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Magnetizing behaviour of permanent magnets

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Magnetizing behaviour of permanent magnets

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MAGNETIZING BEHAVIOUR OF PERMANENT MAGNETS

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 62517, which is a technical report, has been prepared by IEC technical committee 68: Magnetic alloys and steels.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
68/377/DTR	68/384/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

The full performance of a permanent magnet can only be obtained if it is magnetized properly to saturation. In IEC 60404-5 a definition of the saturation of a permanent magnet is given. Accordingly, a magnet is defined as saturated at a magnetizing field strength H_1 if a 50 % higher field strength leads to an increase of $(BH)_{max}$ or H_{cB} of less than 1 %. However, such a definition cannot explain the substantial differences in the magnetizing behaviour of modern permanent magnets which is mainly determined by their coercivity mechanisms. Unfortunately the variety of magnetizing behaviours cannot be accommodated by a simple recommendation such as “magnetize with magnetizing field strengths of three to five times the coercivity H_{cJ}”. In particular for RE permanent magnets with high coercivity H_{cJ} this simplification would lead to unacceptable overestimations of the required magnetizing field strengths.

MAGNETIZING BEHAVIOUR OF PERMANENT MAGNETS

1 Scope

It is within the scope of this technical report to describe the magnetizing behaviour of permanent magnets in detail. Firstly, in Clause 3 the relationship between the applied magnetic field strength and the effectively acting internal field strength is reviewed. In Clause 4 the initial state prior to magnetization is discussed. Then, in the main Clause 5, the magnetizing behaviour of all common types of permanent magnets is outlined. The clause is subdivided according to the dominant coercivity mechanisms, namely the nucleation type for sintered Ferrites, RE-Fe-B and $SmCo_5$ magnets, the pinning type for carbon steel and Sm_2Co_{17} [1] magnets and the single domain type for nano-crystalline RE-Fe-B, Alnico and Cr-Fe-Co magnets. Finally, the recommended magnetizing field strengths for modern permanent magnets are compiled in a comprehensive table.

2 Effective magnetizing field strength

For magnetization of permanent magnets, the internal magnetic field strength H_{int} in the magnet is the critical parameter. The internal field strength is determined by the applied field strength H_{appl} and the self-demagnetizing field strength H_{demag} of the magnet or the magnet assembly. The self-demagnetizing field strength depends on the dimensions of the magnet or the load line of a magnet assembly and the polarization of the magnet material, see equation (1):

$$H_{int} = H_{appl} - H_{demag} = H_{appl} - N \cdot J/\mu_0 \qquad (1)$$

N denotes the demagnetization coefficient and J the polarization of the magnet material.

Most advanced magnets are magnetized by a short pulse field, achieved by discharging a capacitor bank through a copper coil. The duration of the field pulse must last sufficiently long, in order to overcome the eddy currents at the surface of the magnets, in particular for large blocks. In general, a pulse duration of 5 ms to 10 ms is sufficient for complete penetration. The penetration depth λ, see equation (2), depends on the electrical resistance ρ, the permeability μ of the magnet material and the frequency f of the field pulse [1][2]:

$$\lambda = K \cdot \sqrt{\frac{\rho}{\mu \cdot f}} \qquad (2)$$

K denotes a constant.

Preferably, magnets will be magnetized after assembly, since handling of unmagnetized magnets is easier and prevents contamination by ferromagnetic particles. In addition chipping of magnet-edges due to the mutual attraction of magnet parts is avoided.

1 The composition Sm_2Co_{17} is used as the generic name for a series of binary and multiphase alloys with transition elements such as Fe, Cu and Zr replacing Co, see also IEC 60404-8-1; 2nd edition 2001.

2 The figures in brackets refer to the Bibliography.

3 Initial magnetization state

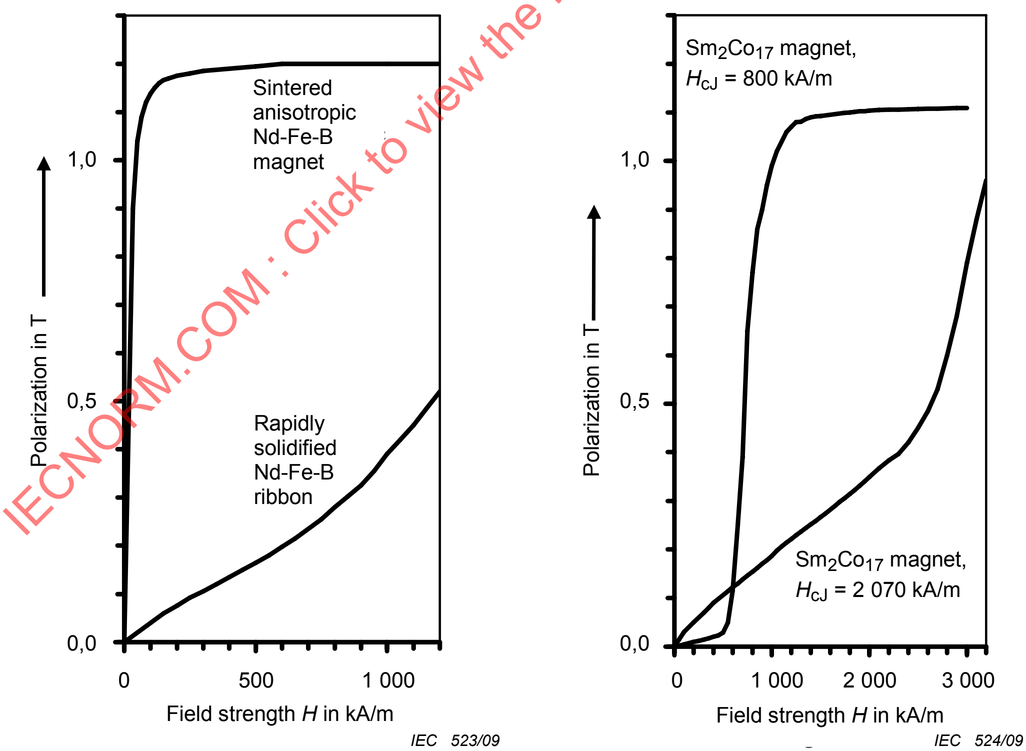
For nucleation type ferrite, SmCo5 and REFeB magnets, the initial state prior to magnetizing is usually the state after the final heat treatment, i.e. after sintering. This state shows no net remanent magnetization and is often called the thermally demagnetized, or virgin, state. Ferrite and REFeB magnets, once magnetized, may be reset to the initial state by heating them to above the Curie temperature. This will return them to the thermally demagnetized state without permanent loss of properties. $SmCo_5$ magnets can be reset to the initial state only by repeating the full final heat treatment. To prevent chemical changes which can lead to surface damage and permanent loss of properties, rare earth magnets shall be protected in an inert atmosphere during this procedure.

