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MATERIAL SELECTION OF PERMANENT MAGNETS, CONSIDERING THERMAL PROPERTIES CORRECTLY

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Spontaneous Materials

Abstract: Permanent magnets are used in a wide variety of applications: sensors, motors, actuators, alternators, hard drives, and speakers. While ceramic magnets (hard ferrite) were the material of choice for the last three decades, neodymium iron boron magnets, bonded and sintered, have surpassed ceramic magnets as the benchmark material for new designs. Three factors are key to the preference for rare earth magnets: superior room temperature magnetic properties, declining material cost, and improved corrosion resistance. With a bewildering array of data available, designers occasionally associate the wrong magnetic property with an important design parameter, leading to disappointing performance. This is particularly true for thermal characteristics. We review the thermal properties of the common permanent magnet materials, with emphasis on neodymium iron boron, and relate the characteristics to material selection.

Key words: permanent magnets, thermal properties, magnetic design

I. INTRODUCTION

Permanent magnets provide most, if not all of the magnetic flux in the devices where they are used, and sintered neodymium iron boron magnets are the clear champions at delivering the most flux from the smallest package, see Table I. But the proliferation of neodymium iron boron magnets has been held back by three objections:

- Cost
- Corrosion
- Temperature

The first two objections have largely been settled, or at least show signs of improvement. Neodymium magnets continue to decline in cost. Corrosion difficulties are mitigated by the use of coatings, although there is a cost associated with coating and selecting the proper coating is still a little difficult for many engineers.

The temperature objection remains problematic, with negative consequences associated with any attempt to address it. There is near universal recognition that neodymium magnets have the lowest Curie temperature of all the popular permanent magnet materials and somehow this limits high temperature usage. The other thermal characteristics are vaguely understood and often ignored in the design process, sometimes with disastrous results. This is not due to a lack of information. Thermal characteristics are presented on most suppliers' data sheets, but unfortunately, not in a particularly helpful way for designers. Consequently there can be difficulty in selecting the correct parameters for a given design situation. All too frequently, excessive importance is attached to the wrong parameter or a critical parameter is overlooked.

Table I. The Four Families of Permanent Magnets

	Ferrite	Alnico	SmCo			NdFeB	
Property	Ceramic 8	Alnico 5	1-5	1-5 TC	2-17	Bonded	Sintered
B_r (kG)	4.0	12.5	9.0	6.1	10.4	6.9	13.4
α (%/°C)	-0.18	-0.02	-0.045	-0.001	-0.035	-0.105	-0.12
$(BH)_{max}$ MGOe	3.8	5.5	20	9	26	10	43
H_{ci} (kOe)	3.3	0.64	30	30	25	9	15
β (%/°C)	+0.4	-0.015	-0.3	-0.02	-0.3	-0.4	-0.6
H_s (kOe)	10	3	20	40	30	35	35
T_c (°C)	460	890	727	729	825	360	310

Notes:
The quantity α is the reversible temperature coefficient of B_r. (20 ºC to 100 ºC minimum)
The quantity β is the reversible temperature coefficient of H_{ci}. (20 ºC to 100 ºC minimum)
The field required to saturate the magnet is H_s.
TC means temperature compensated. [References 1, 2]

II. THERMAL PROPERTIES

While there is general understanding of the basic properties of a permanent magnet, B_r, H_c, H_{ci} and $(BH)_{max}$, as shown in figure 1, thermal characteristics are a bit more complicated.

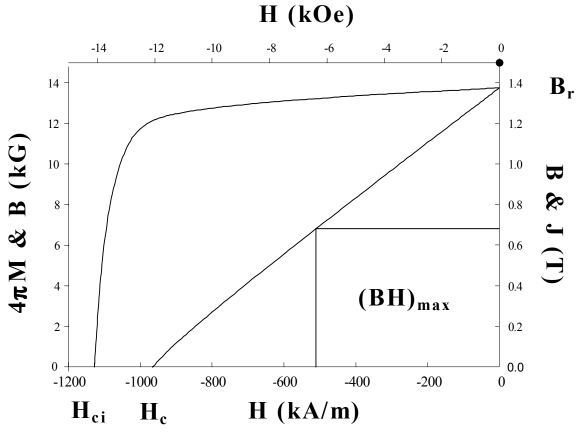

Figure 1. Second quadrant demagnetization curves, with the major parameters indicated, for a sintered NdFeB magnet. [Reference 3].

