

How to Select the Appropriate Permanent Magnet Material

There are at least four questions the engineer needs to answer when working on a new magnetic design.

1. What are the magnetic requirements?
2. What are the physical needs of the material?
3. What are the maximum and minimum temperatures that the material will be exposed to?
4. What kind of cost is the application going to require: is it very price sensitive or driven more by performance?

There are many permanent magnetic materials utilized today. Alnico, ferrite (ceramic), samarium cobalt, neodymium iron boron, iron-chrome-cobalt and bonded products consisting of rubber, plastic and epoxy-based materials.

relates to how much flux loss will occur when the material is raised 1°C.

Another attribute of Alnico is that a curved field can be established through the material. One of the old Alnico shapes is a horseshoe shape, a curved magnet with the north and south poles aligned adjacent to each other so that they can pick up a bar of steel.

One of the shortcomings of alnico is that it is very hard and brittle. It cannot be milled or machined other than by abrasive grinding or with EDM.

Alnico has low coercive force. The Hc of Alnico grades run between 640 and 1,900 oersteds. The coercive force, another characteristic of magnetic material, relates to the magnet's resistance to demagnetization.

Commercially Available Permanent Magnets

MATERIAL	Manufacturing Process						
	METALLURGY and PM			BONDED			
	CAST	EXTRUDED or ROLLED	SINTERED FULLY DENSE	INJECTION MOLDED	COMPRESSION BONDED	FLEXIBLE	RIGID EXTRUDED
Alnico	Y		Y	(Y)			
Iron-Chrome-Cobalt	Y	Y					
CuNiFe and CuNiCo		Y					
SmCo			Y	Y	Y		
SmFeN				Y	Y		
NdFeB			Y	Y	Y	Y	Y
Ferrite			Y	Y		Y	
Hybrids				Y	Y	Y	

All magnetic materials have a variety of characteristics, Br, Flux, Coercive force, temperature coefficient, etc. Another characteristic is the 'Curie temperature', the temperature at which the permanent magnet loses essentially all of its flux output.

FERRITE (CERAMIC)

Philips, a company located in the Netherlands, engineered ferrite magnets in the late 50's. It is the most economical material to design with. It has moderately high Hc and the Hci, around 3200 to 4500 oersteds, is considerably higher than Alnico. Its electrical resistivity is very high, around 10 Meg ohms. When we think of ceramic materials, we think of a material that is an electrical insulator where-as virtually all the other magnetic materials are metallic and are moderately to very conductive.

Prior to determining how to choose the appropriate material, we are going to review the advantages and the shortcomings of most of these materials. Knowing the strengths and weaknesses will assist in selecting the best material for any application need.

ALNICO

Alnico is one of the older magnetic materials, engineered just prior to World War II with further development occurring through 1970. There are some great attributes with this material. It has very high flux output characteristics, called Br, which range anywhere from 6,700 to 13,500 Gauss.

Alnico has a very high Curie temperature (T_c) of approximately 840°C. It is very temperature stable. The temperature coefficient of induction, another characteristic of magnetic materials, is -0.02°C, lower than any other commonly available material. The temperature coefficient

The detriments of ferrite material are that it has a moderately low curie temperature, approximately 450 °C, and it is very poor in temperature stability. The temperature coefficient of induction of ferrite material is -0.2%/°C. It is 10 times less stable than Alnico which is at -0.02%/°C. Ferrite magnets are used in motor applications where the magnetic material needs a high coercive force so it does not demagnetize as the rotor spins in the circuit, especially at elevated temperatures and where a relatively high flux output is required. The Br of this material runs approximately 2,500 to about 4,000. It is very useful for automotive DC motor applications such as for window lifts, windshield wiper motors, fan motors, antenna lift motors, etc. It has been a main stay in the magnet business since 1965. Its most important attributes are low cost and corrosion resistance. For most applications and designs it is the initial material that you should consider.

