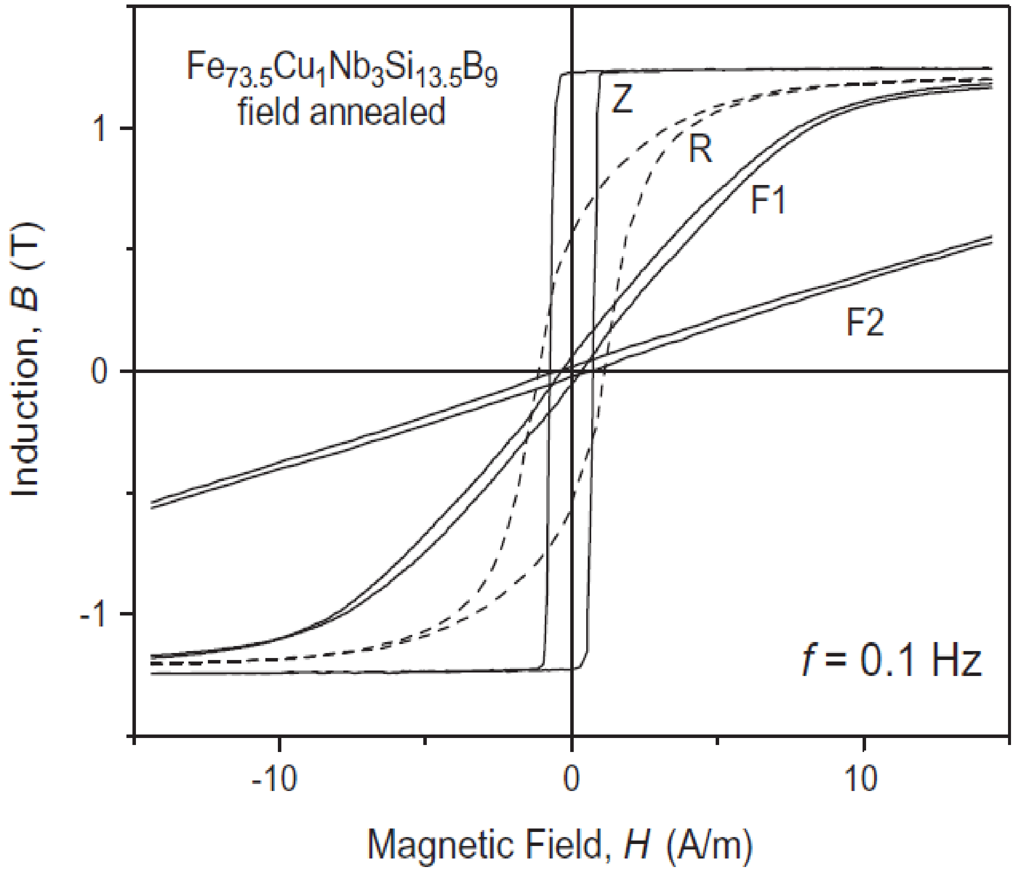
Nanocrystalline Magnetic Ribbons

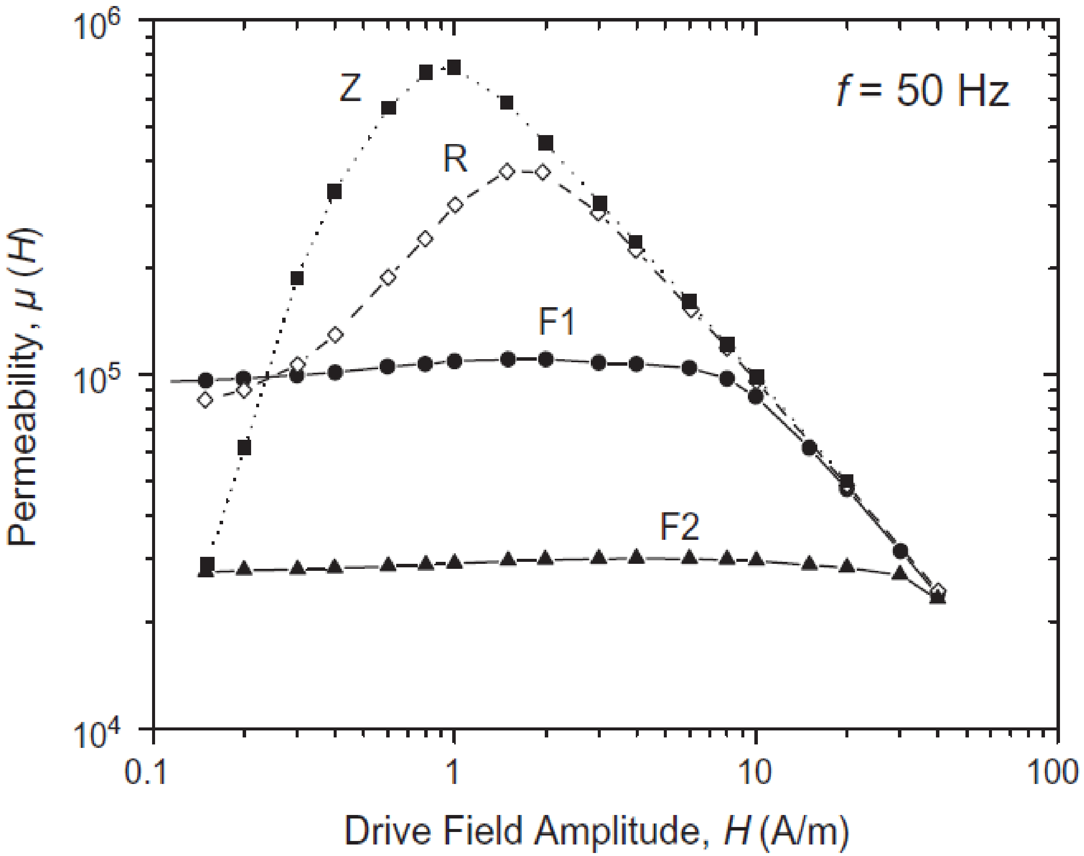


$$\lambda_s \approx x_{cr} \cdot \lambda_s^{FeSi} + (1 - x_{cr}) \cdot \lambda_s^{am}$$

After G. Herzer, Acta Materialia 61 (2013) 718.

