Soft Magnetic Materials – Hysteresis and eddy current

Learning outcome

At the end of this lecture you will be able to:

- Analyze the hysteresis phenomenon in magnetic materials
- Describe the process of Eddy current in conducting materials
- Compute Eddy current and Hysteresis losses in electrical sheet

Brain storming

- Take 10 min and think of what kind of measurements you need to characterize magnetic materials (electrical steel, e.g.)
- Write down the devices and components needed for these measurements, we will compile the results during the lecture
- List of quantities to measure:
- List of devices needed

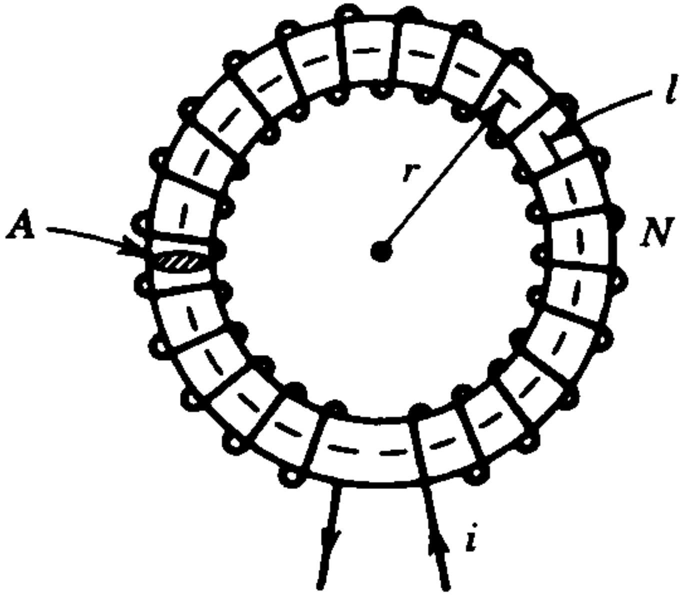
Characterization of magnetic materials: Simple scenario

- The toroid has 2 coils
  - Current is supplied to the first coil to magnetize the core according to Ampere's law
  - Faraday law induces voltage in the second coil whenever the flux is time-varying
- Assume homogeneous flux in the toroid core
- Ampere's law states that:

$$H = \frac{N_1 i}{l}$$

- Faraday law states that

$$B = \frac{1}{N_2 A}\int u(t)dt$$

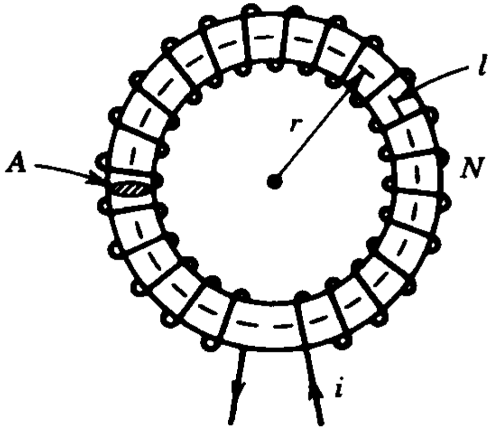


Toroidal core with two windings

- Measuring the current and the induced voltage, allows us to plot the B-H relationship

Magnetic materials and fields: Hysteresis

- Magnetic materials are described by the H-B relationship: permeability.
- This relationship is neither linear nor single-valued.
- The curves are obtained by increasing the current to a given value and then reversing it to the opposite value (slow process avoids dynamic effects)



$$H = \frac{N_1 i}{l}$$

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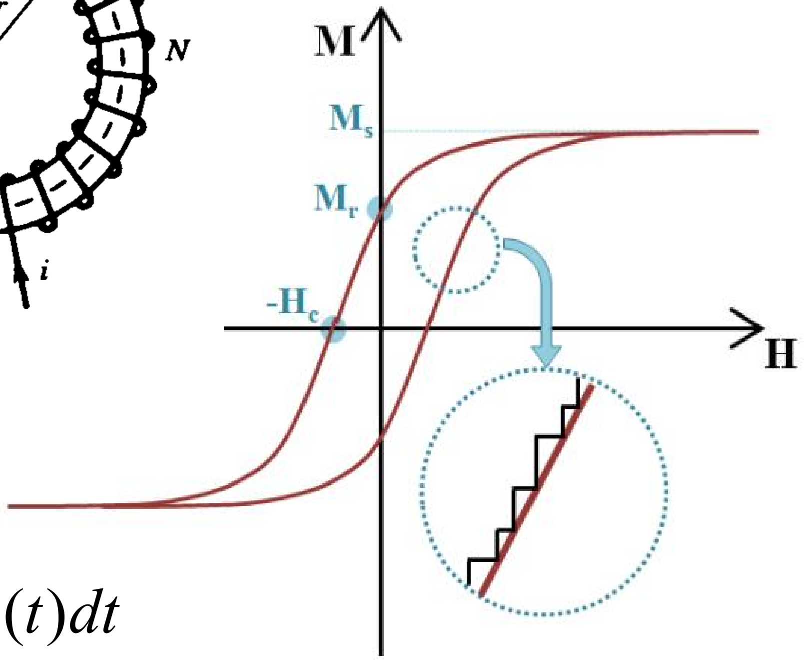
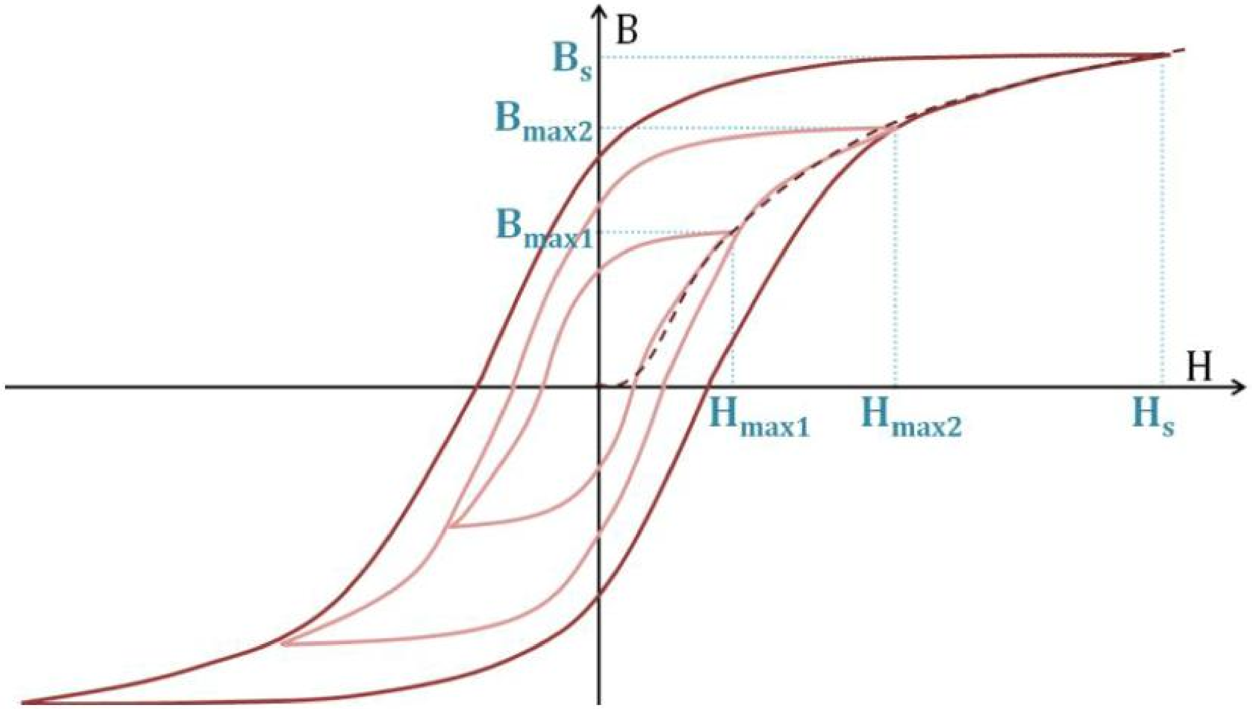
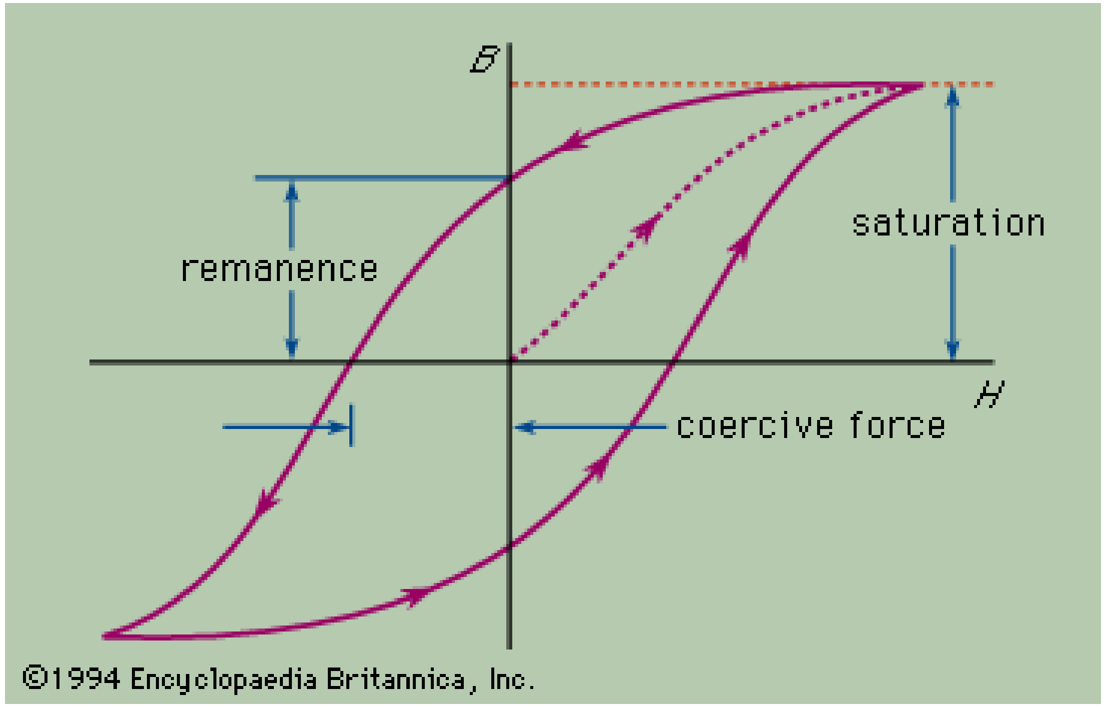




Characteristics of electrical steel: Hysteresis

- B-H relationship is nonlinear and multi-valued; B lags behind H
- B_r residual flux density (H=0)
- H_c coercitive magnetic field strength (B=0)
- The locus of the tip of the hysteresis loops is the magnetization curve



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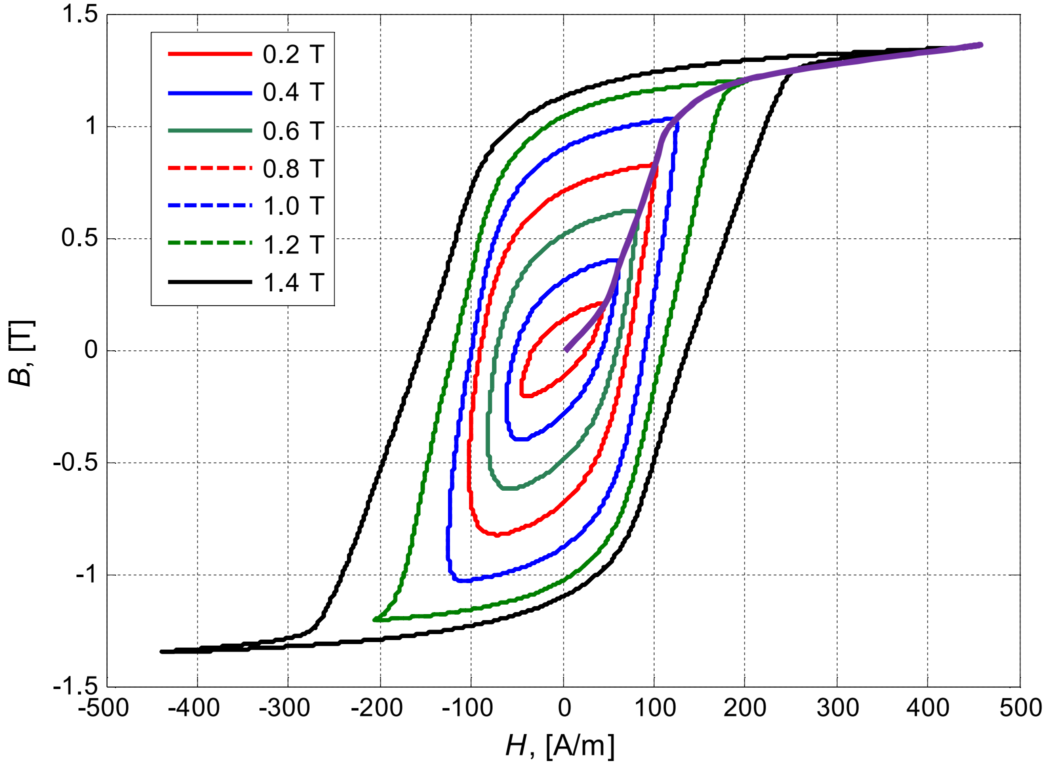


Soft magnetic materials

- Soft magnetic materials usually mean materials with
  - Low coercivity (H_c=1 – 100 A/m)
  - Low field to saturation (H=1000 – 5000 A/m)
  - High saturation flux density (B= 1 – 2 T)

- Such material class includes:
  - Low-carbon steels (construction steel sheet used in small household appliance motors)
  - Non-oriented Fe-Si laminations
  - Grain-oriented Fe-Si laminations
  - Amorphous alloys
  - Fe-Ni and Fe-Co cores
  - Powder cores (SMC)
  - Soft ferrites

	Max relative permeability	Coercivity (A/m)	Saturation polarization (T)
Polycrystalline Fe	3 – 50.10^3	10 – 100	2.16
NO Fe 1.0 wt % Si	3 – 10.10^3	30 – 80	1.96 – 2.12
GO Fe 3 wt % Si	15 – 80.10^3	4 – 15	2.02
Bounded-sintered Fe powder	10^2 – 10^3	100 – 500	1.65 – 1.95
$Fe_{50}Ni_{50}$	10^5	4	1.60
Sintered ferrites (Mn-Zn and Ni-Zn	Mn-Zn 10^3 – 10^4 Ni-Zn 10^2 – 10^3	5 – 20 20 – 200	0.4 – 0.5 0.2 – 0.35
Amorphous alloys (Fe- and Co-based	10^5	2 – 5	1.56