SAMARIUM COBALT

Samarium cobalt was engineered in the late 60s early 70s as part of a U.S. Air Force Project conducted at the University of Dayton Research Institute. This material was able to produce much higher energy than Alnico and with excellent temperature stability and resistance to demagnetization.

Both Alnico and Samarium magnet materials are widely utilized by the military. Ferrite magnets are not as widely used for Military applications because of their temperature instability and low coercivity at low temperatures.

Samarium cobalt attributes include very high flux output, Br of typically 11,000 Gauss (1.1 Tesla) or more, and Hci of >18,000 oersteds (1430 kA/m). It is rock solid as far as maintaining flux output. Samarium cobalt also has a high curie temperature. There are two grades: the 1:5 alloy which has a curie temperature of 750 and the 2:17 alloy which has a curie temperature of 825 °C. They have very good temperature stability - -0.035 %/°C temperature coefficient of induction which is just slightly larger (poorer) than Alnico. They have high energy for the volume of material used, referred to as "maximum energy product" (BH_{max}) and which is 18 to 25 MGOe for SmCo 1:5 grades and 24 to 32 MGOe (190 to 255 kJ/m³) for SmCo 2:17 grades.

There are some differences between the 1:5 and the 2:17 alloys. The 1:5 alloy was the initial material developed and combines only Samarium and Cobalt. The 2:17 materials are a little less expensive because iron is substituted for some of the cobalt and the alloy contains less Samarium. The 2:17 materials deliver 50% higher magnetic output. In addition to standard grades of 1:5 and 2:17, substituting gadolinium for a portion of the samarium provides for greatly improved temperature stability, albeit with a reduced Br near room temperature. With 2:17 grades, one can design a smaller magnet system than with the 1:5 grades. This is the principle reason that most new Samarium Cobalt designs utilize 2:17 grades as opposed to 1:5.

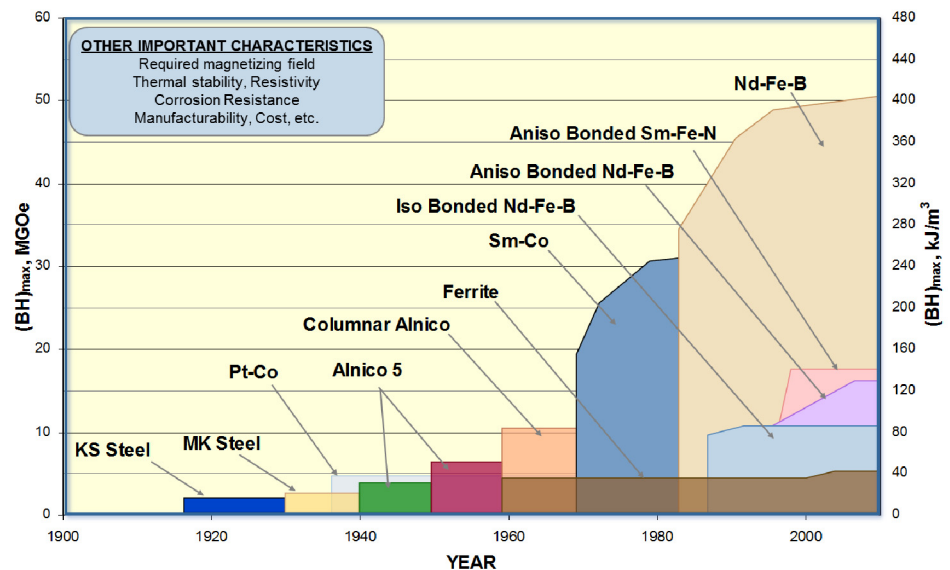
Shortcomings of Samarium Cobalt include, as with all rare earth-based magnets, its high cost and its lack of toughness. Samarium Cobalt is difficult to work with: it must be handled with care to prevent chipping. Customers are usually advised to have Samarium Cobalt magnets tumbled (honed) to create a slight radius (0.004" to 0.007") on the edge. Sharp edges from grinding or slicing and dicing magnets are more fragile and have an

increased tendency to chip. The fragments that come off can stick magnetically back onto the magnet creating a "dirty" magnet. The edge radius also provides a more uniform edge coating where plating or painting is required.

