Permanent Magnet Selection and Design Handbook

MAGCRAFT®
ADVANCED MAGNETIC MATERIALS

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I. Introduction

This handbook is designed to assist engineers and product designers select a permanent magnet that will best address their requirements at the lowest cost. Contained in this handbook is information on all types of modern magnetic materials as well as additional information on coatings, magnetic orientations, working temperatures, magnetic assemblies, and terminology. This handbook was written to provide practical advice on permanent magnets and is not intended to be a comprehensive treatise on the science of magnetics.

II. Modern Magnetic Materials

A. Ceramic

Ceramic, also known as ferrite, magnets are made of a composite of iron oxide and barium carbonate ($BaCO_3$) or strontium carbonate ($SrCO_3$). Widely available since the 1950's, this material is commonly available and at a lower cost than other types of materials used in permanent magnets. Ceramic magnets are made using pressing and sintering. Sintered magnets are a type of ceramic composed of the compressed powder of the alloy material being used. Sintering involves the compaction of fine alloy powder in a die and then fusing the powder into a solid material with heat. While the sintered magnets are solid, their physical properties are more similar to a ceramic and are easily broken and chipped.

Ceramic magnets are brittle and hard generally requiring diamond wheels to grind and shape. These magnets come in a number of different grades. Ceramic-1 is an isotropic grade with equal magnetic properties in all directions. Ceramic grades 5 and 8 are anisotropic grades. Anisotropic magnets are magnetized in the direction of pressing. The anisotropic method delivers the highest energy product among ceramic magnets at values up to 3.5 MGOe (Mega Gauss Oersted). Ceramic magnets have a good balance of magnetic strength, resistance to demagnetizing and economy. They are the most widely used magnets today.

Beneficial characteristics of ceramic magnets include their low cost, high coercive force, resistance to corrosion, and high heat tolerance. Drawbacks include their low energy product or "strength", low mechanical strength, and the ferrite powder on the surface of the material which can rub of and cause soiling.

B. Alnico

Alnico magnets are made up of an alloy of aluminum (Al), nickel (Ni) and cobalt (Co) with small amounts of other elements added to enhance the properties of the magnet. Alnico magnets have good temperature stability, good resistance to corrosion but are prone to demagnetization due to shock. Alnico magnets are produced by two typical methods, casting or sintering. Sintering offers superior mechanical characteristics, whereas casting delivers higher energy products (up to 5.5 MGOe) and allows for the design of intricate shapes. Two very common grades of Alnico magnets are 5 and 8. These are anisotropic grades and provide for a preferred direction of magnetic orientation. Alnico magnets have been replaced in many applications by ceramic and rare earth magnets.

Beneficial characteristics of Alnico magnets include their high corrosion resistance, high mechanical strength, and very high working temperatures. Drawbacks include their higher cost, low coercive force, and low energy product.

C. Rare Earth Magnets

Rare earth magnets are magnets composed of alloys of the Lanthanide group of elements. The two Lanthanide elements most prevalent in the production of permanent magnets are Neodymium (Nd) and Samarium (Sm). There are numerous alloy formulations of rare earth magnets covered under many different patents but the most common commercial varieties are Neodymium-Iron-Boron ($Nd_2Fe_{14}B$) and Samarium Cobalt ($SmCo_5$, Sm_2Co_{17}).

Rare earth magnets are available in sintered and bonded forms. Bonded magnets use a polymer base to hold the alloy powder together. The energy product of bonded magnets is much lower than that of the sintered magnets. Sintered NdFeB magnets are generally plated or coated with a material to prevent corrosion.

1. Samarium Cobalt

Samarium cobalt is a type of rare earth magnet material that is highly resistant to oxidation, has a higher magnetic strength than ceramic and alnico and better temperature resistance than neodymium materials. Introduced to the market in the 1970's, samarium cobalt magnets continue to be used today. Samarium cobalt magnets are divided into two main groups: $SmCo_5$ and Sm_2Co_{17} (commonly referred to as 1-5 and 2-17). The energy product range for the 1-5 series is 15 to 22 MGOe, with the 2-17 series falling between 22 and 32 MGOe. These magnets offer the best temperature characteristics of all rare earth magnets and can withstand temperatures up to 350° C. Sintered samarium cobalt magnets are brittle and prone to chipping and cracking and may fracture when exposed to thermal shock. Due to the high cost of the material samarium, samarium cobalt magnets are used for applications where high temperature and corrosion resistance is critical.

