Bulletin of the *Transilvania* University of Braşov
Series I: Engineering Sciences • Vol. 6 (55) No. 2 - 2013

MAGNETIC MATERIALS FOR ACCELERATOR ELECTROMAGNETS

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Abstract: *Accelerator electromagnets are used in synchrotrons for the guidance of particles. For the successful operation of such synchrotrons, high field homogeneity is required to be provided by the electromagnets. Furthermore, the magnetic field characteristics of all electromagnets of one type installed have to be identical. A high field homogeneity and equal performance from electromagnet to electromagnet can only be achieved if great care is taken when the selection of magnetic materials is done, and if a rigorous quality assurance plan is implemented during manufacturing. In this paper a procedure is presented for selecting the magnetic material and mandatory steps during manufacturing are outlined.*

Key words: *magnetic materials, high-energy particles, electromagnet, accelerator.*

1. Introduction

Particle accelerators are used to generate high-energy particles which are for example brought to collision to perform fundamental particle research, to generate light with high-brightness, or to produce ions for medical treatment. Modern research fields would not be possible without controlled access to these high-energy particles.

For the successful operation of such synchrotrons, electromagnets with high field homogeneity and equal magnetic properties from electromagnet to electromagnet within one type are required. To achieve these requirements the choice of the material to be used for the core of an electromagnet and the quality assurance during manufacturing is of paramount concern.

The required steps of the selection procedure for the core material are presented in Figure 1. The designer of the electromagnet has to decide on the magnetic material based on the field requirements. The first decision considers the dynamic requirements of the magnetic field. In case of static operation a solid magnetic core can be used.

If the electromagnet will be ramped, the core will have to be laminated to minimize the effects of the magnetic field due to eddy currents. If the electromagnet will not be ramped the magnetic saturation and permeability of the material in the working range will be the driving factors.

If the electromagnet will be ramped, saturation, coercivity, remanence, permeability, resistivity and lamination thickness is usually taken into account during the selection process of the material.

Typically synchrotrons contain a small number of different electromagnet types which are partially powered in series. Therefore, it is extremely important that all

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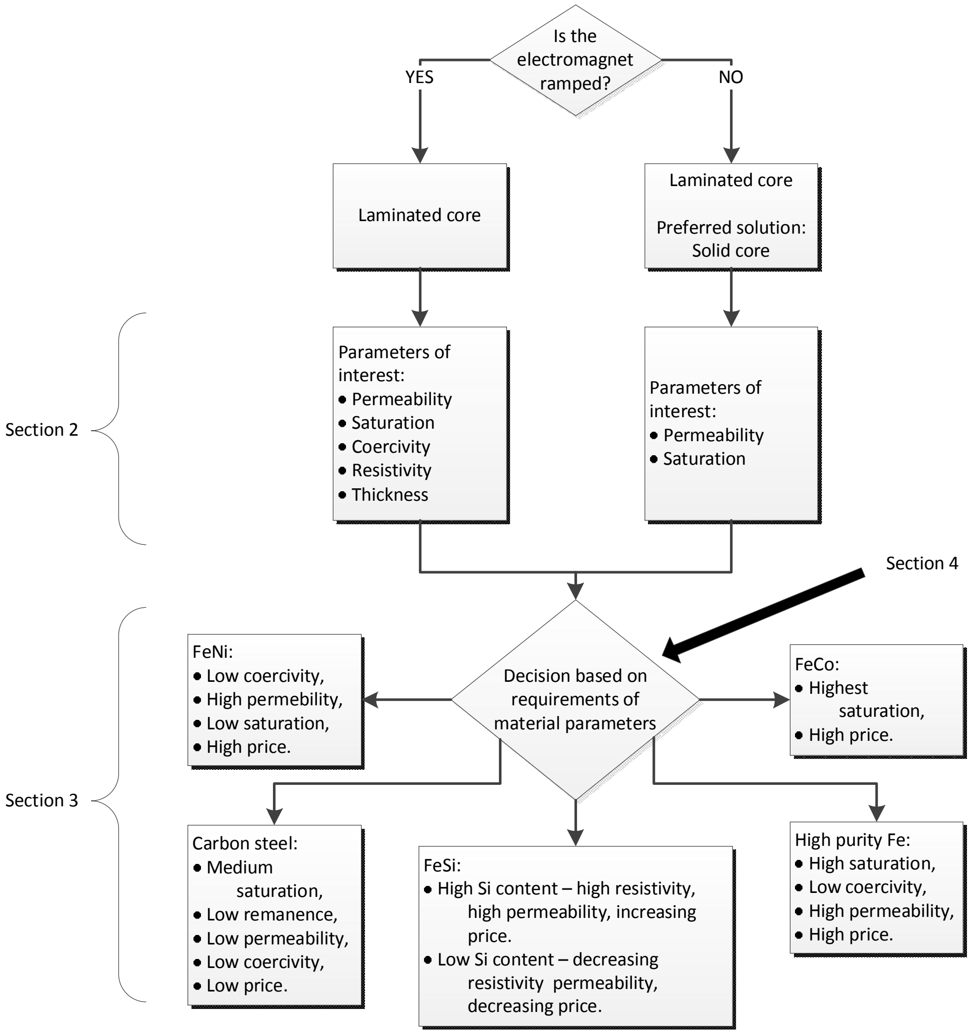