Curie temperature, T_c, is the most fundamental thermal characteristic, defined as the temperature where the saturation magnetization, $4\pi M_s$, becomes zero, see figure 2 and Table I. It marks the transition from the ferromagnetic, or ferrimagnetic in the cases of ferrites, to the paramagnetic state, as the temperature rises. Figure 2 shows the $4\pi M_s$ vs. temperature data for pure nickel, displaying typical ferromagnetic behavior, highest $4\pi M_s$ near absolute zero, modest reduction as the temperature increases, until a relatively rapid reduction to zero at the Curie temperature, 358 °C.

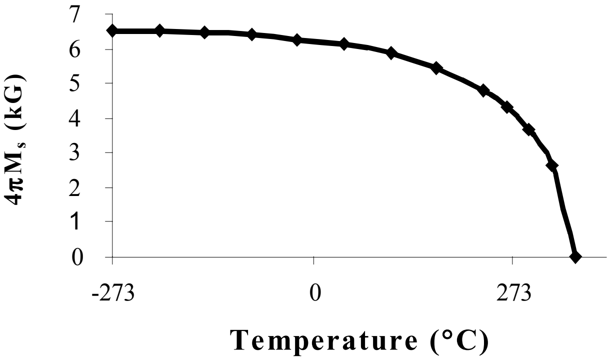

Figure 2. Saturation magnetization as a function of temperature for pure nickel. [Reference 4].

The next parameters to consider are reversible losses. Reversible losses are described by two temperature coefficients, α and β. Alpha is the reversible temperature coefficient of B_r and beta is the reversible temperature coefficient of H_{ci}, as defined in the following equations.

$$(1) \qquad \alpha = (1/B_r)\,(\Delta B_r/\Delta T) \times 100\%$$

$$(2) \qquad \beta = (1/H_{ci})\,(\Delta H_{ci}/\Delta T) \times 100\%$$

Both coefficients attempt to quantify the percentage of the parameter lost or gained per degree change in temperature, generally starting at room temperature. By definition, any loss or gain in B_r or H_{ci} is completely recovered when the temperature returns to the starting point. Because of the way they are defined, the temperature coefficients imply linear behavior. However, the actual behavior is nonlinear, similar to figure 2. A temperature range should accompany either temperature coefficient, to make it meaningful.

The temperature coefficient of B_r is inversely related to the Curie temperature, a higher T_c generally means a lower α. Although an interesting and useful exception to the above statement is found in the SmCo system. The temperature coefficients of $SmCo_5$ magnets may be adjusted by the partial substitution of a heavy rare earth, gadolinium, for some of the samarium. With essentially no change in Curie temperature, both B_r and $(BH)_{max}$ are reduced considerably, and α is nearly zero, see Table I.

The temperature coefficient of H_{ci}, β, does not correlate well to any basic permanent magnet property and is generally much larger in magnitude than α, by as much as a factor of twenty, see Table I. The value of β for ferrite is positive, unique among permanent magnets, meaning H_{ci} for ferrites decrease as the temperature decreases.

The temperature coefficients are derived from measuring demagnetization curves at various temperatures, as shown in figure 3, and applying equations 1 and 2 to the temperature range of interest. The temperature coefficients may be used to estimate demagnetization curves at intermediate temperatures, with excellent accuracy.

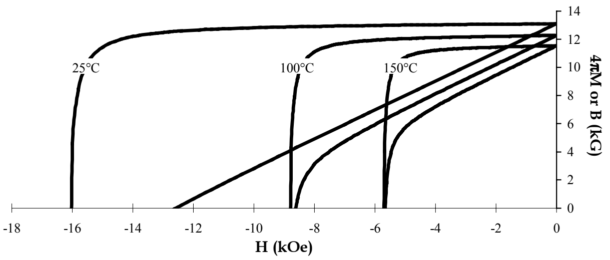

Figure 3. Demagnetization curves as a function of temperature for an MQ3-F42 material. [Reference 5].