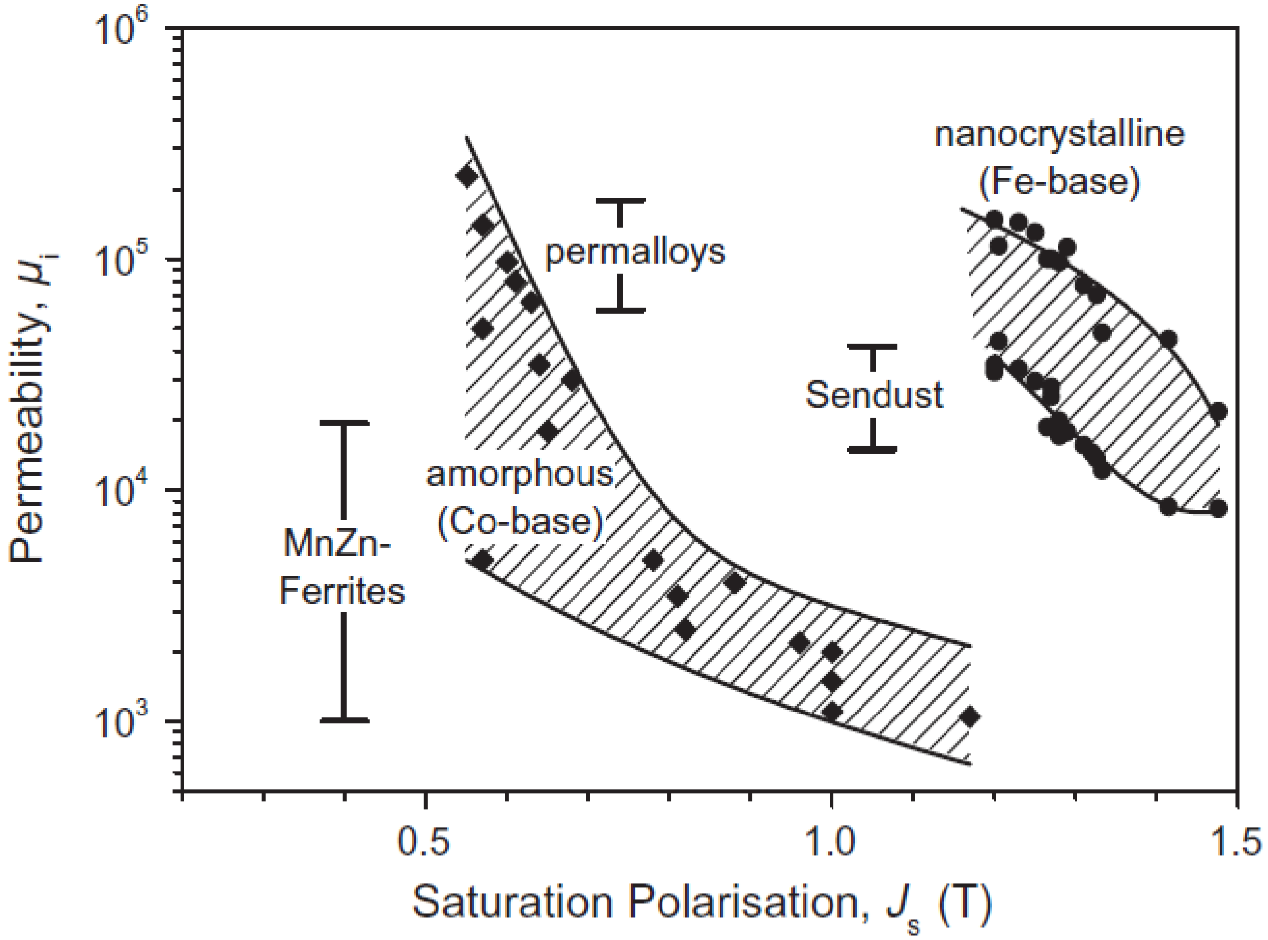
Nanocrystalline Magnetic Ribbons





DC hysteresis loops and 50 Hz permeability of nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ annealed for 1 h at 540^0C without (R) and with a magnetic field applied parallel (Z) and transversal (F2) to the magnetic path. Sample F1 was first crystallized at 540^0C and subsequently transverse field annealed at 350^0C.

Nanocrystalline Magnetic Ribbons



Initial permeability vs. saturation polarization for low magnetostrictive, soft magnetic materials.

Toroidal wound cores and components of nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ (Vitroperm 800) (https://vacuumschmelze.com/Assets-Web/VITROPERM%20500%20-%20800.pdf)

Magnetic micro/nanowires

Magnetic micro/nanowires

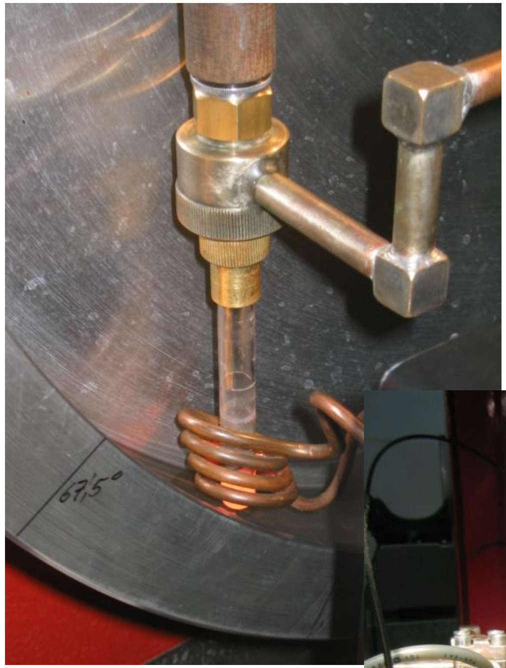
Magnetic amorphous and nanocrystalline wires and micro/nanowires obtained by rapid quenching from the melt show specific magnetic characteristics determined by their disordered or partially disordered structures, but also because of the cylindrical symmetry which cause the formation of magnetic domains structures extremely favorable to different applications, with a special emphasis on magnetic sensors.

- The first Pd-based amorphous wires - synthesized by in-rotating-water method in Japan *(Ohnaka et al., 1981)*.
- The first FM amorphous wires with Φ = 100÷140 µm - produced from Fe–Si–B (Hagiwara et al., 1982), Fe–P–C *(Inoue et al., 1982)* and Co–Si–B *(Hagiwara et al., 1982)* alloys, using the same technique.