Beneficial characteristics of samarium cobalt magnets include their high corrosion resistance, high energy product and high temperature stability. Drawbacks include their high cost and very low mechanical strength.

2. Neodymium Iron Boron

Neodymium iron boron ($Nd_2Fe_{14}B$) is another type of rare earth magnetic material. NdFeB is the most advanced commercialized permanent magnet material available today. This material has similar properties as the samarium cobalt except that it is more easily oxidized and generally doesn't have the same temperature resistance. However, NdFeB magnets have the highest energy products approaching 52MGOe and are mechanically stronger than samarium cobalt magnets. NdFeB material is more costly by weight than ceramic or alnico but produces the highest amount of flux per unit of volume or mass making it very economical for many applications. Their high energy products lend themselves to compact designs that result in innovative applications and lower manufacturing costs. Unprotected NdFeB magnets are subject to corrosion. Surface treatments have been developed that allow them to be used in most applications. These treatments include copper, silver, gold, nickel, zinc and tin plating and epoxy resin coating.

Beneficial characteristics of NdFeB magnets include their very high energy product, very high coercive force, and moderate temperature stability. Drawbacks include lower mechanical strength, and low corrosion resistance when not properly coated or plated.

D. Polymer Based Magnets

All of the magnetic materials described above can be mixed with various polymers to create a broad range magnetic materials with their own magnetic and mechanical properties. The primary reason for mixing magnetic materials with polymers is to gain material flexibility, allow for increased shape complexity or increased control over the shape and direction of the magnetic fields. Once a magnetic material powder has been mixed into a polymer it can be injection molded, cast, or calendared into flexible sheet magnets. The primary drawback to polymer based magnets is their low energy product.

E. Properties of Selected Magnetics Materials

This chart presents some of the magnetic properties of a subset of magnetic materials:

	Maximum Energy Product *Bhmax(MGOe)*	**Residual Flux Density** *Br(G)*	**Coercive Force** *Hc(Koe)*	**Working Temperature** *ºC*
Ceramic 5	3.4	3950	2400	400
Sintered Alnico 5	3.9	10900	620	540
Cast Alnico 8	5.3	8200	1650	540
Samarium Cobalt 20 (1,5)	20	9000	8000	260
Samarium Cobalt 28 (2,17)	28	10500	9500	350
Neodymium N45	45	13500	10800	80
Neodymium 33UH	33	11500	10700	180

Table 1- Selected Material Magnetic Properties

III. Magnetic Grades

The grade of a magnet directly refers to the Maximum Energy Product of the material that composes the magnet. It in no way refers to the physical properties of the magnet. Grade is generally used to describe how "strong" a permanent magnet material is. The energy product is specified in the units Gauss Oersted. One MGOe is 1,000,000 Gauss Oersted. A grade forty (N40) would have a Maximum Energy Product of 40 MGOe. The higher the grade the “stronger” the magnet.

The following table presents the generally available grades of each type of rare earth magnetic material with their corresponding residual flux density and coercive force:

Material	Grade	Remanence Flux Density Br KGs	Coercive Force Hcb KOe	Maximum Energy Product (BH)max MGOe
Nd2Fe14B	N35	12.1	11.4	35
	N38	12.6	11.7	38
	N40	12.9	11.9	40
	N42	13.3	12.3	42
	N45	13.6	12.1	45
	N48	14	12.1	48
	N50	14.3	12.3	50
	38M	12.6	12.2	38
	40M	12.9	12.3	40
	42M	13.3	12.4	42
	45M	13.6	12.1	45
	48M	13.9	12.9	50
	30H	11.2	10.7	30
	35H	12.1	11.6	35
	38H	12.6	12.1	38
	40H	13	12	40
	42H	13.1	12	42
	44H	13.5	12	45
	46H	13.7	13	46
	30SH	11.2	10.7	30
	35SH	12	11.6	35
	38SH	12.6	12.1	38
	40SH	13	12.3	40
	42SH	13.1	12.4	42
	44SH	13.5	12.8	44
	28UH	10.9	10.4	28
	30UH	11.2	10.3	30
	33UH	11.5	10.8	33
	35UH	12	11.6	35
	38UH	12.6	12.1	38
	40UH	13	12.3	40
	42UH	13.1	12.4	42
	30EH	11.2	10.3	30
	33EH	11.5	10.8	33
	35EH	12	11.6	35
Sm1Co5	18	8.5	8	18
	20	9	8	20
Sm2Co17	24	10	8.5	24
	26	10.5	9.2	26
	28	10.5	9.5	28
	30	11	9.5	30
	32	12	11	32