Beyond reversible behavior, irreversible behavior needs to be understood. An irreversible loss is observed after a permanent magnet is exposed to elevated temperatures for a period of time. Besides the material and how it was processed, irreversible loss depends on four factors

- Temperature
- Time at temperature
- Loadline, or self demagnetization
- Any applied adverse magnetic fields

The decay is generally logarithmic as shown in figure 4, with losses increasing as the temperature increases, the time at temperature increases, the loadline decreases, the adverse field increases, or any combination of these factors.

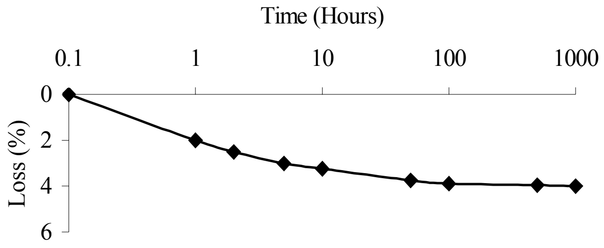

Figure 4. A generic representation of irreversible loss as a function of temperature for a specific load line. Note the logarithmic time axis.

Irreversible loss is caused by a thermally activated event, specifically the reversal of an individual domain. The magnetization switches or flips from being parallel to the magnetization of the sample, to being anti-parallel. The self-demagnetizing field and adverse field, if present, are also anti-parallel to the net magnetization. Because the anti-parallel orientation is parallel to the self-demagnetizing field, it is more stable and generally will not reverse unless a magnetizing field is applied again parallel to M, see figure 5. An incremental drop in the total magnetization occurs every time a domain's magnetization is reversed. The longer a domain is exposed to temperature, the greater chance it has to reverse. Self-demagnetization or loadline and adverse fields have a similar effect on the sample. Both effects are really applying a demagnetizing field to the sample and increasing the chances for a domain reversal.

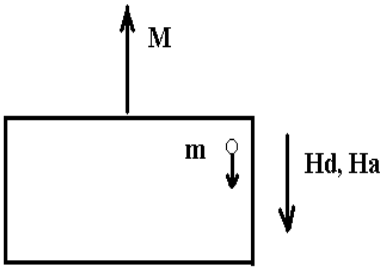

Figure 5. The magnetization of a single domain is reversed by exposure to temperature, H_d is the self-demagnetizing field, H_a is the applied field, M is the magnetization of the sample, and m is the magnetization of a single domain, shown in the reversed condition

Irreversible loss happens just once. If a thermal cycle is repeated, little or no additional loss is observed, because a domain can only be reversed once after it is magnetized. In spite of the onerous name "irreversible", the losses are recovered by remagnetizing the sample, by definition.

After exposure to temperature, some flux loss may not be completely recovered by remagnetizing the sample. This is a structural or irrecoverable loss, generally due to oxidation or degradation in microstructure. In most cases, it is very small effect compared to irreversible losses, generally less than 1%. Sometimes total flux loss is reported, the sum of irreversible and structural losses. It may be the more significant parameter for design purposes. A designer wants to know how much flux is lost after exposure to temperature and isn't as concerned with how much is irreversible and how much is structural.

Maximum operating temperature is a frequently stated parameter, yet it has no standard definition. The two most commonly given definitions are

- The temperature above which the B vs. H curve becomes non-linear, usually at a loadline near the point of $(BH)_{max}$, typically B/H=1.

- The temperature above which the total flux loss reaches a specified level, often 5%, after exposure to a given temperature and at a given loadline.

While roughly similar in nature, the two definitions are clearly not interchangeable. It is important to understand the definition being used in any discussion of maximum operating temperature, before drawing any conclusions.

III. MATERIAL SELECTION

How should the above information on thermal properties be applied in device design?

Of the thermal characteristics, T_c is the best-understood and most reproducible parameter but the least useful in material selection. The reason is that, with very rare exception, no design should operate at or near the Curie temperature. Typical operation is well below this extreme upper limit. Some people believe that there is, or should be, a well-accepted percentage of T_c (in absolute temperature, of course) that could be used as a practical limit, but this is not the case. For the person developing new magnetic materials Curie temperature is an excellent benchmark to establish potential, so it is frequently reported in the literature. But for someone trying to put a magnet in a device, it isn't nearly as useful. Other parameters need to be considered.