For anisotropic Alnico and CrFeCo magnets, where heat treatment in a magnetic field and tempering are involved, some residual magnetization may remain in the magnets. These magnets may be completely demagnetized from any degree of magnetization by applying a slowly reducing alternating magnetic field. The same holds for any pinning or single domain type magnet such as Sm_2Co_{17} and rapidly quenched or HDDR-treated REFeB magnets.

4 Magnetizing behaviour of permanent magnets

4.1 General

The magnetizing behaviour of permanent magnets is closely related to their coercivity mechanisms, therefore they need to be discussed. Modern permanent magnets may be divided into three groups with respect to their coercivity mechanism. The principal magnetization behaviour for these groups, the nucleation type, the pinning type and the single domain particle type is illustrated in Figure 1.



(a) (b)

a) Nucleation-type anisotropic RE-TM magnets, for instance sintered Nd-Fe-B or $SmCo_5$ magnets, or single domain particle type isotropic nanocrystalline RE-TM magnets, for instance rapidly solidified Nd-Fe-B ribbons

b) Pinning-type RE-TM magnets, for instance Sm_2Co_{17} magnets with coercivities H_{cJ} of 800kA/m or 2 070 kA/m, respectively.

Figure 1 – Principal magnetizing behaviour of RE-TM magnets after final heat treatment

4.2 Nucleation type magnets, sintered Ferrites, RE-Fe-B, $SmCo_5$

4.2.1 General

The commercially very important sintered Ferrites, RE-Fe-B and $SmCo_5$ magnets are nucleation type materials. In the following discussion, the magnetization behaviour of nucleation type magnets will be discussed using anisotropic sintered RE-Fe-B magnets as an example.

4.2.2 Initial magnetization curve after final heat treatment

For nucleation type magnets such as sintered Ferrites and Rare Earth Transition Metal (RE-TM) magnets based on Nd-Fe-B or $SmCo_5$, the grains contain multiple magnetic domains after final heat treatment. The magnetic domains are separated by domain walls which can move easily within the grains, so that the polarization increases steeply, even in small magnetizing fields, see Figure 1 a) [2]. For sintered RE-Fe-B magnets, a polarization of about 95 % of the saturation polarization results even after magnetizing with a small magnetizing field strength of about 200 kA/m.

4.2.3 Approach to saturation after final heat treatment

The polarization decreases, once a low magnetizing field is removed, since no significant coercivity H_{cJ} has been developed. In the multidomain grains, the domain walls are free to move back toward their original positions, to minimize the magnetic stray field energy, see Figure 2.