In-Rotating Water Spinning (INROWASP) equipment for amorphous and nanocrystalline wires preparation.

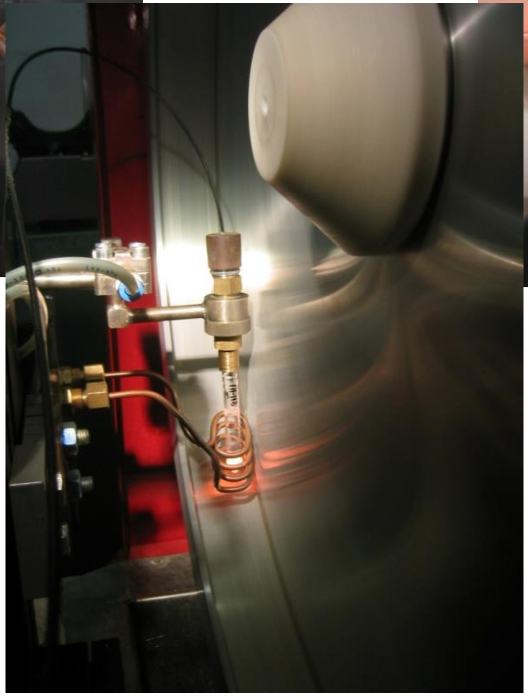
Magnetic micro/nanowires

Amorphous and nanocrystalline wires prepared by In-Rotating Water Spinning (INROWASP).



1

2



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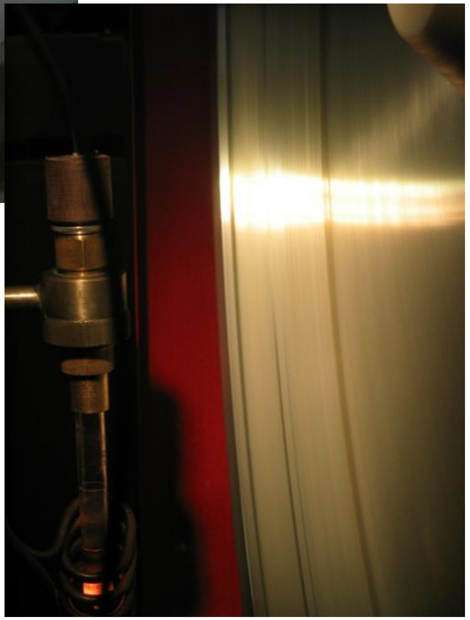


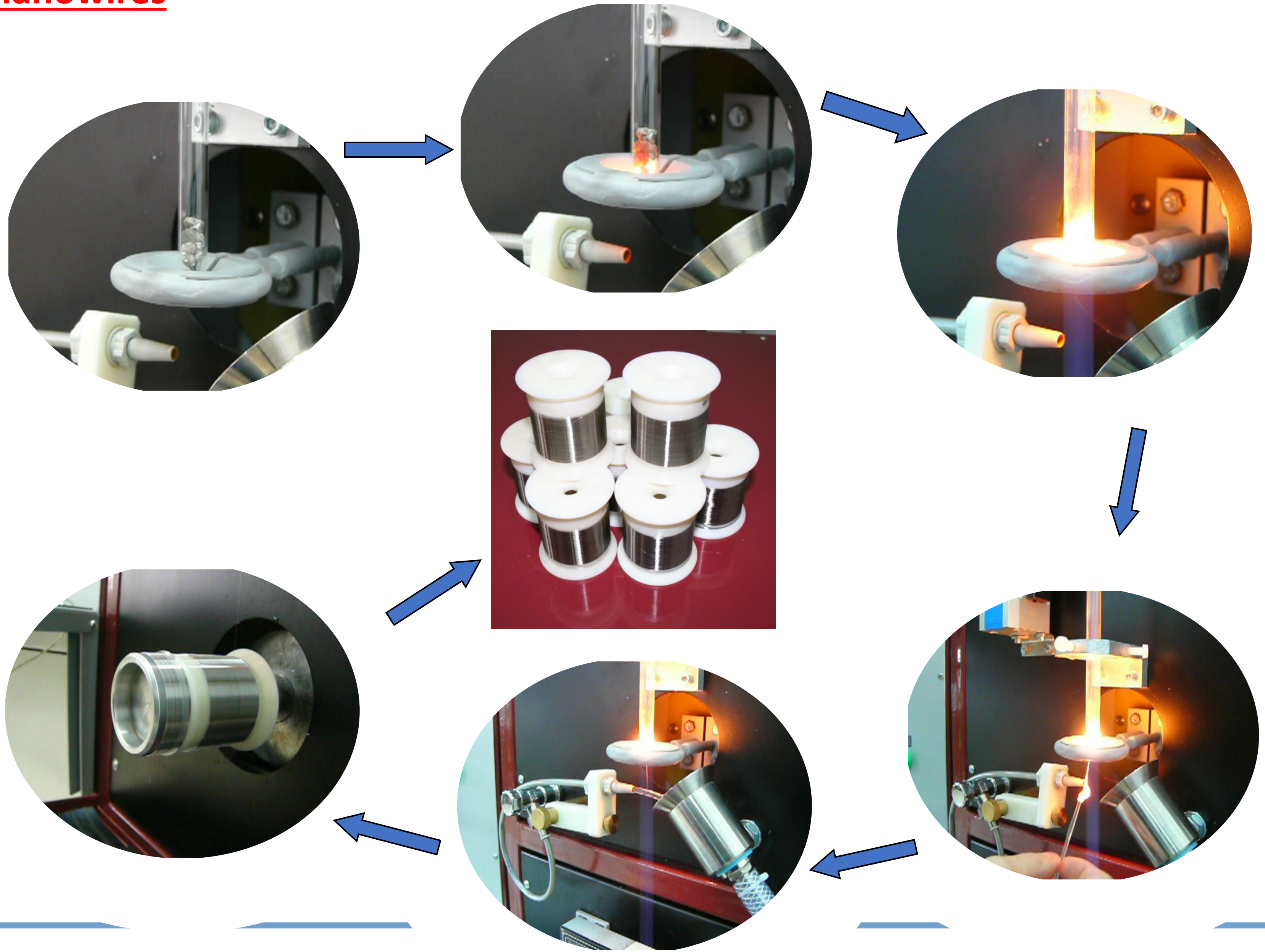
4

Magnetic micro/nanowires

H. Chiriac and T.A. Óvári, "Amorphous glass-covered magnetic wires: Preparation, properties, applications", Prog. Mater. Sci. 40(5) (1996) 333-407

Glass-covered micro/nanowires preparation equipment.