Fig. 1. *Flowchart of selection process of magnetic materials for the core of an electromagnet*

electromagnets of one type show the same performance. The most common reason why electromagnets within one family are different is because of mechanical manufacturing errors and differences of the magnetic performance of the selected core material from electromagnet to electromagnet. Laminating the yoke opens the possibility to shuffle the laminations used for the manufacturing of one type of electromagnet. The shuffling ensures that inequalities in the magnetic material are averaged out and that all electromagnets of one type show the same performance if their mechanical construction is the same.

First, we present the influence of the core material to the operation of the electromagnet. Second, we present the most important classes of materials. Finally, we present a procedure for selecting the most suitable class of material, depending on the boundary conditions of the project.

Following we will limit our discussion to dipole electromagnets. The results may be easily extended to other types of electromagnets such as quadrupoles and sextupoles. Additional information regarding electromagnets with multiple pairs of poles can be found in [6].

2. Relevant Magnetic Properties of the Materials

In this section the relevant magnetic properties of typical materials employed in electromagnets for accelerators, and the effect on the operation of an electromagnet are analysed.

Following, we limit our discussion to properties of soft ferromagnetic materials, because these are the materials most often employed for the construction of electromagnet cores.

2.1. Magnetic Characterization of a Material

The state of magnetization of a material is determined by the magnetic field strength $\overline{H}$ and is characterized by the magnetic flux density $\overline{B}$ and magnetic polarization $\overline{J}$. The relation between these quantities is:

$$\overline{B} = \mu_0 \overline{H} + \overline{J}. \quad (1)$$

Ferromagnetic materials behave nonlinearly due to hysteresis effects and eddy-currents. Magnetic hysteresis phenomenon represents the offset in response of the magnetic polarization to the excitation field. When the magnetization of a ferromagnetic material is changed by some amount, energy is dissipated.

A full hysteresis cycle is presented in Figure 2. In this figure, relevant quantities like saturation, remanence and coercivity are presented as well.

The slope of the hysteresis curve represents the relative permeability of the material. It is determined with the following equation:

$$\mu_r = \frac{1}{\mu_0} \frac{\mathrm{d}B}{\mathrm{d}H}. \quad (2)$$

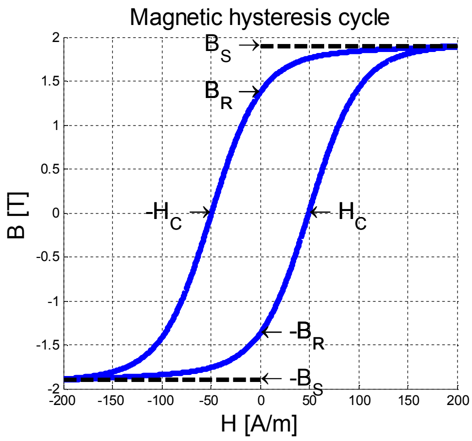

Fig. 2. *Magnetic hysteresis cycle and relevant quantities*

Remanence represents the level of magnetization characterizing a material when the excitation field is switched off, B_R in Figure 2.

Coercivity represents the value of the magnetic field strength required to bring the magnetization of the material from the remanence level to zero, H_C in Figure 2.

Saturation represents the state of the material when an increase of the excitation field strength no longer leads to an increase of the magnetization of the material, B_S in Figure 2.

The magnetic characterization of a material is related to the shape of the hysteresis cycle. The shape of the cycle is determined by the properties of the substance and is strongly influenced by eddy-currents and temperature.

When magnetic materials are exposed to a time-varying magnetic field, eddy-currents will be induced in the material: the penetration of the magnetic field in the material will be limited in depth and its phase will be shifted to the excitation field.