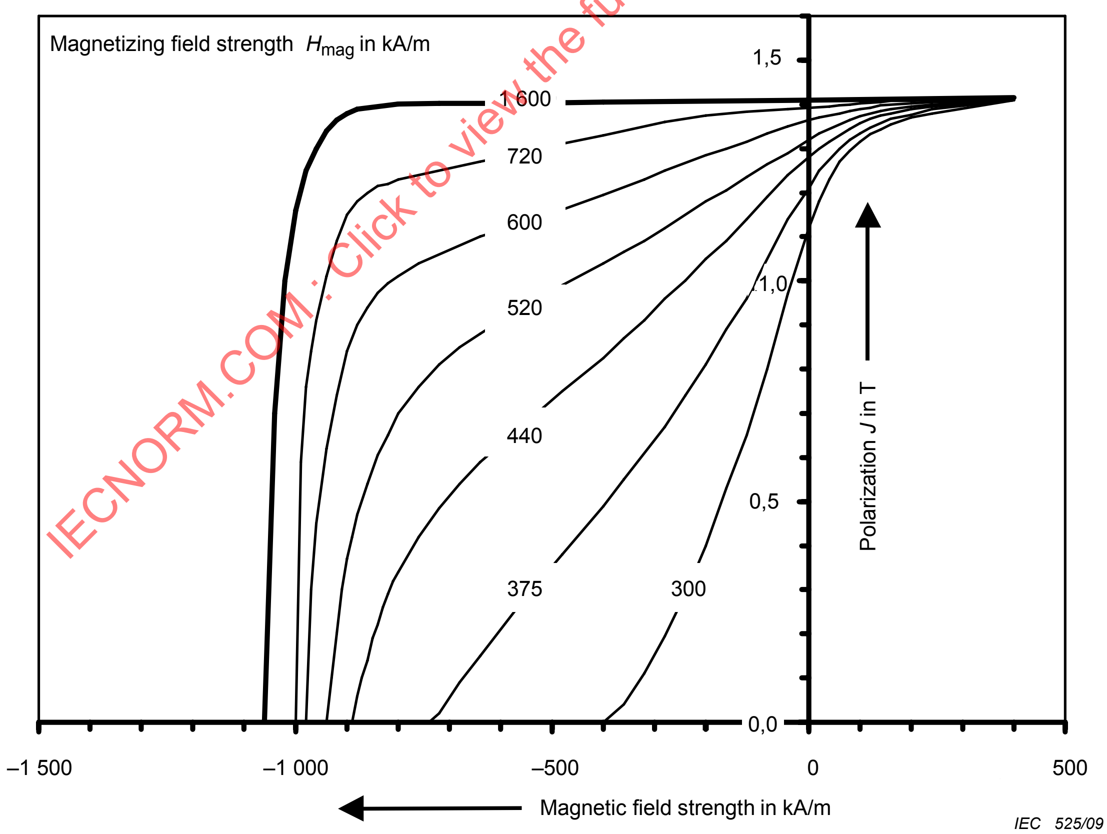


Figure 2 – Magnetizing behaviour of sintered Nd-Dy-Fe-B magnets

The demagnetization curves $J(H)$ were measured on different samples, each in the state after the final heat treatment, after magnetization by the indicated field strengths H_{mag}. For complete magnetization an applied field of 2 000 kA/m is recommended.

Magnetization by a field strength of about 500 kA/m saturates some grains, resulting in some coercivity. Such grains do not contain domain walls anymore. Since most of the grains are still multidomain, the $J(H)$ demagnetization curves of such partially magnetized magnets show a very poor squareness, see Figure 2.

To saturate a nucleation type magnet after final heat treatment, all domain walls within every single grain must be removed. To achieve this, the internal field strength must become positive at every point in the material, since strong local demagnetizing stray fields can occur at the grain edges [3,4]. The magnitude of the local stray fields can be estimated from the following equation:

$$H_{local} = -N_{eff} \cdot J/\mu_0 \tag{3}$$

J denotes the polarization of the magnet material and N_{eff} presents an effective demagnetization coefficient, which depends on the local microstructure. In practice, N_{eff} can be of the order of two [4]. As a result, perfect saturation requires a magnetizing field strength of at least twice the saturation polarization J_s (divided by μ_0) of the magnet material [4,5]. For the RE-Fe-B magnet shown in Figure 2, complete magnetization requires a strong internal field strength of more than 1 600 kA/m. In that case, nearly every grain is saturated: hardly any grains contain small reversed domains.

In conclusion, the internal magnetizing field strength for complete saturation of anisotropic nucleation type permanent magnets after final heat treatment can be written as

$$H_{mag} \approx 2 \cdot J_s / \mu_0 \tag{4}$$

where J_s denotes the saturation polarization of the magnet material. The factor 2 describes the effect of the local stray fields as discussed above. It is worth mentioning that the magnetizing field strength required to saturate such magnets does not depend on the coercivity H_{cJ} at all, but instead it increases with increasing remanent polarization, see Figure 3 and Reference [6].

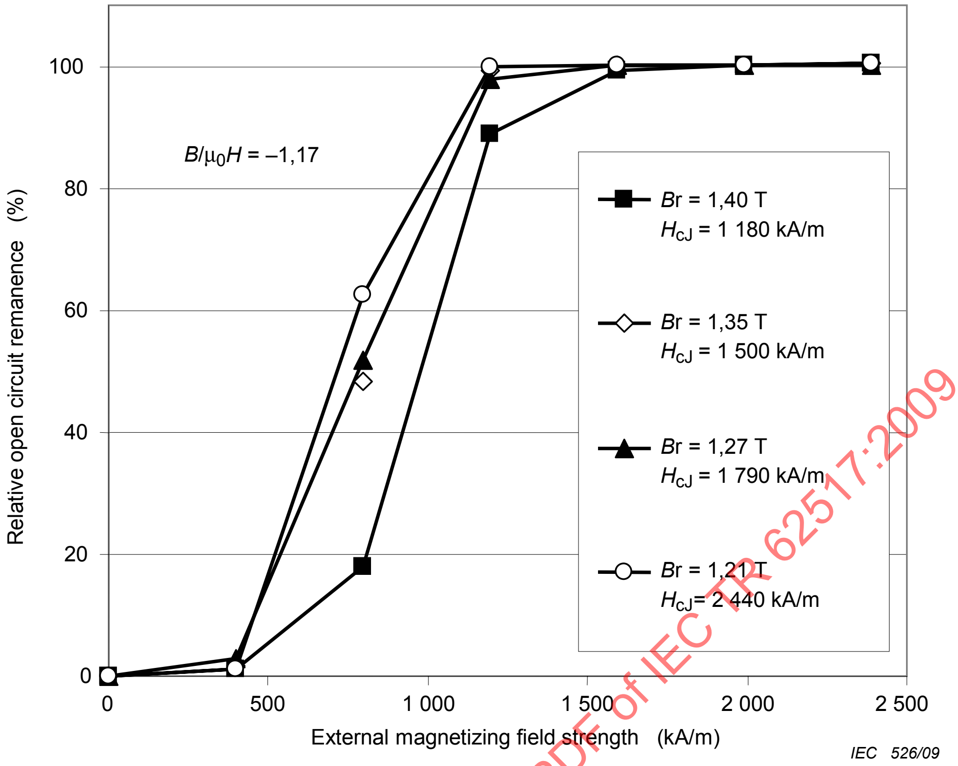


Figure 3 – Magnetizing behaviour of sintered Nd-Dy-Fe-B magnets with various remanence B_r and coercivity H_{cJ} values after final heat treatment

