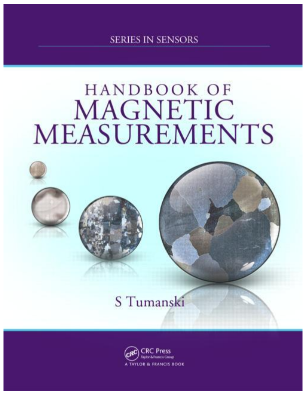

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Magnetic Materials

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3

Magnetic Materials

3.1 Soft Magnetic Materials: General Information

3.1.1 Properties and Classification

Commonly, ferromagnetic or ferrimagnetic materials are considered as magnetic materials although other materials (diamagnetic and paramagnetic) also exhibit some magnetic properties, as discussed earlier. The magnetic materials can be further classified into two clearly separate categories: soft magnetic materials and hard magnetic materials. Coercivity is assumed as the main criterion, and IEC Standard 404-1 recommends the coercivity of 1000 A/m as a value to distinguish both groups. This border is rather symbolic because both classes are completely different. From soft magnetic materials, we require the coercivity to be as small as possible (usually much less than 100 A/m) while hard magnetic materials should have coercivity as high as possible (commonly above 100,000 A/m). There is also a subclass of hard magnetic materials called semi-hard magnetic materials (with coercivity between 1,000 and 100,000 A/m). Figure 3.1 presents magnetic materials taking into account their coercivity available Vacuumschemlze who is one of the main manufacturers.

Soft magnetic materials cover huge market of various products: about 7×10^6 tons annually and about 10^{10} Euro (Moses 2003). We can divide these products taking onto account their magnetic performance, applications, cost, and other properties. For example, grain-oriented silicon steel is mechanically much harder than the nonoriented, so the same punching die will wear off after producing smaller quantity of elements. Even in the case of SiFe electrical steel, the best grade can be 10 times more expensive than ordinary grades of steel. And between cheep ferrites and high-quality soft magnetic materials, these differences in cost can be much larger.

Therefore, selection of appropriate kind and quality of material for a given application is an important knowledge. For example, the best quality steel after preparation of the product can be much more deteriorated than cheaper material that after the same technology can exhibit better performance (Schneider et al. 1998, Schoppa et al. 2000, Wilczynski et al. 2004). Figure 3.2 presents a comparison of the main parameters of typical soft magnetic materials including their cost.

It would be nice to be able to find the soft magnetic material with all excellent properties (high saturation polarization, small losses, small coercivity, small magnetostriction, good mechanical properties, etc.) even at much higher price. But such material simply does not exist. We have to accept always some compromises—high permeability at the cost of saturation polarization (Figure 3.3), small power loss at the cost of saturation polarization, better magnetic parameters at the cost of mechanical properties, etc. Fortunately, there is a plethora of various magnetic materials and appropriate technology often helps to find desirable material (Fish 1990, Moses 1990, 1992, 2003, Pfützner 1992, Arai and Ishiyama 1994, McCurrie 1994, Kronmüller 1995, Stodolny 1995, Fiorillo 1996, Schneider et al. 1998, Goldman 1999, O'Handley 2000, Beckley 2000, 2002, Geoffroy and Porteseil 2005, Peuzin 2005, Degauque et al. 2006, De Wulf 2006, Lebourgeois and Guyot 2006, Waecklerle 2006, Waeckerle and Alves 2006a,b, Kazimierczuk 2009).

Taking into account the main applications of soft magnetic materials, it should be noted that this situation continues to change and develop. For example, it was traditionally assumed that the main area of application of silicon steel is electric power industry. But recently, more and more power electric and power electronics devices use higher frequency signals, up to MHz. In high frequency range, electrical steel exhibits prohibitively high power loss and should be substituted by nanocrystalline and even ferrite materials (Figure 3.4). Consequently, in such applications, other accompanying devices, for example, measuring transformers, should be also made from high-frequency materials. In turn, the progress in nanocrystalline/amorphous materials resulted in development of new classical electrical steel (e.g., thinner gauge of even 0.15 mm).

Taking into account the importance of various groups of soft magnetic materials, it should be noted that almost 80% of the market is occupied by SiFe electrical steel (Figure 3.5). With ferrites and permalloys (NIFe), it is more than 95% and we can see that other materials, including amorphous and nanocrystalline are marginal in value.