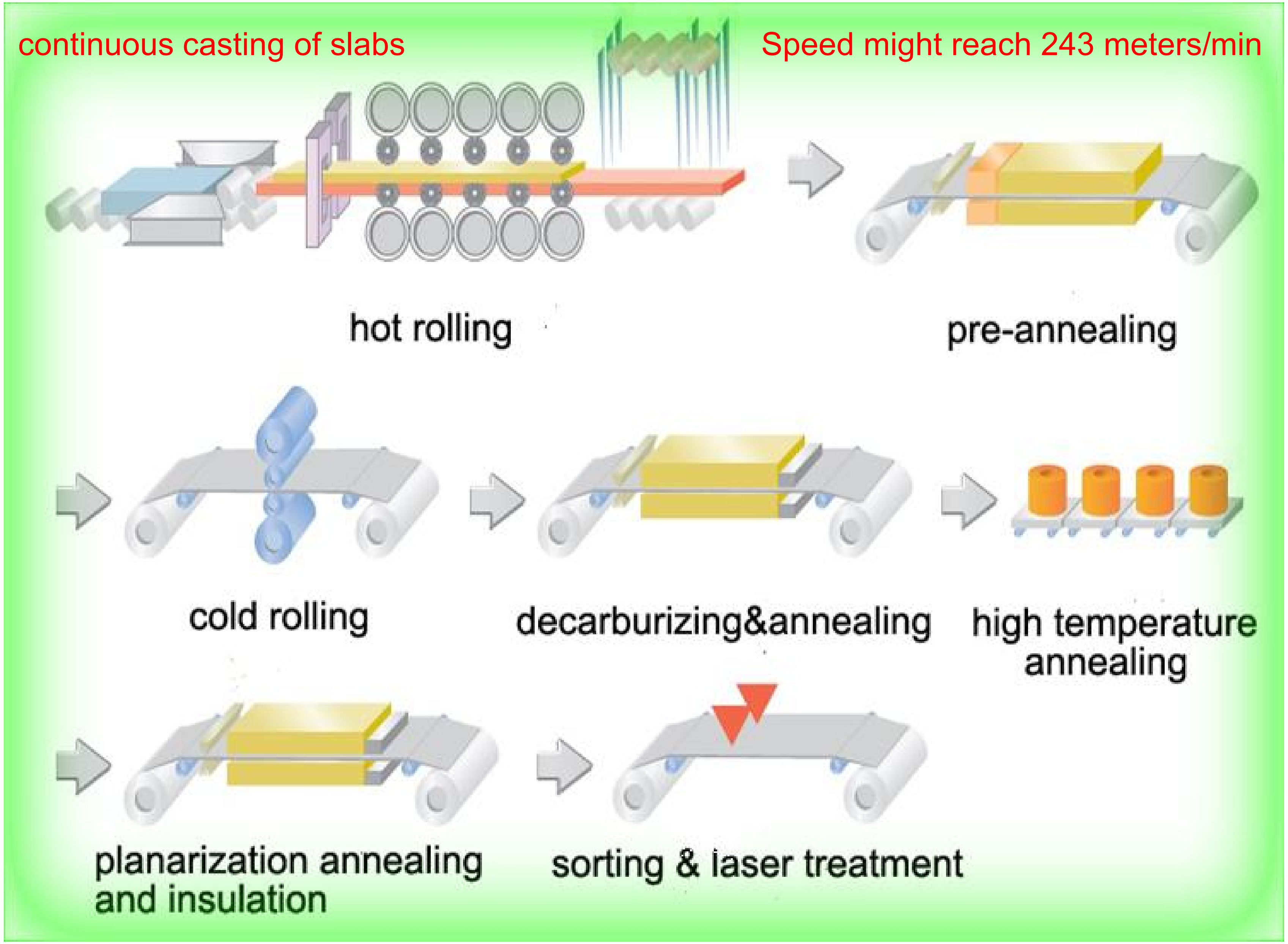
Soft magnetic materials

- High purity iron contains few 100 ppm of impurity (C, N, O, P, S, Si, Al)
  - Not common, used only for special purposes (calibration)
- Steel usually has higher carbon contents, Low Carbon Steel
- In soft magnetic materials, Silicon is intentionally diluted in iron. Silicon steel
  - Decrease saturation and coercivity
  - Increase resistivity
  - Decrease AC losses
  - Increase mechanical hardness
- Standard materials (NO):

  IEC 60404-8-2, IEC 60404-8-4
  IEC 60404-8-6, IEC 60404-8-8

  - Other standards also exist

Soft magnetic materials – Manufacturing process



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Preparation stages - fully processed NO Fe-Si laminations

- Composition [wt%]: Si (0.9…3.7), Al (0.2…0.8), Mn (0.1…0.3).
- Melting, degassing, continuous casting of slabs.
- Re-heating (1000 °C – 1250 °C) and hot rolling to thickness 1.8 mm - 2.3 mm.
- Pickling and cold rolling to intermediate gauge.
- Intermediate annealing (750 °C – 900 °C).
- Cold rolling to final gauge (0.65 mm – 0.35 mm).
- Decarburization and re-crystallization annealing (830 °C – 900 °C).
- Final grain-growth annealing (850 °C – 1100°C).
- Coating.
- Punching and core assemblage (this is the device manufacturing process)

Standards and meanings

- IEC: International Electrotechnical Commission
  - 250-35A5: 2.5 W/kg losses at 50 Hz (1.5T peak induction), 0.35 mm thickness
- JIS: Japanese Industrial Standards
- AISI: American Iron and Steel Institute
- ASTM: American Society for Testing and Material
- EN: European Norm
- GOST/ГОСТ (SUST): State Union Standard

IEC 404-8-4 (1986)	EN 10106 (1995)	AISI	ASTM A677 (1989)	JIS 2552 (1986)	GOST 214270-75
250-35A5	M235-50A	M15	36F145	35A250	2413
270-35A5	M270-35A	M19	36F158	35A270	2412
290-50A5	M290-50A	M15	47F168	50A290	2413
310-50A5	M310-50A	M19	47F174	50A310	2412

Hysteresis eddy current and losses

- Magnetic materials present hysteresis and they are conductors.

- Hysteresis means that the flux or flux density does not establish immediately when the current or filed strength is established
  - the flux density is lagging behind the field strength.

- The conductivity of the material means that it is subject to Faraday law in the same manner as other non magnetic conductors.

- Eddy currents are induced in the conducting magnetic material as a consequence of time-varying magnetic flux density

Investigation work 20 min

- Look in internet for the difference between alternating and rotating hysteresis (5 min)

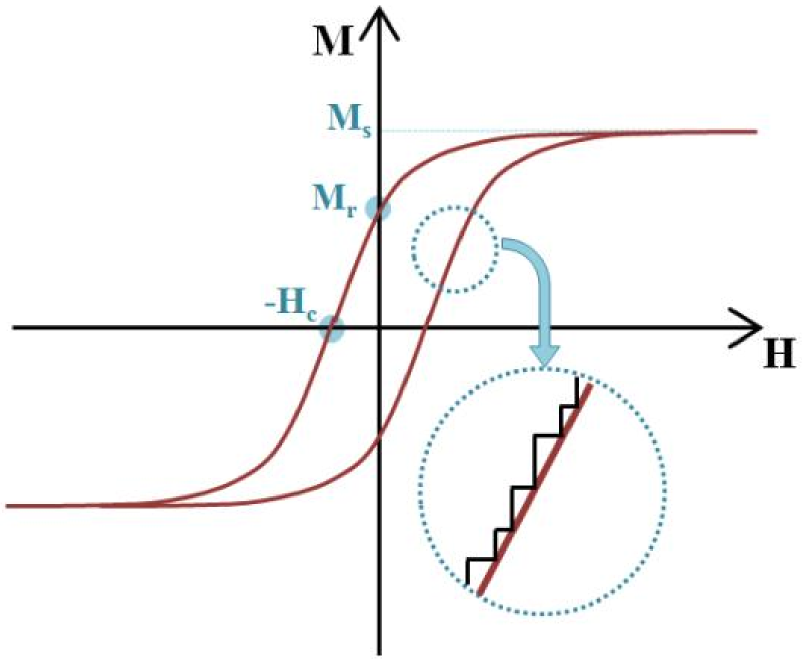
- With your mates, decide on what are the most important differences (5 min)

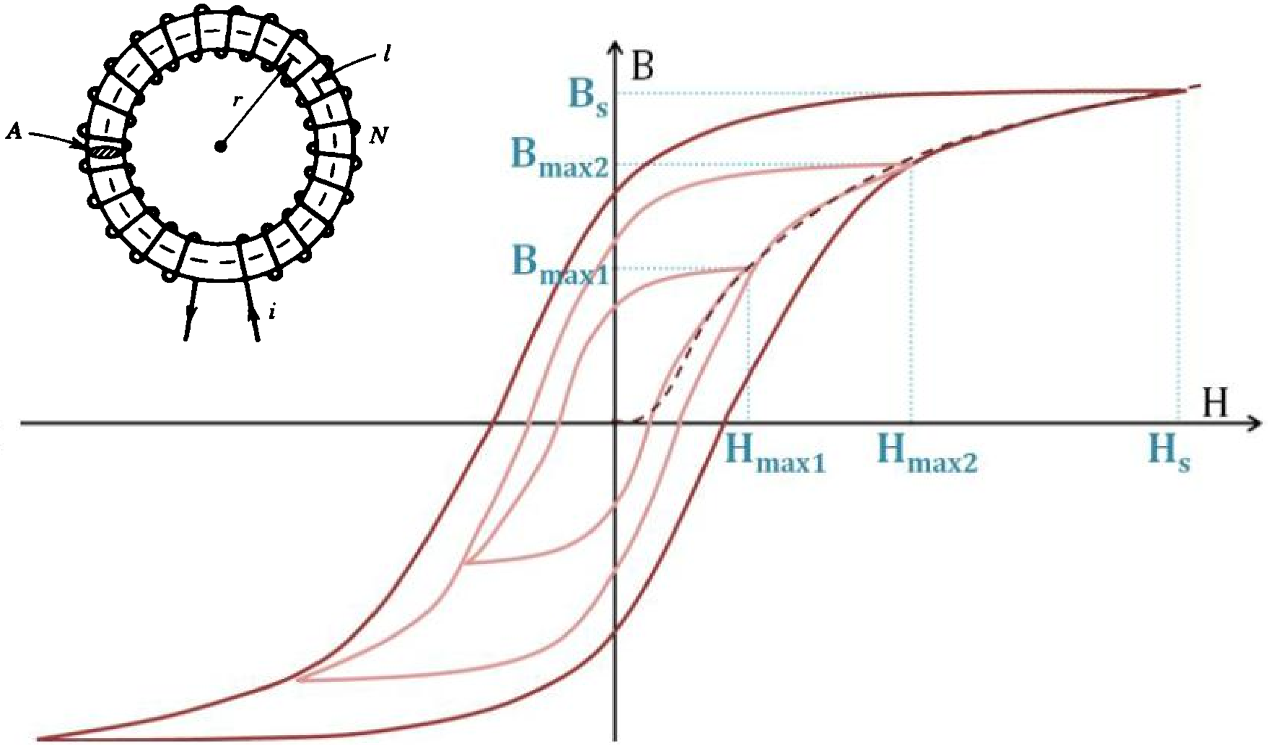
- Present your list and decision to the class (10 min)

  - You might use internet

Alternating hysteresis

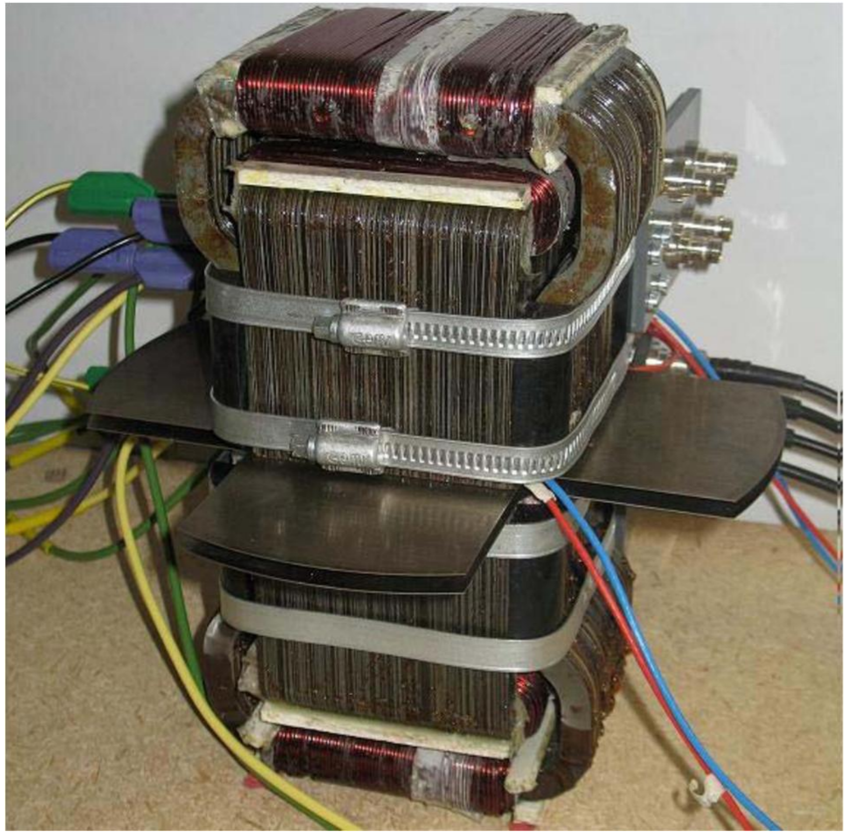
- Experience with the toroid:
  - In a very slow process, increase the current and then reverse it to the opposite value and draw the HB-curve
- The obtained curve is a unidirectional or alternating hysteresis characteristic

