Understanding Permanent Magnets

Theory and Applications

Modern permanent magnets play a vital role in a wide range of industrial, consumer and defense products. Efficient use of permanent magnets in these devices requires a basic understanding of magnetic theory. To achieve this end it is helpful to understand that all magnetic fields are the result of electrons in motion.
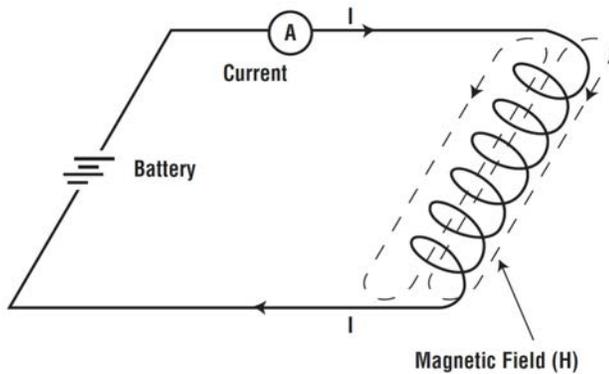

Figure 1: Magnetic field resulting from current flow in a coil.

In the electrical circuit in Figure 1, a DC voltage is provided by the battery which causes a current, I, to flow through the wires to the load. This current flow, which is the movement of electrons along atoms in the conductor, causes a magnetic field to be established around the wire. The magnitude of the field is measured in ampere-turns per meter in the International System (SI) or in oersteds in the gram-centimeter-second (cgs) system and is designated by the symbol **H**.

In permanent magnets the electrons-in-motion phenomenon still explains the magnetic field produced within a magnet.
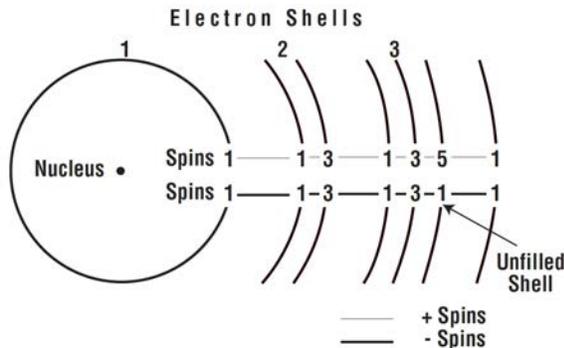

Figure 2: Electron shells in an atom of iron.

As shown in figure 2, within the third electron shell of the iron atom, there exists an imbalance in the spin direction of the electrons. This imbalance creates a magnetic moment in the iron atom. However, this atomic magnetic

moment alone is insufficient to cause ferromagnetism. Additionally, there must be cooperative interatomic exchange forces between electrons of neighboring atoms. The groups of atoms form domains or regions within the ferro-magnetic body that exhibit a net magnetic moment. The magnetization direction of the many domains need not be parallel. When a magnet is demagnetized it is only demagnetized in that there is no net external field. The individual domains are not "demagnetized" but domains are magnetized in random, opposite and mutually canceling directions. The magnet becomes "magnetized" when an external magnetizing field is applied to the magnet of sufficient magnitude to cause all the domains to align in the direction of the applied field.
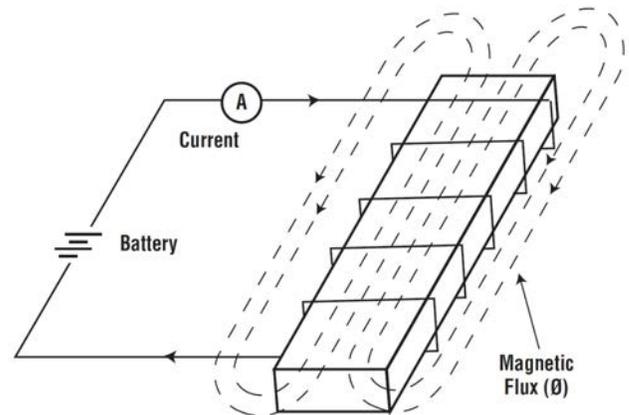

Figure 3: Magnetic induction – flux (Φ)

When a ferromagnetic material is placed in the coil of Figure 1, a magnetic field is induced in the material as shown in Figure 3. This induced field, or induction, increases the total observed field. This field is frequently called "flux" from the Greek verb meaning to flow. (The symbol for flux is Φ). However, there is no observed flow of matter as there are electrons flowing in an electric current.
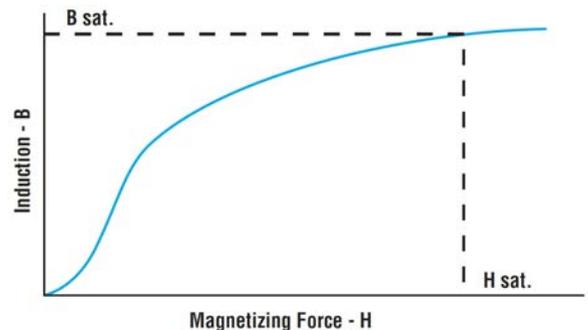

Figure 4: Normal magnetization curve.