The harmonic skin depth is defined as the depth in the material where the magnetic field reaches 1/*e* (36.8%) of its value at the surface, and it is defined as:

$$\delta_s = \sqrt{\frac{1}{\pi \cdot \mu_0 \cdot \mu_r \cdot \sigma \cdot f}}, \quad (3)$$

where: δ_S is the skin depth [m]; σ is the electrical conductivity of the material [S/m]; f is the frequency of the excitation field [Hz].

The response of the magnetic field in the material, to a linearly ramped excitation field, will be delayed with a time constant τ_d [3]:

$$\tau_d = \sqrt{\frac{x^2 \sigma \mu}{2}}, \quad (4)$$

where x is the depth in the material [m].

The choice of lamination thickness will be determined by the ramp rate of the electromagnet, requirements for damping the ripples of the power converter, and by economic considerations (thicker laminations are often cheaper to manufacture).

2.2. Transfer Function

The value of the magnetic flux density generated by an electromagnet in its air gap depends on its geometry and on the material parameters of the core:

$$B_{gap} = \frac{\mu_0 NI}{h + \frac{l}{\mu_r}}, \quad (5)$$

where: B_{gap} is the value of the magnetic flux density in the gap of the electromagnet [T]; μ_0 is the magnetic permeability of free space [H/m]; NI is the magnetomotive force of the electromagnet [A]; h is the height of the electromagnet's air gap [m]; l is the length of the magnetic circuit of the core [m]; μ_r is the relative magnetic permeability of the magnetic circuit material.

The influence of the relative magnetic permeability on the transfer function of an electromagnet is presented in Figure 3. The material has to have a high permeability in the working range in order to achieve linear operation of the electromagnet (the term l/μ_r has to be much smaller than h).

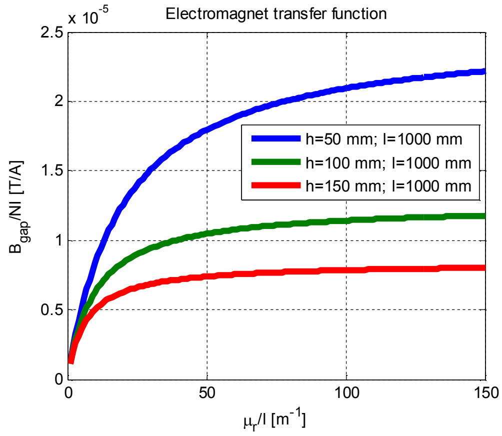

Fig. 3. *The influence of the relative magnetic permeability on the transfer function of an electromagnet*

To achieve a linear operation of the electromagnet (saturation of the curves in Figure 3) the core material has to operate in the high, and preferably linear, permeability region. The closer to saturation a material is, the lower its permeability, and the field of the electromagnet decreases. The higher the saturation of the material is, the wider the range in which it can operate linearly. Saturation does not occur homogenously through the yoke and therefore will also change the field distribution within the pole tips, resulting in reduced field homogeneity.

2.3. Residual Field

The residual field represents the electromagnetic field generated by the electromagnet when the coils are no longer powered. The effect of the residual field is the yield to different field levels for the same current through the coils. The residual field can be cancelled by inverting the current through the coils, which requires at least a more expensive bi-polar power supply.

The flux density of the residual field in the gap can be assumed to be [9]:

$$B_r = -\mu_0 H_C \frac{l}{h}, \tag{5}$$

where: B_r is the value of the residual field's flux density [T]; H_C is the value of the coercive field strength [A/m]; l is the length of the magnetic circuit in the core [m]; h is the height of the gap [m].

The residual field often forces the repetition of the same cycles in accelerators in order to stabilize the operation point of the material. From Equation 6 can be observed that lower coercivity of the material leads to lower residual induction in the gap of the electromagnet.

3. Important Classes of Soft Magnetic Materials

Magnetic materials are classified according to: main alloying element, metallurgical state and physical properties of the material [12]. According to their coercive force, materials are classified as soft or hard. Soft magnetic materials are characterised by coercivity lower than 1000 A/m. In order to obtain small residual field, the material is desired to be characterised by small coercive force. For accelerator electromagnets usually materials with coercive force smaller than 100 A/m are used.

3.1. Alloys of Iron with Silicon - Electrical Steel

Silicon steels are alloys of iron and silicon mainly, additional alloying elements exist. Alloying iron with silicon presents advantages mainly for AC applications due to the increased electrical resistivity, with the effect of reducing the eddy-currents in the material.