Magnetic micro/nanowires



Magnetic micro/nanowires

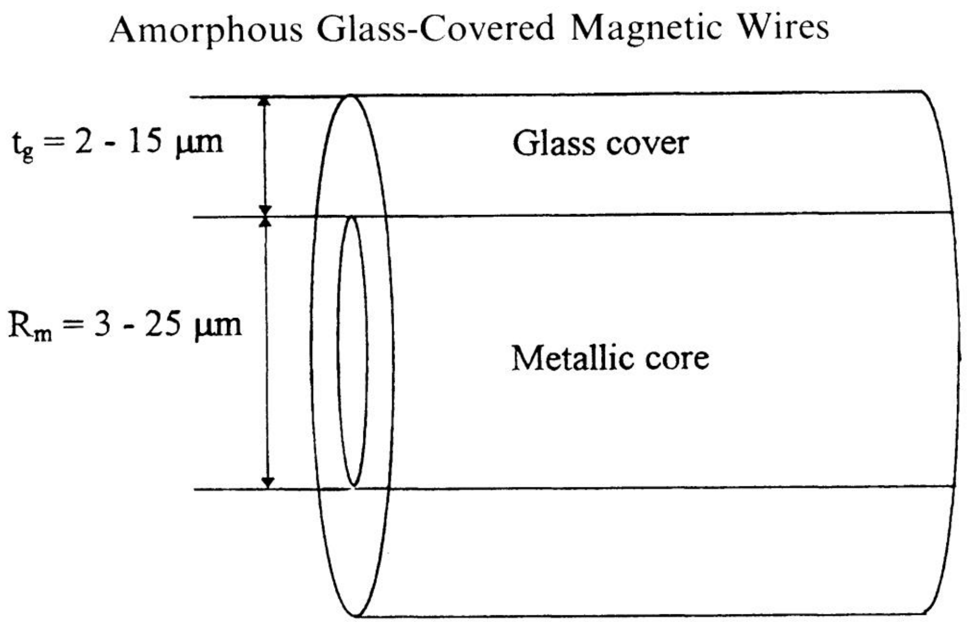
Typical compositions for magnetic micro/nanowires

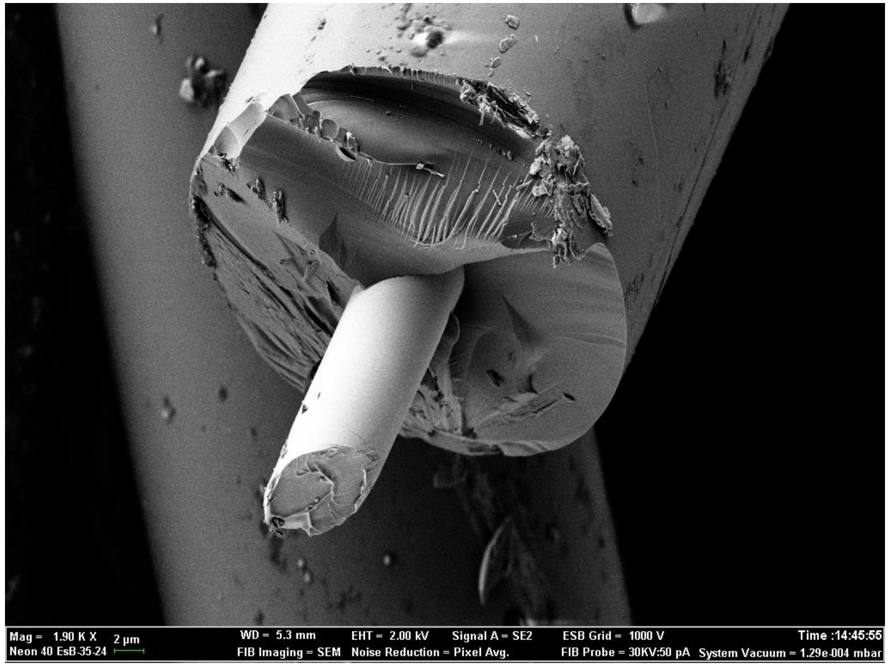
- Fe-based soft magnetic amorphous alloys with relatively high positive magnetostriction ($+35\times10^{-6}$);
- Co-based soft magnetic amorphous alloys with small negative magnetostriction (-8×10^{-6});
- Co-based soft magnetic amorphous alloys with small additions of Fe with almost zero magnetostriction;

- FeCuNbSiB–based soft magnetic nanocrystalline alloys;
- FeAuCuB-based glassy alloys;
- NdFeB-based amorphous and nanocrystalline hard magnetic materials;
- others, depending on application.

- The technological parameters have a strong influence on the characteristics of these wires.
- High quenching rates + presence of glass coating $\Rightarrow$ *large internal stresses* induced during preparation.

Magnetic micro/nanowires

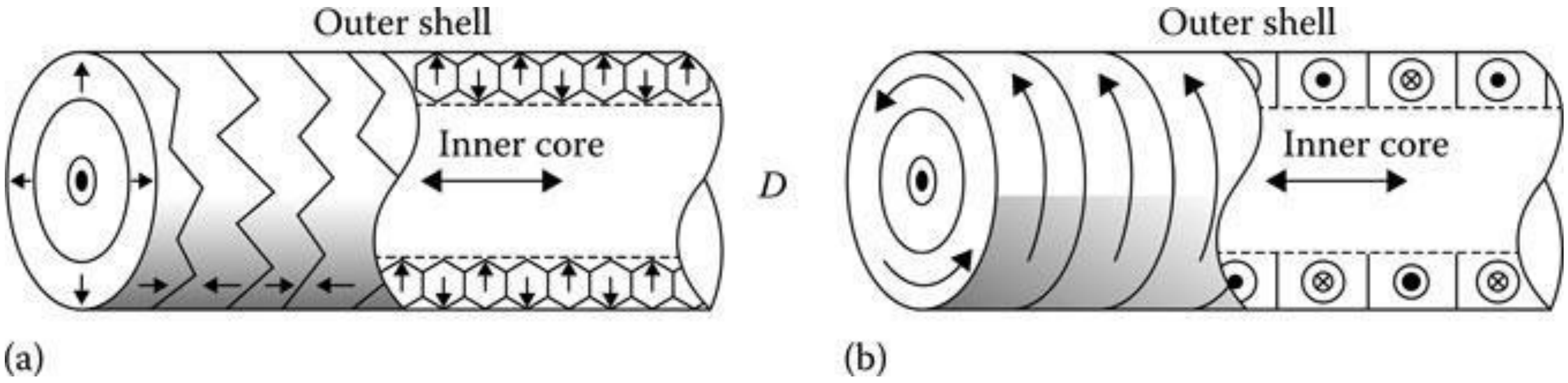




The rigorous control of the process parameters have led to a significant breakthrough as concerns the dimensions of the wire shaped materials which can be obtained through this method.