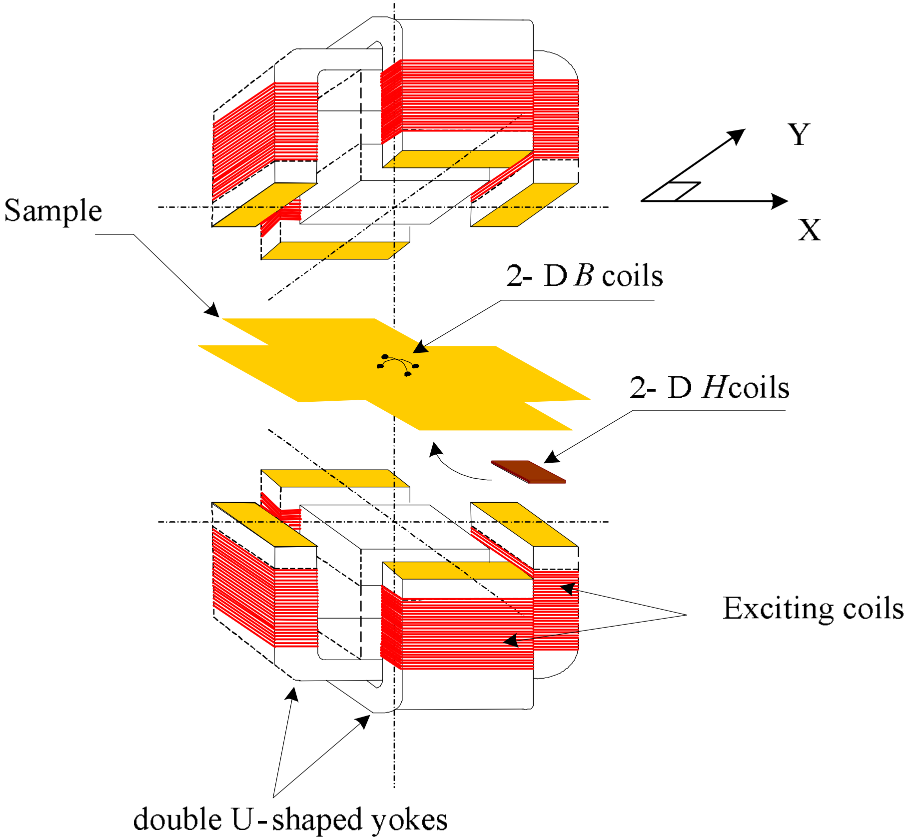




Rotational hysteresis

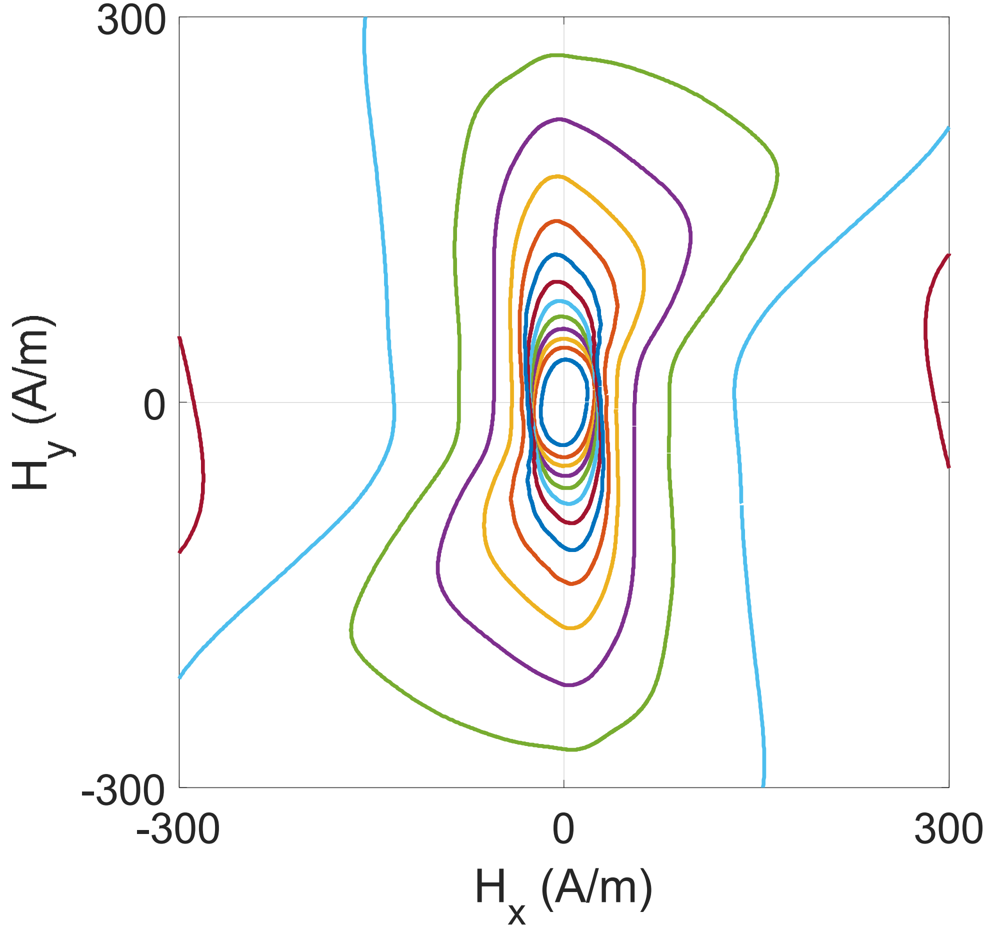
- Consider the single sheet tester below.
- The flux density in the sheet can be controlled to a rotational form
- In a very slow process, while keeping the flux density amplitude constant, increase its angle with respect to the x-axis and draw the ***H***-locus (H_xH_y)

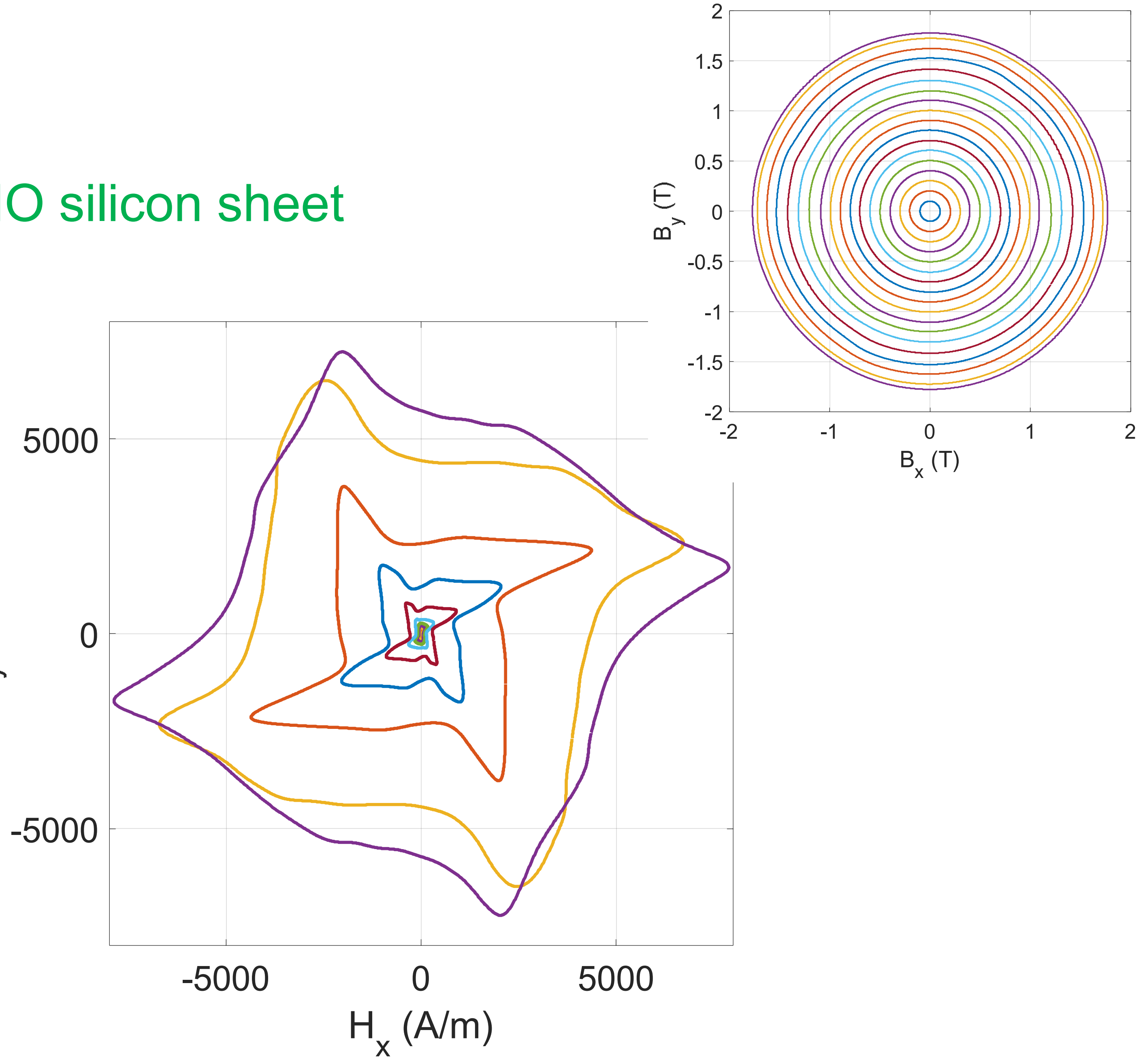




Rotational hysteresis

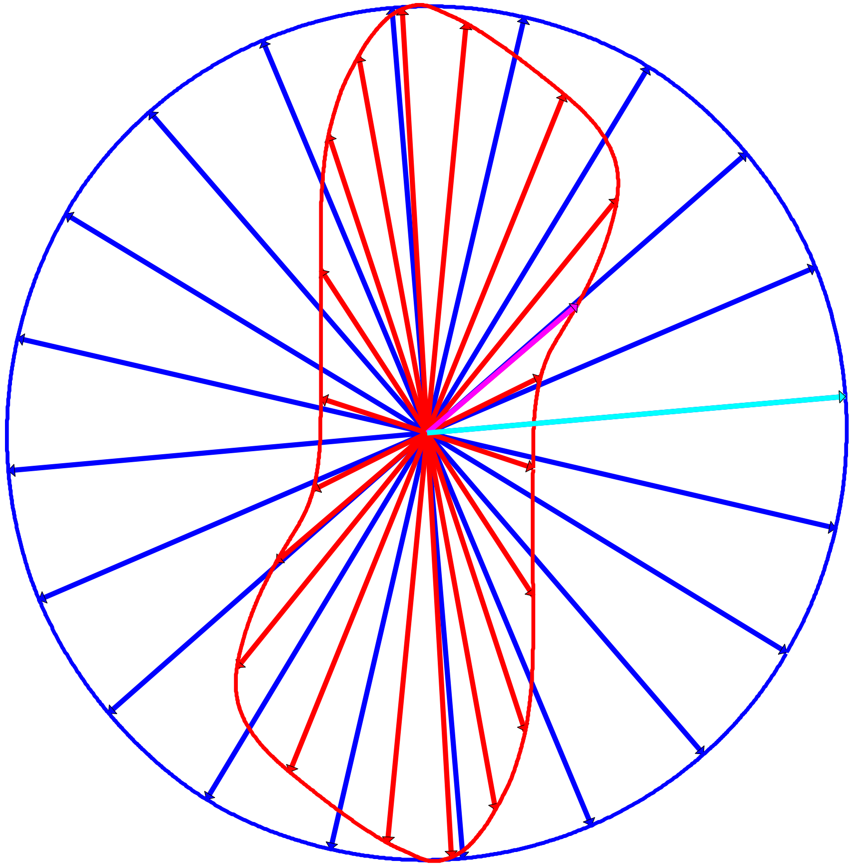
- Measured ***B***- and ***H***-loci for a NO silicon sheet

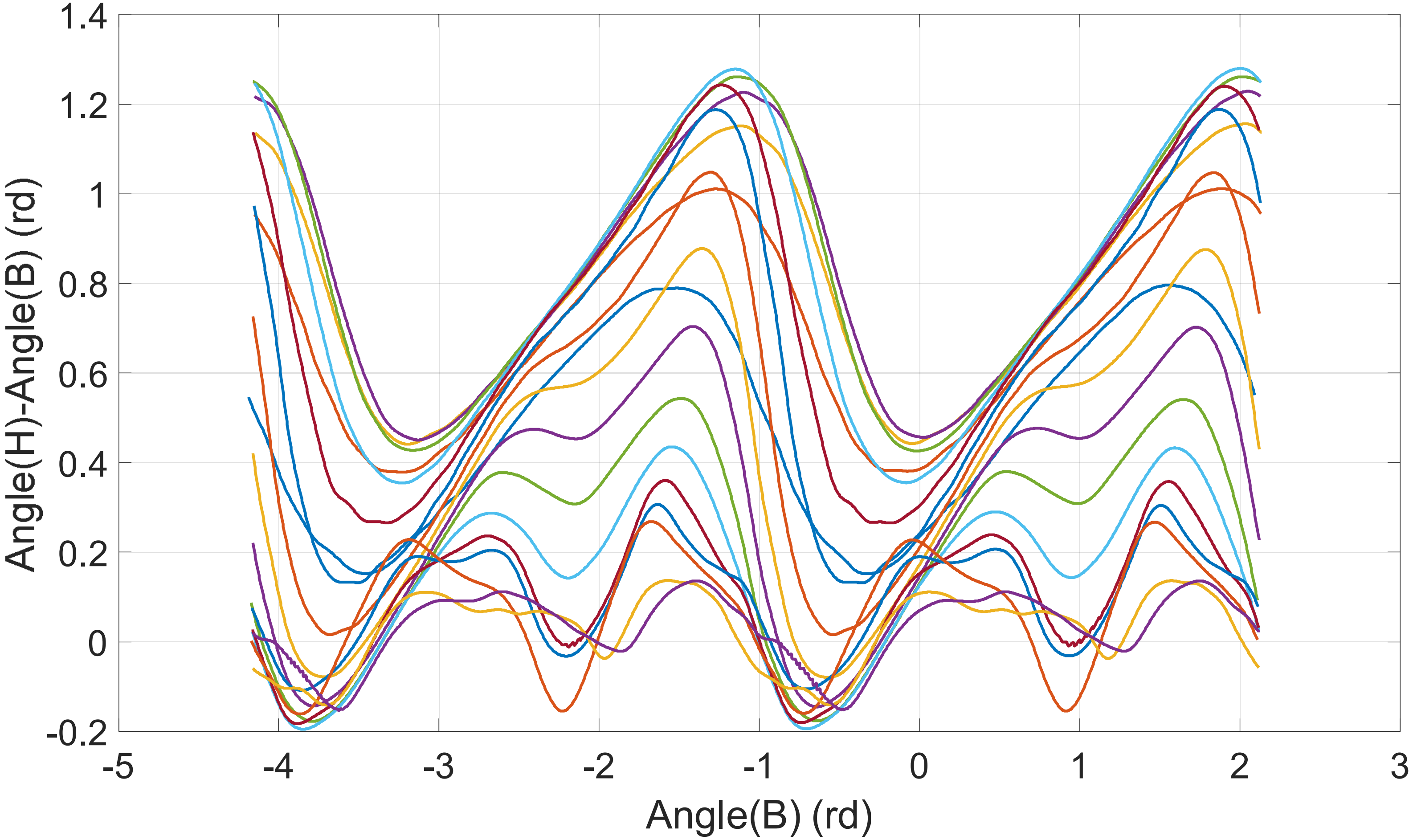




Rotational hysteresis

- Phase angle between ***B*** and ***H***
- ***B*** is never alternating or rotating in actual device it is more or less elliptic



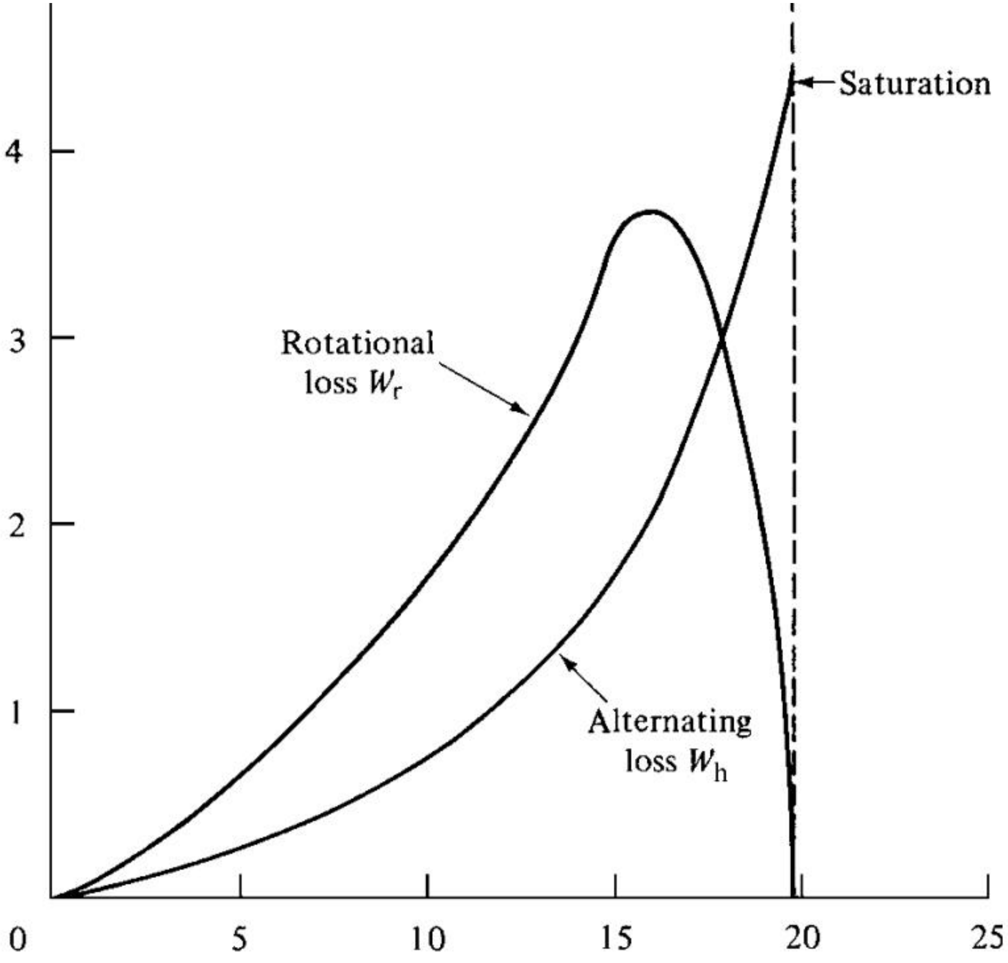


Rotational hysteresis

- The magnetization process is different in alternating and rotating field
- This is seen in the hysteresis loss behavior