Samarium Cobalt has replaced Alnico in many military and aerospace applications. TWTs, traveling wave tubes, and coupled-cavity designs now use Samarium Cobalt magnets. Although the magnet is often more expensive, the overall design can be made smaller and lighter due to the higher energy that the Samarium Cobalt produces. By miniaturizing, weight and space can be minimized.

NEODYMIUM IRON BORON

Neodymium-Iron-Boron was developed in the early 80's and commercially available starting in November 1984. To avoid the cost and price variability experienced by Samarium Cobalt in the late 1970s, manufacturers were looking for a material that was just as magnetically strong as Samarium Cobalt but at a lower cost and with greater



availability. Neodymium Iron Boron is a very high energy material with commercial energy products of over 52 MGOe (440 kJ/m³). It is also more economical since the transition metal is mostly iron with only a small amount of cobalt.

Neodymium-Iron-Boron ("Neo") is a good material for applications between -40 and 150 °C. Selected grades may be used to over 200°C, but with a reduction in flux output and performance below that of SmCo.

Neo is not as temperature stable as Samarium Cobalt. The temperature coefficient of induction of -0.07 to -0.13 %/°C is mediocre (though not as poor as ferrite). For example, because of this high temperature coefficient of induction, above about 160°C, Samarium Cobalt produces greater flux output than Neo.

Neo magnets will oxidize and corrode relatively easily if not protected with an E-coat, epoxy, nickel plating or similar coating to seal air, moisture, salts and some gases from getting to the material. Furthermore, the material must be made in the absence of air to avoid making unstable oxide compounds in the alloy structure.

Neo has a low curie temperature of 310°C. This temperature can be increased through the addition of cobalt. The use of cobalt (in place of some iron) increases the material cost. The temperature characteristics of Neo material are poor when compared to Alnico and Samarium Cobalt though better than ferrite.

The corrosion / oxidization problem with Neo needs to be addressed with coatings. Paint, E-coat, epoxy are fine for general use, but the coating adds a gap between the magnet and the pole pieces. This air gap creates reluctance in the magnetic circuit, similar to a resistance in an electrical circuit. Nickel plating and E-coat are both advantageous because they provide excellent protection with a thin coating. Electrolytic nickel is especially effective as it provides a hermetic seal, protecting the magnet from air, moisture and gases. It is also one of the less expensive methods of coating to prevent oxidation.

With oxidation or corrosion there is a loss in energy as well as the generation of particulates. Magnet producers have come a long way in improving both temperature stability and corrosion resistance. However, engineers designing with Neo would be wise to apply or specify a coating.

Magnets are available doped with various materials such as dysprosium, cobalt, niobium, copper, aluminum, gallium, etc. These are designed to maximize the stability of the magnet from both a temperature and a corrosion standpoint while maximizing magnetic performance. These modified materials may be used to 200°C+. For successful use at elevated temperatures, care must be taken in the magnetic circuit design to ensure operating high enough up on the de-mag curve to prevent demagnetization due to temperature effects.

