New Magnet Materials For Relay Designers

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Abstract - It is quite common in modern relays to use a permanent magnet for assisting both the energized and the deenergized conditions. These magnets must maintain their strength under all temperature and vibration extremes seen by the relay. Loss of magnetic field strength could cause the relay to change key operating parameters.

Recently, advances have been made in the development of permanent magnet materials. In particular, new techniques for fabricating the magnet alloys, as well as, fundamentally new materials. Some of the recent advances in SmCo magnets have demonstrated stable field strength into the range of 350 degrees C. In addition, some of these materials enable a designer to obtain a certain field strength with a great reduction in magnet volume and weight. This paper itemizes some of these new magnet materials and discusses their advantages and disadvantages.

I. BASIC MAGNETICS AND RELAY DESIGN

The purpose of this section is to review the common terminology used in discussing permanent magnets. We will review some of the basic physics behind permanent magnets and magnetic circuit design. This will help the reader appreciate the strengths and weaknesses associated with the presented magnetic materials. Fig. 1 displays a typical hysteresis curve for a ferromagnetic material.

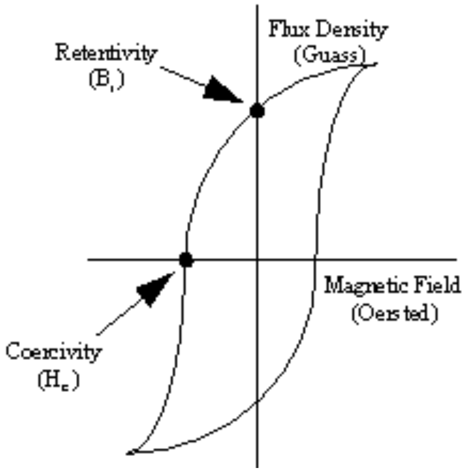

Fig. 1. Hysteresis Curve

The hysteresis curve graphically shows you the relationship between Magnetic field strength (H) and Flux density (B). Key parameters to define from this curve involve the amount of Flux density (B) present when the Magnetic field strength (H) is reduced to zero. Essentially this means how much flux density is left once the magnetizing field is removed. For this reason, that amount of flux density for a given material is defined as the residual flux density, B_r , or a materials *retentivity.* Another common parameter defined when discussing magnetic materials is the amount of reversed magnetic field necessary to bring the flux density in the magnet to zero. This amount of magnetic field strength is defined as a materials *coercivity*, H_c. Both the retentivity and coercivity are important parameters when comparing magnetic materials. High values indicate the material will be able to both support and hold a high flux density. To the relay designer this means there will be adequate flux density to apply armature forces, but perhaps more importantly, the high coercivity implies the flux density will remain despite high demagnetization effects. In relay design, the permanent magnet is typically used to aid or repel the forces of an electro-magnet. The balance of these forces is critical in determining the speed and strengthen at which an armature changes position. The characterization of this movement is measured in terms of pull-in and drop-out voltages for the relay. If the permanent magnet loses strength as a result of any demagnetizing effects, the balance of forces will be affected. This in turn will affect the critical performance parameters of the relay. A permanent magnet that is resistant to demagnetizing forces will give the relay designer the most robust and stable design. High coercively is a key measure in establishing a magnets resistance to demagnetization. Both coercively and retentivity are shown in fig. 1.

The next parameters we need to discuss reflect how much energy will be available to the magnetic circuit. To do this we must refer to fig. 2.