Table 2 - Rare Earth Material Grades

IV. Working Temperatures

Magnetic materials have a wide range of working temperatures. The following chart list the various materials and their maximum working temperature. NdFeB material comes in many different heat tolerances but as the heat tolerance increases the maximum available flux density decreases:

Material	Maximum Working Temperature	
	ºC	ºF
Ceramic	400	752
Alnico	540	1004
SmCo 1,5	260	500
SmCo 2, 17	350	662
NdFeB N	80	176
NdFeB M	100	212
NdFeB H	120	248
NdFeB SH	150	302
NdFeB UH	180	356
NdFeB EH	200	392

Table 3 - Working Temperatures

V. Plating and Coatings

There are various coatings available for permanent magnets. Ceramic, alnico, and samarium cobalt magnets are not prone to corrosion and are therefore only coated to meet an aesthetic or mechanical requirement. NdFeB magnets are prone to corrosion unless they are coated in some manner. NdFeB magnets are most commonly plated with nickel. Nickel provides a hard and shiny surface to the magnets that is corrosion resistant. In addition to nickel, other metals such as zinc, copper, tin, silver, and gold are used in the plating of permanent magnets. Many high quality manufacturers use multiple metals to increase the effectiveness of their plating. Nickel-copper-nickel plating has proved to be one of the most corrosion resistant and durable types of plating while providing an aesthetically pleasing appearance.

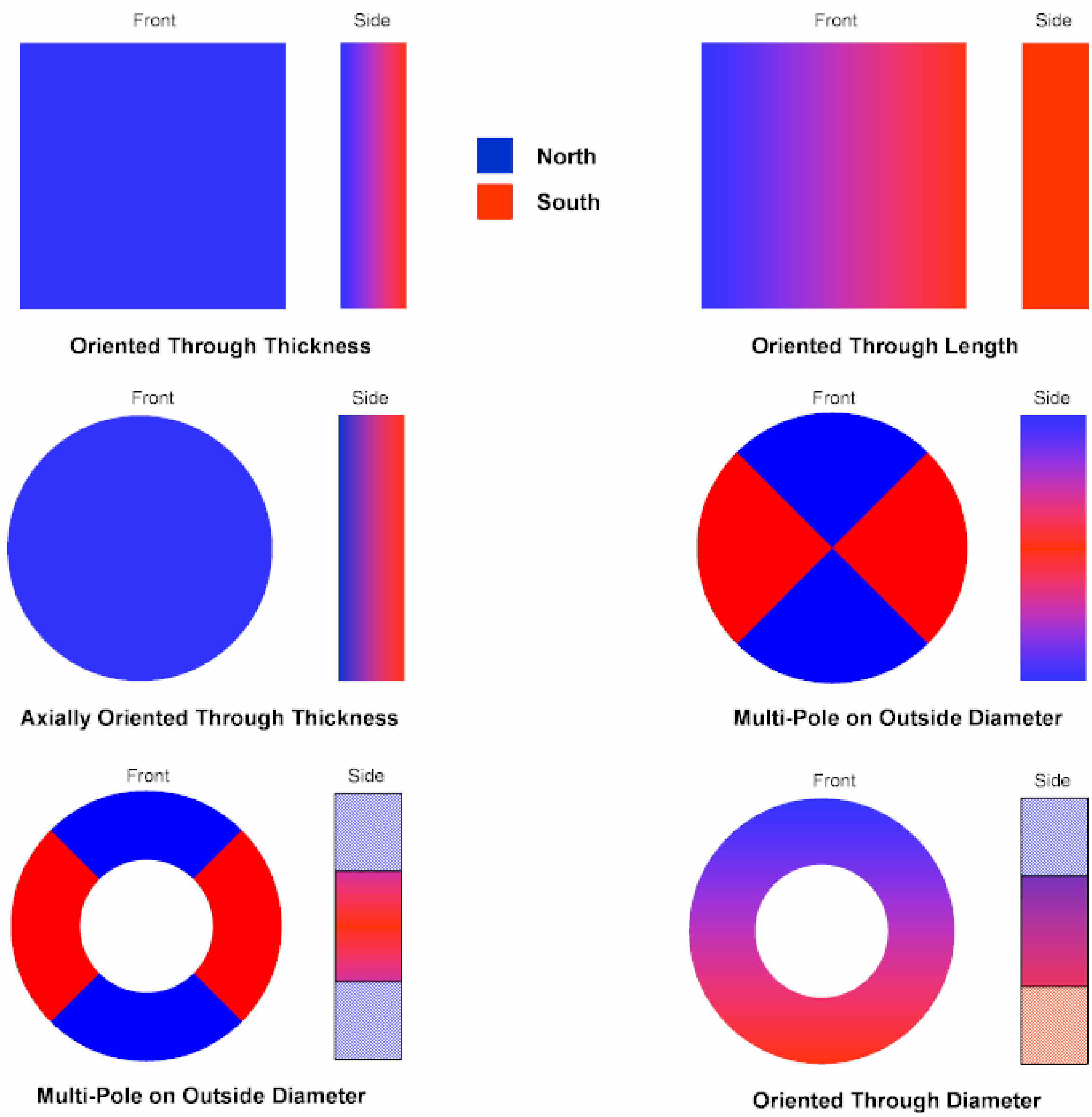
In addition to metal plating, magnets can be coated with organic coatings such as epoxy resins. Very small magnets can be subjected to conformal vapor deposition coatings to preserve dimensional tolerances. Below is a listing of some of the many types and combinations of coatings found on magnets:

Types of Coating		
Ni	NiCuZn	NiCuNiEpoxy
Zn	NiCuNiSn	Colored Ni
Epoxy	ZnEpoxy	Colored Zn
Double Ni	NiCuNiAu	Colored Epoxy
NiCuNi	NiCuNiAg	Phosphored
NiCuSn	NiCuNiZn	Parylene Conformal

Table 4 - Magnet Coatings

VI. Magnetic Orientations

Magnets can be delivered magnetized and un-magnetized. Many automated production methods rely on the magnets being incorporated into assemblies in a un-magnetized state and later magnetized once the assembly is completed. A magnet can be magnetized in a variety of directions. The diagrams below depict various magnetic orientations available for magnets. Anisotropic materials must be magnetically oriented during the production of the material. They therefore are inclined to a fixed orientation. The radial orientations below are difficult to produce and currently only available in some isotropic materials.



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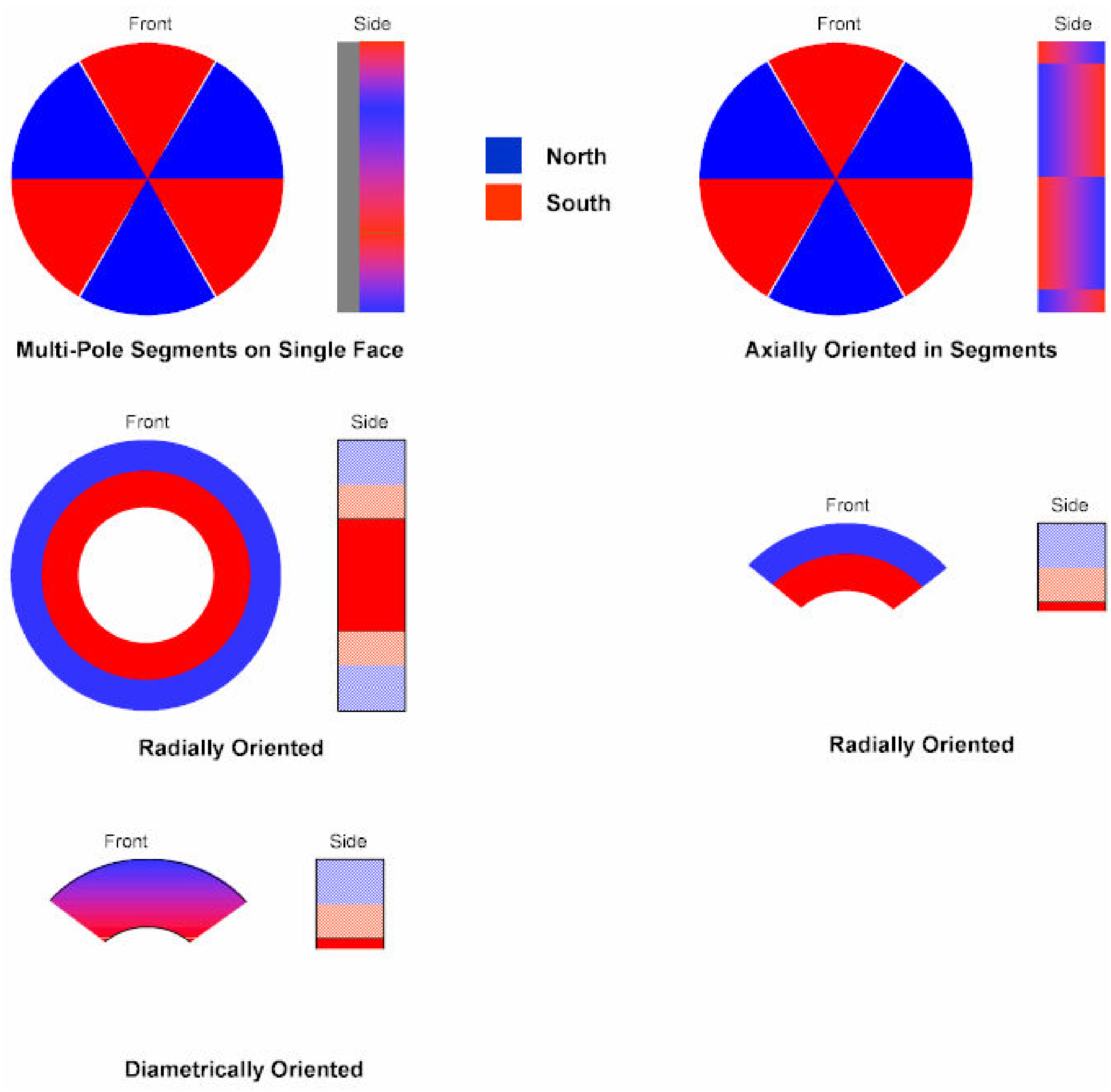

Table 5 - Magnetic Orientations

VII. Assemblies and Circuits

Permanent magnets are commonly incorporated into assemblies that protect the brittle magnetic material and/or provide additional mechanical components that are not easily fashioned out of magnetic material. A common example of this are cup and channel magnets where the magnet is placed inside a steel cup or channel to protect the magnets and to redirect the magnetic flux from one side of the magnet to the other. The redirection of flux creates a magnetic circuit, or path, where the flux can more easily follow. In holding applications, this redirection significantly increases the holding force of the magnet. Magnetic circuit assemblies can be created to direct the flux into a very specific area. This approach is commonly used in electronic equipment designed to record onto magnetic media.

Magnetic circuits can also be utilized to produce mechanically switchable magnets. By forming or disrupting a circuit, the magnetic flux can be redirected which in essence turns the circuit on or off. This technique has been used extensively in magnetic chucks and work holding devices for metal working.

Because of the brittle nature of most magnetic materials, they should generally not be used as a structural component in a mechanical device.

VIII. Packaging

Magnets pose a unique challenge in packaging. They not only need to be protected physically but they also need to be either isolated or shielded so that their magnetic fields do not damage themselves or other objects. Magnets are often shipped in steel lined boxes to shield the magnetic flux from the outside of the box. In actuality, the steel provides a circuit or path for the flux to move. Magnetic flux can only be redirected it can never really be absorbed or blocked.