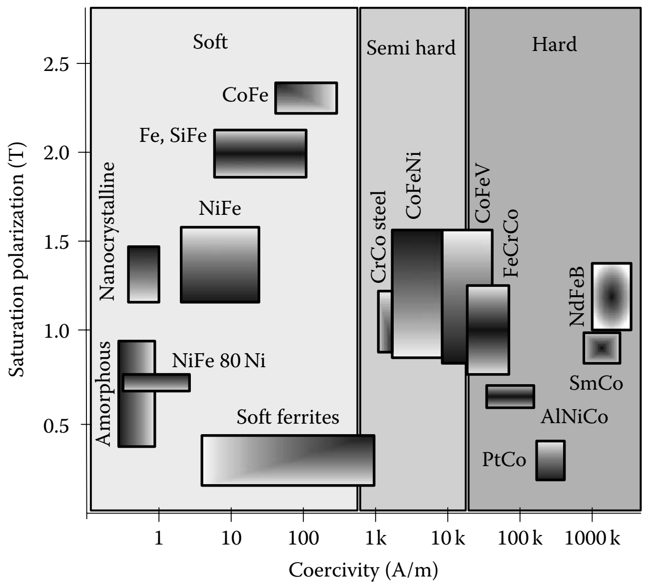

FIGURE 3.1
Ranges of commercially available magnetic materials (as an example of products offered by Vacuumschmelze).

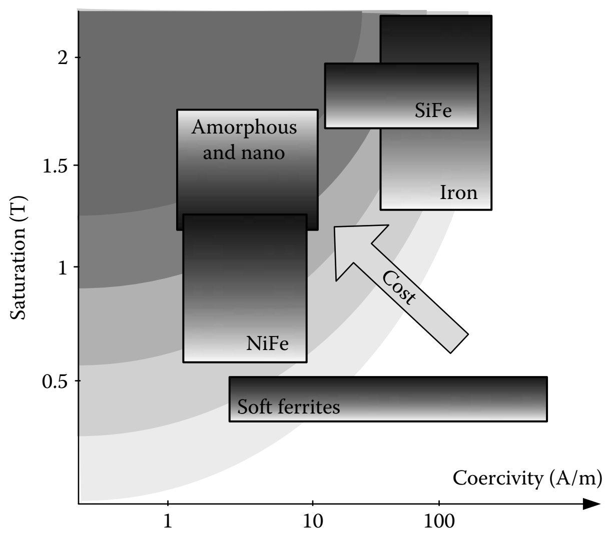

FIGURE 3.2
Comparison of the coercivity, saturation, and cost of typical soft magnetic materials.

Depending on application, various properties are required. In the case of electric power devices (power and distribution transformers, electric machines), the most important factors are low power loss and high saturation polarization. If we would like to choose only between silicon steel and amorphous materials (neglecting other factors), we arrive at a contradiction—amorphous materials exhibit smaller power loss but also significantly smaller saturation polarization and vice versa. Table 3.1 presents the comparison of parameters for the main soft magnetic materials.

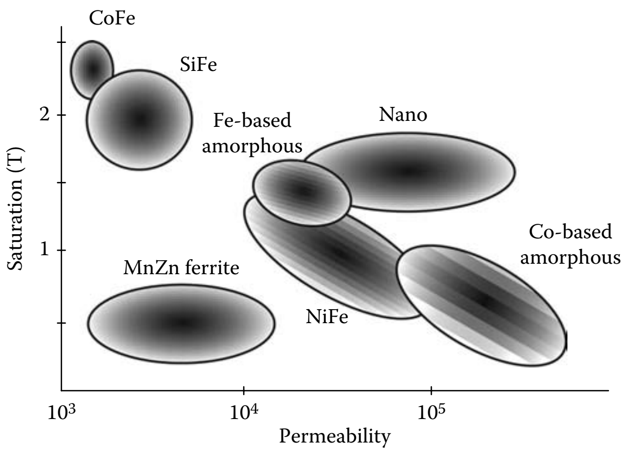

FIGURE 3.3
Comparison of the permeability and coercivity of the typical soft magnetic materials. (After Moses, A.J., *Przegl. Elektr.*, 79, 457, 2003.)

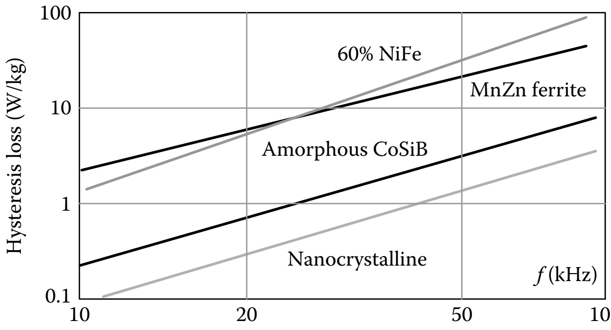

FIGURE 3.4
Hysteresis power loss versus frequency of high-frequency materials. (From Kolano, R. and Kolano-Burian, A., *Przegl. Elektr.*, 78, 241, 2002.)