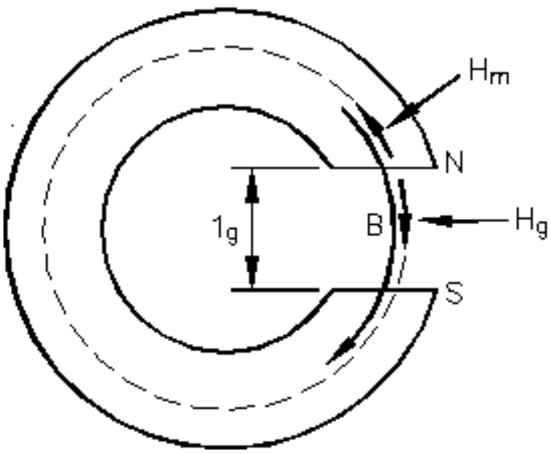

Fig. 2. Ring Magnet with air gap

Fig. 2 shows a ring shaped sample of magnetic material. In addition, we have put an air gap in the ring. The distance of the gap is l_g. Without the air gap, the amount of flux inside the material is simply B_r. This assumes the magnet has been fully charged with an external magnetic field and

The closed path of integration is the dashed line through the center of the ring magnet. No current is contained within the dashed path so the integral can be set to zero. Solving the integral we get;

$$- H_m l_m + H_g l_g = 0 \quad (2)$$

Where l_m is the length of the integral contour within the magnet. We can make the substitution;

$$B = m_0 H_g \quad (3)$$

Where m_0 is the permeability of free space. We then have left;

$$B = m_0 (l_m / l_g) H_m \quad (4)$$

This is the equation of a straight line with slope $m_0(l_m/l_g)$. This line is referred to as the *load line* [2]. The intersection of this line with the hysteresis curve determines the magnets operating point. Notice how increasing gap lengths, l_g, lowers the flux density. Fig. 3 shows the 2nd quadrant of the hysteresis curve (typically called the demagnetization curve) and the intersecting load line. From this figure we can see how important a magnets coercively is. A high coercively will allow a designer to use a large air gap. This will allow the designer a volume of space in which interaction and displacements can occur. Despite the large opposing H_m generated by the air gap, the magnet will still maintain a high flux now that magnetic field is removed. By creating the air gap in the ring we are now essentially adding a demagnetizing magnetic field. The reason for this is the gap creates North and South magnetic poles on the faces of the gap. Within the gap the magnetic field, $_g$, is from N to S and is in the same direction as the flux density in the gap, B_g. This is not the case inside the magnet. Notice the magnetic field inside the magnet, H_m, now opposes the internal flux density [2], [1]. The result is that the internal magnetic field, H_m, is reducing the internal flux density, B_m. This means we are riding down the 2nd quadrant of the hysteresis curve, fig. 1. As the gap gets larger, the magnitude of H_m increases and B_m continues to drop. When the magnitude of H_m equals the coercively, the flux density will go to zero. We must realize that it is the air gap that allows the magnet to do work. A solid ring magnet has little practical value on it’s own. It is only with an air gap that we can get the magnet to perform a function like move a relay armature. The message here is that the gap must be optimized to create enough gap volume for work to be done, yet not so large that the internal H_m drastically reduces the available flux density. The trade off of gap size and flux density determines the magnets operating point. The operating point is essentially where you are operating on the hysteresis curve. We can easily determine the operating point as a function of gap size by considering Ampere’s law;

$$\oint \mathbf{H}\bullet d\mathbf{l} = 0 \tag{1}$$

H_m generated by the air gap, the magnet will still maintain a high flux density.

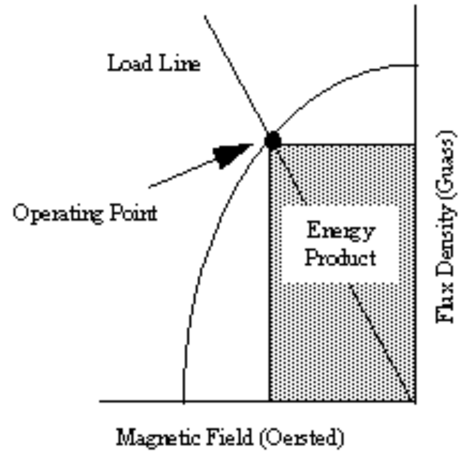

Fig. 3 Demagnetization Curve

The actual energy that can be supplied to the air gap can be seen from equation 5, where the energy per unit volume, u, in a magnetic field is;

$$u = \int \mathbf{H}\bullet d\mathbf{B} \tag{5}$$

(5)

