Soft Magnetic Materials and Applications

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Fields of applications of prior importance for Magnetic Materials can be crudely distinguished as follows : Transformation of Energy, Actuation, Sensors (including Tags and RFID), Recording, … Operating materials are magnetically soft, hard, or characterised by coupling properties (transport properties, magnetostriction, magnetooptic, magnetocaloric, shape memory…). This brief presentation will focus on soft materials, other aspects being treated in dedicated topics.

Soft materials are used to drive the magnetic flux, to concentrate it in the air gaps, for shielding. The first point to be considered is the permeability μ, obeying the general formulation $1/\mu = 1/\mu_{qs}+1/\mu_{dyn}$. Different parameters act on the value μ_{qs} measured under quasi-static excitation or on its dynamical part μ_{dyn}. Related questions will be treated in parallel with the application fields.

1 Transformation of Energy at low frequency (f < 1 kHz)

The transformation of energy at low frequency (≈ 50 Hz) involves different kinds of sources, that is Mechanical ⇆ Electrical (Motors, actuators, generators) or Electrical ⇆ Electrical (transformers).

1 1 Mechanical ⇆ Electrical

The torque is the result of the interaction of the field produced by the moving part (rotor in a rotating machine) and the static part (stator). Fields can be produced by magnets or coils associated with soft magnetic materials. Scaling rules show that for little power (P ≈ 100 W) magnets are more powerful than coils, the coil generation more interesting for big machines.

Soft materials are used to reinforce in the air gap the fields generated by coils by the way of a mirror effect (the soft material forbids the penetration of the excitation field inside it and as a result reinforces H outside, that is inside the air gap). By this way the magnetic forces exerted are increased. The mirror effect is based on the assumption of high permeability, that is no magnetic saturation. This leads for machines big enough to the volumic maximum available torque

$\Gamma \approx J_s^2\, e/R$ J_s = Saturation Magnetization e = air gap R = Rotor radius

➨ Need of Material featuring high J_s ➨ Use of **iron based alloys** (**J_{SFe} = 2,2 T**)

Classical design for rotating machines : cylindrical symmetry ➨ The fields are in the plane ⊥ to the axis ➨ The magnetic circuits are made of sheets stacked. The ideal sheet should exhibit planar or cubic texture (in practise, magnetization properties are more or less isotropic with **$\mu_r \approx 5000$**)

! Most of the magneto motive force being developed in the air gap, the relatively low μ of magnetic sheets is not critical.

! The stacked circuits offer the opportunity to control Iron losses due to eddy currents. Total Losses originating from mechanical friction and Joule effect in coils too, Iron contribution is thus of second importance and Electrical Insulation between sheets often simply obtained by superficial oxidation of sheets. The FeSi3% alloys (cf. Fig.1 the evolution of principal parameters with Si) correspond to the best grades (**$\rho_{Fe} = 10\ 10^{-8}\ \Omega m$, $\rho_{FeSi} = 48\ 10^{-8}\ \Omega m$**)

! Specific problem relating to Very Big machines (Production of energy : P > 1 GW) : The high velocity (3000 trs/min for

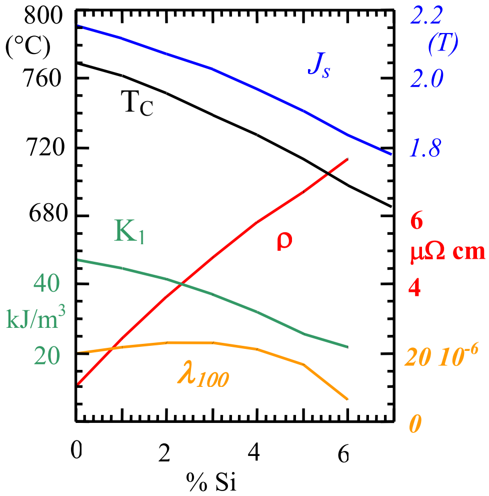


Fig. 1 : influence of Si content on the principal characteristics of FeSi alloys

the rotor of a two poles machines, 50 Hz), coupled to a large diameter leads to high centrifugal forces. The mechanical resistance is achieved using high tensile strength steel (**R ≈ 550 GPa**) with Cr, Mo, Va, Mn additions to machine a massive rotor (static field in the rotor reference system ➨ no induced currents).

