SURVEY OF REQUIREMENTS TO PERMANENT MAGNETS

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Abstract. A survey of requirements to characteristics of permanent magnets and their selection according to their expedient applications are made. The requirements to magnetic flux density of magnetizing and demagnetizing magnetic fields and calibration of permanent magnet systems are also systematized. A special attention is paid to magnetic fields induced into the adjoining armature because of permanent magnets demagnetizing.

Keywords: demagnetizing field, magnetizing field, permanent magnet characteristic.

INTRODUCTION

The progress in the field of permanent magnets has been dramatic since the 1960s. This would have been impossible without a fundamental understanding of the physical phenomena responsible for hard magnet properties, which led to the discovery of new families of permanent magnet materials based on rare earth(R)–transition metal (T) compounds. The role of hard magnetic materials, in particular high-energy permanent magnets, in electric motors is replacement of the field winding. In any application, including motors, there is a multitude of factors that require consideration to ensure that the optimum magnet material is selected. Of importance are:

- magnetic parameters: remanence, intrinsic coercivity, and magnetic energy product, BH_{max};
- temperature stability of the magnetic parameters;
- ease of magnetizing the material;
- ease of forming the magnet into the desired shape;
- environmental factors, such as resistance to corrosion; and
- cost (cost can be treated in a variety of ways, and includes material cost, cost per unit of magnetic energy product, and the cost of forming the material into the desired shape and its magnetization)

The purpose of the present work is to make a survey of permanent magnet characteristics and their expedient applications as well as to systematize the requirements to magnetic flux density of magnetizing and demagnetizing magnetic fields and calibration of permanent magnet systems. Magnetic fields induced by eddy currents into the adjoining armature could cause demagnetizing of permanent magnets that is why a special attention is paid to them.

DEFINING THE PROBLEM

Selection of the permanent magnet material impacts on the motor design. It is also desirable for motors that the magnet material has a linear B–H curve in the second, or demagnetizing, quadrant of the hysteresis loop. Both hard ferrite and rare-earth magnets have this characteristic, whereas AlNiCo differs by exhibiting a highly nonlinear demagnetization behavior.

For the motor designer rare-earth permanent magnets offer the advantages of a high BH_{max}, which reduces the amount of magnet material required, and high-intrinsic coercivity, which is important if the motor is to withstand high armature currents, which could lead to demagnetization of the magnets [1], [2], [3], [4], [5], [6].

Typical properties for a range of permanent magnet materials are given in Table 1 and Table 2.

Table 1. Typical properties of some common permanent magnet materials.

Material	**Remanence (T)**	**Intrinsic coercivity (kAm^{-1})**	**Energy product (kJm^{-3})**
Sintered $Nd_2Fe_{14}B$	1-1.4	3200-1000	190-380
Sintered Sm_2Co_{17}	1.04-1.12	2070-800	200-240
Sintered $SmCo_5$	0.90-1.01	2400-1500	160-200
Anisotropic bonded HDDR $Nd_2Fe_{14}B$	0.81-0.87	915-1154	123
Isotropic plastic bonded $Nd_2Fe_{14}B$	0.4-0.7	1000-600	30-76
Sintered anisotropic AlNiCo	0.72-1.26	1920-610	20-44
Sintered isotropic AlNiCo	0.62-0.84	1190-125	4-18
Hard ferrite, anisotropic	0.36-0.40	180-270	25-31
Hard ferrite plastic bonded anisotropic	0.22-0.36	240-190	15-18
Hard ferrite isotropic	0.22-0.28	230-300	8.5-10
Hard ferrite plastic bonded isotropic	0.1-0.15	180-230	2-4

Table 2. Thermal characteristics for some permanent magnet materials (α is the reversible temperature coefficient of the remanence and β is the reversible temperature coefficient of the intrinsic coercivity).

