ARNOLD®
MAGNETIC TECHNOLOGIES

TECHNotes

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.

Commercially Available Permanent Magnets

	Manufacturing Process						
	METALLURGY and PM			BONDED			
MATERIAL	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	

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 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.

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)

Since the 1050s, Ferrite has been 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. Ceramic material is an electrical insulator where-as virtually all the other magnetic materials are metallic and are moderately to very conductive.

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. Its most important attributes are low cost and corrosion resistance. For most applications and designs it is the initial material that you should consider.

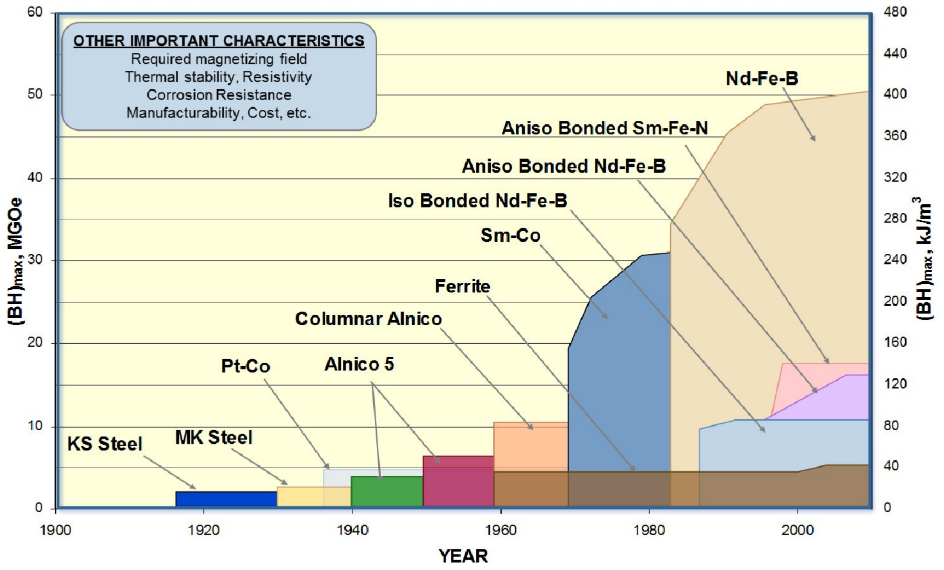
SAMARIUM COBALT

By the early 70s, Samarium cobalt (SmCo) became an effective option for more demanding applications. This material wasable 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 has a curie temperature of 825 ºC. They have very good temperature stability - - -0.035 %/ºC 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” (BHmax) and which is 18 to 25 MGOe for SmCo 1:5 grades and 24 to 32 MGOe (190 to 255 kJ/m^3) 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 SmCo designs utilize 2:17 grades as opposed to 1:5.



Shortcomings of SmCo include, as with all rareearth-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.

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 80s and commercially available starting in November 1984. To avoid the cost and price variability experienced by Samarium Cobalt, manufacturers looked 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/m^3). 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 ºC. Selected grades may be used to over 200ºC, 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 %/ºC is mediocre (though not as poor as ferrite). For example, because of this high temperature coefficient of induction, above about 160ºC, SmCo 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 310ºC. 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 SmCo though better than ferrite.