The open circuit flux was measured with a Helmholtz coil after each magnetizing pulse and related to the remanent flux density after saturation with 4 780 kA/m.

However, the magnetizing field strength depends on the texture of the magnets, too. For misaligned grains, the effective magnetizing field strength decreases with the cosine of the misalignment angle. Consequently, the required magnetizing field strengths for poorly aligned magnets, in particular for isotropic magnets, are higher.

4.2.4 Coercivity mechanism of nucleation type magnets

The coercivity mechanism in nucleation-type magnets has been described by the micromagnetic theory for nucleation of reversed domains [3, 7-10] or by an empirical model for the existence and expansion of nuclei of reversed domains [11-14].

The coercivity H_{cJ} of nucleation-type magnets, including sintered anisotropic ferrites, $SmCo_5$ and Nd-Fe-B magnets, is determined by the nucleation of reversed magnetic domains in each previously fully saturated grain, since the grains are decoupled magnetically from each other. Once a reversed domain has been nucleated, it expands and the whole grain is demagnetized immediately. The minimum volume of such a reversed magnetic domain is proportional to the domain wall thickness cubed [11,12]. In general, nucleation will occur at crystal defects, where the magnetocrystalline anisotropy is reduced or at edges of grains, where strong local stray fields assist the nucleation.

There is a dominant impact of the microstructure of a magnet on the coercivity H_{cJ} in these magnets. Besides having a high anisotropy field strength H_A, the coercivity H_{cJ} depends on local demagnetizing stray fields, which are described by an effective demagnetizing coefficient N_{eff} [3, 8, 10, 16], see equation (5).

$$H_{cJ} = c \cdot H_A - N_{eff} \cdot J/\mu_0 \qquad (5)$$

The anisotropy field strength, H_A , is the field strength required to saturate the magnet material perpendicular to its easy magnetization direction, J is the polarization of the magnet material, c is a factor describing the decoupling of neighbouring grains and N_{eff} is an effective demagnetization coefficient, which depends on the local microstructure.

4.2.5 Reversing the magnetization after magnetic saturation

The magnetizing behaviour of nucleation type magnets which have been demagnetized by a magnetic field may differ considerably from the state after the final heat treatment described in 4.2.2 and 4.2.3. If the coercivity H_{cJ} of the magnet is small compared to the corresponding magnetizing field strength, e.g. $H_{cJ} < J_s / \mu_0$, then multidomain grains may be formed during field demagnetization. Then, the reversing behaviour of field demagnetized magnets is similar to that of magnets after the final heat treatment, see 4.2.3.

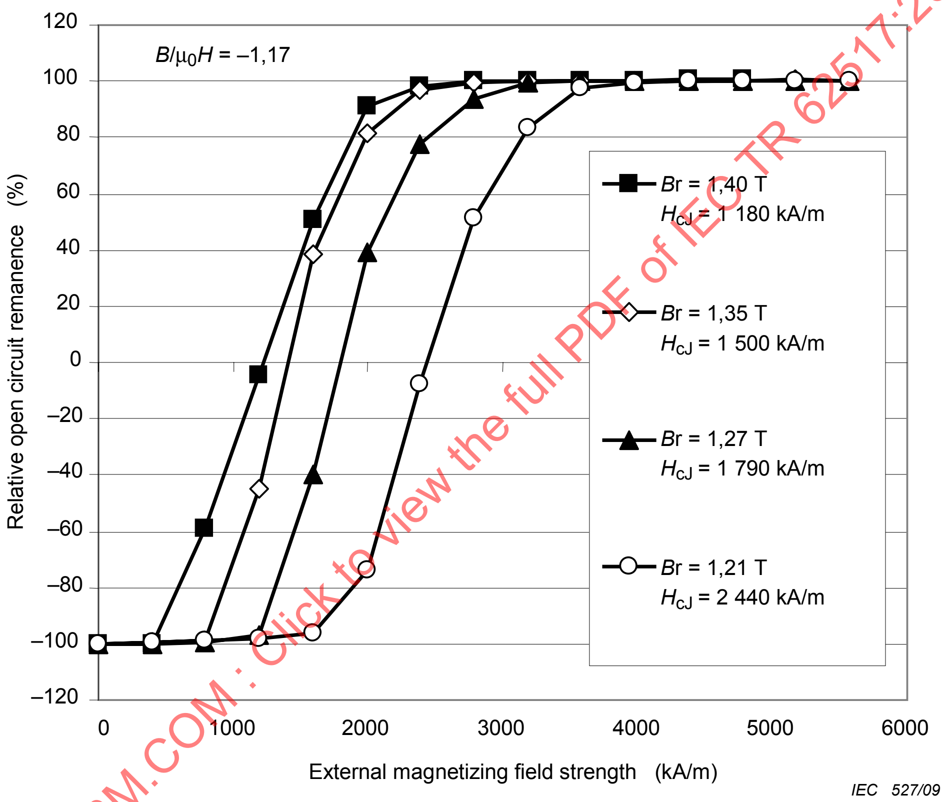


Figure 4 – Magnetizing behaviour of sintered Nd-Dy-Fe-B magnets with various remanence B_r and coercivity H_{cJ} values after magnetic saturation in the reverse direction

The open circuit flux was measured with a Helmholtz coil after each magnetizing pulse and related to the remanent flux density after saturation with 4 780 kA/m.