If a material is used for magnetic shielding, then its losses are not as important as the permeability, and hence amorphous materials or permalloy is advisable. In the case of high-frequency applications, apart from the losses, deterioration of magnetic properties (e.g., permeability) with frequency is important, so from Table 3.1 we can see that, in this case, the materials would be ordered as follows: SiFe, NiFe, amorphous/nanocrystalline, MnZn ferrite, NiZn ferrite (and in microwave range, garnets).

Especially important are the CoFe alloys because they exhibit high saturation polarization with the highest known value of 2.46 T. Table 3.2 presents the typical applications of soft magnetic materials.

Figure 3.6 presents a diversity of soft magnetic materials currently available commercially. The properties of such materials will discussed in more detail in the following sections.

3.1.2 Pure Iron

Pure iron has excellent magnetic properties: large saturation polarization $J_S = 2.15$ T, low coercivity

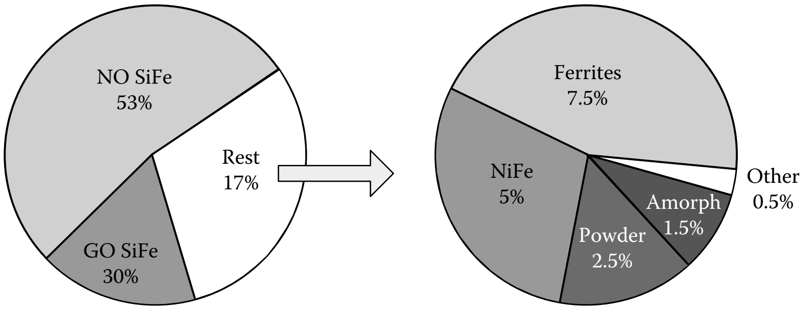

FIGURE 3.5
Annual value of world production of soft magnetic materials. (After Schneider, J. et al., *J. Phys.*, 8, Pr2-755, 1998.)

TABLE 3.1

Comparison of Parameters for the Main Soft Magnetic Materials

Parameter	3% SiFe GO	FeSiB Metglas	Ni80Fe20 Permalloy	Co50Fe50 Permendur	MnZn Ferrite
B_s (T)	2.03	1.56	0.82	2.46	0.2–0.5
H_c (A/m)	4–15	0.5–2	0.4–2	160	20–80
P1.5 T/50 Hz (W/kg)	0.83	0.27		1	
*P*1 T/1 kHz (W/kg)	20	5	10	20	
$\mu_{max} \times 1000$	20–80	100–500	100–1,000	2–6	3–6
Frequency range (kHz)	3	250	20	up to 1 kHz	2,000 NiZn—100,000

TABLE 3.2

Typical Applications of the Main Soft Magnetic Materials

Application	Electrical Steel	Fe-Based Amorphous	Powder	CoFe	Ferrite
Power transformers	▨	▨			▨
Distribution transformers	▨	▨			
Lamp ballasts	▨				
Induction motors	▨				
Generators	▨			▨	
Reactors	▨	▨			
Other motors	▨	▨	▨		
Special transformers	▨	▨		▨	▨
Chokes	▨		▨		▨
Power electronics		▨		▨	▨
Instrumentation	▨				▨
Pulsed power		▨			▨
Shielding	▨	▨			

Source: After Moses, A.J., *Przegl. Elektr.*, 80, 1181, 2004. With permission.

$H_c = 3–12$ A/m, and high permeability $\mu_{max} = 280{,}000$ (single crystal magnetically annealed even up to 1,400,000). But the main problem is that such performance is displayed only by pure iron: even small quantities of impurities cause significant deterioration of magnetic properties (Figure 3.7). In practice, such extremely pure material is expensive and possible to use only in laboratory.

Commercially available pure iron has much smaller permeability $\mu_{max} = 10{,}000–20{,}000$ and larger coercivity $H_c = 20–100$ A/m because impurities such as C, Mn, P, S, N, and O impede the domain wall motion. By annealing such material in hydrogen at 1200°C–1500°C, it is possible to remove most of these impurities but such process is also quite expensive.

Pure iron has low resistivity $\rho = 10\,\mu\Omega$ cm (in comparison with 45 $\mu\Omega$ cm of GO SiFe and 140 $\mu\Omega$ cm of amorphous material). Such good conductivity causes large eddy current loss and practically precludes pure iron from AC application.