Glass-coated metallic wires (amorphous and nanocrystalline) with sub-micron metallic diameters (100÷900 nm) and the thickness of the glass cover of a few tens of μm have been obtained.

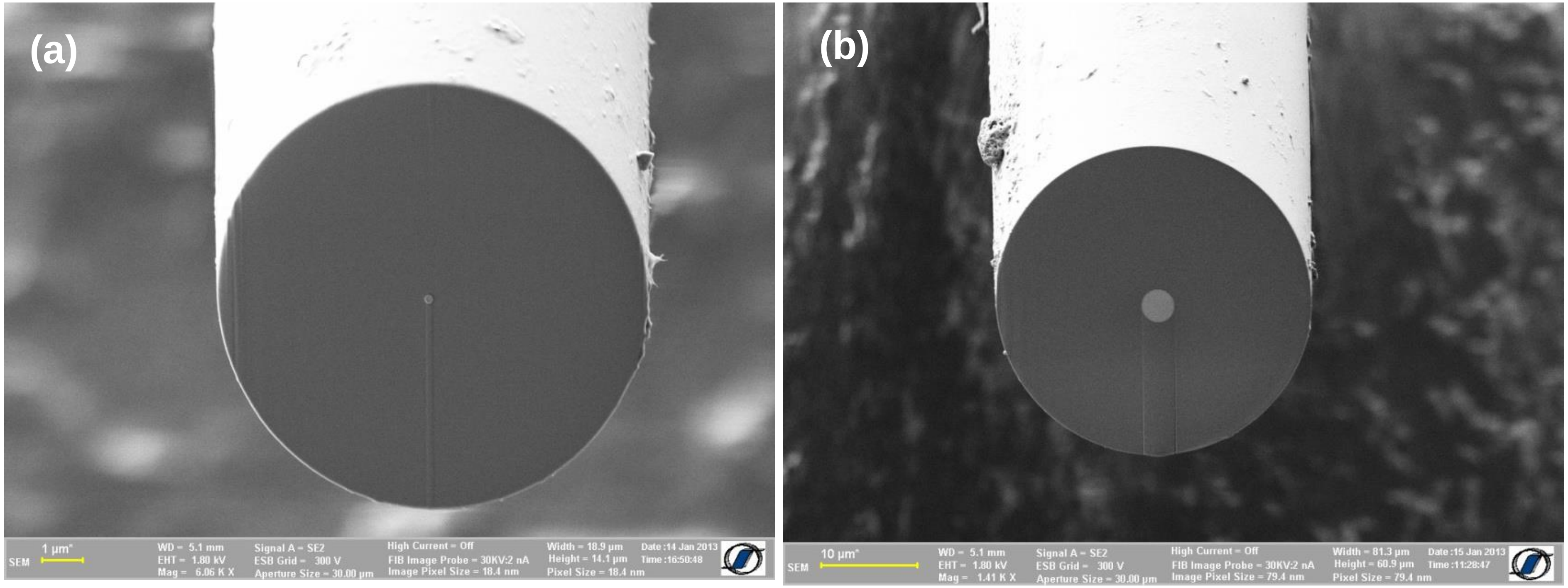
Magnetic micro/nanowires



Domain walls configuration in two main classes of amorphous wires:
(a) positive magnetostrictive (λ > 0) and
(b) negative magnetostrictive (λ < 0)

After K. Mohri et al., IEEE Trans. Magn, 26 (1990) 1789.

Magnetic micro/nanowires



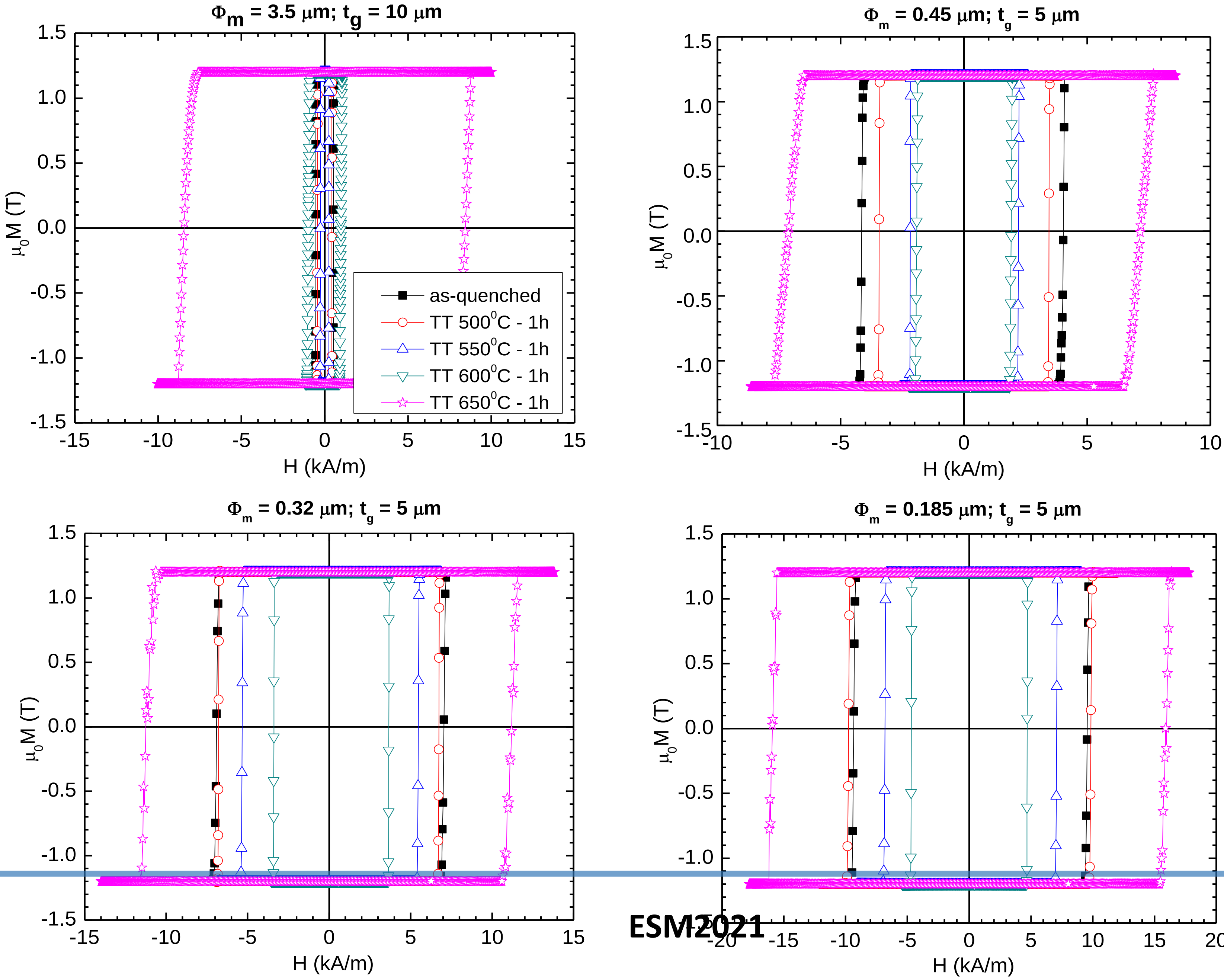
SEM micrographs of:

(a) a glass-coated $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ nanowire with the metallic nucleus diameter of 185 nm and the glass coating thickness of 5 µm; and

(b) a glass-coated microwire with the same composition, but with the nucleus diameter of 3.5 µm and the glass coating thickness of 10 µm.

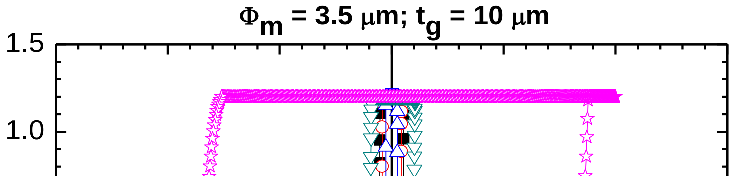
Magnetic micro/nanowires

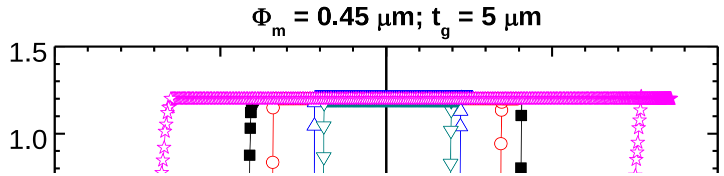
Magnetic bistability



H. Chiriac et al., Crystals 7(2) (2017) 48

Magnetic bistability



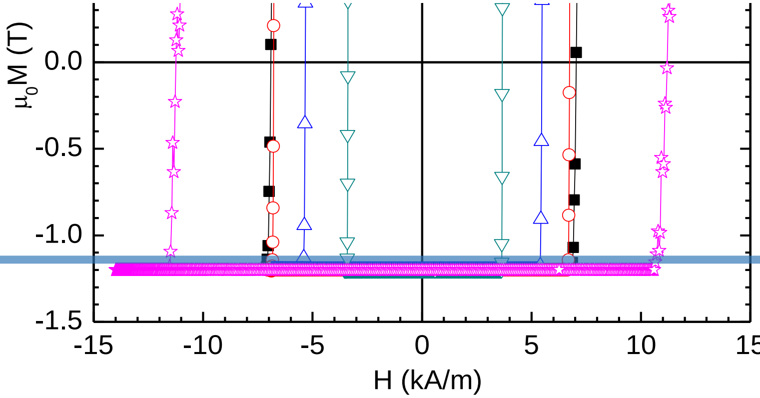


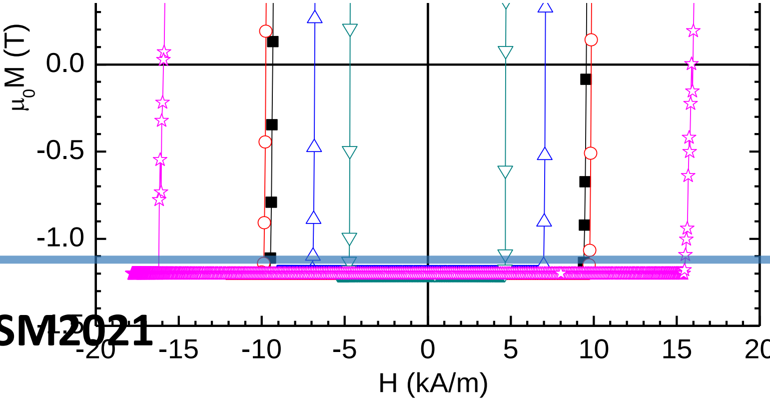
1) all samples are magnetically bistable, irrespective of dimensions and structure;

2) the bistability - *a characteristic of the uniaxially magnetized materials* - indicates the formation of a central magnetic domain in the amorphous state, which is preserved even after annealing at temperatures below 600^{0}C and obtaining of the optimally nanocrystalline state;

3) after annealing at 650^{0}C the bistability is still present;

The inclination of the demagnetization curve appears as a result of the switching field fluctuations (i.e. the nanocrystals growth over the critical limit) and of the averaging over multiple hysteresis loops.