1 2 The Electrical $\leftrightarrows$ Electrical conversion

The fields in the core transformer are unidirectional (cf. Fig.2)

➨ Possibility to use **G**rain **O**riented **S**ilicon **S**teel sheets (see Fig.3) which offer an easy magnetization direction in the plane of the sheet and thus a great increase of permeability (μ_r > **50 000**) compared to non oriented sheets ($\mu_r \approx 5000$).

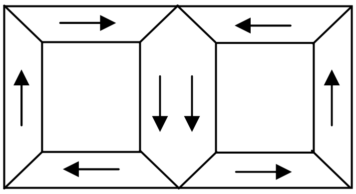
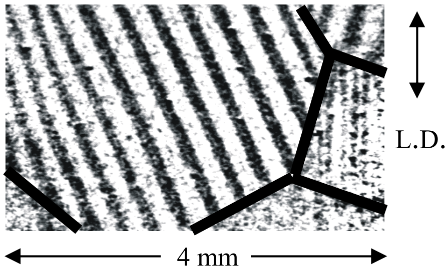
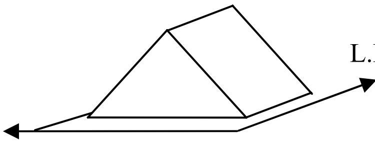


Figure 2 : Flux directions in a core transformer

Figure 3 : Magnetic domains in a FeSi GOSS imaged by Kerr Effect under a 9 MPa elongating stress and crystallographic orientation with respect to the lamination direction.





The easy magnetization directions lie along the edges of the cubic cell.

Optimization of dynamical Magnetization properties

Classical theory of eddy currents developed at a frequency f in the magnetic sheet of thickness e leads to choose $e \approx \delta = [\rho/(\mu\pi f)]^{1/2}$, where δ denotes the skin depth.
➨ $e_{50Hz} \approx 0.3$ mm, $e_{400Hz} \approx 100$ µm (400 Hz = operating frequency of in board electrical machines).

Classical volumic losses are thus obtained : $P_{vclas} / f = \lambda f \qquad \lambda = \sigma B_m^2 e^2 \pi^2 / 6$ (1)

! Taking into account the domain walls magnetization mechanism leads to the more accurate results :

$$\mu_{dyn} = \frac{\pi^2}{16\,\ell\, e\, \sigma}\,\frac{1}{f} \qquad P_v = 1{,}628\, P_{vclas}\, 2\ell / e \qquad 2\ell = \text{width of a domain in the demagnetized state} \quad (2)$$

➨ An elongating stress ($\sigma \approx 10$ MPa) is applied by the mean of the isolating coating allows to eliminates additional unproductive local domains (spikes…), increasing the number of domain walls and improving thus the properties of dynamical Magnetization.

! Due to the great grain sizes ($\Phi \approx 1$ cm) featured by the best grades (Hi B FeSi), additional refining techniques (Laser scratching, Plasma grooving…) are involve to increase the number of domain walls.

! Adding Si to Fe to increase resistivity leads to brittle alloys. As a result, the minimum thicknesses obtained laminating $Si_{3\%}Fe$ are 50 or 100 µm, with a maximum operating frequency towards 400 Hz. Recently, commercial SiFe alloys featuring 6%Si have been proposed, the enrichment being obtained starting from conventional $Si_{3\%}Fe$ by Chemical Vapour Deposition. The main interest in the 6% amount Si is the vanishing λ_{100} and the increase of the resistivity (cf. Fig.1). Those points are of prior importance regarding the increase of the operating frequency in air-crafts electrical devices, especially concerning the problem of acoustic noise generated by in board transformers.

