# SELECTION AND SPECIFICATION OF PERMANENT MAGNET MATERIALS

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Spontaneous Materials

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**Abstract: The selection and specification of permanent magnets is often done in an incomplete or confusing manner, frequently leading to poor product performance or an unnecessarily expensive design. It is important to conduct a thorough analysis, from the earliest stages of the design, by considering all the characteristics and deciding which ones are pertinent. This paper attempts to introduce a methodology that can be applied to selecting and specifying the best available grade for any application of a permanent magnet.**

## I. INTRODUCTION

Selecting the correct permanent magnet for a new design is a complicated engineering task. There are many factors to consider, some subtle, yet critical to the ultimate success of the product. With limited training and excess information available, it is not surprising that engineers often overlook one or more important considerations when selecting a magnet. This can come as a very unpleasant surprise, as a product moves from the design stage to production.

Once the material is identified for a design, the next natural question to be addressed is how this magnet should be specified. It needs to be specified in a way that any magnet that meets the print will always work, yet allows for manufacturability and multiple sources.

In a general way, we attempt to outline all the things that a designer should consider when selecting and specifying a permanent magnet.

## II. SELECTION

### A. Available Choices

The most popular permanent magnet materials are: ferrite, alnico, SmCo and NdFeB. While there are several processing options, magnets can be divided into fully dense or bonded, leading to isotropic or anisotropic magnets, and a large number of choices.

### B. Primary Magnetic Properties

Table I shows the basic magnetic properties of the commonly available permanent magnet materials. Figure 1 is a graphical representation of typical property ranges for two fundamental parameters, $B_r$ and $H_{ci}$. It is essential to establish the relative importance of each parameter to the design under consideration. Many engineers say, “All the properties are equally important”, but this statement is rarely true. In each design, usually one or two parameters are critical to proper performance. They need to be established early in the design stage and considered when comparing the performance of other materials or suppliers, when establishing a good test of the magnet and when writing a meaningful specification.

Table I
Commonly Available Permanent Magnet Materials [1]

| | 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 |
| $\alpha$ (%/°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 |
| $\beta$ (%/°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 $\alpha$ is the reversible temperature coefficient of $B_r$. (20 ºC to 100 ºC minimum)
The quantity $\beta$ is the reversible temperature coefficient of $H_{ci}$. (20 ºC to 100 ºC minimum)
$H_s$ is the field required to saturate the magnet.
TC means temperature compensated.