$$P_{hys} = \frac{1}{T}\int_0^T \boldsymbol{H}.d\boldsymbol{B}$$

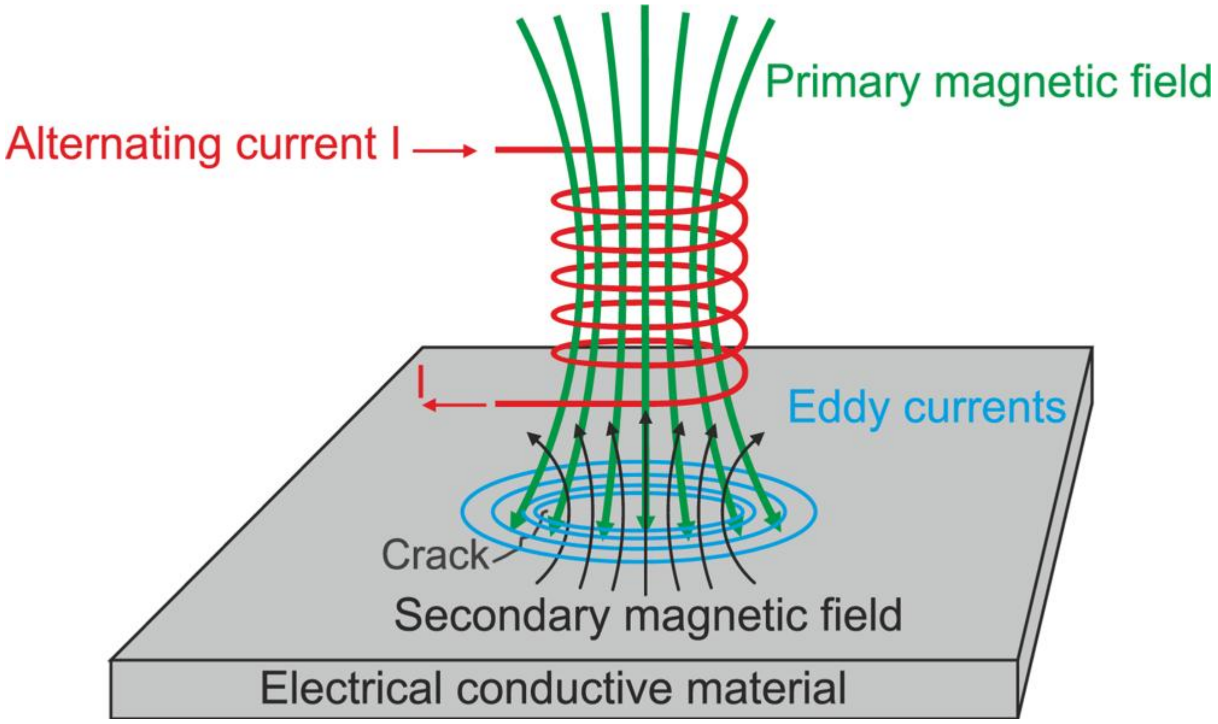
$$= \frac{1}{T}\int_0^T H_x dB_x + H_y dB_y$$

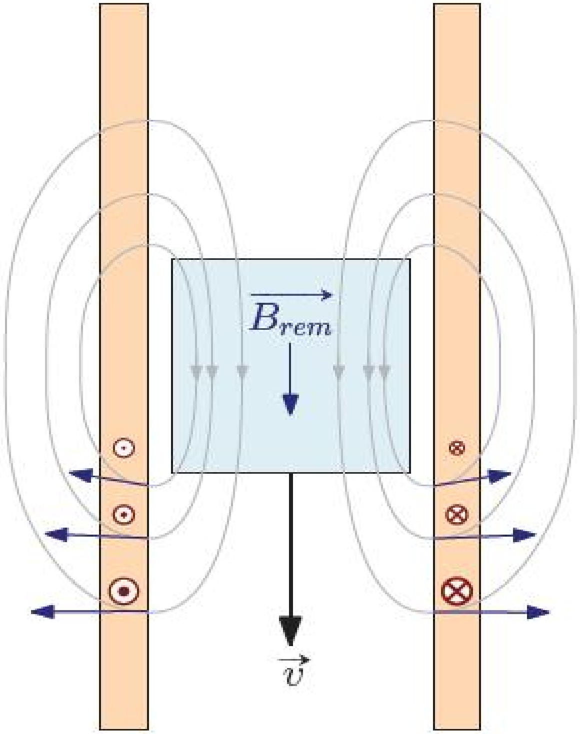


Eddy current

- Eddy currents are induced in the conducting magnetic material as a consequence of time-varying magnetic flux density and Faraday law

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad J = \sigma E$$





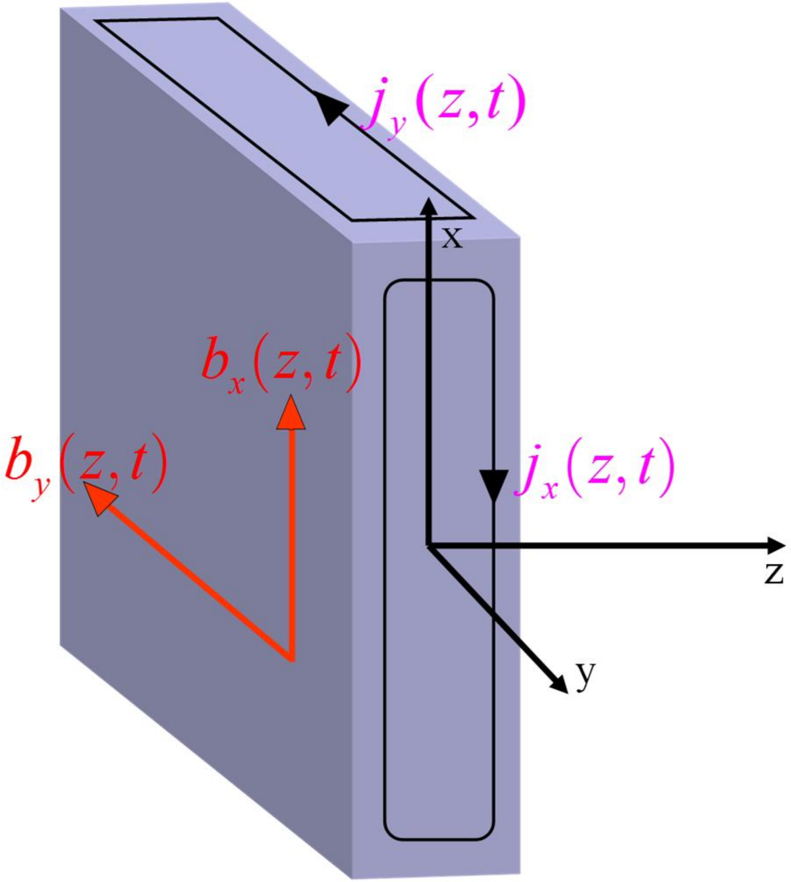
Eddy current

- Eddy currents in electrical sheet are generally 3-dimensional
- If the return path is short and can be ignored, the problem reduces to two separated 1D problems
- The two problems are coupled through material characteristics

$$\frac{\partial^2 h_x(z,t)}{\partial z^2} = \sigma \frac{\partial b_x(z,t)}{\partial t}$$

$$\frac{\partial^2 h_y(z,t)}{\partial z^2} = \sigma \frac{\partial b_y(z,t)}{\partial t}$$

$$\boldsymbol{j} = j_x(z,t)\boldsymbol{e}_x + j_y(z,t)\boldsymbol{e}_y$$



Eddy current

alternating_field_and_EC.avi

rotating_field_and_EC.avi

$$P_{eddy} = \int_V \left(\frac{1}{T} \int_0^T \frac{J^2}{\sigma} dt \right) dV$$

Soft Magnetic Materials – material types

Learning outcome

At the end of this lecture you will be able to:

- List different materials and how they are manufactured
- Describe the physical properties of these materials
- Explain the magnetic and mechanical coupling of these materials
- Explain how this coupling affects some of their properties

Brain storming

- Take 10 min and think of what are the most important physical properties of soft magnetic materials
- Write them down, we will compile the results during the lecture
- List of quantities to measure:

No Oriented electrical sheets

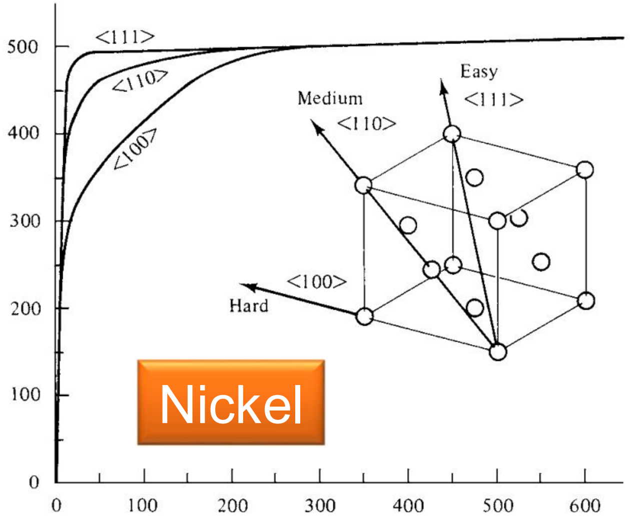
- Fe-Si alloy used in rotating electrical machines and small transformers
- Coercive field Hc = 40 - 80 A/m
- The magnetocrystalline anisotropy decreases with increasing Si
- A phosphate-based or chromate-based coating thickness 0.5 µm – 5 µm
  - provides the necessary interlaminar insulation, and ensures good lamination punchability
- Never isotropic, exhibiting some 10% - 20% variation of the loss along different directions in the lamination plane
- Gauge of 0.35 mm – 0.50 mm
  - Losses: 2.10 – 2.30 W/kg at 1.5 T and 50 Hz
  - Induction: of 1.50 – 1.60 T at 2500 A/m.
- Gauge of 0.10 mm to 0.27 mm for high speed machines
- Main producers : ThyssenKrupp Electrical Steel GmbH, Mittal-Arcelor, Nippon Steel Corporation, Cogent Steel, POSCO Steel.

Grain Oriented electrical sheets

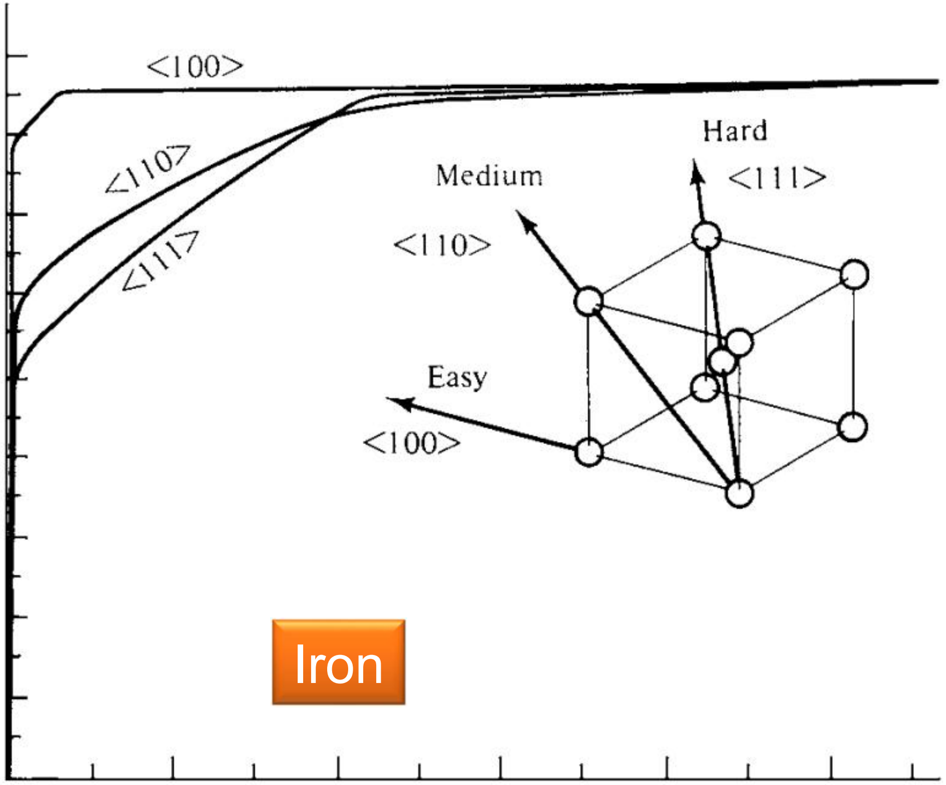
- Applied field must do work against anisotropy:
  - Crystal anisotropy energy *E* is stored in any crystal.
  - *E* can be expressed in terms of a series expansion of the direction cosines of M_s
  - In a cubic crystal, let M_s make angles a, b, c with the crystal axes, and α_1, α_2, α_3 the cosines of these angles, which are called direction cosines