MATERIAL	MAGNETIC PROPERTIES	PHYSICAL PROPERTIES	CURIE TEMP and TEMP COEFF. of Br	APPROXIMATE COST, \$/kg **
CAST ALNICO	Br: 5,500 - 13,500 Hc: 475 - 1,900 BHmax: 1.4 - 10.5	CAST TO SHAPE; HARD; BRITTLE. GRIND OR EDM	840 °C -0.02 %/ °C	\$55.00
SINTERED ALNICO	Br: 6,000 - 10,800 Hc: 650 - 1,900 BHmax: 1.4 - 5.0	POWDER PRESSED TO SHAPE; HARD; BRITTLE. GRIND OR EDM	840 °C -0.02 %/ °C	\$80.00
FERRITE (CERAMIC, Std. grades)	Br: 3,450 - 4,200 Hc: 3,000 - 4,800 BHmax: 2.7 - 4.2	SIMPLE SHAPES (ARCS, RECT., PLUGS, RINGS) HARD-GRIND	450 °C -0.2 %/ °C	\$5.00
FERRITE (CERAMIC, La-Co grades)	Br: 4,000 - 5,500 Hc: 3,000 - 4,800 BHmax: 2.7 - 4.2	SIMPLE SHAPES (ARCS, RECT., PLUGS, RINGS) HARD-GRIND	450 °C -0.2 %/ °C	\$12.00
SAMARIUM COBALT	Br: 8,800 - 11,300 Hc: 9,000 - 21,000 BHmax: 18 - 32	POWDERED METAL PROCESS; VERY BRITTLE. GRIND OR EDM	750 - 825 °C -0.035 %/ °C	\$125.00
NEODYMIUM-IRON-BORON	Br: 10,700 - 14,000 Hc: 12,000 - 30,000 BHmax: 27 - 52	POWDERED METAL PROCESS; COAT TO PREVENT CORROSION GRIND OR EDM	310 - 365 °C -0.07 to -0.13 %/ °C	\$160.00
IRON-CHROME-COBALT	Br: 9,000 - 13,500 Hc: 50 - 600 BHmax: 4.25 - 5.25	MALLEABLE; CAN BE FORMED, STAMPED, THIN ROLLED 0.0005 - 0.050"	600 °C -0.02 %/ °C	\$65.00
FLEXIBLE BONDED	Br: 2,300 - 5,600 Hc: 3,500 - 16,000 BHmax: 0.7 - 6.2	FLEXIBLE; THERMAL SHOCK RESISTANT; LOW-TO-NO TOOLING CHARGE; AVAILABLE IN WIDE RANGE OF SIZES AND SHAPES	FERRITE: 450 °C -0.2 %/ °C NEO: 310 - 470 °C -0.07 to -0.13 %/ °C	\$5.00 \$40 - \$65
INJECTION MOLDED	Br: 2,300 - 6,900 Hc: 3,000 - 16,000 BHmax: 1.5 - 12.0	COMPLEX SHAPES; THIN WALLS; TIGHT TOLERANCES W/O MACHINING; GOOD STRENGTH	FERRITE: 450 °C -0.2 %/ °C NEO: 310 - 470 °C -0.07 to -0.13 %/ °C	\$7.00 \$70 - \$95
COMPRESSION BONDED	Br: 6,200 - 8,200 Hc: 4,300 - 18,000 BHmax: 7.5 - 16.0	SIMPLE GEOMETRIES; CLOSE TOLERANCES W/O MACHINING; HIGHER BHmax THAN INJ. MOLDED WITH LOWER TOOLING COSTS	NEO: 310 - 470 °C -0.07 to 0.13 %/ °C	\$35 - \$65

* Pricing is highly variable for some materials. Use these values only as a general guide

Devices using Neo magnets are those benefiting from its high output in non-destructive environments such as in hard disk drive voice coil motors (for computers). In the 1970's, these used ferrite magnets. Then, later, they used Samarium Cobalt to take advantage of the higher magnetic strength. By the late 1980s they were universally Neo magnets. The stronger magnets allowed miniaturization of the disc drives. Head read/write motors (VCMs) and spindle drive motors all use neodymium iron boron – the VCM motor being sintered Neo and the spindle drive motor using compression bonded Neo. Lap top computer disk drives are as small as they are in part because of the high output of Neo magnets. In 1990 hard disk drives consumed about 75% of all Neo magnet produced and HDDs still represent the second largest market for Neo magnets.

The use of grain boundary diffusion (GBD) to add heavy rare earths (HRE) to Neo magnets to improve resistance to demagnetization at high temperatures is a process that was patented and developed in the early 2000s. It reduces the overall required amount of HRE while minimizing reduction of Br and energy product (i.e. at room temperature). It does not, however, reduce the loss of flux with temperature. Net result: reduction of HRE requirement in magnets still limited to optimal performance at or below 180 °C. This is a complex subject best discussed in detail elsewhere.