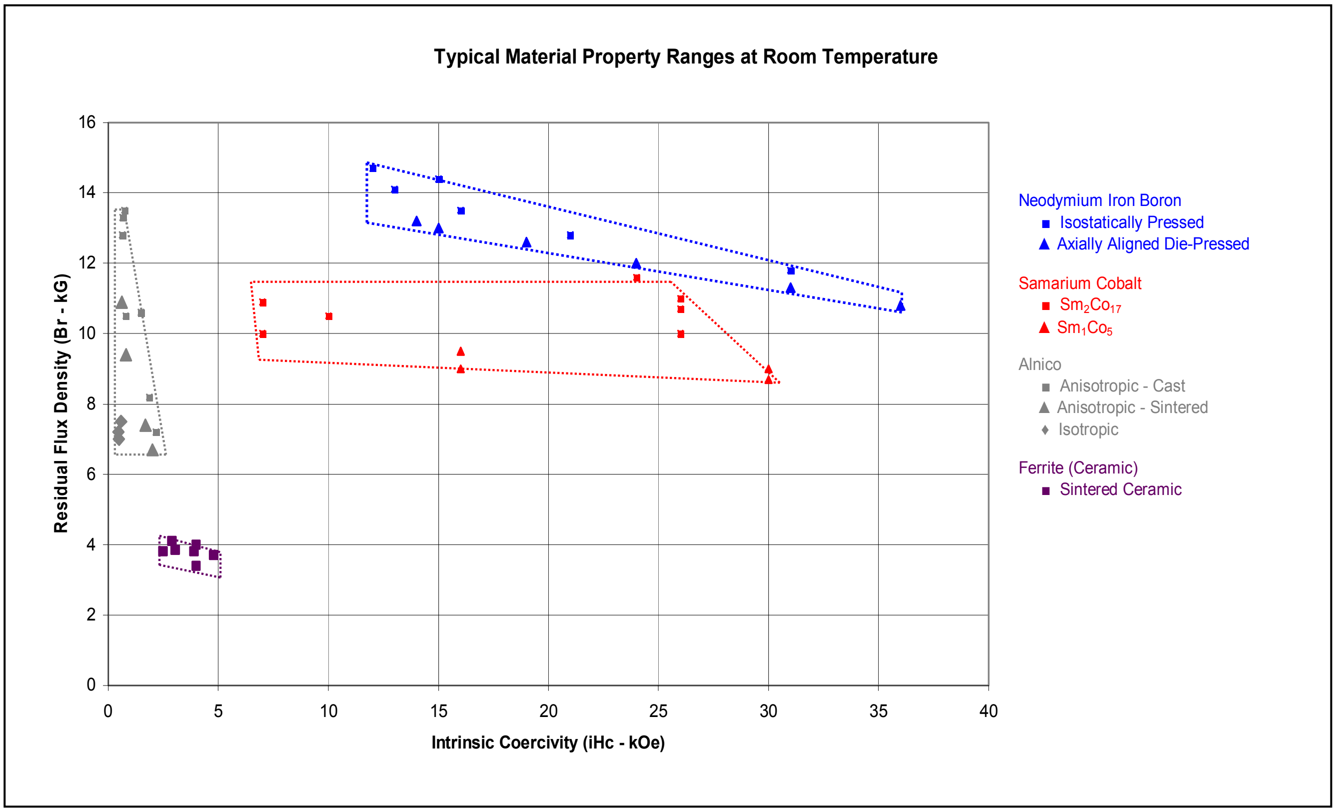

Figure 1. A graphical representation of permanent magnet materials in terms of available ranges of $B_r$ and $H_{ci}$.

It is imperative to consider the operating conditions of a magnet, including typical and extreme conditions. Most published tables typically reflect properties at room temperature. If a magnet is expected to operate at some elevated temperature, the magnetic properties at that temperature must be considered to ensure sufficient flux production (primarily related to $\alpha$) as well as resistance to demagnetization (primarily related to $\beta$). Several manufacturers publish recommended "Maximum Operating Temperatures", but these guidelines are fuzzy and poorly defined. Specific design factors including magnetic circuit geometry and the presence of external demagnetizing fields can greatly influence the actual thermal limitations.

### C. Geometries, Dimensions and Tolerances

Depending upon their application, permanent magnets vary greatly in shapes and sizes. These include disks, blocks, bread loaves, various arcs and rings. Sizes range from tiny magnets for implanted hearing aids and watch motors to massive MRI and ship propulsion motors. Furthermore, assemblies consisting of individual magnet segments are possible, and include Halbach array configurations such as quadrupoles, sextupoles, etc. [2]

For any design; however, the engineer must factor in tradeoffs between magnet configuration, tolerance limits and the resulting cost impact. For example, a motor designer may favor skewed arcs or offset radius designs for reducing cogging torque. Perhaps the ideal solution from the perspective of cogging torque would be a skewed, offset radius, helix-shaped magnet. However, the resulting cost to machine such magnets would almost certainly result in too costly a machine, compared to other options.

Another example of similar tradeoffs exists when comparing individual arc magnets to rings. For brushless motor rotors, rings are easier to assemble. However, tightly toleranced rings may result in higher magnet costs. On the other hand, if a skewed magnet configuration is required, a less expensive option is to use a ring magnet with a skewed magnetization fixture.

As with any component, specifying excessively tight tolerances increases the cost. Understanding the actual fit and function in a design can have dramatic impact. A motor engineer often specifies tight tolerances for an arc magnet's radius so that it will mate well with a core (IR) or frame (OR). Although this may sometimes be required, in the case of narrow angle arcs (in some cases even up to an included angle of 60°) the actual relationship between magnet radius and fit is much more forgiving than might be expected. In general, tight tolerances require extra machining, so you pay for both the material as well as its removal.

### D. Mechanical Considerations

Permanent magnets tend to be rather brittle, in varying degrees. Sintered samarium cobalt and ferrite are extremely brittle, while sintered NdFeB is less so. However, it is important to understand that magnets should never be incorporated as load-bearing members in a design, particularly in tension or shear. On a related note, magnets should not be designed with threads or pins to serve as mechanical fasteners. The role of a magnet is simply to introduce flux into a magnetic circuit!

### E. Coatings and Corrosion Resistance

The different magnet materials vary greatly in their need for corrosion protection. Ferrite, alnico and samarium cobalt magnets are generally stable in this regard, and rarely require any special coating to ensure corrosion resistance. Fully-dense NdFeB tends to be more reactive, and generally requires some sort of protective coating. It is worth noting, however, that even the more stable magnets may benefit from certain coatings in case there are concerns about appearance, protection against loose magnetic particles, or handling issues.

Magnet coatings fall into two categories, metallic and organic. Metallic coatings include plating with materials such as nickel, tin or a combination of the two in layers. These metallic coatings also include ion vapor deposition (IVD), typically employing aluminum. Organic coatings include special paints and e-coat treatments. With the selection of appropriate coatings, even NdFeB can provide satisfactory results in such harsh environments as salt-spray.

As various coatings are being considered, one must also factor in the impact they will have on final dimensions and tolerances. Even though such coatings are often very thin (typically $< 15$ μm), preprocessing steps such as chemical etching may also introduce variation.

### F. Magnetizing

The sole purpose of the magnetizing step is to fully saturate the magnet. If it is not fully saturated, the magnetic properties will generally be reduced, in a poorly controlled way. Assuring saturation is a major concern for NdFeB and SmCo magnets, and less of a concern for alnico and ferrite. (See the $H_s$ values given in Table I.)