H. Chiriac et al., Crystals 7(2) (2017) 48

Magnetic micro/nanowires

Magnetic properties vs. nanograins

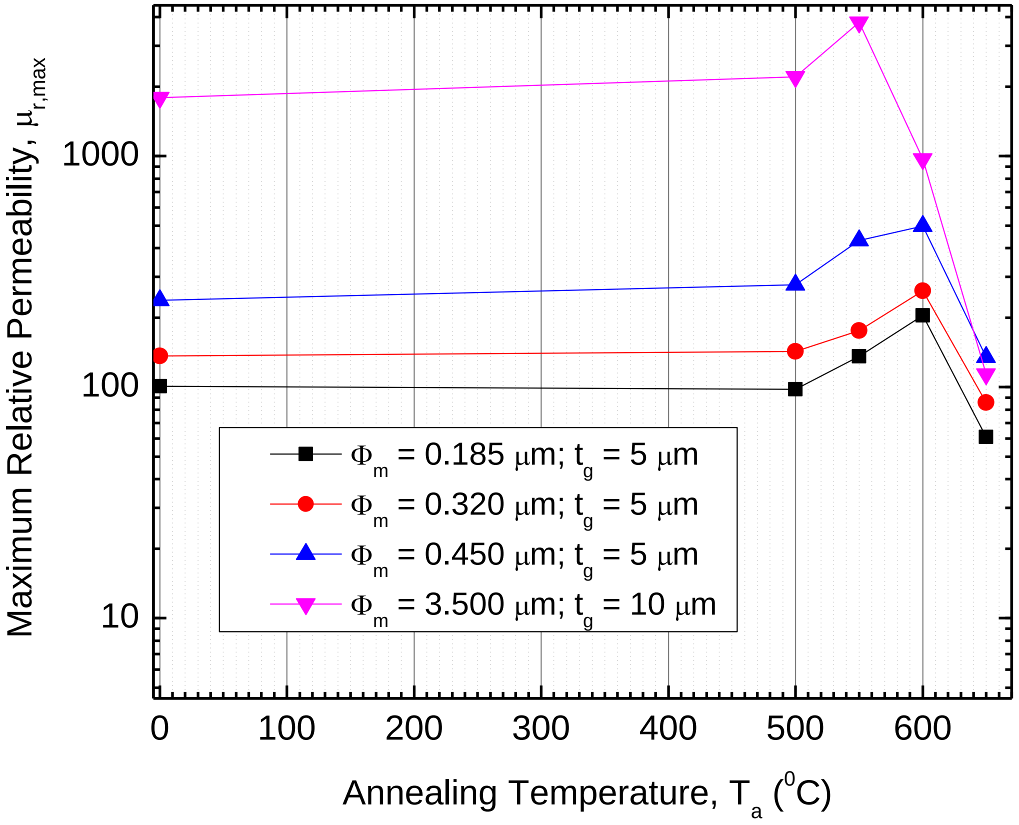
It is well known that:

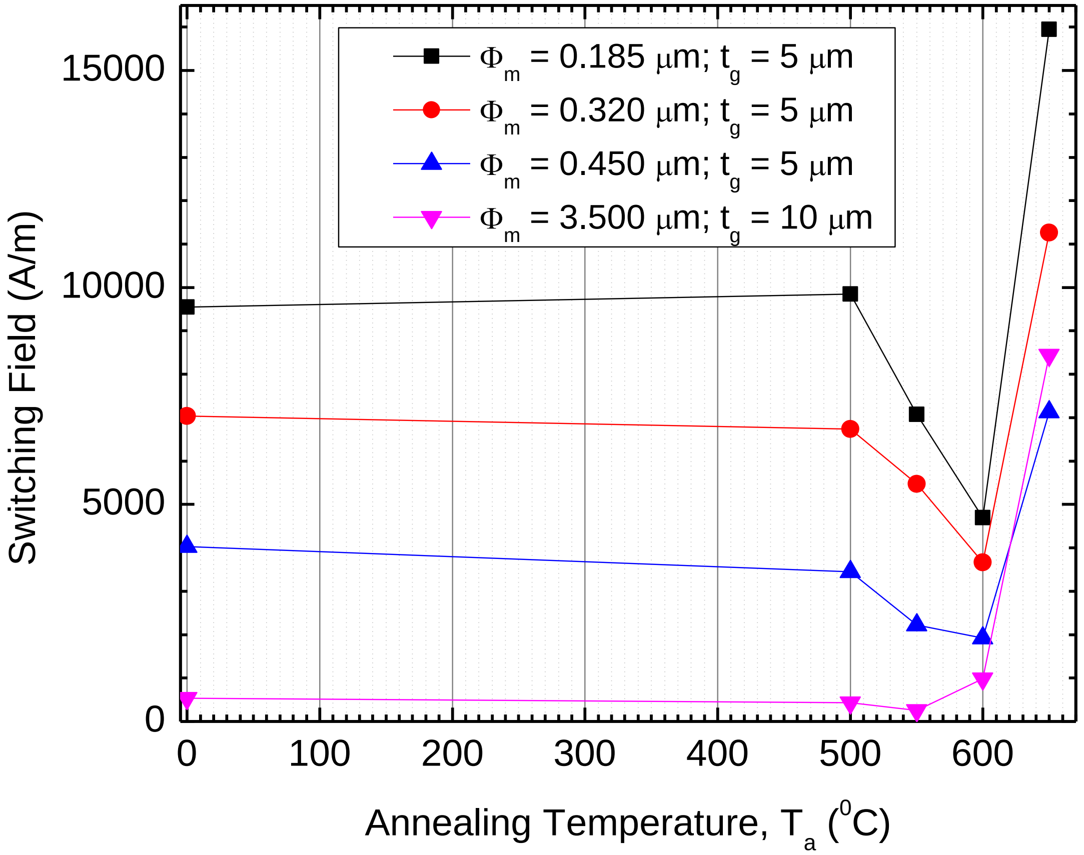
1) if $\delta < L_{ex}$, then the nanosized grains are exchange coupled and they behave as a single phase from the magnetic point of view
2) in the absence of exchange coupling ($\delta > L_{ex}$), the individual nanosized grains do not represent a phase with a well-defined collective magnetic behavior, and, therefore, the magnetic response of the material is determined by the residual amorphous matrix.