$$E = K_0 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + \cdots$$

  - Only K_1 is important and is expressed in J/m^3



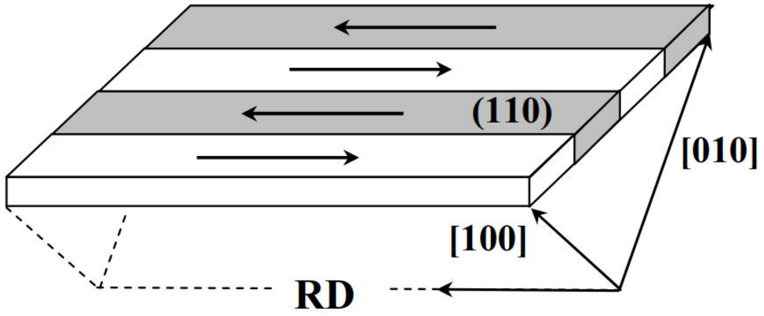
Nickel

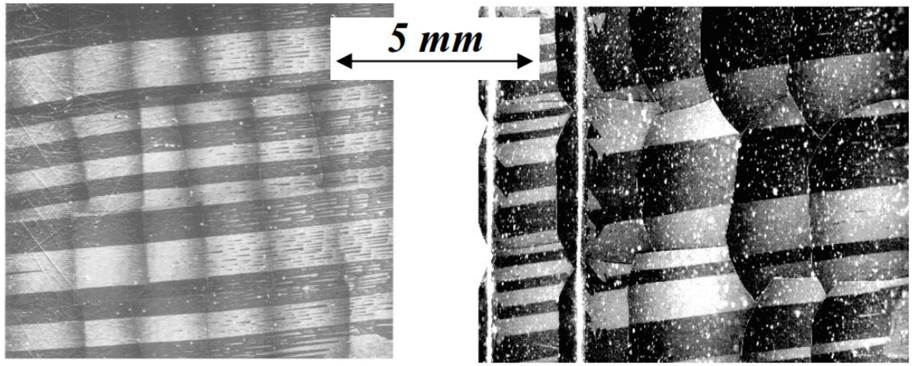


Iron

Grain Oriented electrical sheets

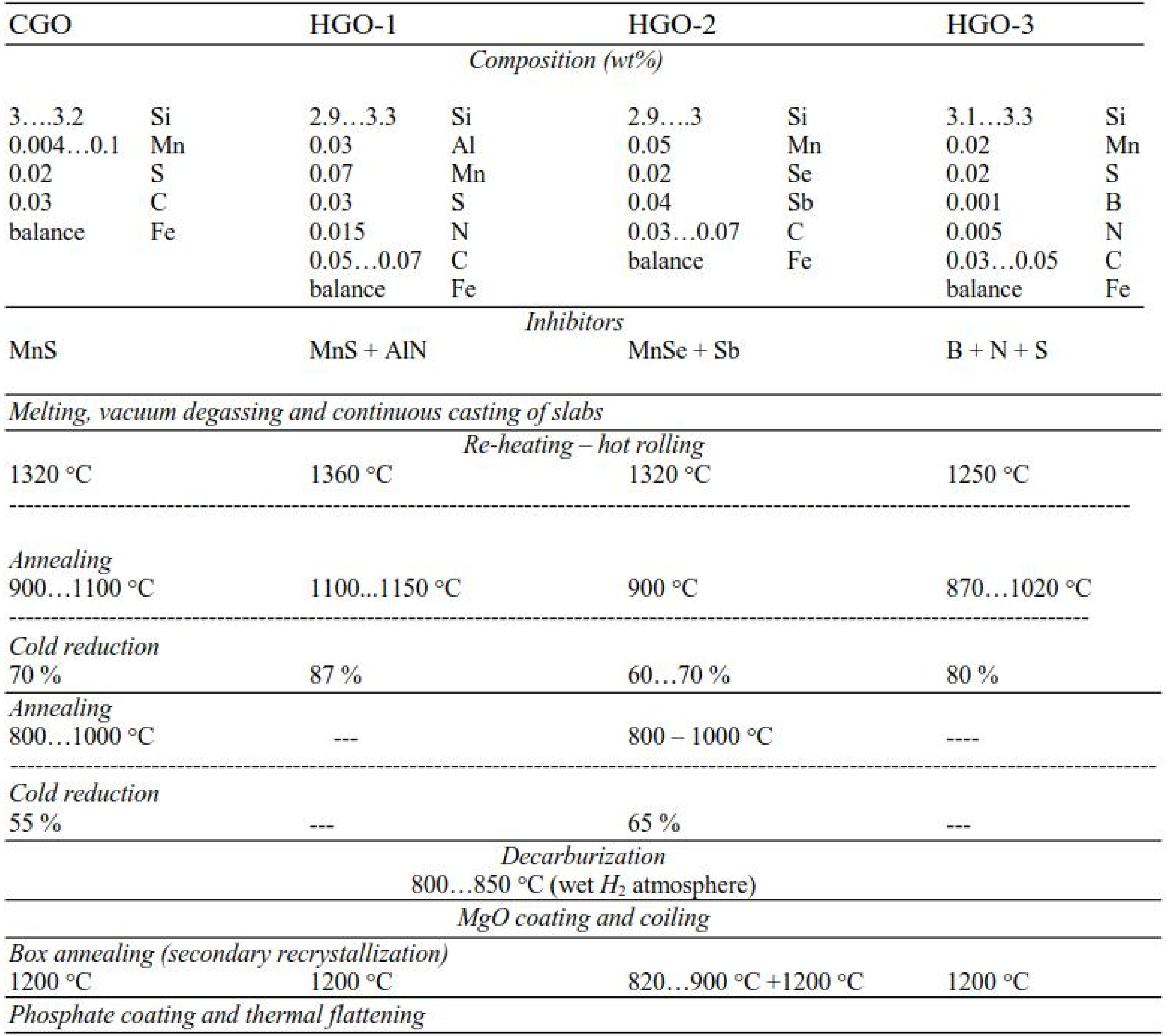
- Grain-oriented (GO) Fe-Si laminations, the crystallites have their easy axis close to the rolling direction (RD) and the (110) plane nearly parallel to the lamination surface
  - This is the so-called Goss texture
  - large grain size (from a few millimeters to a few centimeters)
  - little content of impurities, coercive fields as low as 4 – 10 A/m





- conventional grain oriented (CGO) and high permeability (HGO) alloys
  - Dispersion of the [001] axes of the crystallites around RD ~7° and ~3°, respectively
  - W17/50 = 1.40 – 0.80 W/kg at 1.7 T and 50 Hz

Some parameters of the manufacturing process



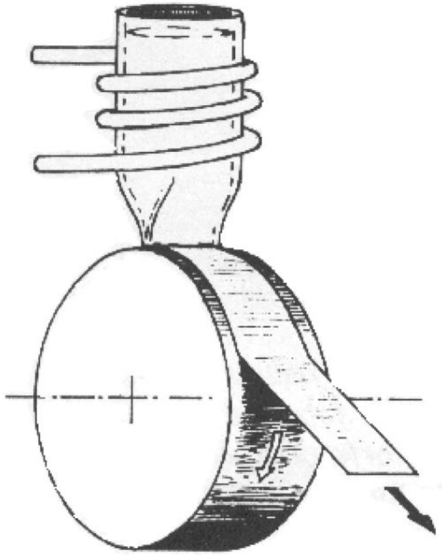
CGO		HGO-1		HGO-2		HGO-3	
Composition (wt%)							
3….3.2	Si	2.9…3.3	Si	2.9….3	Si	3.1…3.3	Si
0.004…0.1	Mn	0.03	Al	0.05	Mn	0.02	Mn
0.02	S	0.07	Mn	0.02	Se	0.02	S
0.03	C	0.03	S	0.04	Sb	0.001	B
balance	Fe	0.015	N	0.03…0.07	C	0.005	N
		0.05…0.07	C	balance	Fe	0.03…0.05	C
		balance	Fe			balance	Fe
Inhibitors							
MnS		MnS + AlN		MnSe + Sb		B + N + S	
Melting, vacuum degassing and continuous casting of slabs							
Re-heating – hot rolling							
1320 °C		1360 °C		1320 °C		1250 °C	
Annealing							
900…1100 °C		1100...1150 °C		900 °C		870…1020 °C	
Cold reduction							
70 %		87 %		60…70 %		80 %	
Annealing							
800…1000 °C		---		800 – 1000 °C		----	
Cold reduction							
55 %		---		65 %		---	
Decarburization							
800…850 °C (wet H_2 atmosphere)							
MgO coating and coiling							
Box annealing (secondary recrystallization)							
1200 °C		1200 °C		820…900 °C +1200 °C		1200 °C	
Phosphate coating and thermal flattening							

Amorphous alloys

- Ribbons of variable width (up to 100 - 200 mm)
- Thickness ranging between 15 µm and 40 µm.
- The composition of soft magnetic amorphous alloys is T70-80M30-20
  - T=Fe, Co, and Ni
  - M=combination of metalloids (e.g. B, Si, P, C)
- Fe-based ribbons reach at best coercive fields of 2- 3 A/m.
- Very high fracture stress σr ~ 2800 Mpa
- Electrical resistivity increased by a factor of 2-3 with respect to their crystalline counterpart

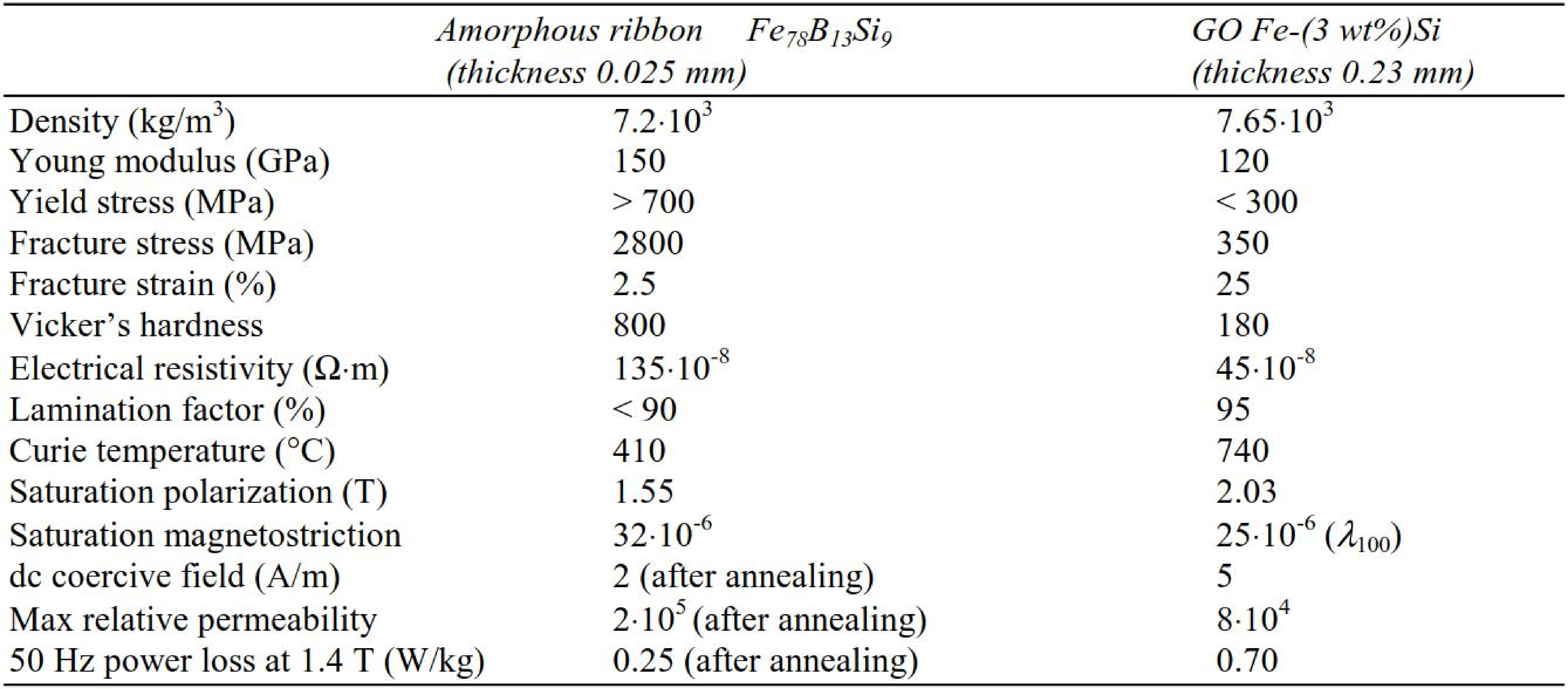
Amorphous alloys

- One may describe an amorphous alloy as a random ensemble of structural units, each extending over a distance δ equal to a few atomic spacing
- Lack of crystalline order does not prevent the formation of ferromagnetic order
- unique combination of mechanical hardness and magnetic softness
- know as noncrystaline or metallic glasses (metaglass)



- velocity of 10 – 40 m/s
- Cooling rate $10^5 – 10^6$ °C/s

Some properties of amorphous materials



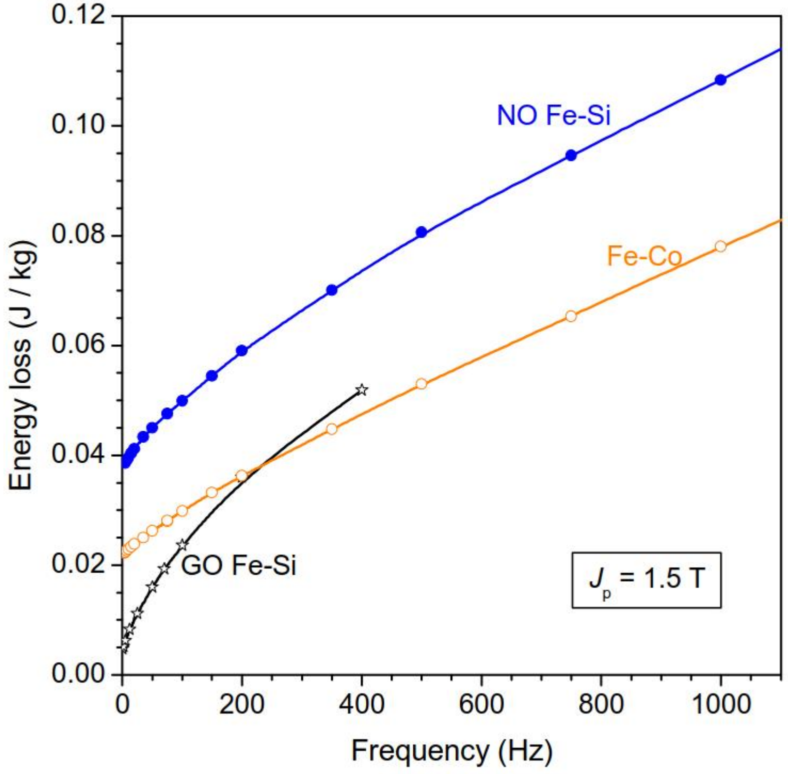
	Amorphous ribbon $Fe_{78}B_{13}Si_9$ *(thickness 0.025 mm)*	*GO Fe-(3 wt%)Si (thickness 0.23 mm)*
Density (kg/m^3)	$7.2\cdot10^3$	$7.65\cdot10^3$
Young modulus (GPa)	150	120
Yield stress (MPa)	> 700	< 300
Fracture stress (MPa)	2800	350
Fracture strain (%)	2.5	25
Vicker's hardness	800	180
Electrical resistivity ($\Omega\cdot m$)	$135\cdot10^{-8}$	$45\cdot10^{-8}$
Lamination factor (%)	< 90	95
Curie temperature (°C)	410	740
Saturation polarization (T)	1.55	2.03
Saturation magnetostriction	$32\cdot10^{-6}$	$25\cdot10^{-6}$ (λ_{100})
dc coercive field (A/m)	2 (after annealing)	5
Max relative permeability	$2\cdot10^5$ (after annealing)	$8\cdot10^4$
50 Hz power loss at 1.4 T (W/kg)	0.25 (after annealing)	0.70

Fe-Ni and Fe-Co

- Alloying Fe with Co increses the saturation and the Curie temperature
- Fe-Co alloys are used in
  - Pole pieces of electromagnets
  - Beam-focusing lenses for electron microscopes
  - Aircraft motors, generators, and transformers
  - Standards IEC 60404-8-6.

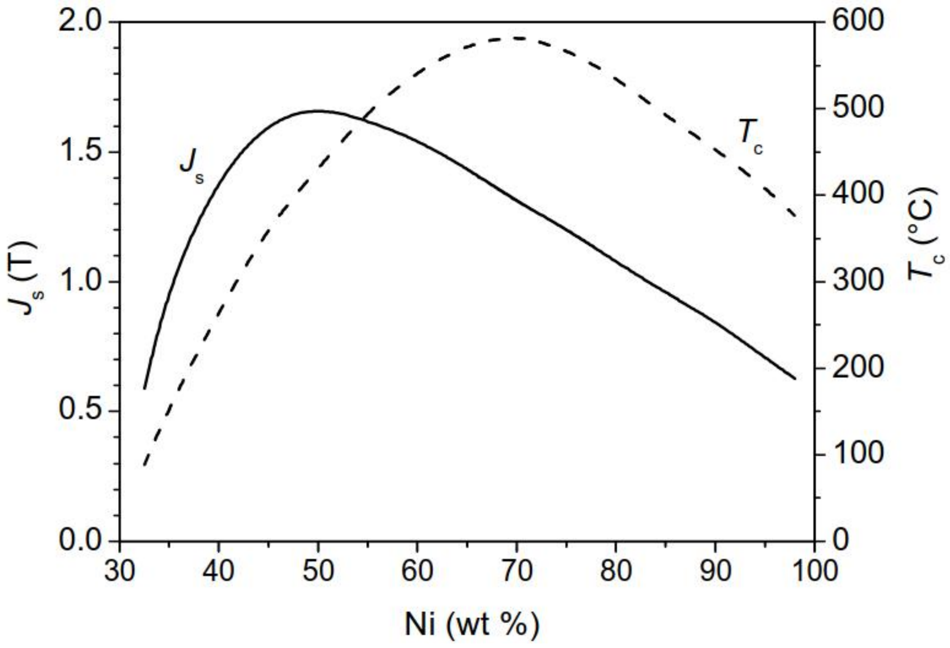
Energy losses versus frequency in Fe-Si and Fe-Co laminations:

- 0.195 mm thick NO Fe-(3 wt%)Si
- 0.290 mm thick GO Fe-(3 wt%)Si
- 0.201 mm thick Fe49Co49V2 (Vacoflux50).