Strong magnets may require separate packaging or spacers to provide a buffer space between the magnets. These spaces allow the magnets to be separated and more easily handled. In addition to spacers between magnets, boxes of magnets may require rigid material between the boxes to prevent the boxes from attracting each other. Below is a photograph of some NdFeB disc magnets with hard plastic spacers to allow easy handling.

Figure 1 - Magnet Spacers

Packaging for the retail environment poses some unique challenges especially for strong rare earth magnets. As permanent magnets became stronger and stronger, the existing methods to package these advanced magnets for retail display fell further and further behind. Most retail packaging continued to utilize existing clamshell and blister packs to display magnets allowing the magnets on display to stick to each other and other objects such as shelving. A low-cost and effective system that would properly contain, protect and display strong permanent magnets in a retail environment was needed. Through a dedicated research program, the MAGPAK™ system was developed. This patent pending system is simple and effective. The unique double tube design shown below directly addresses the inadequacies of previous retail magnet packaging.

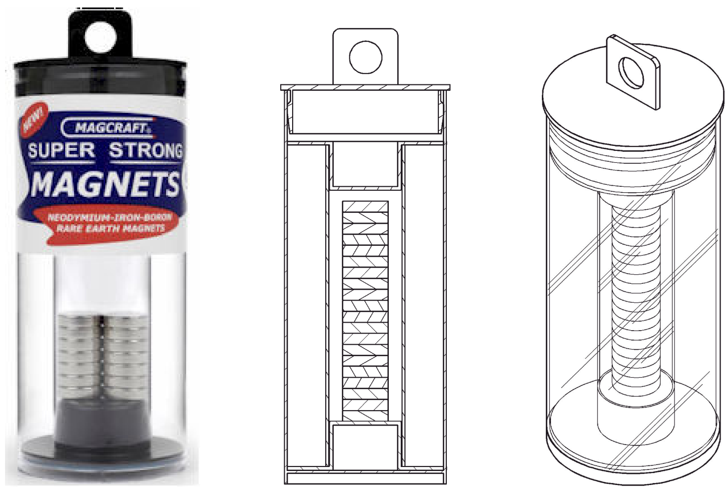

Figure 2 - MAGPAK Retail Packaging

IX. Magnetic Degradation Over Time

Modern high coercive force magnetic materials generally do not degrade significantly over time. Neodymium material may have a loss rate as low as 1% per 100 years or less. Most magnetic material will encounter degradation from corrosion, heat or mechanical impact long before their magnetic properties would degrade because of time. However, if a designer is designing a highly critical sensing application that will have a very long service life, the magnetic service life of the material should be determined.

X. Applications

Magnets are pervasive in the modern environment. From the humble refrigerator magnet to the Hubble Space Telescope, magnets impact almost every aspect of our lives. Magnets are part of most everyday electronic devices. You'll find magnets in almost every device with an electric motor. Televisions, computers, automobiles, loud speakers, cell phones, and microwave ovens, all use magnets. Magnets are used to keep kitchen cabinet doors closed, are part of the sensors in home alarm systems, are placed in cows stomachs to catch barbed wire and nails, are used in magnetic resonance imaging systems, are used to slow elevators, roller coasters and subways, and in countless other devices. Because of the broad used of magnets it is difficult to provide a definitive list of all of their applications. However, the bulk of magnets manufactured today are used primarily in holding applications and electro-motive applications.

XI. Measuring Magnets

A. Magnetic Moment and BH-Curves

The magnetic moment is a measure of the strength of a magnetic source. Using a fluxmeter and a helmholtz coil, the magnetic moment of a particular permanent magnet can be determined. From the magnetic moment, the operating flux density (B_d), operating field strength (H_d), coercive force (H_c), residual flux density (B_r) and maximum energy product (BH_{max}) can be derived.