1 3 The Iron Cobalt alloys

The Iron Cobalt alloys are used instead of SiFe alloys when very high specifications are needed. Their main advantages are a large polarization (**$J_{S\ FeCo25}$ = 2.4 T**) and a high Curie temperature (**$T_{C\ FeCo94}$ = 1040 °C**) . Adding chromium and vanadium allows to reach resistivities to about **$40\ 10^{-8}$ Ωm** comparable to the FeSi one. Vanadium also reduces brittleness, allowing laminating until thickness ≈

0.1 mm. The three main classes used for applications are $Fe_{74.5}Co_{25}Cr_{0.5}$ (noses of electromagnets), $Fe_{49}Co_{49}V_2$ (transformers and rotating machines), Fe_6Co_{94} (electromagnetic pumps for molten metals).

2 Electrical ⇆ Electrical conversion at medium and high frequencies (f > 400 Hz)

According to the skin depth criterion (cf. §112), the materials operating at higher frequencies have to feature higher resistivities or lower thicknesses than conventional SiFe alloys.

2 1 The Iron based amorphous ribbons (f < 100 kHz)

Amorphous magnetic soft alloys were introduced towards 1970. The Fe based alloys are the first member of the family of magnetically soft alloys obtained as ribbons by quenching. Co based amorphous and nanocrystalline alloys belong to the same familv.

The elaboration requires glass formers (B, Hf…), leading to typical atomic composition $Fe_{81}B_{13.5}Si_{3.5}C_2$. In addition, very high cooling rate ($dT/dt > 10^6$ K/s) is needed to prevent crystallisation : This is achieved by the Planar flow casting process, where the liquid metal is falls on a rotative cooled cooper wheel (cf. topic dedicated to soft nanocristalline melt spun ribbons) . Ribbons of several centimetres width (until 20 cm) are obtained.

Ribbons are then annealed ($T_a \approx 400$ °C) to get ride of internal stress due to the quenching process.

The same elaboration process leads to some common characteristics featured by the all members of the family, that is

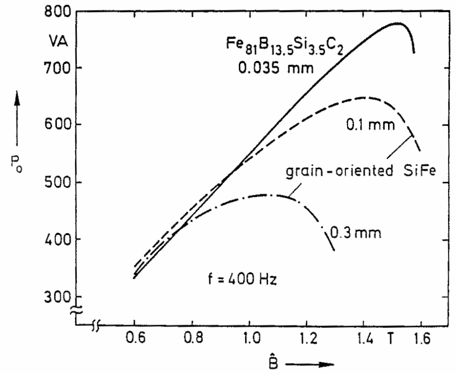


Figure 4 : comparaison of the power featured by different transformers with wounded cores of same sizes made with different materials

* Operating Temperature ≈ **150 °C** limited by the Curie Temperature ($T_C \approx 300$ °C)

* Ribbon thickness **e ≈ 20-30 µm**
* Electrical resistivity $\rho \approx$ **140 10^{-8} Ω**

→ According to (2), good candidates for medium frequencies applications

A specificity of Fe based alloys is the high Polarisation induction **$J_S \approx 1{,}75$ T**. As a result, Fe based alloys can be compared to FeSi (**$J_s = 2.06$ T**) and, very attractive regarding losses, appear to be more interesting for transformers when the operating frequency increases (cf. Fig. 4). Depending on the annealing process, the density of domain walls can be varied and Fe based alloys can be used up to **100 kHz**. More expensive than the FeSi alloys, their use for low frequency (50-60 Hz) is until now restricted to regions characterised by a high cost of electrical energy (USA, Australia…)

2 2 The soft ferrites

The soft ferrites belong to two different families :