Fe-Ni and Fe-Co

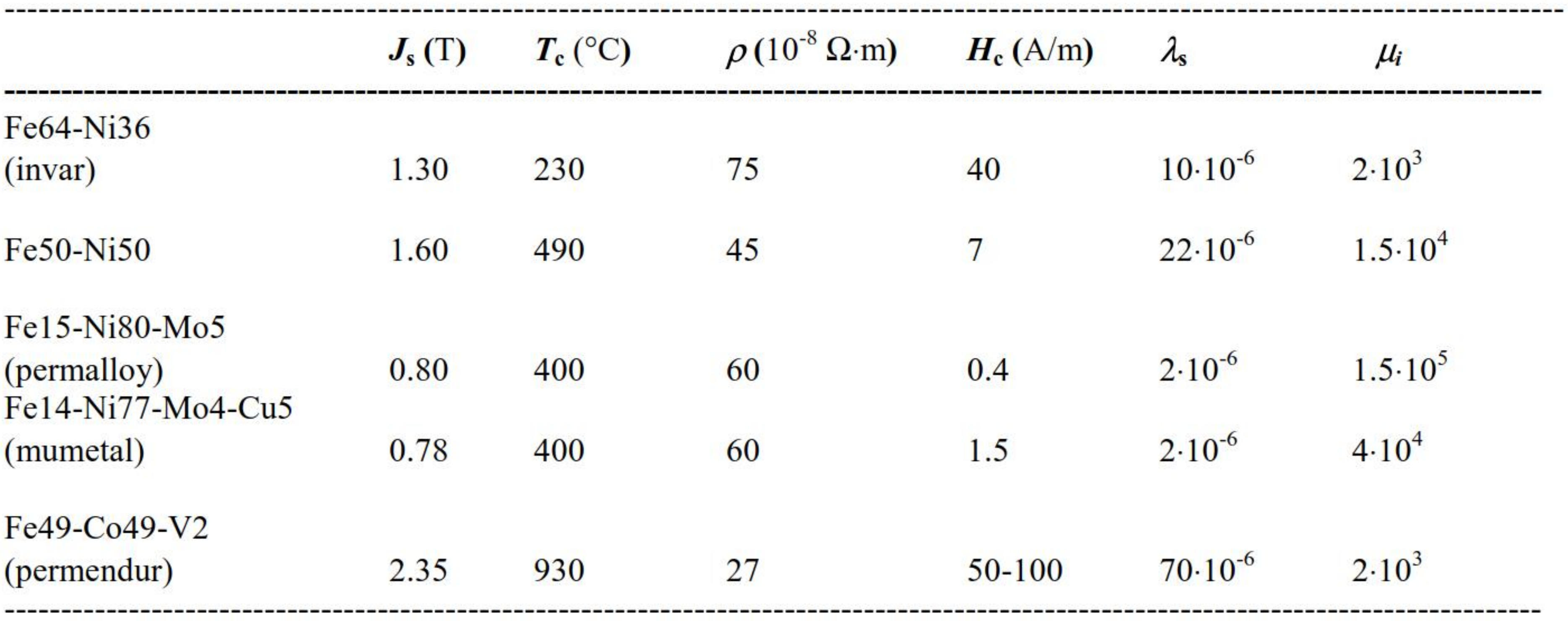
- Alloying with Ni decreases the anisotropy constant and make the material isotropic
- Fe-Ni and Fe-Co laminations are delivered uncoated. If required, they are slightly oxidized by making the final part of the heat treatment in air.
- Fe-Ni alloys are applied in a multitude of devices where high-performance magnetic cores are required.
  - measuring instruments
  - switch-mode power supplies
  - ground fault interrupters
  - magnetic sensors
  - recording heads for magnetic tape systems
  - inductors for applications up to the MHz range.



Fe-Ni and Fe-Co material producers

- Two major producers of high-quality Fe-Ni and Fe-Co alloys
  - IMPHY (Groupe Arcelor-Mittal)
  - Vacuumschmelze GmbH

- Strip wound cores are also offered by
  - Magnetics Inc. (USA) and Telcon Ltd. (UK).



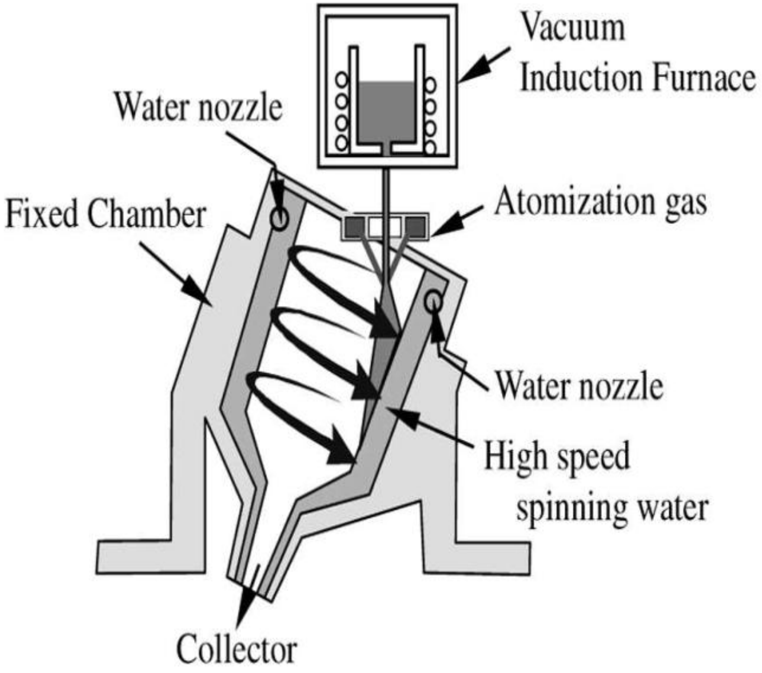
	J_s (T)	T_c (°C)	ρ (10^{-8} Ω·m)	H_c (A/m)	λ_s	μ_i
Fe64-Ni36 (invar)	1.30	230	75	40	$10\cdot10^{-6}$	$2\cdot10^{3}$
Fe50-Ni50	1.60	490	45	7	$22\cdot10^{-6}$	$1.5\cdot10^{4}$
Fe15-Ni80-Mo5 (permalloy)	0.80	400	60	0.4	$2\cdot10^{-6}$	$1.5\cdot10^{5}$
Fe14-Ni77-Mo4-Cu5 (mumetal)	0.78	400	60	1.5	$2\cdot10^{-6}$	$4\cdot10^{4}$
Fe49-Co49-V2 (permendur)	2.35	930	27	50-100	$70\cdot10^{-6}$	$2\cdot10^{3}$

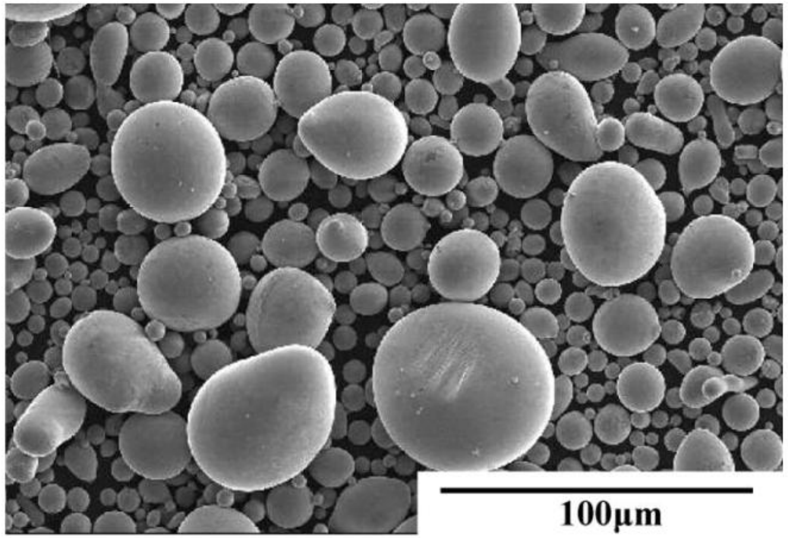
Soft Magnetic Composites SMC

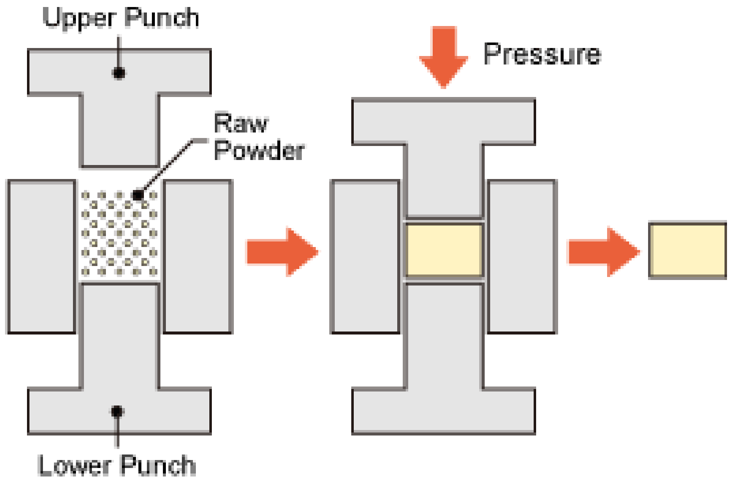
- For applications
  - Medium frequency range, few hundred Hz to few ten kHz
  - Requiring specially shaped cores
    - hardly achievable through lamination stacking. Powder cores provide an attractive solution
- relatively isotropic materials
  - Suited for applications where three-dimensional flux paths are established
- SMC are obtained either by sintering or compacting
- Sintered core
  - high resistivity (2 time the original material)
  - relatively good permeability
- Compacted cores
  - very high resistivity
- low losses (hysteresis and eddy current)

Manufacturing of SMC

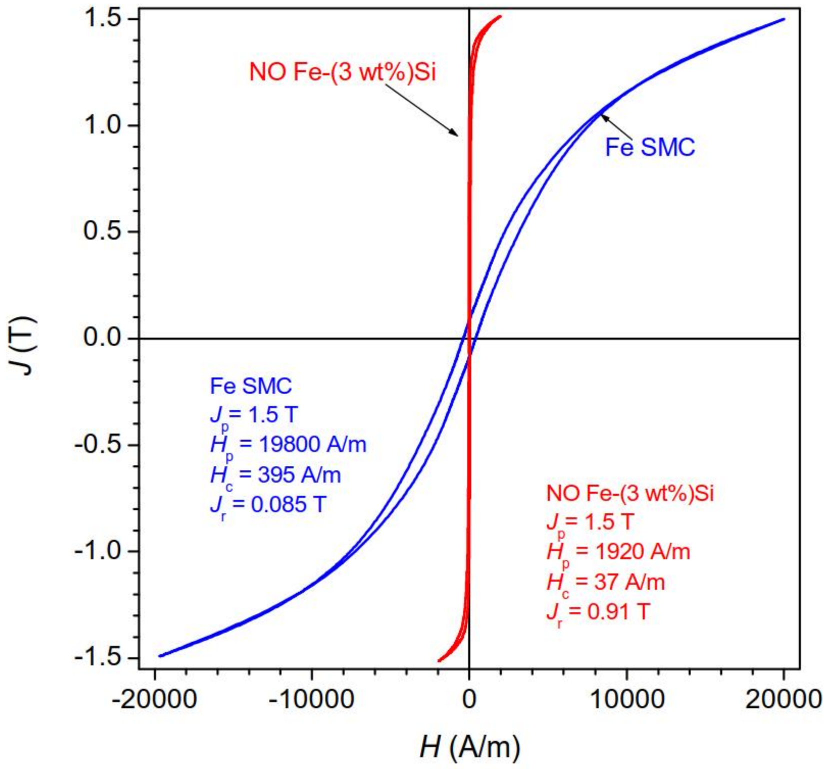
- Nanocrystalline alloys are pulverized by milling due to their brittle nature
- Crystalline particles of average size between 5 μm and 200 μm are obtained by water atomization
- Compacting process permits manufacturing net-shape parts, without need for further tooling.

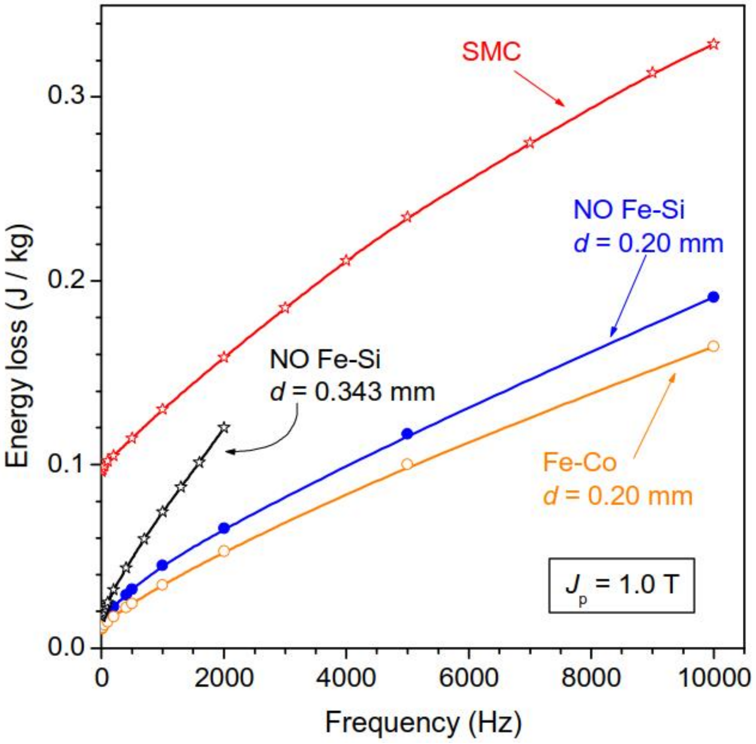






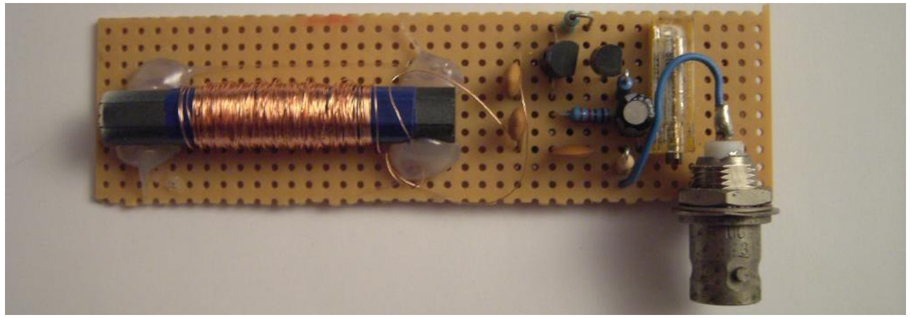
Properties of SMC

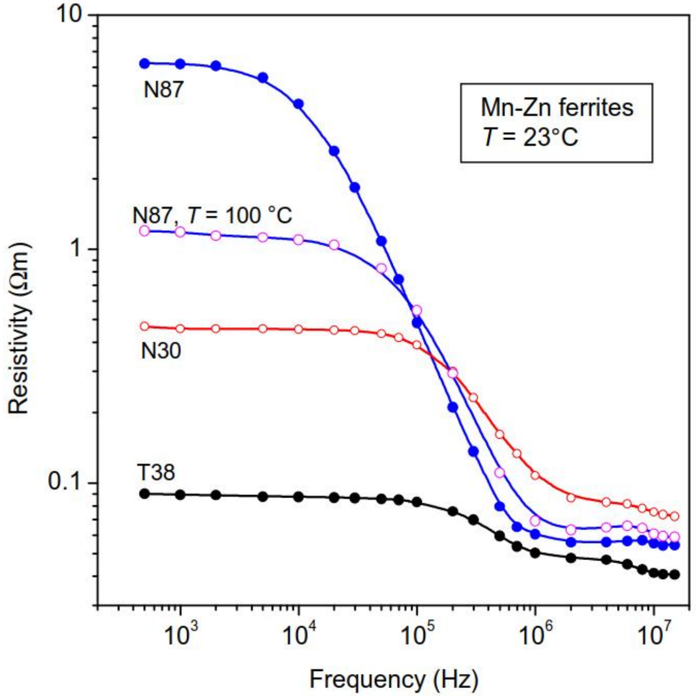




Soft ferrites

- Largely applied at frequencies above the audio range
  - Up to few hundred MHz, because of their non-metallic character
- They have the general composition
  - $MO \cdot Fe_2O_3$, where M is a divalent metal ion such as Fe^{2+}, Mn^{2+}, Ni^{2+}, Zn^{2+}, Mg^{2+}