Material	**α ($\%K^{-1}$)**	**β ($\%K^{-1}$)**	**Max. operating temperature (°C)**	**Curie temperature (°C)**
Sintered $Nd_2Fe_{14}B$	-0.13	-(0.5-0.65)	200	310
Sintered $SmCo_5$	-0.045	-(0.2-0.3)	250	720
Sintered Sm_2Co_{17}	-0.03	-0.19	350	825
AlNiCo	-(0.01-0.02)	0.01-0.03	500	830
Ferrites	-0.2	0.3-0.4	300	450

The use of any permanent magnet material in a particular application is not only governed by the magnetic, physical, and chemical parameters, but also by the cost of the material. Applications and products are driven by markets, and the success or failure of a product in a particular market is driven by cost. [

Rare-earth Cobalt Magnets

Sintered and polymer-bonded magnets based on both the $SmCo_5$ and Sm_2Co_{17} alloy composition are available from a variety of manufacturers. The main advantage of Sm–Co-based magnets is their high Curie temperature, making them suitable for use in applications at elevated temperatures, but they suffer from the disadvantage of high cost. The sintered material tends to be somewhat harder and more brittle than $Nd_2Fe_{14}B$, but it has excellent corrosion resistance. Sintered Sm–Co magnets are used in applications where arduous conditions apply, for example, in motors that are used in oil-wells, high-temperature automotive sensors, and microwave switches in telecommunication satellites [1], [2], [3], [4]

Neodymium–Iron–Boron ($Nd_2Fe_{14}B$) Magnets

$Nd_2Fe_{14}B$ magnets are commercially available in a number of forms—anisotropic sintered and anisotropic and isotropic powders for polymer bonded magnets. Isotropic powders are prepared using a rapid solidification method and anisotropic powders by the HDDR (hydrogenation, desorption, disproportionation, recombination) process. The great advantage of polymer-bonded magnets is that complicated shapes and geometries can be prepared to near-net or net shape using very low cost production processes. For applications requiring magnets of the highest possible energy product, sintered $Nd_2Fe_{14}B$ is the magnet of choice. The thermal stability of sintered $Nd_2Fe_{14}B$ magnets has improved, with operating temperatures of 200°C now attainable. Similar advances have been made in corrosion resistance with the addition of cobalt and other alloying components. Sintered magnets find uses in applications that require the best possible performance, for example, servomotors in machine tools. Polymer-bonded magnets are the most rapidly growing section of the permanent magnet market. The reason for this rapid expansion is the demand for magnets for computer disk drives.

There is also considerable demand for polymer-bonded magnets for small motors in video recorders, camcorders, printers, facsimile machines, office automation, automotive, and portable drills [1], [2], [3], [4].

Aluminum–Nickel–Cobalt (AlNiCo) Magnets

AlNiCo magnets are manufactured by a powder metallurgy process or by casting, and are available in both isotropic and anisotropic forms. They tend to be expensive due to the cost of the raw materials, but they have good corrosion resistance and a very respectable remanence, 1.26 T, when compared with the value of 1–1.4 T for $Nd_2Fe_{14}B$. The major disadvantage of AlNiCo is its low coercivity, which creates problems in handling and its use in electric motors. For example, removal of AlNiCo magnets from the magnetic circuit in a small electric motor often results in their partial, or complete, self-demagnetization. A consequence of this is that it is usually necessary to magnetize AlNiCo magnets in situ. The advantage that AlNiCo has compared with other commonly used permanent magnets is its excellent temperature stability. The excellent temperature stability of AlNiCo makes it the magnet of choice for watt-hour meters, ammeters, and voltmeters. Additionally, AlNiCo magnets are frequently used in small servomotors in aircraft and military hardware [1], [2], [3], [4].

Hard Ferrite Magnets

In terms of the global permanent magnet market hard ferrite magnets still dominate. They are ceramic materials that have hexagonal crystal structures. Ferrite magnets have the stoichiometry $BaFe_{12}O_{19}$ or $SrFe_{12}O_{19}$, the latter being increasingly used due to its higher coercivity. They are very cheap, as the raw materials from which they are made are abundant. A further advantage is their resistance to many chemicals, and being an oxide they are ideal for use in damp or wet environments. Isotropic and anisotropic sintered magnets, and polymer-bonded magnets formed from the milled powder, are widely available and used extensively. The temperature coefficient of the intrinsic coercivity is positive for the hard ferrites, in contrast to rare-earth permanent magnets, and consequently there is a risk of demagnetization if the hard ferrite magnet is exposed to too low a temperature. Hard ferrite magnets are found in applications ranging from door seals in refrigerators to small electric motors used in dishwashers and washing machines [1], [2], [3], [4].