Curie temperatures have been raised through the addition of cobalt at up to typically 3 weight percent with resulting range of Tc from 310 – 330 °C. Neo is increasingly used in commercial motor, sensor and actuator applications. However, aerospace and military equipment designs have not yet and may never be fully converted from alnico and samarium cobalt.

IRON CHROME COBALT

This material was developed more than a half century ago. It has properties similar to Alnico 5 in that the Br is quite high, 9,000 to 13,500 gauss and the coercive force (Hc) is low, between 50 to 600 oersteds. Unlike alnico FeCrCo is ductile: it can be rolled, stamped and bent prior to the final heat treatment. It can be rolled down to very thin strip and is often used at <0.015" thick in hysteresis coupled drives.

One use for FeCrCo is in EAS (Electronic Article Surveillance). The thin magnetic strip is embedded with another material in a housing and attached to a book, CD, or other store or library item. Upon exiting the premise, one passes between sensing coils on either side of the aisle. These are large antennae for sending a signal to and receiving a response from the magnetic "tag" on the product. If the tag has been "desensitized" prior to leaving, there is no response. However, an active tag will provide a signal to the surveillance system.

In addition to the low coercivity, another shortcoming of this material is the moderately high cost. Although mostly iron, there is significant cobalt and chrome content.

BONDED MAGNETS

Bonded magnets are made by mixing magnetic powders with a non-magnetic bonding agent. Hence the name bonded magnets. The binder can be rubber (typically nitrile), thermoplastic (such as nylon or PPS), thermo-elastomer (urethane, polyethylene, vinyl) or thermoset (epoxy resin).

The blended "compound" is turned into a magnet by processing:

- **Calendering:** formed into a continuous sheet through compression between two or more rollers
- **Extrusion:** heated compound is pushed through a shaping orifice to form a continuous sheet or strip
- **Injection molding:** the heated compound is squeezed through a series of channels into a mold cavity where it is allowed to cool to become firm, the mold opened and the part removed
- **Compression bonding:** binder-coated magnetic powder is fed into a die cavity and compacted by punches at moderately high pressure. The compacted "green" part is heat treated to cure the binder.

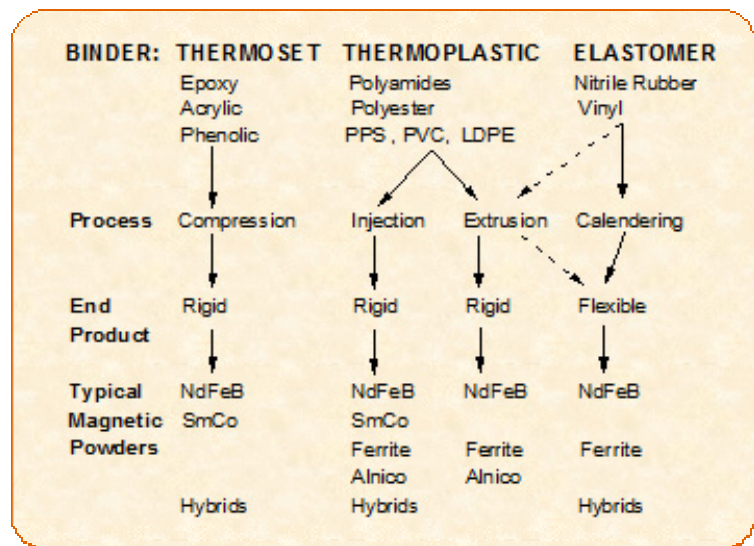
Bonded magnets acquire physical properties typical of the binding material. A rubber bonded magnet is flexible and resistant to chipping, cracking and breaking. Epoxies used in compression bonded magnets are very resistant to oils, gasoline, and ordinary solvents. On the other hand, organic binder systems:

- Limit the maximum use temperature to the temperature where the binder softens or decomposes, usually in the range 80 to 220 °C
- With some exceptions, they are not hermetic, thus allowing moisture and air to permeate and react with the magnet powder
- The binder will swell upon absorption of liquid causing dimensional change and weakening of the binder - - proper binder selection can minimize negative effects

Brass, aluminum, steel and even high temperature plastics can be insert molded, a process where the magnet compound is formed on, around or inside the other component, bonding to it. An advantage of insert molding is a reduction in subsequent manufacturing assembly steps. The design can often produce a superior joining process.