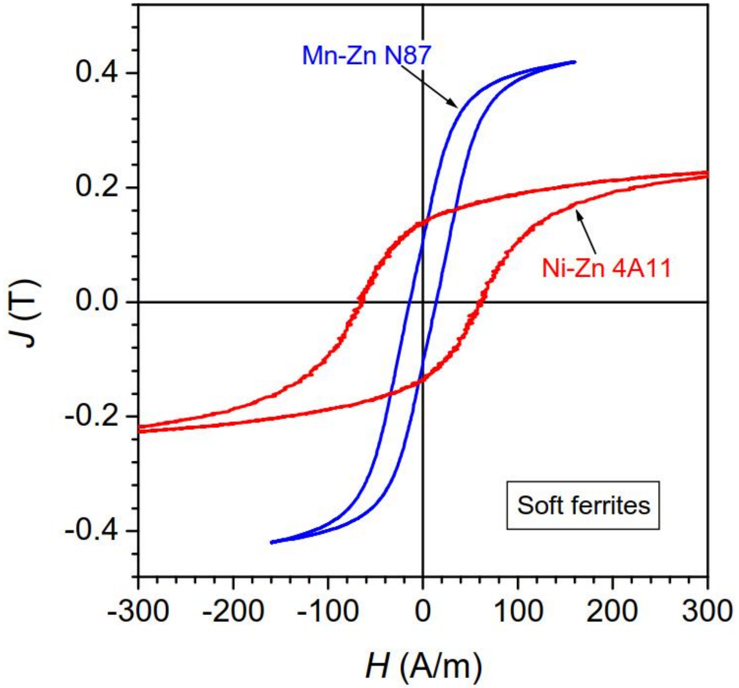


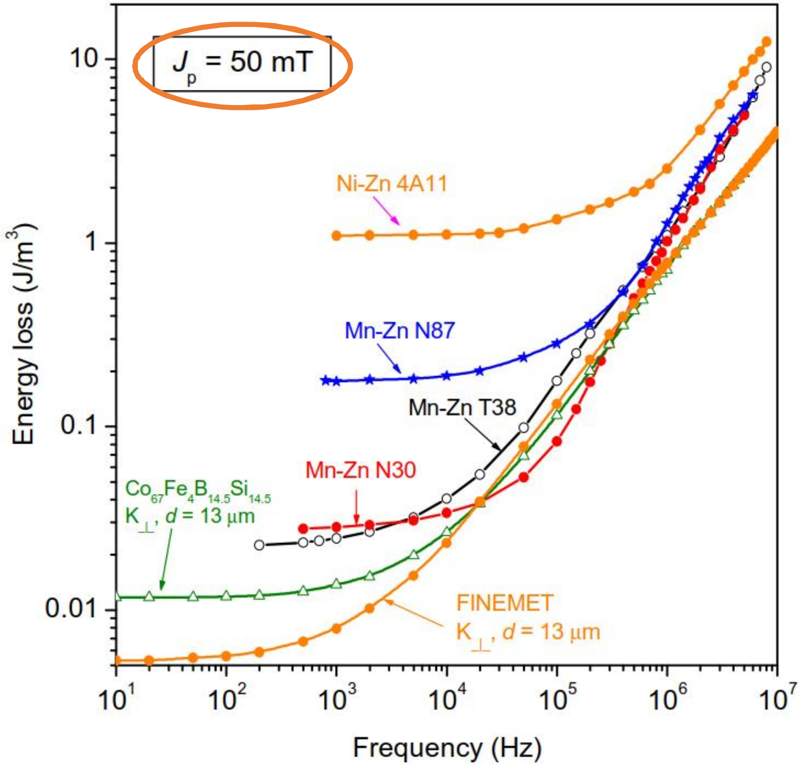


- Typical applications include
  - magnetic heads
  - antenna rods
  - inductor cores in switched-mode power supplies
  - cores for electromagnetic interference suppression
  - pulse and wide-band transformers for television and telecommunications

Soft ferrites

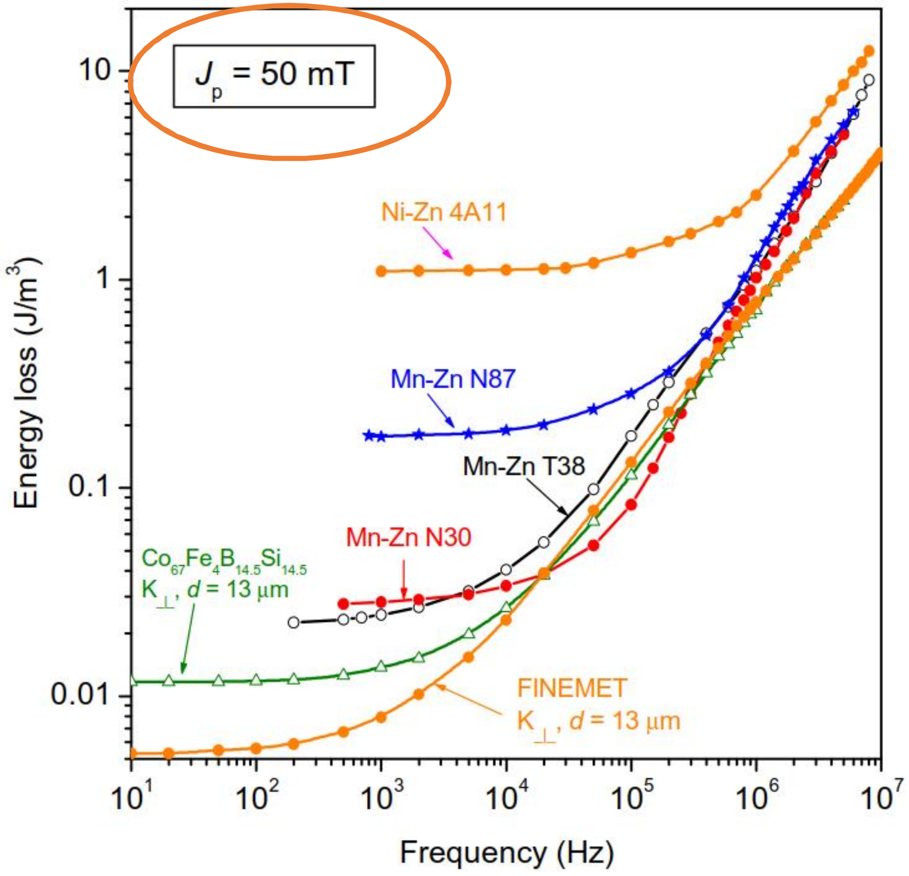
- Magnetic properties of ferrites are due to the magnetic moments of the metal ions
- Nonmagnetic Zn ferrite is often added to increase magnetization saturation
- During sintering, all linear dimensions of a part shrink from 10 to 25%, and allowance for this must be made in designing the pressing mold or extrusion die.





Two broad classes of ferrites

- Mn–Zn Ferrites
  - initial permeability of 1000–2000
  - coercivity less than 80 A/m
  - Low losses up to frequencies of about 1 MHz
  - Resistivity is about 20–100 ohm-cm.
- Ni–Zn Ferrites
  - Very high frequency operation, 100 MHz
  - Initial permeability 10–1000
  - Coercivity of few hundreds A/m
  - Very high resistivity 105 ohm-cm.



- The value of permeability and coercivity controlled by the addition of Fe^{2+} ions (Mn-Zn) or Co^{2+} ions (Ni-Zn ferrite)

Investigation work 20 min

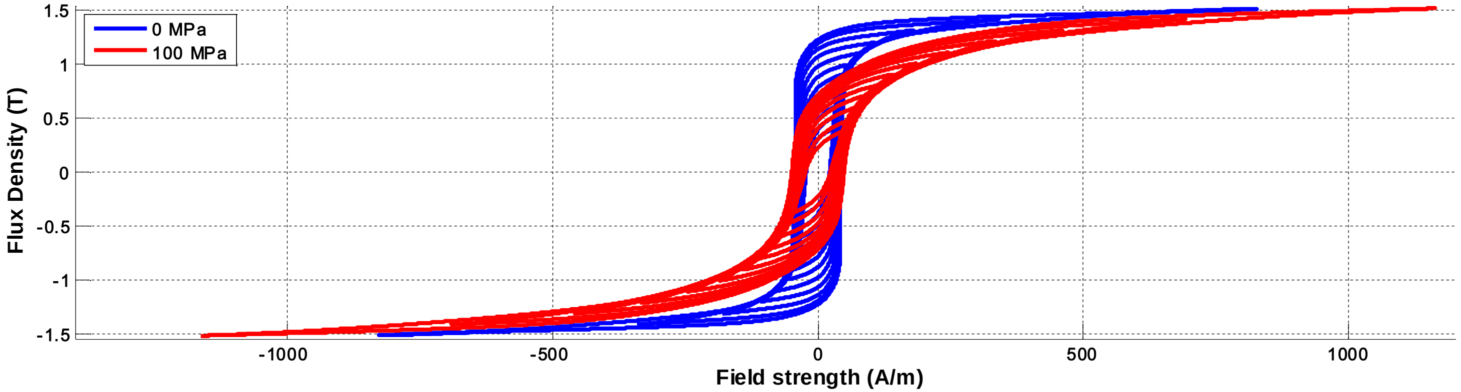
- Look in internet for what is meant by magnetostriction and magneto-mechanical effects in soft magnetic materials (5 min)

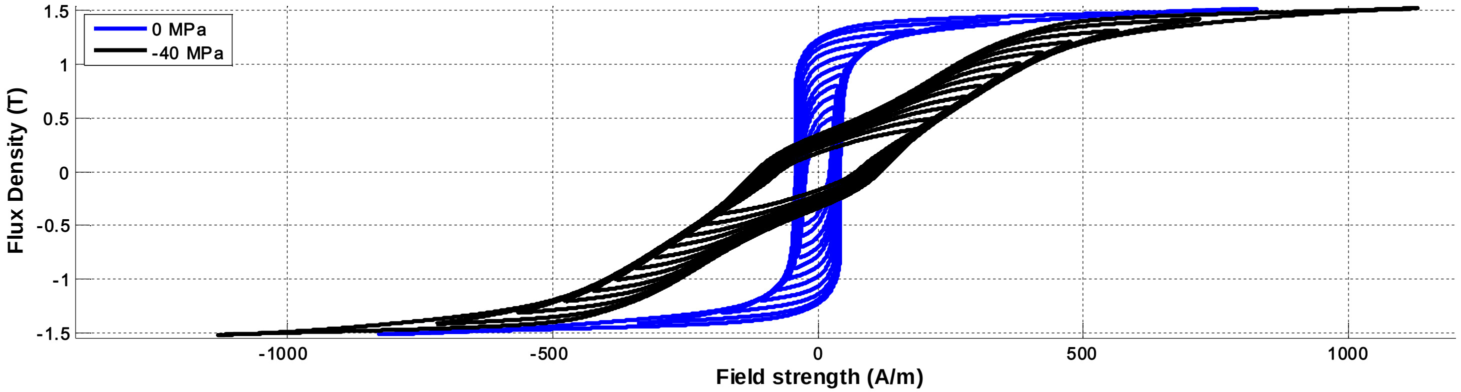
- With your mates, try to explain from where these effect come from (5 min)

- Present your findings and explanations (10 min)
  - You might use internet

Magnetomechanical coupling

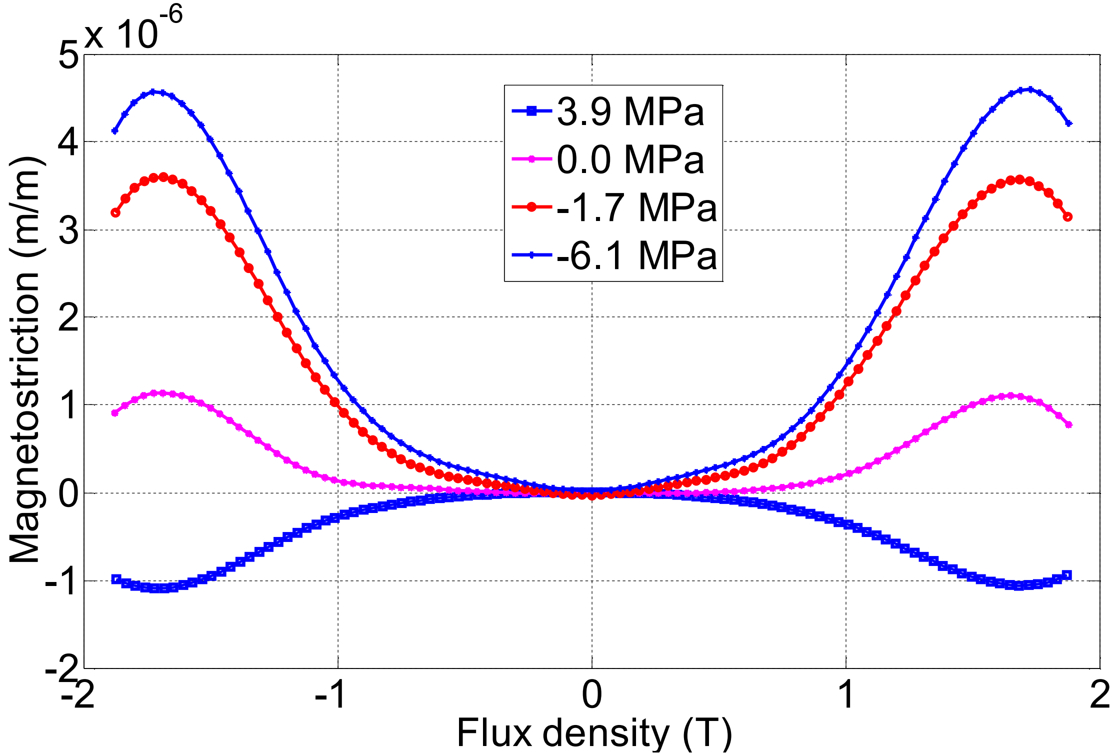
- In magnetic materials, magnetism and mechanics are coupled
- Any mechanical loading will change the magnetic properties of the material
- The mechanical stress induced magnetization is called Villri-effect