Modern, powerful hard magnetic materials are of metallic type. They are based on compounds combining the magnetic characteristics of transition metals and rare-earth metals, mainly cobalt or iron combined with samarium, neodymium, or praseodymium [1].

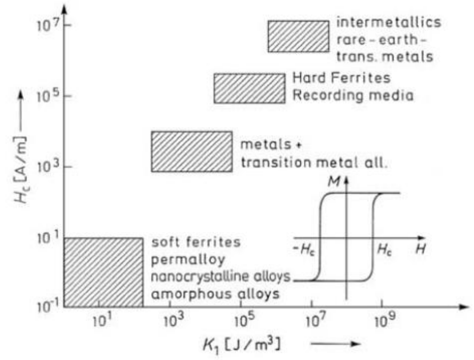

Figure 1. Schematic plot of coercive field Hc vs. crystal anisotropy K_1 for prominent soft, hard, and extremely hard magnetic materials.

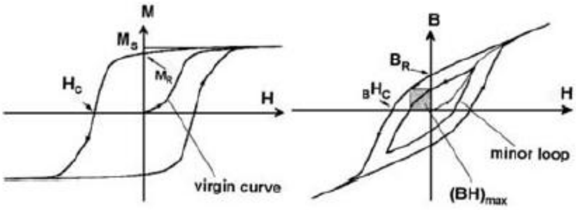

Figure 2. Hysteresis loops for a permanent magnet: (left) M–H loop and (right) B–H loop. The initial magnetization curve after thermal demagnetization starts at the origin; a minor loop arising after the application of fields insufficient for saturation is also shown. The energy product (BH)max is the shaded area in the second quadrant of the B–H loop.

For an ideal permanent magnet the second quadrant B–H loop is a straight line, with slope m0. The remanence Br or m0Mr is the flux density or remanent magnetization that persists after removing the magnetizing field H. The maximum energy density $(BH)_{max}$, or also energy product, of rare-earth permanent magnets is a measure of the magnetostatic energy stored and, thus, describes the performance of the magnet (the shaded area in Fig. 2). It is the most widely spread figure of merit and is found where the product of B and H is maximized, which is equal to twice the potential energy of the magnetic field outside the magnet divided by its volume [1], [4], [5].

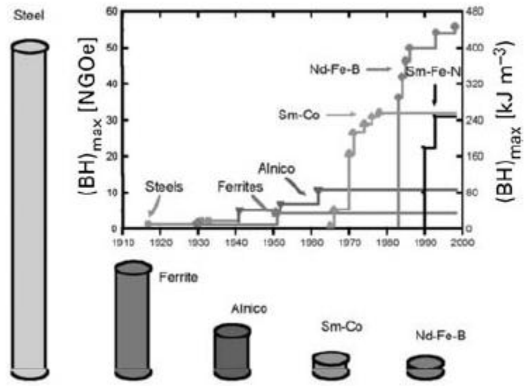

Figure 3. Development in the energy density $(BH)_{max}$ of hard magnetic materials in the twentieth century and presentation of different types of materials with comparable energy density.

Some special features of magnetizing the permanent magnets

One very important question about permanent magnets is about the requisite magnetizing force for fully magnetizing the permanent magnet. The answer of the question is not so easy and the important role in the discussion plays term "saturation". To reach the maximum energy output of the magnet, it should be saturated, that is magnetized fully even though the magnet may be later stabilized either thermally or using a "knockdown" (reverse) field. The magnetizing force required to saturate a magnet depends on the coercivity of the magnetic material and to a lesser extent, physical characteristics of the magnet and components to which it may be fastened during magnetizing. The general rule is that to saturate a magnet, one must apply a peak field of between 2 and 2.5 times the intrinsic coercivity. For example, an H_{ci} of 1600kA/m will require at least 3200kA/m to saturate. If the magnets are attached to the conductive fixtures, the established eddy currents in the material sets up a reverse magnetic field during the extremely short magnetizing pulse. This prevents the magnetizing flux from fully penetrating the conductor, perhaps even the magnet, and reduces the field the magnet sees and sometimes also the flux path (direction of the flux) in the magnet. In these cases, it is necessary for the equipment manufacturer to adjust the LC (inductance capacitance ratio) of the magnetizing circuit to extend the magnetizing pulse width. An extended pulse generates more heat which slows the production magnetizing rate. So a careful compromise must be reached [7].