The demagnetization curves at temperature are probably the most useful design tools. They permit a reasonable estimate of performance at any temperature shown, see figure 3. Curves for intermediate temperatures, where no data are shown, can be accurately estimated using the reversible temperature coefficients, α and β. For most permanent magnet materials, only the highest operating temperature needs to be considered for establishing a design, but for ferrites, both the high and low temperature extremes need to be considered in the design process, because β is positive for ferrite.

If having flux available at elevated temperatures is the most important objective of a design, then looking at the demagnetization curves at temperature or α would be appropriate. In the neodymium iron boron alloy system, there is a trade off at work. Cobalt may be substituted for iron, which increases the Curie temperature, decreases α, increases the cost of the alloy, and decreases B_r and $(BH)_{max}$. The reduction in B_r and $(BH)_{max}$ come from the fact that cobalt has a slightly smaller magnetic moment than iron.

If a device will operate at a temperature for an extended period of time, say 100 hours or more, then irreversible loss must be considered in addition to the curves at temperature. As previously stated, irreversible loss depends on many factors, not just the material. The supplier's data indicate what to expect, however an independent determination of the flux loss under the actual operating conditions is prudent. Again, an alloying trade off is available for NdFeB, a very modest substitution of niobium and other elements have been shown to reduce irreversible losses. However, B_r and $(BH)_{max}$ are reduced by the substitution, as nonmagnetic niobium displaces the iron and increases the alloy cost slightly. As a general rule, the demagnetization curves should be de-rated for the amount of irreversible loss expected, to accurately predict the performance of the device.

When stability over time and temperature are critical considerations, in instrument applications for example, the entire magnet assembly is often baked to deliberately induce a few percent of irreversible loss. The thinking behind this process is that the few domains reversed are generally the weakest ones that are most likely to reverse at some point in the future, without the soak. With these few domains reversed, the magnetization, while slightly reduced, is now extremely stable over time. Generally, the bake cycle conditions are chosen to exceed any temperature that the device might see in its lifetime. A similar effect can also be achieved via magnetic knockdown. That is, applying a small demagnetizing field to the magnet. The mechanism is similar, a few domains are reversed, although the exact domains reversed by each method may be different. However, one caveat with magnetic knockdown is the risk of thermal remagnetization, an *increase* in magnetization after subsequent exposure to temperature. [6]

Occasionally, magnets are exposed to elevated temperatures as part of the assembly process. Curing an adhesive after magnets are put in a housing, for example. If the exposure to temperature is brief, a few minutes or less, and the magnets are magnetized *after* exposure to temperature, no losses are expected. Neither reversible nor irreversible losses are possible for an *unmagnetized* magnet, although structural losses may occur. However, the minimum temperature and time conditions required for any significant structural losses are usually much higher and longer than those encountered in normal assembly procedures.

Had it been set up correctly, maximum operating temperature would be the most helpful thermal characteristic. But without a clear and consistent definition, it is the most misleading parameter in use today. Other components, such as wire insulation, have clear maximum operating temperatures, and engineers know not exceed them. For permanent magnets, the situation is complex, because the decline in magnetic properties is a gradual transition, not a sharp one, as shown in figure 2 and because any potential temperature limits would be very design dependent. The industry needs a standard definition. The one I would propose is an approximate combination of the two definitions given earlier.

- The highest temperature where the B vs. H curve remains linear from B_r to B/H=1, *and* where the irreversible losses at B/H=1 flatten out over time, i.e. show essentially no additional irreversible loss after 100 hours.

This definition recognizes the two distinct ways that permanent magnets become unstable at elevated temperatures, nonlinear B vs. H curves, and ongoing irreversible losses. Both modes must be considered to provide a practical temperature limit. Designers working at higher loadlines might adjust the definition to suite their needs. Again, the fundamental question comes back to verifying the permanent magnet's stability in a specific design, good advice for anyone wanting a definitive answer.