The quantity of silicon in the silicon-iron alloy has the following effects:

- Due to the impurities inherent to alloying process, the relative permeability decreases and the coercive force increases, the extent of the influence is determined by the chemical composition, grain size, manufacturing process and crystallographic orientation.
- The saturation polarization decreased, from 2.15 T for pure iron to 1.3 T for 6.5 wt% Si content [8].
- Increased electrical resistivity, from 9.8×10^{-8} Ωm for pure iron to 70×10^{-8} Ωm for 6.5 wt% Si content [2].
- The magnetostriction of the alloy decrease with the content of silicon, from $\lambda_{100} > 20 \times 10^{-6}$ and $\lambda_{111} < -20 \times 10^{-6}$ for high purity Fe, becoming very small for 6.5 wt% Si: $\lambda_{100} = 0.5 \times 10^{-6}$ and $\lambda_{111} = 2 \times 10^{-6}$ [2].

According to the isotropy of its magnetic properties, silicon steel can be divided into two categories:

- Non Grain Oriented (NGO) silicon steel, characterized by an approximately isotropic grain texture. When iron crystallizes, the crystalline grains are randomly arranged and the magnetic properties of the bulk material represent an average for the various crystal directions.
- Anisotropic silicon steels or Grain Oriented (GO) silicon steel, characterized by increased magnetic properties along a direction, also known as the easy magnetization axis. Applying a series of metallurgical rolling and heat treatment operations, a Goss texture can be obtained for the material: iron crystalline grains are aligned along the rolling direction with the <001> axis and are parallel to the surface of the material with <011> plane [2].

In Figure 4 the configuration of magnetic domains in silicon steel is presented. The magnetic domains in GO steel are long and parallel; magnetizing field applied along their direction produces optimal performance: low coercivity, and high permeability.

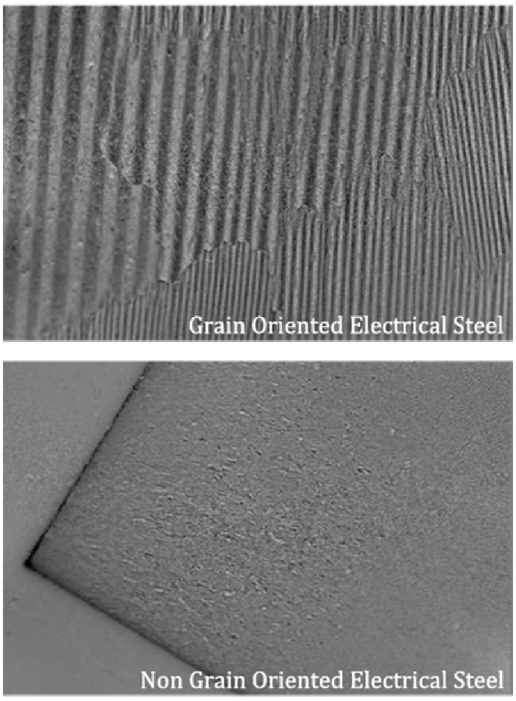

Fig. 4. *Magnetic domains in grain oriented and non-grain oriented silicon steel, from Ref.* [11]

The drawback of high silicon content in the alloy is that the saturation level decreases, the procurement price increases, and the material is very hard and brittle, therefore it is difficult to process [2]. Silicon steel with acceptable punchability and performance is achieved for silicon content in the range 3 wt% to 4 wt% [8]. Additional quantities of aluminium or manganese can be added to further increase the electrical resistivity of the alloy without affecting its mechanical properties [5].

Silicon steel is the workhorse of the electrotechnical industry due to its affordable price and good magnetic properties. For accelerator electromagnets, the choice of silicon steel has to take into consideration both material and electromagnet requirements: high permeability in rolling-direction is favoured by GO silicon steel, while isotropic properties are favoured by NGO steel.

In electromagnets where the field lines orientation is uniform, mainly in one direction, GO silicon steel might be the better choice. In electromagnets, where the rolling direction of the magnetic material cannot be placed in parallel to the field lines, isotropic NGO silicon steel might be the better choice.

3.2. Alloys of Iron with Nickel

Useful magnetic properties can be achieved by alloying nickel with iron. The most important property of Fe-Ni alloys is the increased magnetic permeability.