Co-injection molding forms a product consisting of two dissimilar materials simultaneously injected and joined to each other during the molding process. These can be two different magnetic materials or a magnet compound and a plastic material. A variation of this process is called multi-step injection molding wherein the dissimilar materials are molded sequentially rather than simultaneously.

These processes give the engineer an opportunity to create shapes ranging from the very simple to the very complex; with magnetic orientation that ranges from simple straight-through, to radial, to multiple poles.



The temperatures used to form bonded magnets are relatively low (less than 340 °C) compared to temperatures used in making the magnetic powders. Therefore, different magnetic powders can be mixed to result in what is called a "hybrid" magnet. Particularly useful hybrids are mixes of ferrite powder with a small amount of rare earth powder, usually neodymium iron

boron or SmFeN. These can be mixed in various percentages to get a variety of magnetic properties tailored to the application requirements.

A shortcoming of bonded magnet materials is the upper temperature limit dictated by the bonding material. Maximum use temperatures range from 80°C to 220°C. PPS (polyphenylene sulfide) offers good high temperature performance with minimal absorption of liquids and good resistance to oils and other solvents. Manufacturers have utilized PPS to supply product to the automotive applications especially where exposure to gasoline, oils or grease is possible.

Thermo-elastomers used in very flexible bonded sheet magnets soften starting at low temperatures. Maximum recommended use is typically 80 °C. At even moderate temperatures the magnet softens enough to permit distortion – magnet powder particles pulling on each other. At higher temperatures, the organic decomposes becoming stiff and suffering permanent dimensional change.

Energy product (BHmax) of bonded magnets is also lower than for a fully dense material due to the magnetic material being diluted by the binder. Typical volume fractions of magnetic powder in magnets are limited by processing requirements and are:

- Calendered: 65%
- Extruded: 65 (flexible) to 80% (stiff)
- Injection molded: 55 to 65%
- Compression bonded: 78 to 80%

DESIGN CONSIDERATIONS

Two important considerations are cost and temperature capability.

Cost is always an important issue. Costs in the accompanying table are based upon order volume, material type, size and the shape, and magnetic orientation or field pattern of the magnet. The numbers shown are based upon recent industry information for simple part geometry and in moderate order quantities. These are general numbers, but provide insight as to relative pricing for the different materials.

In designing:

- Consider ferrite magnets first because of their cost advantage
- Alnico applications typically benefit from a long magnet (relative to diameter or width)
- Short magnets benefit from the high coercivity of the ferrite and rare earth family of magnets
- What are the maximum and minimum temperature requirements
- What temperature stability is required
- What are the ambient conditions: solvents, gases, moisture with or without salt

SUMMARY

A permanent magnet has the ability to act contactlessly on other magnetic materials, either by attraction or repulsion. This is the beauty of permanent magnet materials: they supply flux to the circuit “for free”.

There is a wide range of materials available including bonded magnets that can be tailored to meet specific product requirements.

When you need assistance as to choice of material or how to optimize the magnetic design, your magnet manufacturer will always be ready to help you.

Need More Information?

For additional information or assistance, please contact Arnold via phone or e-mail (see contact information on last page).



770 Linden Avenue • Rochester • NY 14625 USA
800-593-9127 • (+1) 585-385-9010 • Fax: (+1) 585-385-9017
E-mail: infoNA@arnoldmagnetics.com
www.arnoldmagnetics.com

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