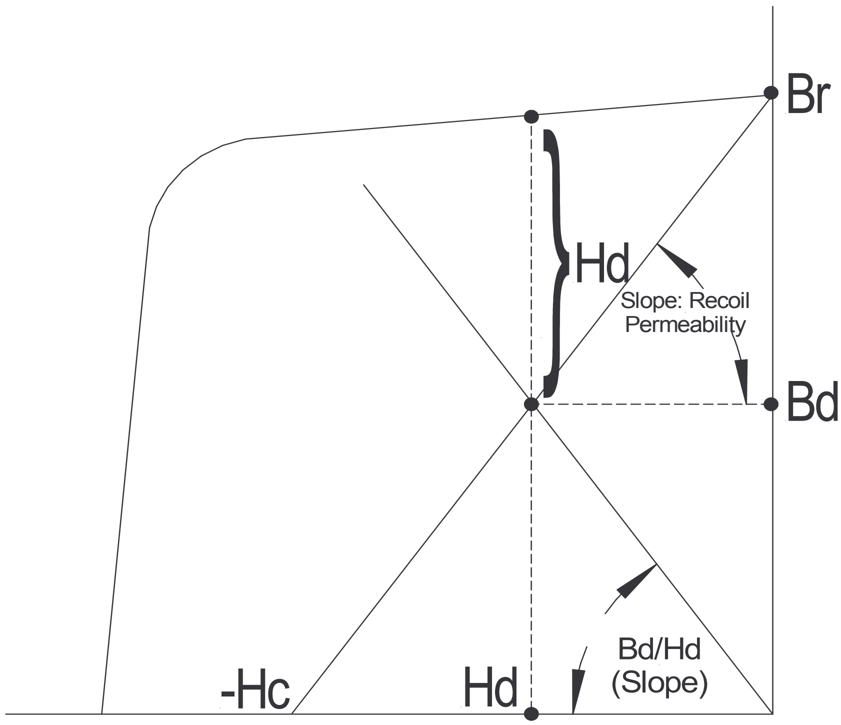

Figure 3 - BH-Curve

B. Flux Density

The measurement of flux density is made using a gauss/tesla meter. Generally this simple measurement is made at the surface of the magnet. Most gauss meters use a hall effect sensor to produce a flux density measurement. The gauss meter provides a constant input current to the hall sensor which then produces an output voltage that is proportional to the density of the magnetic field passing through it. The resulting measurement is usually expressed as gauss or tesla.

C. Pull Force

Pull force measurements are a mechanical method of obtaining a measurement of the holding or pulling strength of a magnet. In this measurement test, a magnet is attached to an actuator with an integrated strain gauge. The opposite side of the magnet is attached to fixed piece of ferromagnetic material such as a plate of mild steel. As the actuator forces the magnet from the steel plate, the force needed to separate the two is recorded by the strain gauge. Pull force tests are not standardized and pull force values provided by manufacturers vary widely and should not be used as the basis of final magnet selection.

XII. Terminology

Anisotropic Magnet
A magnet having a preferred direction of magnetic orientation.

Coercive force, Hc
The demagnetizing force, measured in Oersteds necessary to reduce the induction, B to zero after a magnet has been previously saturated.

Curie temperature, Tc
The transition temperature above which a material looses its magnetic properties.

Flux
The condition existing in a material subjected to magnetizing force. The unit of flux is the Maxwell.

Gauss
Lines of magnetic flux per square centimeter. This is a measure of flux density.

Induction, B
The magnetic flux per unit area of a section normal to the direction of flux. This is measured in Gauss.

Intrinsic Coercive Force, Hci
This is a measure of a materials ability to resist demagnetization. This is measured in Oersteds.

Irreversible Loss
This is defined as the partial demagnetizing of a magnet caused by external factors.

Isotropic magnet
A magnet material whose magnetic properties are the same in any direction.

Magnetic Field strength, H
A measurement of the magnetic ability to induce a magnetic field at a given point. This is measured in Oersteds.

Magnetic Flux

The total magnetic induction over a certain area.

Magnetizing Force, H
The magnetomotive force per unit length at any point in the magnetic circuit. this is measured in Oersteds.

Magnetomotive Force, F
The magnetic potential difference between any two points.

Maxwell
A unit of magnetic flux. One Maxwell is one line of magnetic flux.

Oersted, Oe
A unit of magnetic field strength or magnetizing force.

Orientation Direction
The direction in which an anisotropic magnet should be magnetized in order to optimize the magnetic properties.

Saturation
This is a condition where all magnetic moments have become oriented in one direction.

Stabilization
Exposing a magnet to demagnetizing influences which are expected in the application in order to prevent irreversible loss during the operation of the magnet.

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