- The Spinels feature a cubic crystal structure type and a general formula MO, Fe_2O_3, M = divalent metallic ion (Mn^{2+}, Fe^{2+}, Ni^{2+}, Zn^{2+}, Mg^{2+}, Li^{2+}…). The small amount of magnetic ions and a ferrimagnetic coupling between neighbouring Fe^{3+} and M^{2+} leads to low Polarization induction (**$J_{SMn\text{-}Zn} \approx 0.5$ T**). In addition, indirect coupling of magnetic ions leads to low Curie temperatures (**$T_{CMn\text{-}Zn} \approx 240$ °C**)
  The main interest of those compounds is their very high resistivity (**$\rho_{MnZn} \approx 1\text{-}10$ Ωm, $\rho_{NiZn} \approx 10^5$ Ωm**). This allows, starting from powder, to elaborate massive magnetic cores (moulding followed by sintering) operating up to **f = 1 MHz** for Mn-Zn and up to **f = 100 MHz** for Ni-Zn ferrites. This industrial process is very convenient for mass product, leading to very cheap cores.
- The ferrimagnetic garnets with the $Mn_3Al_2Si_3O_{12}$ structure and general formula ($5Fe_2O_3$ $3T_2O_3$) where T = rare earth element or Yttrium, Yttrium ferrite garnet commonly named YIG. The saturation polarization is lower than for spinels (**$J_S < 0.2$ T**) but their resistivity very high (until

10^{10} Ωm), the dissipative mechanism due to rotation damping of spins. As a result, ferrimagnetic garnets are extremely suitable for microwaves applications **(100 MHz < f < 100 GHz).**

3 Highest permeabilities and vanishing anisotropies alloys

The highest permeabilities are needed for applications such as magnetic shielding, low voltage circuits breakers (low frequency) or filtering. The quasi-static permeability is given by

$$\mu_{qs} \approx J_S / \sqrt{b + K_1 + K_u + 3/2\,\lambda\sigma} \qquad (3)$$

Where K_1 = magnetocristalline anisotropy, K_u = induced anisotropy, $3/2\,\lambda\sigma$ = magnetoelastic anisotropy (λ = magnetostriction, σ = stress supported). b corresponds to a magnetostatic energy associated to inhomogeneities. To obtain a high permeability (**$\mu_r > 300\,000$**), it is necessary first of all to control perfectly the metallurgical process to get ride of the b term, and secondly to minimize the various anisotropies in (3). Dealing with magnetoelastic effects, this implies $\lambda < 10^{-6.}$

Three kinds of materials fulfil the purpose in view, that is $Ni_{80}Fe_{15}Mo_5$ permalloys (**$J_S \approx 0.8$ T**), Co based amorphous (**$J_S \approx 0.7$ T**) and soft nanocristalline ribbons (**$J_S \approx 1.3$ T**).

The vanishing K_1 is in Co based amorphous and soft nanocristalline ribbons a consequence of the structural disorder state, the vanishing λ obtained through composition (cf. topic dedicated to soft nanocristalline melt spun ribbons). One can notice that although its disorded state, Fe based amorphous do not belong to this family due to their high λ (**$\approx 30\ 10^{-6}$**)

Thought its crystalline state, it is possible to obtain vanishing K_1 in NiFe alloys by an accurate heat treatment (≈ 500 °C) which induces a short range order sufficient to bring K_1 to 0 for composition around 75% Ni. It is observed that λ_{100} and λ_{111} vanishes towards the same composition (cf. Fig. 5). Adding a small amount of Molybdenum allows to make λ_{100}, λ_{111} and K_1 vanish together. In addition, Mo increases ρ to 55 10^{-8} Ωm, which becomes comparable to ρ_{FeSi}.

Due to their higher Polarization saturation and low cost compared to permalloys and Co based amorphous, nanocristalline ribbons seem to be called to take a major part in the applications field.