But, if the coercivity H_{cJ} is higher compared to the magnetizing field strength, e.g. $H_{cJ} > J_s / \mu_0$, the individual grains will be completely reversed upon demagnetization and no multidomain grains will be formed. The magnetic field strength necessary for reverse magnetization will then be proportional to the coercivity H_{cJ}. Generally, for field demagnetized nucleation type magnets, the magnetizing field strength should be at least twice the coercivity H_{cJ}, see Figure 4.

This behaviour is most pronounced for sintered anisotropic $SmCo_5$ magnets. Because of the relatively low saturation polarization, about 1,1 T, an internal magnetic field strength of 1 600 kA/m is sufficient to saturate a magnet after the final heat treatment. After field demagnetization, however, magnetic field strengths of up to 8 000 kA/m are required for complete resaturation, see also Figure 7 and Figure 8.

4.3 Pinning type magnets, Sm_2Co_{17}

4.3.1 General

In pinning type magnets the domain walls are pinned at phase boundaries, precipitates or planar crystal defects [2]. The old carbon steel magnets and modern Sm_2Co_{17} magnets are examples of this behaviour. The magnetization behaviour of pinning type magnets is discussed below for the latter material only.

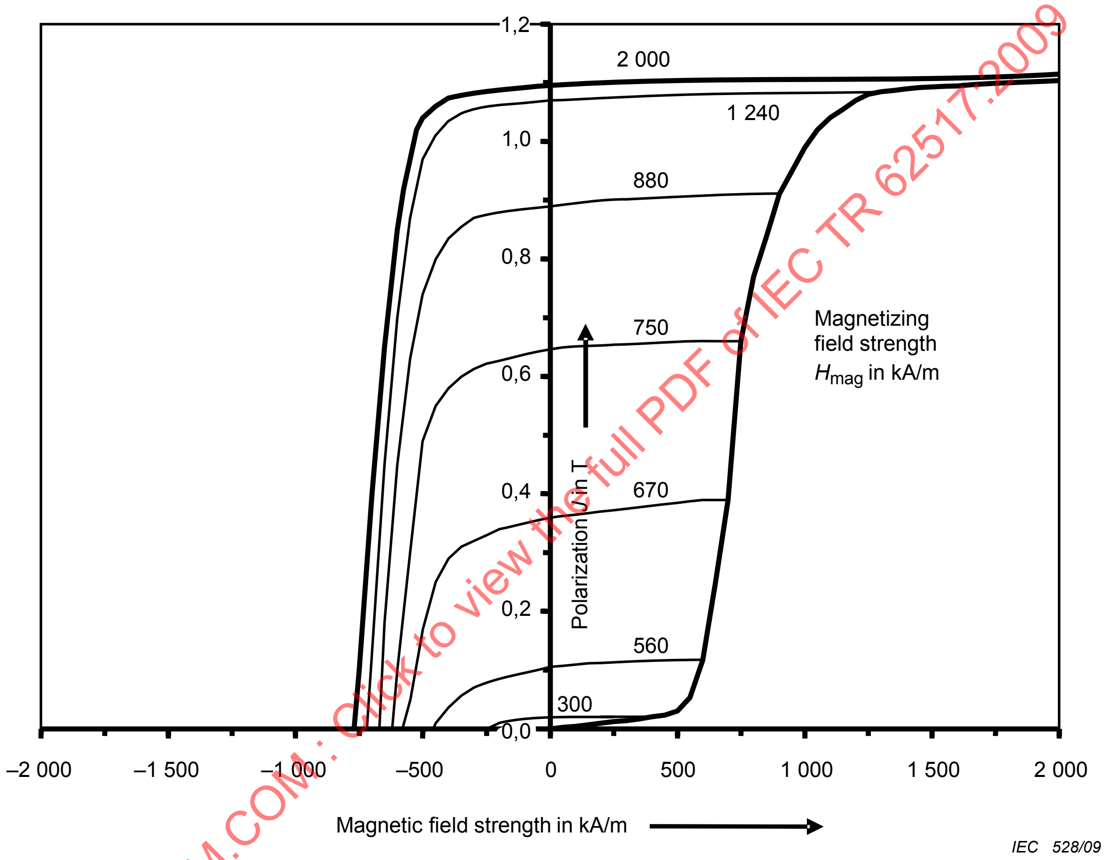


Figure 5 – Magnetizing behaviour of sintered Sm_2Co_{17} magnets with a coercivity H_{cJ} of about 800 kA/m

The demagnetization curves $J(H)$ were measured on different samples, each in the state after final heat treatment, after magnetization by the indicated field strengths H_{mag}. For complete magnetization an applied field of 2 000 kA/m is recommended.