From this it can be shown that the total energy available in the gap is proportional to the product B*H in the demagnetization curve. This value is typically called the energy product. This area (the energy product) is shaded on fig. 3 [2]. Notice how the energy product is also dependent upon the load line and the operating point. It is easy to see how the energy product reaches a maximum depending upon the operating point [2]. This can be seen from fig. 4. There is a certain combination of B and H that produces the maximum energy product. This is typically denoted BH_{max}. The BH_{max} value is a good figure of merit when comparing different magnetic materials. The higher the energy product the more work your magnet can do. This can give a designer a terrific edge. With a high energy product magnet the amount of magnet volume (and weight) necessary to do work can be greatly reduced. The designer must also realize that the energy product is dependent upon the operating point of the magnet. As we saw earlier, the operating point is determined by air gap length. It is therefore possible to use a high energy product magnetic material but design the air gap to not take advantage of the high BH_{max}. Again this can be seen from fig. 4. Fig. 4 shows the energy product as a function of operating point (and hence, air gap distance).

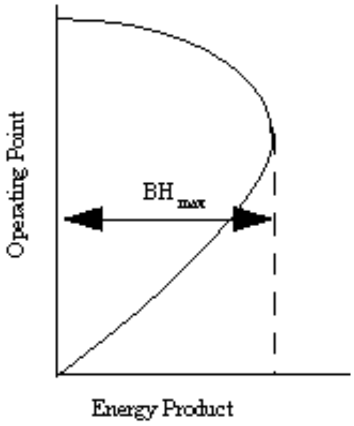

Fig. 4 Energy Product change with Operating Point

II. MAGNETIC MATERIALS

The three primary types of magnetic materials that will be discussed are;

A) Ceramic Types
B) Alnico Types
C) Rare Earth Types

A. Ceramic Types

Ceramic magnets are composed of Strontium or Barium Ferrite and a ceramic base material. Ceramic magnets are hard and brittle and are extensively used in consumer products.

Advantages
1) They are the least expensive magnets.
2) They are very resistant to corrosion.
3) They are stable up to approximately 300°C.

Disadvantages
1) They are difficult to machine.
2) They have a low energy product (3MGOe).
3) They have a low/moderate coercively (2KOe).

The primary advantage to these magnets is cost. If the application is very sensitive to cost then these magnets should be considered. The low energy product will drive up the volume of magnet you will need. The low coercively should be watched carefully. From our earlier discussions we realize this means you can lose magnetic flux rapidly with the introduction of small demagnetizing forces

B. Alnico Types

Alnico magnets are made of alloys of Aluminum, Nickel and Cobalt. Although this family of magnets was developed in the 1940’s, many advances have taken place. Before the introduction of Alnico, permanent magnets were very limited in their application. The magnetic properties of Alnico were vastly superior to what was available at the time.

Advantages
1) They are relatively inexpensive.
2) They are stable up to very high temperatures (550°C).
3) They are very resistant to corrosion.

Disadvantages
1) They are very difficult to machine.
2) They have a low coercively (1KOe).
3) They have a moderate energy product (5MGOe).

A key area to watch with Alnico is the low coercively. Certain types of Alnico are better than others. Alnico 8 has the largest coercively at about 1.9KOe. Alnico 5 on the other hand has a coercivity of approximately 0.6KOe. This value is quite low and is unsuitable for many applications. Although Alnico does hold its magnetic properties at very high temperatures, it can lose it's magnetic strength under conditions of shock. If the application requires high vibration or shock levels, be careful in your usage of Alnico.

C. Rare Earth Types

Alloys of the Lanthanide group on the periodic table (Rare Earths) are the most advanced commercialized permanent magnet materials. These materials represent a significant step function of improvement in permanent magnet properties. The two primary materials are the Samarium-Cobalt family and the Neodymium-Iron-Boron family.