The requisite duration of magnetizing impulse for permanent magnets without adjoining armature is about 100 μs. For permanent magnetic systems with the adjoining armature the duration of this impulse has to be about 10 ms [8].

Bonded rare earth magnets pose another problem. The magnetic powder is separated with non-magnetic binder which affects the penetration of flux through the magnet during the pulse and requires a higher magnetic field than one would expect from the rule above. For example, powder with an Hci of 796 kA/m requires at least 239kA/m to saturate. Most magnet manufacturers should be able to provide you with a curve of peak applied field versus percent of saturation for induction and Hci or percent of maximum flux output. Approximate required magnetizing fields for various magnet types to reach at least 98% of maximum output are listed on the back of this sheet. These are general and affected by fixturing and LC circuit, etc [7].

Table 3. Typical Required Magnetizing Field Strengths.

Material	**H, kA/m**
Alnico 5, 6, 8 and 9	239 - 557
Ceramic (Hard Ferrite)	796 - 955
Neodymium-iron-boron, motor grade	2 786 - 3 980
Neodymium-iron-boron, high energy grade	2 388 - 3 184
Neodymium-iron-boron, most bonded	2 388 - 3 184
Neodymium-iron-boron, high temp bonded	2 786 - 4 776
$SmCo_{1-5}$	2 786 - 3 980
$SmCo_{2-17}$	1 592 - 2 388
SmCo low H_{ci} bonded grade	1 592 - 3 980
SmCo high temperature grade	2 786 - 3 980

Handling magnetized magnets

The fully saturated magnets are subjected to a constant demagnetizing field which causes the output of each magnet to be reduced a certain percentage below its saturated value. Typical values for reduction (or knockdown) are 5% to 15%. The magnets are now "stable" to normal demagnetizing influences. It must be noted that if there is an 8% to 10% range in the saturated output for the group of magnets, their stabilized values will also exhibit an approximate 8% to 10% range. If an 8% to 10% output range from the magnets is undesirable, the fourth condition: magnetized and calibrated, should be specified. In this case the saturated magnets are stabilized by varying the demagnetizing field in order to "calibrate" the magnetic output to a very tight range. Values of less than ± 1% can be obtained. After any magnet is magnetized care must be exercised to prevent physical damage to the magnet. Almost all permanent magnet materials are very brittle and can be easily chipped or broken when they come into contact with a hard surface. This problem is intensified when handling the high magnetic energy rare earth magnets. While the lower coercive force allows Alnico type magnets to be more easily demagnetized, the main reason Alnico magnets become partially demagnetized as a result of improper handling is the non-linear characteristic of their normal demagnetization curve, commonly referred to as a demagnetization curve with a "knee". The Fig. 4 below illustrates the effect of the knee.

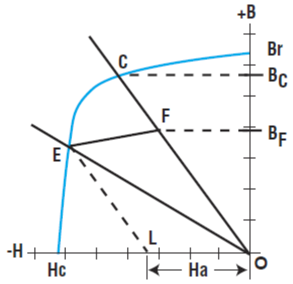

Figure 4. Externally applied field, Ha

The externally applied field, Ha, represents the demagnetizing force two opposing poles exert on each other. Line OC depicts the operating slope of a magnet and Bc represents the flux density in the magnet. When opposing poles are brought together, their mutual demagnetizing force causes the flux density in each magnet to decrease to point E. When the magnets are moved apart, the flux density in each magnet does not return to point C, but will instead follow an interior loop to F on the operating slope line OC. The new flux density in each magnet is B_F [9], [10].

CONCLUSIONS

There is a wide range of hard magnetic materials available that can be tailored to meet specific product requirements. It is essential to consider all the important features of a magnet when selecting the correct material for a given application. The specific requirements to magnitude and duration of magnetizing fields and calibration of permanent magnet systems are also of great importance.

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