4.3.2 Initial magnetization curve

In pinning type magnets, domain walls are nucleated easily. Therefore, in order to magnetize a pinning-type magnet, the domain walls must be removed from the pinning sites, requiring magnetizing fields larger than the pinning field strength, see Figure 1 b). However, in some magnet materials, the pinning field strength is not well-defined, for instance in Sm_2Co_{17} magnets with coercivities H_{cJ} above 1 600 kA/m, see Figure 1 b). To saturate these magnets, a magnetizing field of at least twice the coercivity H_{cJ} is needed. Since Sm_2Co_{17} magnets are produced with a wide range of coercivities H_{cJ}, the required internal magnetizing field strength may vary from about 2 000 kA/m to more than 4 000 kA/m.

4.3.3 Approach to saturation

Magnetization of pinning-type magnets, for instance sintered Sm_2Co_{17} magnets with coercivities H_{cJ} in the range of 600 kA/m to 800 kA/m, needs an internal magnetizing field strength strong enough to overcome the pinning forces. If a small magnetizing field is applied to such a magnet, the magnetic domain walls are not moved and there is only a negligible increase of the polarization, see Figure 5. If it is magnetized with 750 kA/m, which is in the order of its coercivity H_{cJ}, it will reach a remanence of about 60 % of its saturation value. But in contrast to partly magnetized nucleation type magnets, the demagnetization curve already shows a good squareness. This is because pinning type magnets never contain freely moveable domain walls. The domain walls are always pinned, irrespective of how the actual magnetization state has been achieved. As a result, pinning type magnets, irrespective of their coercivity H_{cJ}, are very well-suited for adjusting to a very narrow range of flux values, either by incomplete magnetizing or by partial demagnetizing. For nucleation type magnets like Nd-Fe-B and $SmCo_5$ this holds only for grades with high coercivities H_{cJ}, in particular with $H_{cJ} > 2 \cdot J_s / \mu_0$, if they were properly saturated at the beginning of the adjusting procedure.

When the internal magnetizing field is about the same as the coercive field H_{cJ}, domain walls can be pulled away from the pinning sites and domains with a polarization parallel to the magnetic field will grow significantly. Since the strength of the pinning sites may vary within the microstructure, the complete magnetization requires a magnetizing field strength of at least twice the coercivity H_{cJ}.

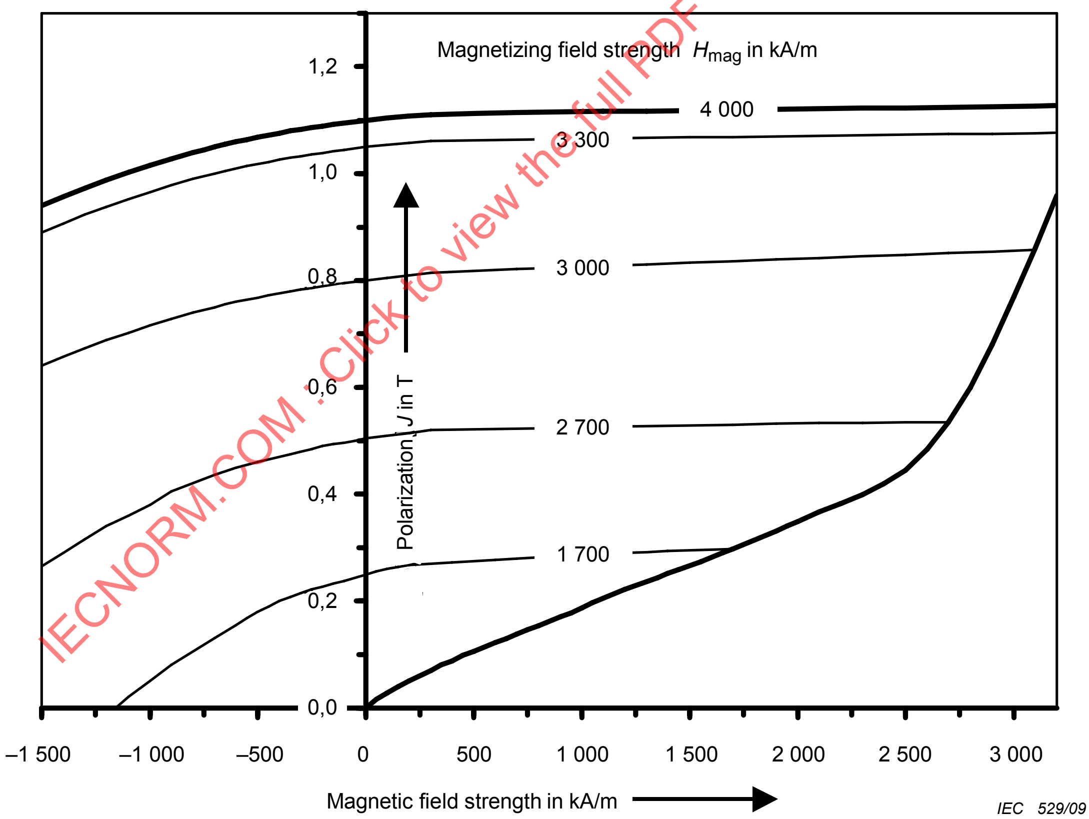


Figure 6 – Magnetizing behaviour of sintered Sm2Co17 magnets with a coercivity HcJ of about 2 800 kA/m

The demagnetization curves $J(H)$ were measured on different samples, each in the state after final heat treatment, after magnetization by the indicated field strengths H_{mag}. For complete magnetization an applied field of 3 650 kA/m is recommended.