With increasing quantity of nickel, the Fe-Ni alloys present the following properties, achievable after a well-tailored annealing process [8]:

- the coercivity decreases, from 40 A/m for 36 wt% Ni to 0.4 A/m for 80 wt% Ni,
- the permeability increases, from 20,000 for 36 wt% Ni to 100,000 for 80 wt% Ni,
- the electrical resistivity decreases, from 75×10^{-8} Ωm for 36 wt% Ni to 16×10^{-8} Ωm for 80 wt% Ni,
- the saturation polarization decreases, from 1.3 T for 36 wt% Ni to 1.1 T for 80 wt% Ni.

Nickel is an expensive material but its alloys with iron present magnetic properties useful for distinct applications, like magnetic shielding or magnetic cores where high magnetic permeability and a low coercive force are essential [7]. The magnetic properties of the Ni-Fe alloys are highly sensitive to mechanical stress; therefore their handling, manufacture and required annealing operations create additional costs.

3.3. Alloys of Iron with Cobalt

The Fe-Co alloys are less versatile and more expensive, due to the cost of cobalt (27,100 US$/tonne for Co vs. 14,565 US$/tonne for Ni for 20 August 2013). The addition of cobalt to iron raises the saturation and the Curie point of the alloy. Permendur ($Fe_{50}Co_{50}$) offers the highest polarization saturation level (2.45 T) of any bulk material at room temperature and the Curie temperature reaches the level of 980 $^{\circ}$C. By adding vanadium to the alloy, the machinability of the material is improved with the additional benefit of increased electrical resistivity [2].

Although their advantages are evident, the alloys of iron with cobalt are expensive. These alloys are employed especially for high field applications, to take advantage of the high saturation level of 2.45 T, compared to 1.9 T for standard Fe-Si.

4. Discussion

In order to minimize the influence of eddy-currents, the magnetic cores are assembled from a stack of insulated laminations. The thickness of the material is selected such that the effect on the quality of the field by induced eddy-currents is minimized. Also, proper selection of the thickness of the material may lead to damping of the higher frequency power supply ripples. Shuffling the lamination during manufacturing helps to achieve equal magnetic properties between electromagnets of one series.

Insulation between the layers can be achieved either by application of coatings to the surface of the sheet or through oxide layers. The organic coating of the material usually improves the punchability. Backlack bonding varnishes, which are becoming the standard for most steel manufacturers, allow for the gluing of the laminations [4].

The influence of the core material to the operation of the electromagnet is determined with Equations (3), (4), (5) and (6). It can be observed that a good material would be characterised by: high permeability over a wide range, high saturation level, high electrical resistivity, and low coercivity.

A list of relevant properties for magnetic materials usable for cores of accelerator electromagnets is presented in Table 1.

Following, the main advantages of the presented materials are summarized. Alloys of iron with cobalt provide the highest saturation level, but due to the prohibitive price of cobalt (27,000 US $/tonne [10]) these alloys are used only when their properties are detrimental.

The alloys of iron with nickel provide the highest permeability and the smallest coercivity but the lowest saturation level. Nickel also has a high price (13,900 US $/tonne [10]), therefore its use in large series production is not an economical option.

Magnetic materials properties, from [1], [2], [8] Table 1

Material	B_S [T]	B_R [T]	H_C [A/m]	$\mu_{r\,max} \times 1{,}000$	ρ [Ωm]
High purity Fe	2.1	1.3	4-240	30	9.6×10^{-8}
Carbon steel	1.55	0.7-1.1	40-400	0.6	-
NGO Si-Fe M400-50AP	1.7	1.23	98.2	6.9	70×10^{-8}
GO Si-Fe M089-27N	1.9	1.72	33	41.4	70×10^{-8}
$Ni_{80}Fe_{20}$	1.1	-	0.4	100	100×10^{-8}
$Co_{50}Fe_{50}$	2.45	1.5-2.2	160	5	7×10^{-8}

High purity iron offer large saturation, high permeability and depending on grade low coercivity. Due to its favourable magnetic properties, but low electrical resistivity, it can be used for cores of non-ramped electromagnets. The favourable magnetic properties are highly sensitive to impurities, and are achieved after well-tailored annealing. The level of impurities depend highly on the melt, therefore, similar magnetic properties between different melts and different manufactures are very difficult to achieve.

Carbon steel provides poor magnetic properties: low saturation level, high coercivity, and low permeability. Still, it can be employed for less demanding projects due to its low price and large availability.

Silicon steels are characterised by high electrical resistivity, high permeability and fair saturation level. They provide the best compromise between performance and price and are therefore often the first choice for laminated electromagnets.

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