MATERIAL	MAGNETIC PROPERTIES	PHYSICAL PROPERTIES	CURIE TEMP and TEMP COEFF. of Br	COST COMPARISON **
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	$$
SINTERED ALNICO	Br: 6,000 - 10,800 Hc: 550 - 1,900 BHmax: 1.4 - 5.0	POWDER PRESSED TO SHAPE; HARD; BRITTLE GRIND OR EDM	840 °C -0.02 %/ °C	$$$
FERRITE (CERAMIC, Std. grades)	Br: 3,450 - 4,200 Hci: 3,000 - 4,800 BHmax: 2.7 - 4.2	SIMPLE SHAPES (ARCS, RECT., PLUGS, RINGS) HARD-GRIND	450 °C -0.2 %/ °C	$
FERRITE (CERAMIC, La-Co grades)	Br: 4,000 - 5,500 Hci: 3,000 - 4,800 BHmax: 2.7 - 4.2	SIMPLE SHAPES (ARCS, RECT., PLUGS, RINGS) HARD-GRIND	450 °C -0.2 %/ °C	$
SAMARIUM COBALT	Br: 8,800 - 11,900 Hci: 9,000 - 23,000 BHmax: 18 – 33.3	POWDERED METAL PROCESS; VERY BRITTLE. GRIND OR EDM	750 - 825 °C -0.035 %/ °C	$$$$
NEODYMIUM-IRON-BORON	Br: 10,700 - 14,000 Hci: 12,000 - 30,000 BHmax: 27 - 52	POWDERED METAL PROCESS; COAT TO PREVENT CORROSION GRIND OR EDM	310 - 365 °C -0.07 to -0.13 %/ °C	$$$$$
FLEXIBLE BONDED	Br: 2,300 - 5,600 Hci: 3,500 - 16,000 BHmax: 0.7 - 6.2	FLEXIBLE; THERMAL SHOCK RESISTANT; LOW-TO-NO TOOLING CHARGE; AVAILABLE IN WIDE RANGE OF SIZES AND SHAPES	**FERRITE**: 450 °C -0.2 %/ °C **NEO**: 310 - 470 °C -0.07 to -0.13 %/ °C	$ $$-$$$
INJECTION MOLDED	Br: 2,300 - 6,900 Hci: 3,000 - 16,000 BHmax: 1.5 - 12.0	COMPLEX SHAPES; THIN WALLS; TIGHT TOLERANCES W/O MACHINING; GOOD STRENGTH	**FERRITE**: 450 °C -0.2 %/ °C **NEO**: 310 - 470 °C -0.07 to -0.13 %/ °C	$ $$$
COMPRESSION BONDED	Br: 6,200 - 8,200 Hci: 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	$$-$$$

**Pricing is highly variable for some materials. Contact Arnold for current pricing.

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 200ºC+. 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.

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 ºC.

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).

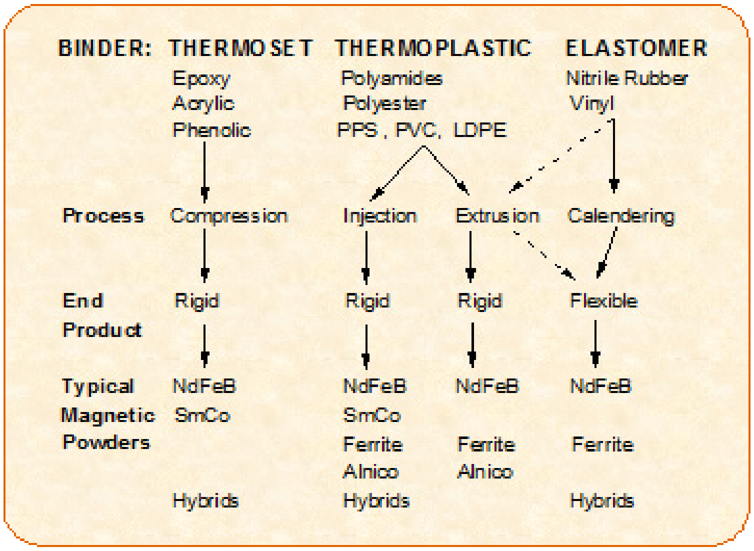
The blended "compound" is turned into a magnet by processing:

- **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 ºC
- 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

Insert molding and co-injection molding are two other processes that can 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 80ºC to 220ºC. 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 ºC. 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. Cost generalizations in the accompanying table are based upon order volume, material type, size and the shape, and magnetic orientation or field pattern of the magnet.

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”.

A wide range of materials are available 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 visit our website at www.arnoldmagnetics.com.

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