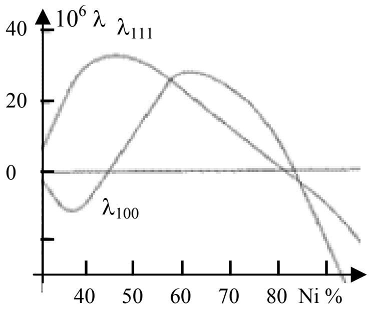


Fig. 5 : evolution of λ_{100} and λ_{111} for NiFe alloys

4 Special hysteresis cycles and induced anisotropy

A very interesting characteristic featured by vanishing anisotropies alloys (cf. § 13) is the possibility to tailor the shape of the hysteresis cycle by the mean of induced anisotropy K_u. The shape is characterised by the ratio B_r/B_{max} (B_r = remanent induction). $B_r/B_{max} > 0.9$ => rectangular cycles; $B_r/B_{max} < 0.25$ => flat cycles.

Rectangular cycles alloys are obtained annealing the alloy under a longitudinal magnetic field (cf. fig.6 of topic dedicated to soft nanocristalline melt spun ribbons). they are of main interest for Magnetic amplifiers, fluxgates sensors…

Flat cycles alloys obtained by the means of K_u feature coherent rotation magnetization instead of domain walls displacements magnetization mechanism (cf. Fig.6). As a result, the coercitivity is nil and a nearly perfectly linear behaviour can be observed (cf. Fig.7). In addition, the dynamical behaviour is improved, leading to low losses and excellent quality factors, point of prior importance for filtering components. The way to induce K_u depends of the permeability needed :

- For unipolar electronics (pulse transformers, homopolar ground fault circuits breakers…), high permeabilities ($5\,000 < \mu_r < 100\,000$) are needed.

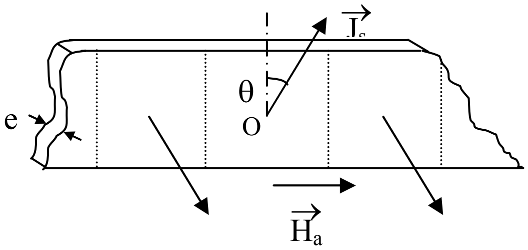
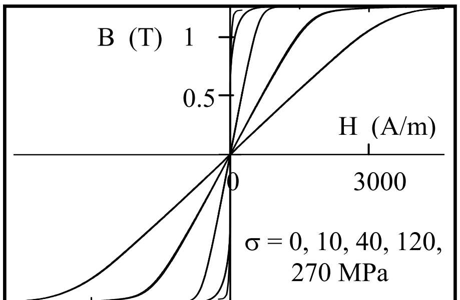


Figure 6 : coherent magnetization rotation in a sample featuring transversal domains



With $\mu_r = J_S^2 / (2 \mu_0 K_u)$, such levels are obtained for $4 < K_u < 80$ J/m^3, annealing the alloy under a transverse magnetic field.

- For energy storage (Fly-back transformers…), lower permeabilities are needed. The range $200<\mu_r<1000$ is obtained annealing under elongating stress. The very low range $10<\mu_r<200$ is obtained by other ways.

5 Low permeabilities and composites

The way to obtain an apparent low permeability with a magnetic circuit made from a high permeability material is to make an airgap. The latter introduces radiation harmful for the neighbouring devices, and even more for the inductance coil the turns of which are located near the airgap, especially under high operating frequencies.

This can be avoided considering circuits made from compressed soft magnetic powders in a non magnetic matrix: the magnetic poles that appear at the particle/matrix interface warrant a weak relative permeability of the compressed material, so that the air gap is no more necessary. On the other hand, the particles being electrically insulated from each other (by the binder and if necessary by an insulating layer on the particles them-selves), iron alloys powder with high J_S can be used. Depending on the frequency range and permeability needed, commercial powders are made of iron, carbonyl iron, $Fe_{50}Ni_{50}$ or $Fe_{17}Ni_{81}Mo_2$. Recently, powders obtained by mechanical allowing have been studied (cf. dedicated topic).