Sm_2Co_{17} magnets with high coercivities H_{cJ} in the range 1 500 kA/m up to 2 100 kA/m demonstrate a more heterogeneous pinning behaviour. For magnetizing field strengths which are lower than the coercivity H_{cJ}, there is an increase of the polarization up to about a third of the remanence, see Figure 6. Probably not all pinning sites exert the same pinning strength on the magnetic domain walls. In fact, in well annealed Sm_2Co_{17} magnets with strong coercivities H_{cJ}, it seems that two kinds of pinning sites exist, with different pinning strengths [17]. The different pinning sites were revealed by the different temperature dependences of the corresponding coercivities. Increasing the internal magnetizing field strength beyond the coercive field strength H_{cJ} results in a strong increase of the polarization, see Figure 6. However, complete saturation of Sm_2Co_{17} magnets requires a magnetizing field strength of at least twice the coercivity H_{cJ}.

4.3.4 Coercivity mechanism of pinning type magnets

Microscopic models for the coercivity-mechanism of pinning type magnets have been compiled by several authors [15, 18, 19]. Because domain walls are easily nucleated in such magnets, the coercivity mechanism is only determined by the pinning of the domain walls at phase boundaries or precipitates. As a result, there is no difference between the magnetizing and the demagnetizing behaviour of such magnets. In particular, there is no difference between the required magnetizing field after the final heat treatment and after field demagnetization, compare the Sm_2Co_{17} grades in Figure 7. In contrast to this, it is also evident from Figure 7 that nucleation type $SmCo_5$ magnets are quite easy to magnetize from the state after final heat treatment but are much harder to magnetize after reverse magnetic saturation, see also 4.2.5.

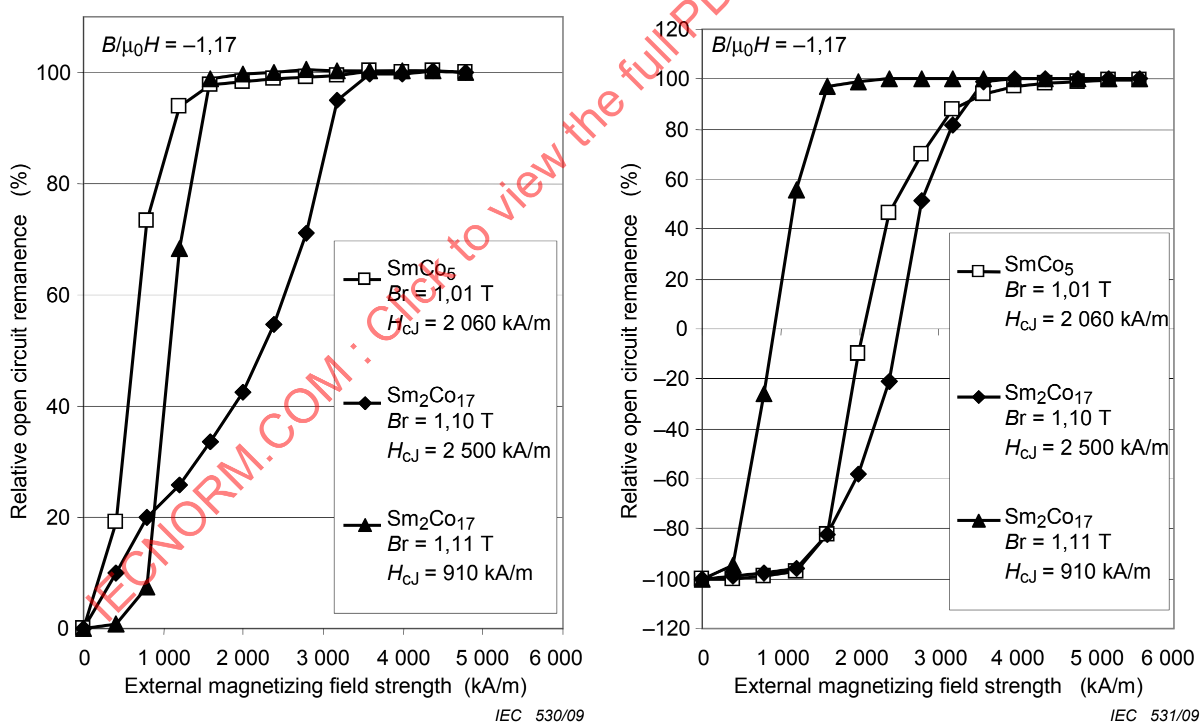


Figure 7 – Magnetizing behaviour of sintered Sm-Co magnets with various remanence Br and coercivity HcJ values, left: after final heat treatment and right: after magnetic saturation in the reverse direction

The open circuit flux was measured with a Helmholtz coil after each magnetizing pulse and related to the remanent flux density after saturation with 4 780 kA/m.

4.4 Single domain particle magnets

4.4.1 General

In single domain particle magnets, the size of the magnetic grains or cells is comparable to, or smaller than, the corresponding single domain diameter. Within these grains, no domain walls can exist at all. The magnetization of these cells can only rotate towards the direction of the applied magnetic field and, at a certain critical field, the magnetization of the whole grain jumps into the direction of the applied field. Alnico, Cr-Fe-Co and nano-crystalline RE-Fe-B magnets prepared by rapid quenching or the HDDR process [20] belong to this type of magnet.