Magnetomechanical coupling

- In magnetic materials, magnetism and mechanics are coupled
- Any magnetic loading (magnetization) will induce mechanical deformation
- The magnetization induced deformation is called magnetostricion



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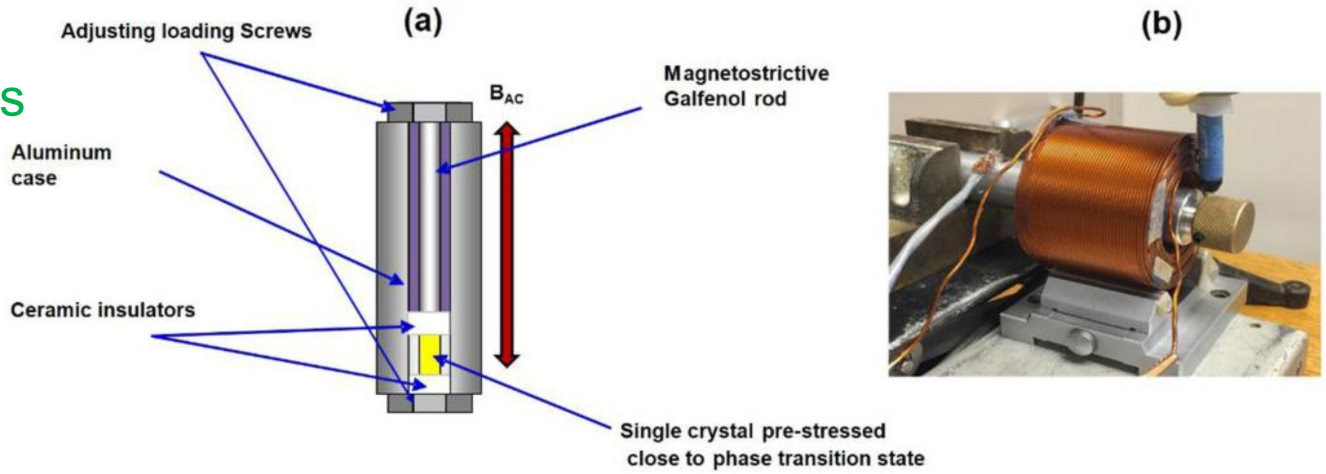
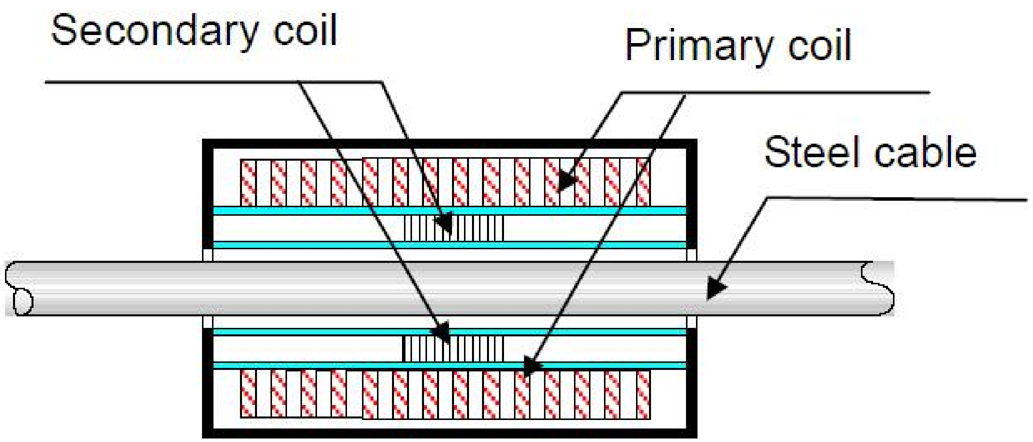
Magnetomechanical coupling

- Magnetostriction have useful applications and harmful consequences
  - ultrasound actuators and sensors
  - Energy harvesters
  - Vibrations and acoustic noise

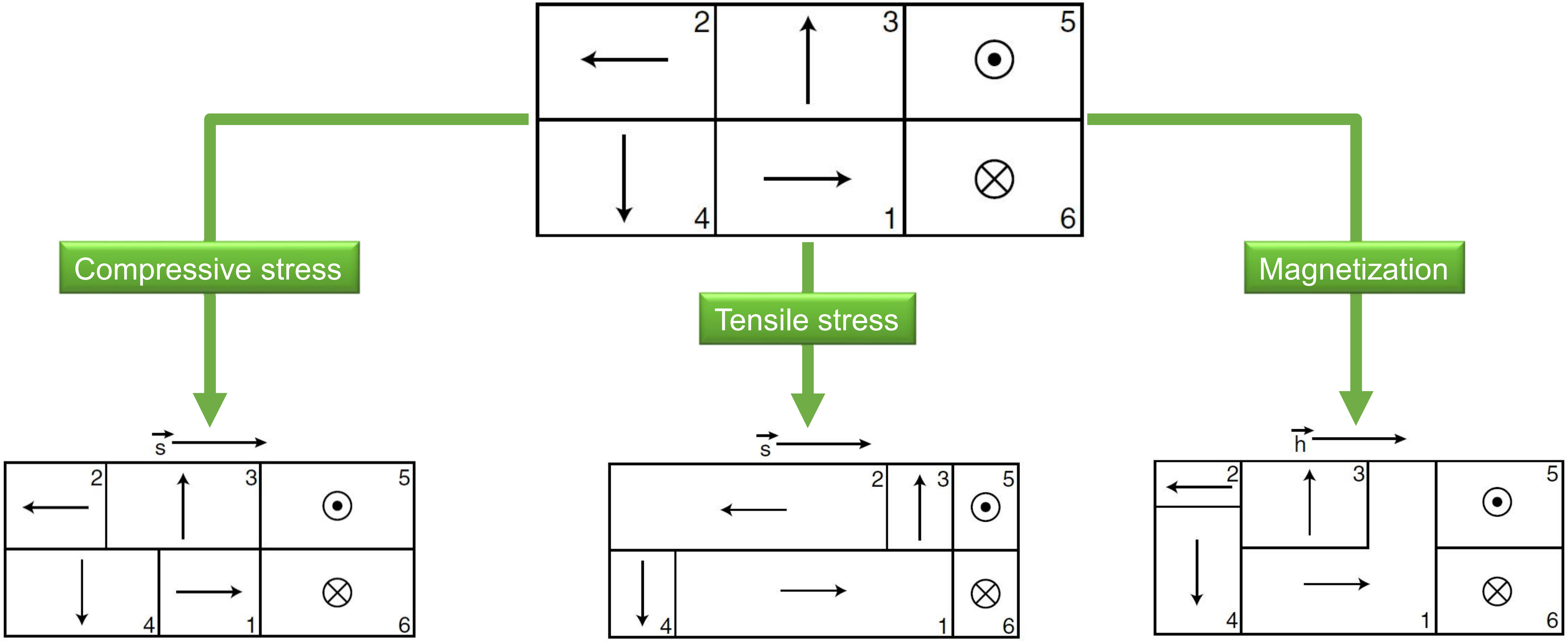


- Villari effect has very harmful consequences but can also be useful
  - Higher energy losses and low permeability
  - Use in contactless stress sensors



Magnetomechanical coupling

- magnetomechanical effects are manifestations of the same phenomenon:
  - Motion of magnetic domain walls accompanied by lattice and grain rearrangement



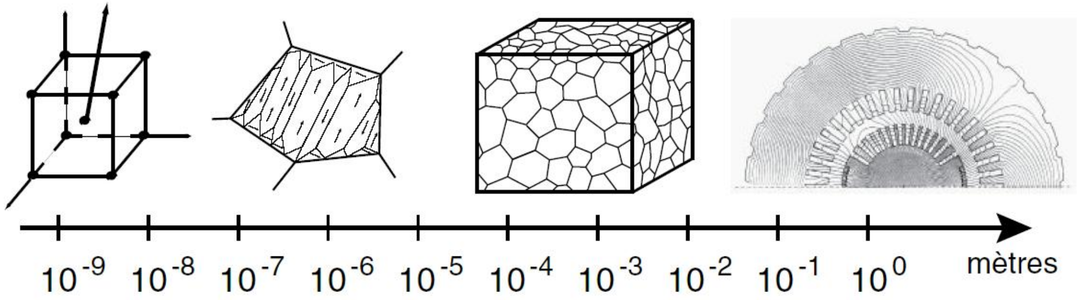
Compressive stress

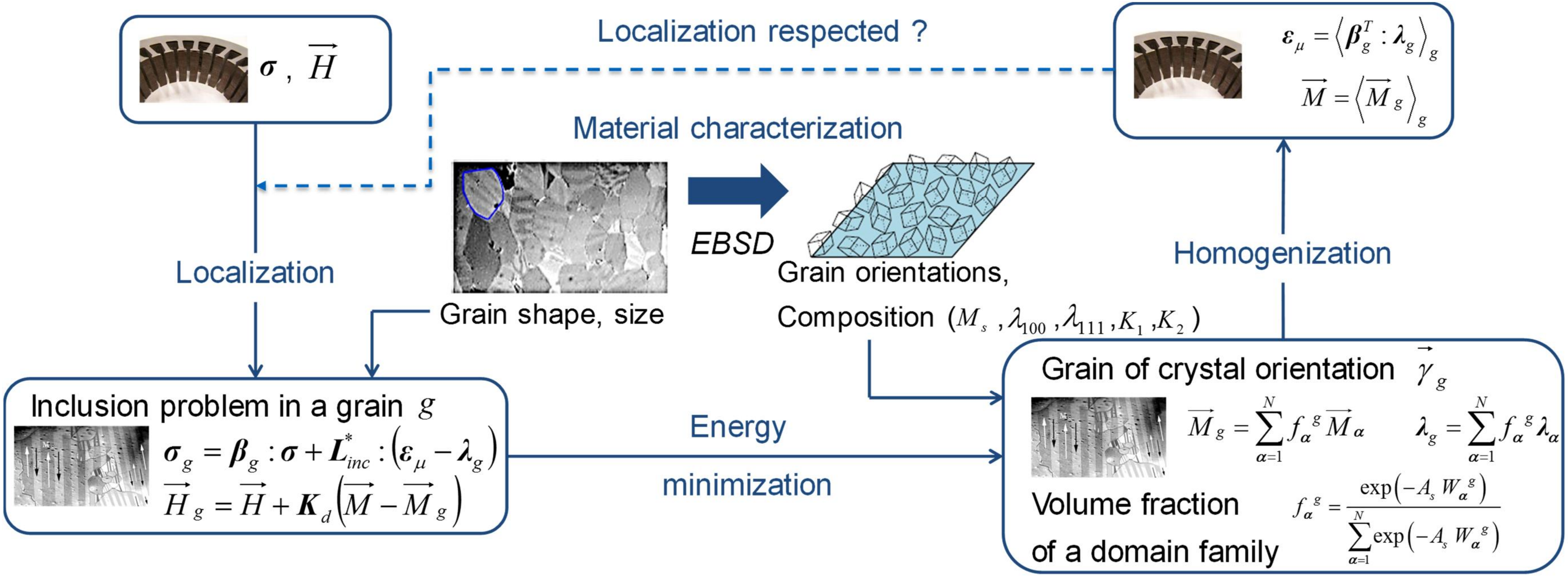
Tensile stress

Magnetization

Magnetomechanical modelling issues

- Multiscale model





$\boldsymbol{\sigma}$, $\overrightarrow{H}$

Localization respected ?

$\boldsymbol{\varepsilon}_\mu = \left\langle \boldsymbol{\beta}_g^T : \boldsymbol{\lambda}_g \right\rangle_g$

$\overrightarrow{M} = \left\langle \overrightarrow{M}_g \right\rangle_g$

Material characterization

EBSD

Grain orientations,

Composition $(M_s, \lambda_{100}, \lambda_{111}, K_1, K_2)$

Grain shape, size

Localization

Homogenization

Inclusion problem in a grain g

$$\boldsymbol{\sigma}_g = \boldsymbol{\beta}_g : \boldsymbol{\sigma} + \boldsymbol{L}^*_{inc} : \left(\boldsymbol{\varepsilon}_\mu - \boldsymbol{\lambda}_g\right)$$

$$\overrightarrow{H}_g = \overrightarrow{H} + \boldsymbol{K}_d\left(\overrightarrow{M} - \overrightarrow{M}_g\right)$$

Energy

minimization

Grain of crystal orientation $\overrightarrow{\gamma}_g$

$$\overrightarrow{M}_g = \sum_{\alpha=1}^{N} f_\alpha{}^g \overrightarrow{M}_\alpha \qquad \boldsymbol{\lambda}_g = \sum_{\alpha=1}^{N} f_\alpha{}^g \boldsymbol{\lambda}_\alpha$$

Volume fraction

of a domain family

$$f_\alpha{}^g = \frac{\exp\left(-A_s W_\alpha{}^g\right)}{\sum_{\alpha=1}^{N} \exp\left(-A_s W_\alpha{}^g\right)}$$

Magnetomechanical modelling issues

- Thermodynamics based model
  - Magnetomechanical invariants and free energy as functions of these invariants

$$I_1 = \mathrm{tr}(\boldsymbol{\varepsilon}),\quad I_2 = \frac{1}{2}\mathrm{tr}(\boldsymbol{\varepsilon}^2),\quad I_3 = \det(\boldsymbol{\varepsilon})$$

$$I_4 = \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{B_{\mathrm{ref}}^2},\quad I_5 = \frac{\boldsymbol{B}\cdot(\tilde{\boldsymbol{\varepsilon}}\boldsymbol{B})}{B_{\mathrm{ref}}^2},\quad I_6 = \frac{\boldsymbol{B}\cdot(\tilde{\boldsymbol{\varepsilon}}^2\boldsymbol{B})}{B_{\mathrm{ref}}^2}$$

$$\psi = \frac{1}{2}\lambda I_1^2 + 2GI_2 - \nu_0\left(\frac{I_4}{2} + \sum_{i=0}^{n_a-1}\frac{\alpha_i}{i+1}I_4^{i+1}\cdots\right.$$

$$\left. + \sum_{i=0}^{n_\beta-1}\frac{\beta_i}{i+1}I_5^{i+1} + \sum_{i=0}^{n_\beta-1}\frac{\gamma_i}{i+1}I_6^{i+1}\right).$$

  - Magnetization and stress from energy

$$\boldsymbol{M}(\boldsymbol{B},\boldsymbol{\varepsilon}) = -\frac{\partial\psi(\boldsymbol{B},\boldsymbol{\varepsilon})}{\partial\boldsymbol{B}}$$

$$\boldsymbol{\sigma}_{me}(\boldsymbol{B},\boldsymbol{\varepsilon}) = \frac{\partial\psi(\boldsymbol{B},\boldsymbol{\varepsilon})}{\partial\boldsymbol{\varepsilon}}.$$

Possible linearization and swap of variable and unknowns

$$\varepsilon = \frac{1}{E^H}\sigma + gH$$

$$B = g^*\sigma + \mu^\sigma H$$