In the specific case of the FINEMET submicron wires and nanowires:

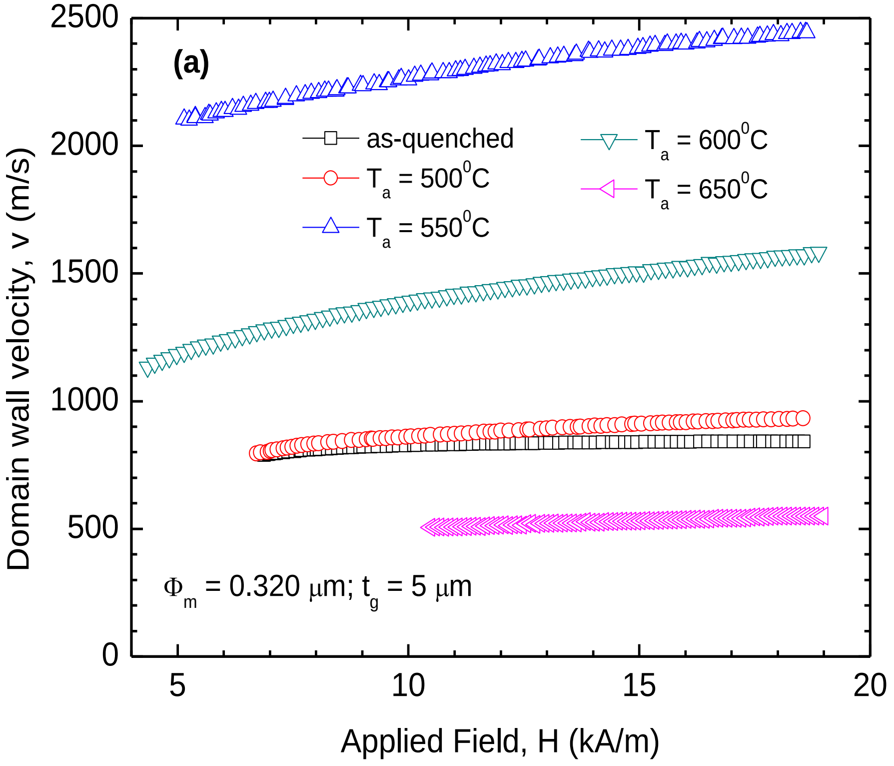
1) the magnetic response is mostly determined by the residual amorphous matrix for annealing temperatures below 600^0C - DO_3 grains are uncoupled or at least not fully exchange coupled
2) optimum soft magnetic properties are reached (maximum permeability and minimum coercivity) after annealing at 600^0C - DO_3 are fully exchange coupled

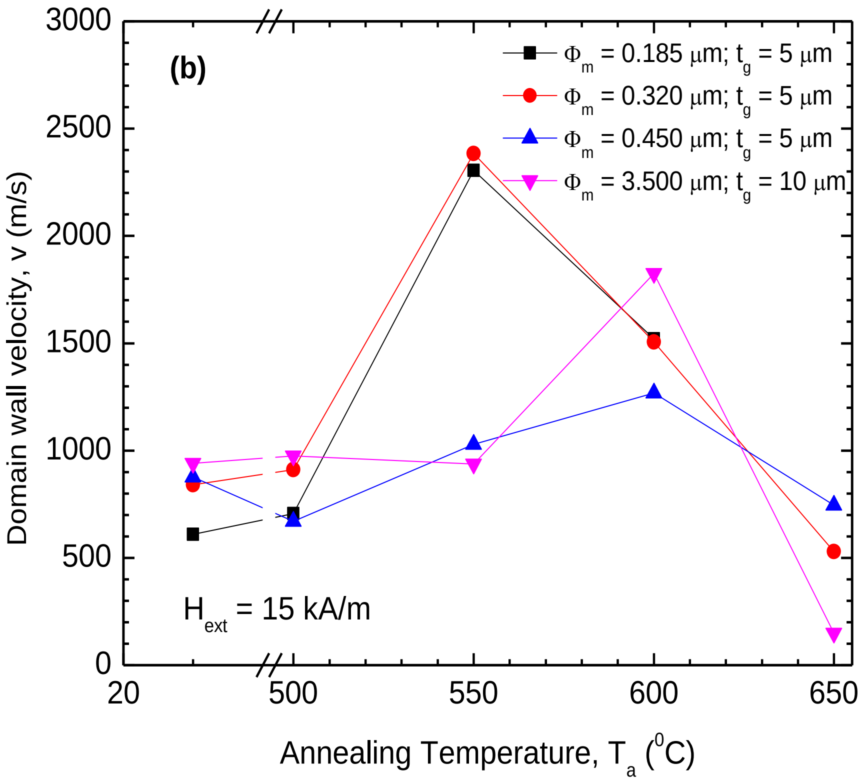
Magnetic micro/nanowires





Domain wall velocity





v > 2000 m/s as a result of the nanocrystalline phase formation after annealing at 550⁰C for 60 min. and starts decreasing by increasing T_a

Larger domain wall velocity values are observed in the ultrathin samples annealed at 550⁰C as compared to those annealed at 600⁰C, when the softest magnetic properties are obtained.

Magnetic micro/nanowires

Applications:

- pulse generator elements and switching devices, in which the sharp magnetization changes over a wide range of frequencies of applied field (large Barkhausen effect jumps can be induced by field strengths as low as 10 A/m (0.125 Oe));
- wires with high permeability can be used as magnetic cores;
- spintronic devices - these cheaper materials could replace nanowires prepared through more complicated and expensive techniques, such as electron and ion beam nanolithography;
- the magnetic bistability of submicron wires allows their direct use to develop devices based on domain wall logic, e.g. one that performs the logical AND function.
- Wires with diameters in the range from hundred of nm to tens of µm are used for the development of magnetic micro-sensors such as: magnetic field, position, identification, security, non-destructive testing with applications in the electronic, automotive, aeronautics, textile, and retail industry, medicine, biology, etc.

The End

Soft magnetic materials and applications

Frequency	Materials	Applications
Static (< 1 Hz)	Soft iron Fe-Co (Permendur) Ni-Fe (Permalloy)	Electromagnets Relays
Low frequency (1 Hz – 1 kHz)	Si steel Permalloy FINEMET Magnetic glasses	Transformers Motors Generators
Audio frequency (100 Hz – 100 kHz)	Permalloy foils FINEMET Metallic Glasses Fe-Si-Al powder (Sendust) Mn-Zn ferrite	Inductors Transformers for switched mode power supplies TV flyback transformers
Radio frequency (0.1 – 1000 MHz)	Mn-Zn ferrite Ni-Zn ferrite	Inductors Antenna rods
Microwave (> 1 GHz)	YIG Li ferrite	Microwave isolators Circulators Phase shifters Filters

Development / History of soft magnetic materials