4.4.2 Single domain particle magnets based on magnetocrystalline anisotropy

In nano-crystalline Nd-Fe-B magnets, for instance isotropic magnets made from rapidly solidified Nd-Fe-B ribbons, there is only a gradual increase of the polarization from the thermally demagnetized state, see Figure 1 a). The polarization of the individual grains must be rotated against the magnetocrystalline anisotropy towards the direction of the magnetizing field. In principle, saturation of isotropic magnets will need a magnetizing field strength similar to the anisotropy field, at least for the grains which are misaligned by 90°. In practice, the required magnetizing field to complete saturation of such magnets is about three to five times the coercivity H_{cJ}, see Figure 8. Similar to the pinning type magnets, there is no significant difference between the magnetizing and the demagnetizing behaviour.

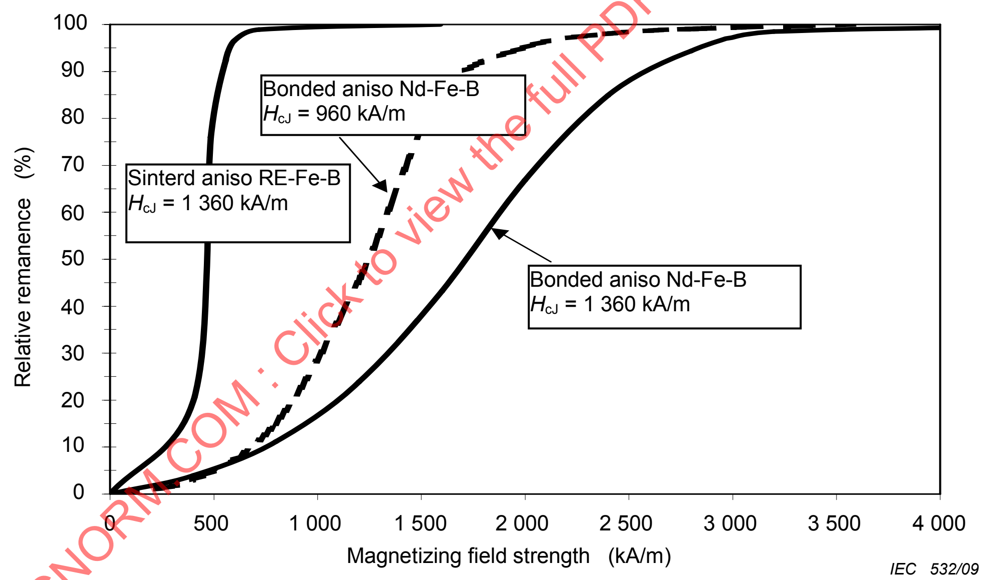


Figure 8 – Magnetization behaviour of bonded anisotropic HDDR RE-Fe-B magnets compared to a sintered anisotropic RE-Fe-B magnet

All magnets have a load line of about $B/\mu_0 H$ = -2,4.

4.4.3 Alnico and CrFeCo magnets

In Alnico and CrFeCo magnets, the coercivity H_{cJ} is determined by the shape anisotropy of the ferromagnetic Fe-Co rods in a non-magnetic matrix. The coercivity H_{cJ} is proportional to the difference between the demagnetizing coefficient $N_\parallel$ parallel to the easy axis and $N_\perp$ perpendicular to the easy axis of the individual Fe-Co rods, see equation (6).

$$H_{cJ} = f(q) \cdot (N_\parallel - N_\perp) \cdot J/\mu_0 \qquad (6)$$

$f(q)$ denotes a distribution function, which takes into account the non-ideal alignment of the easy axes of the Fe-Co rods [21]. For the case of non-interacting uniaxial single domain particles, $f(q)$ amounts to 0,5.

For these magnets, the individual Fe-Co cells are magnetized either parallel or antiparallel to their respective easy axes. Magnetizing or demagnetizing of this type of magnet always means that the magnetization of reversely magnetized cells is rotated against the shape anisotropy into the direction of the applied field, irrespective of how the initial magnetization state was achieved. As a result, the magnetizing field strength for complete saturation is proportional to the coercivity H_{cJ} of the magnet. For anisotropic magnets, the saturation field strength is about 3 times the coercivity H_{cJ}, while for isotropic magnets it amounts to about 5 times the coercivity H_{cJ}. Similar to pinning type magnets, the same field strength is necessary to reverse the magnetization of such magnets as was required to saturate them after the final heat treatment.

5 Conclusions

The magnetizing behaviour of modern permanent magnets is strongly dependant on the coercivity mechanism. Nucleation type magnets such as sintered Ferrites, RE-Fe-B and $SmCo_5$ magnets can be fairly easily magnetized from the initial state after final heat treatment. Magnetic field strengths of twice the saturation polarizations (divided by μ_0) of the magnetic material are sufficient to saturate these magnets. However, they may require much higher fields of about twice the coercivity H_{cJ} for reverse magnetization.

For pinning type magnets such as sintered Sm_2Co_{17} magnets, there is no difference between the magnetizing and the demagnetizing behaviour. For complete saturation, magnetizing fields of about twice the coercivity H_{cJ} are required.

Single domain particle type magnets like nanocrystalline RE-Fe-B or Alnico and Cr-Fe-Co magnets show a similar magnetizing behaviour to pinning type magnets. For anisotropic magnets, magnetizing field strengths of about three times the coercivity H_{cJ} are required for saturation and for isotropic magnets magnetizing field strengths of up to five times the coercivity H_{cJ} are recommended.

The recommended magnetizing field strengths, H_{mag}, for commercial permanent magnets are given in Table 1.