Samarium-Cobalt Family
This family of magnets was developed in the 1970's. The Energy products of these magnets set new standards. As a result of this, many applications requiring high magnetic energy with little volume were addressed by Samarium-Cobalt.

Advantages
1) Very high energy product (30MGOe).
2) Very high coercivity (10KOe).
3) Stable at high temperatures (350°C).
4) They are very resistant to corrosion.

Disadvantages
1) They are the most expensive.
2) They are difficult to machine.

There are two main compositions of Samarium-Cobalt magnets. They are; Sm1Co5 and Sm2Co17. The Sm2Co17 material has the highest energy product at about 30MGOe. The excellent temperature stability can even be enhanced further by doping the material. When doped with a material such as Gadolinium, a further enhancement of the temperature stability can be achieved. The penalty of this extra temperature stability is a slight loss in energy product. The combination of the temperature stability, high coercively and high energy product make the Gadolinium doped Sm2Co17 an ideal permanent magnet[5]. The high energy product allows the designer to drastically reduce the magnet volume and weight. The high temperature stability and coercivity assure the magnetic strength will endure despite any de-magnetizing effects. The cost issue is certainty an item to be considered , but when you compare cost on the basis of cost per unit of energy product, you see Samarium Cobalt is actually comparable to Alnico.

Neodymium-Iron-Boron
The discovery of Neodymium-Iron-Boron magnets was announced almost simultaneously late in 1983 by Sumitono Special Metals and General Motors. These magnets are the highest energy permanent magnets available. Despite their energy product being greater than SmCo, they are substantially less expensive than SmCo. They are principally Iron which is much cheaper than Cobalt, and Neodymium which is the most common of the rare earth materials [3].

Advantages
1) Exceptionally high energy product (40MGOe).
2) Exceptionally high coercivity (15KOe).
3) Relatively easy to machine.
4) They are relatively inexpensive.

Disadvantages
1) They do not resist corrosion.
2) They are not stable above 150°C.

The high energy product certainty makes this material attractive. With an energy product of 40MGOe just a small amount of material is needed to create a substantial magnetic field. The corrosion issue can be dealt with through plating/coatings. It is the temperature issue that is most limiting. Most relay applications demand stable performance in the 200°C range. The commercially available NdFeB magnets can not reliably operate at these temperatures.

D. Future Developments

Advances are being made in permanent magnets quite rapidly. The high energy product of NdFeB has focused a good deal of attention on it. Dopings are being developed to increase the temperature of stable operation. In particular, introduction of heavy rare earths like Dyprosium, doped with Copper and Oxygen, have shown substantial increases in temperature stability[4]. In addition work is being done in combining hard magnetic NdFeB with soft magnetic Iron. The result is a high coercivity material with a very high retentively. This family of magnets has been called the lean rare earths. In addition to NdFeB, several other compounds are being developed that show promise. One such development, labeled the "Y.T." magnet, is reported to show an energy product of 120MGOe [6].

III. SUMMARY

For the relay designer, high coercivity and temperature stabilization is essential. The magnet must hold it's strength under adverse conditions. If it does not, the relay will change in it's performance. High energy product allows for vast size and weight reductions in the magnet. This could ultimately mean a lighter and smaller relay. Until the doped temperature stabilized NdFeB is commercially available, Sm2Co17 doped with Gadolinium (usually referred to as temperature compensated SmCo) exhibits excellent magnetic properties for relays.

Lastly, it should be pointed out the importance of operating point on the demagnetization curve. The magnet energy product is a maximum at a certain operating point. You may use a terrific magnet with

great potential energy product. If your air gap puts you at an operating point far from the max energy product point, you may be wasting some of the potential of your magnet.

ACKNOWLEDGMENTS

The author would like to acknowledge the assistance of several high quality manufacturers of permanent magnet materials; The Dexter Corporation, Magnet Sales and Manufacturing Inc., Australian Magnet Technology LTD., The Katrina Corporation and Ceradyne Inc. The author would also like to thank his colleagues at Leach International for their support and assistance.

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