Once the magnet is magnetized, handling is more difficult, so there is a tendency to delay this step until the end and to magnetize the final assembly. However, magnetizing the final assembly is more difficult in terms of exposing the magnet to sufficient field to saturate it. It is important to confirm that a fixture can really saturate the magnet. The general test is to apply increasing field levels to the assembly. When the output flux no longer increases, the magnet is assumed to be saturated

### G. Assembly Considerations

In addition to the magnetization aspect above, additional issues arise when dealing with magnetic assemblies. If an assembly allows for magnetization after the magnets are secured in place, then general handling is less of a concern. On the other hand, if large magnets (especially the very strong rare earth varieties) must be assembled in a pre-magnetized state, it is critical to remember one of their characteristic traits: they have violent mating habits!

Care must be taken to ensure that magnetized magnets cannot attract each other, and also that the magnetized magnet and any mating pieces (other magnet segments, back iron, etc.) are completely controlled until properly positioned. Steel-based tools such as wrenches, hammers and screwdrivers should be eliminated to avoid mishaps with them. Flying magnets or tools are a danger unto themselves, and chips which result from the magnets' "violent mating habits" can become shrapnel as well. Pinched fingers, blood blisters and cuts are common mishaps from improperly handling magnetized magnets. However, very large rare earth magnets can result in much more serious injury. Some factories, which handle these types of magnets in assemblies, make extra efforts to ensure workers understand the gravity of the situation. In addition to limiting the number of people in such assembly areas, one firm has mounted a hacksaw under a sign stating "For Emergency Use Only!" It serves as both a graphic reminder to be careful, as well as a potential instrument to extricate a magnetically trapped co-worker.

### H. Adhesives

Many types of adhesives are used with magnets, from cyanoacrylates to structural epoxies. The choice depends on the mating materials and the environment that they are expecting to experience. Several manufacturers offer a wealth of information on selecting the correct adhesive. [3]

Besides the mechanical strength of the bond and the chemical compatibility of the materials, the thickness of the bond and its tolerance should be included as part of the dimension and tolerance consideration.

### I. Testing

There are two philosophies on testing magnets. [4] One is to test the intrinsic properties of the magnet and compare them with the data provided by the manufacturer. Because the test methods are similar, the manufacturer and user will probably agree when magnets are out of specification. However, knowing the intrinsic properties of the magnet may poorly predict the final performance of the device. And testing intrinsic properties is often destructive to the part. The other approach is to test the magnet or the assembly similar to the way it will be used, generally with some sort of test fixture. This approach predicts the performance well, but is often difficult to relate back to the intrinsic properties of the magnet. Since there are advantages and disadvantages to either approach, there is no best method for testing; the answer is always a compromise and depends on the situation.

## III. SPECIFICATION

Obviously, a magnet print must show all the important parameters. But what are they? Ideally, any magnet that meets the print will work in the design. There are two distinct philosophies on specification. One is to describe the magnet used in the design stages in great detail. This approach can be helpful, but is frequently overdone. The engineer may inadvertently introduce contradictory specifications. For example, to require both $(BH)_{max}>36$ MGOe and $B_r>11.8$ kG, is somewhat redundant. Only one parameter need be mentioned, with the choice being application sensitive. Over-specifying may unintentionally limit the use of alternate suppliers, often unnecessarily. The preferred method is to categorize the magnet in terms of a broader standard established by an international organization, the International Magnet Association (IMA) [5] or the IEC [6], for example. This approach has the advantages of simplicity in the description and easy sourcing from the widest array of suppliers. Almost as useful is the practice of calling out a specific grade from a well-known producer, with the important phrase “or equivalent” added, to allow alternate suppliers.

## IV. DISCUSSION

Table II is a checklist of all the things a designer should consider in developing a magnetic device. Since any item may easily influence another, they should not be evaluated independently, but rather as **interdependent** considerations. For example, both coatings and adhesives usually affect the dimensions and tolerances. Not every item is important in every situation. Corrosion resistance is not a major concern for ferrite magnets, for example. But we offer the checklist to remind engineers that a magnet is more than an energy product and an $H_{ci}$.

Table II. Permanent Magnet Checklist

- **Magnetic parameters**. Identify the most important magnetic parameters for the design.
- **Flux variations**. What variations in flux output are possible? Likely causes
    - Intrinsic properties
    - Size
    - Temperature
- **Dimensions and tolerances**.
- **Testing**. Determine how and when the magnet or assembly will be tested.
- **Magnetizing**. When will the magnet or assembly be magnetized? Can it be saturated?
- **Coating**. Is corrosion protection necessary? How will the coating affect dimensions and tolerances?
- **Adhesive**. Pick an appropriate adhesive.
- **Assembly**. When and how will the components be assembled?
- **Other considerations**. Establish if the device will be exposed to any other stresses, which may reduce flux output. Examples
    - External magnetic fields
    - Radiation
    - Combined stresses

## V. CONCLUSIONS

It is essential to consider **all** the important features of a magnet when selecting the correct material for a given application. It is equally as important to document these salient features in a drawing which communicates this information to all interested parties.

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