One parameter often discussed along with thermal properties is H_{ci}, the intrinsic coercive field, even though it is not a true thermal property. A high value of H_{ci} is often claimed to predict improved performance at elevated temperature, but this claim is only partially correct. Having a large H_{ci} at room temperature, generally means H_{ci} at higher temperatures will still be acceptable, meaning the B vs. H curve remains linear at least up to the temperature of interest, around the operating point. Under these conditions, stable operation is expected. However the demagnetization curves measured at temperature are a much better source of information, see figure 3. Even so, this is still not the complete picture. First, if the magnet will remain at elevated temperatures for any length of time, irreversible and structural losses must be considered. The value of H_{ci} has been demonstrated not to predict irreversible loss; at best, it is merely an indicator and not a very good one. [7] As seen in figure 6, some suppliers use H_{ci} as an indicator of thermal stability in spite of evidence to the contrary. Second, high H_{ci} comes at a price. In the case of NdFeB magnets, an alloying substitution such as dysprosium, or higher rare earth content is used to increase H_{ci}, which adversely affects B_r and $(BH)_{max}$, and may increase the cost of the alloy. Third, there is a loose connection between H_{ci} and H_s, the field required to saturate the magnet. Very roughly speaking, one should expect more field to be required to saturate a magnet with high H_{ci}. Although it is a mistake to take this observation too strictly. Verification that saturation has been achieved should be done by an independent experiment. The H_{ci} is not a good indicator of magnetic behavior at elevated temperature; the other characteristics mentioned are better.

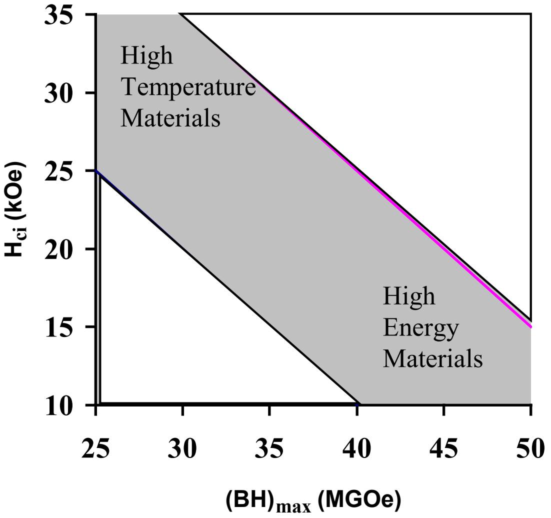

Figure 6. Improper use of H_{ci} to imply improved thermal stability of sintered NdFeB magnets. (Reference 8)

Table II summarizes the parameters and the above discussion.

IV. CONCLUSIONS

Material selection for magnets is a complicated process. Many parameters are required to describe a permanent magnet and deciding which parameters are appropriate in a given situation is not easy.

While the exact answer depends on the situation, the rough order of importance of the parameters discussed is listed below, in decreasing order of importance

- Demagnetization Curves at Temperature
- Irreversible Losses
- Irrecoverable Losses
- Reversible Losses, α and β
- Maximum Operating Temperature
- H_{ci}
- Curie temperature

Table II. Common thermal characteristics of NdFeB magnets and their uses

Parameter	How used?	Comments
Curie temperature, T_c	Absolute temperature limit	Helpful for material development, not helpful for designers
Reversible temperature coefficients, α, β	Estimate curves at temperature when data not available	Good tools
Demagnetization curves at temperature	Model performance at temperature	Fundamental data, essential for modeling
Irreversible loss	To de-rate curves at temperature for accurate performance estimates	Very design specific
Structural loss		
Maximum operating temperature	To compare materials	No standard definition, dangerous to use without considering definition
Intrinsic coercive field, H_{ci}	To compare materials	Not as useful as other parameters

We have reviewed the thermal characteristics of permanent magnets, proposed a new definition for the maximum operating temperature and offered advice on which properties are most important in various design situations.

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Stanley R. Trout (strout@ieee.org) spent the last twenty-seven years in the permanent magnet and rare earth industries, successfully solving problems in a wide variety of technical and commercial roles, collaborating with many international luminaries in the process. Earlier this year, he launched a consultancy called Spontaneous Materials (www.spontaneousmaterials.com), devoted to solving customer problems with magnetic materials and the rare earths, in a technical, commercial and educational capacity. Dr. Trout is a registered professional engineer, received his B.S. in Physics from Lafayette College and his M.S. and Ph.D. in Metallurgy and Materials Science from the University of Pennsylvania. He is a member of SAE and a senior member of the IEEE Magnetics Society.