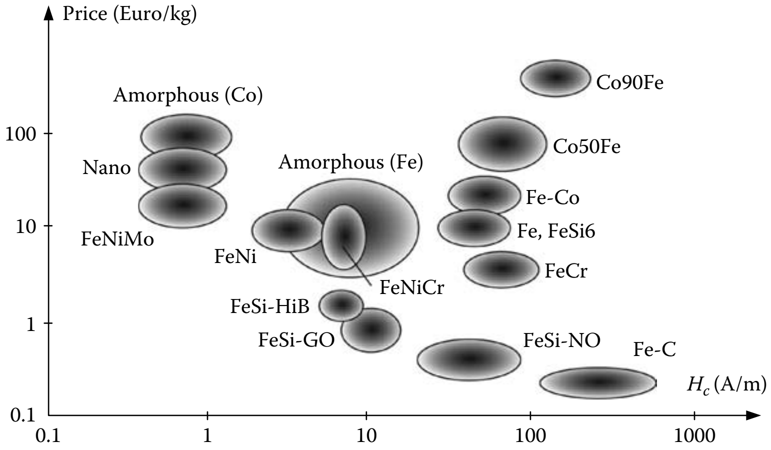

FIGURE 3.6
Diversity of soft magnetic materials. (After Waecklerle, T., Materiaux magnetiques doux speciaux et applications, in *Materiaux magnetiques en genie electrique I*, Kedous-Lebouc, A. (Ed.), Lavoisier, Chapter 3, pp. 153–223, 2006.)

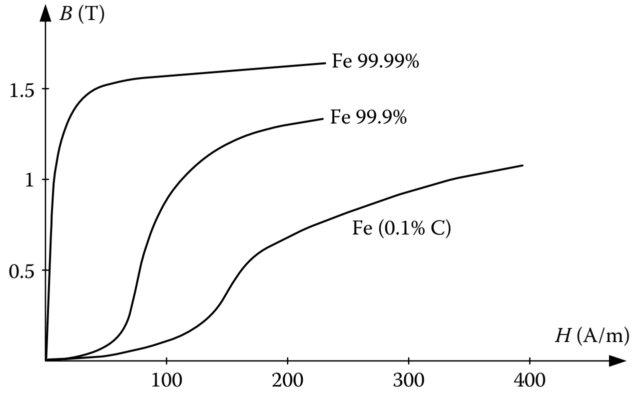

FIGURE 3.7
Magnetization curves of iron. (After McCurrie, R.A., *Ferromagnetic Materials*, Academic Press, London, U.K., 1994.)

Both problems—expensive manufacturing and limited frequency application—can be solved if we use the same material in form of a powder iron. This material is manufactured by grinding iron (or iron alloys[*]) into powder with dimension of particles 5–200 μm and next by pressing this powder with insulating material. Resistivity of such material is of the order of $\rho = 10^4$ μΩ cm and therefore it can be used in high-frequency range to 100 kHz (specially prepared NiFe powder to 100 MHz) (Kazimierczuk 2009).

Instead of cheap pressing, most often sintering technology is used, which results in better magnetic performances of the powder materials (Table 3.3).

As a material for powder iron cores, most commonly, carbonyl iron is used. Technology of obtaining extra pure iron powder from iron pentacarbonyl, $Fe(CO)_5$, was developed in 1925 by BASF Company. By thermal decomposition of iron pentacarbonyl, it is possible to produce 99.8% pure iron powder with spherical particles ranging from 1 to 8 μm.

Although the presence of carbon significantly deteriorate magnetic properties of iron (Figures 3.6 and 3.7), low-carbon steel is widely used as magnetic material mainly due to its low price (Figure 3.6) and good mechanical properties. As "low-carbon" steel it is assumed the material with following: C, 0.04%–0.06%; P, 0.05%–0.15%; Mn, 0.35%–0.8%; S, 0.006%–0.025%; and Si, 0.05%–0.25%. Although the magnetic properties of low-carbon electrical steel are rather poor, they are acceptable for many cheap devices, like small motors, relays, or electromechanical mechanisms. Figure 3.9 presents the part of phase diagram of Fe-C alloys.

Iron exists in two allotropic forms: α-Fe (ferrite Fe-C) ferromagnetic body-centered cubic and γ-Fe (austenite Fe-C) paramagnetic face-centered cubic. Above 0.008% of C in ferrite appears as impurity cementite (iron carbide, Fe_3C) that above 210°C is nonmagnetic. Transition between α-Fe and γ-Fe is at 910°C,[†] but also ferrite is paramagnetic above Curie temperature 768°C.

TABLE 3.3
DC Magnetic Properties of Powder Material

	Pressed	Sintered
B at 8000 A/m	1.65 T	1.75 T
B_r from 8000 A/m	0.34 T	0.93 T
H_c from 8000 A/m	192 A/m	80 A/m
μ_{max}	800	7000

Source: Bularzik, J.H. et al., *J. Phys.*, 8, Pr2-747, 1998.

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[*] In powder materials also other substances, like NiFe or Sendust are used.

[†] Above 1538°C iron again is ferromagnetic in body-centered cubic structure known as δ-Fe.

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