The magnitude of the magnetic field per unit area is flux density. It is measured normal to the direction of

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magnetization and is designated by the symbol **B**. In the cgs system, the magnetic induction is measured in maxwells (or "lines" of magnetic flux) per square centimeter. One maxwell per square centimeter equals one gauss. In the SI system, magnetic induction is measured in tesla (weber per square meter, Wb/m^2). One tesla equals 10,000 gauss. The relationship between B and H for a ferro-magnetic material can be illustrated by its normal magnetization curve shown in Figure 4.
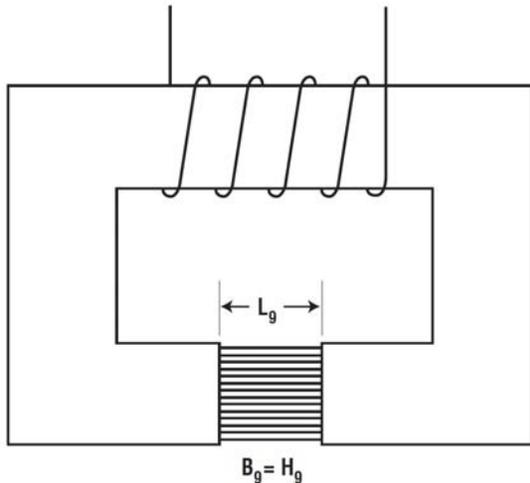

Figure 5: Iron core electromagnet.

When a magnet sample is placed between the poles of an electromagnet with minimal air gap between the poles of the electromagnet and the sample, a magnetization curve (hysteresis loop) of the sample can be generated.
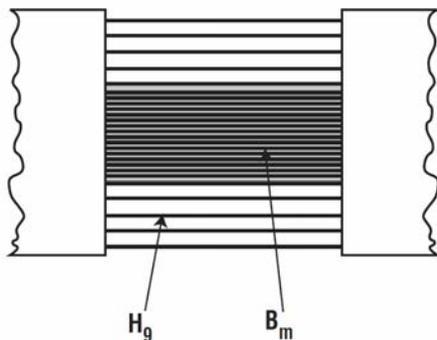

Figure 6: Electromagnet gap and test sample.

When an unmagnetized magnet is placed in the electromagnet and a magnetizing field, H, is applied, the induction, B, will increase proportional to H along a line beginning at 0 (zero) and extending through point, +Bs. At point, +Bs, the slope of the line equals 1 (cgs units), and the magnet is fully magnetized, fully "charges" or saturated. Additional magnetizing force, H, will increase induction only by the amount of the increased applied H.

From point, +Bs, if the magnetization force, H, is gradually reduced to zero, the magnetization in the material will decrease to a value Br, known as residual induction.
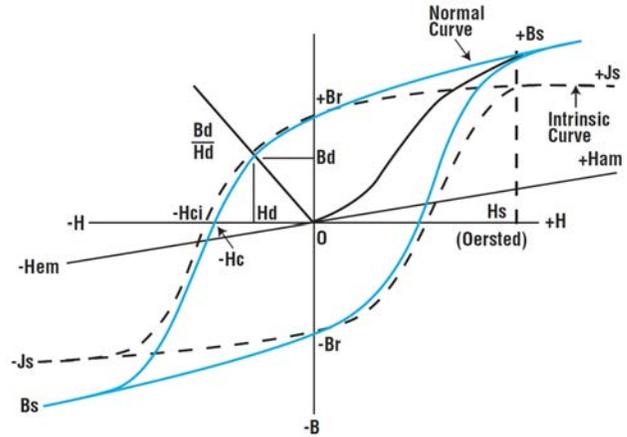

Figure 7: Hysteresis loop.

If the magnetizing force is then reversed (by reversing the current in the coil of the electromagnet) and increased in the negative direction, the resultant magnetization in the material is reduced to zero at H equal to –Hc (or simply Hc or H_{cB}). This value is called the coercive force and indicates a force, H, equal to the magnetic field contributed by the magnet. There is no net external field, but the magnet is not demagnetized at this point.

The value, Hci (or H_{cJ}) is the intrinsic coercivity. When H = Hci, approximately half of the magnetic domains have reversed resulting in no net external magnetic field – the magnet is demagnetized.

Increasing the demagnetizing force in the leftward (negative) direction will magnetize the material in the opposite polarity, saturation being represented by -Bs. Reducing H to zero produces -Br and by once again reversing the current through the coil of wire in the original direction (rightward, increasing H) the material is gradually re-magnetized, thus completing the hysteresis loop.

The "loop" follows the measured "B" in the material and is called the normal curve. It represents values of B versus H where B is the sum of the applied field (H) and the field contributed by the magnet – the induced field.

In the cgs system, one gauss is of the same magnitude as one oersted. With no magnetic material present, the application of H equals one oersted results in an induction of one gauss and the loop that is generated would be a straight line with a 45 degree slope.

Flux density produced by the magnet alone is called intrinsic induction, magnetization (M) or polarization (J) and can be calculated from the normal curve data as J = B - H. (Remember that H is negative in the second quadrant so its value is added to B).

In the first quadrant, normal induction is always greater than intrinsic induction. In the second quadrant (the demagnetization portion of the curve) the intrinsic induction is greater. This is because of the negative value of Hem in the second quadrant. It is also obvious that -Hci, the point on the -H axis where the J curve crosses, is always greater than -Hc due to J = B + Hem in the second quadrant.

In magnetic design, where one is concerned with determining the amount of flux a magnet is capable of producing, the normal demagnetization curve is used. The intrinsic curve is more useful when working with a permanent magnet's reaction to an external magnetic field.
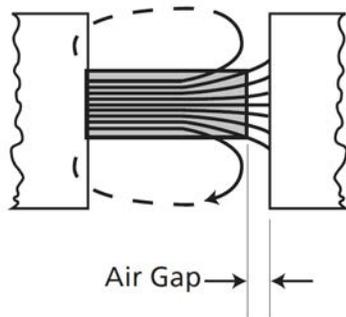

Figure 8: Air gap influence.

Let us look back at the magnetized magnet in the electromagnet. If after returning the applied electromagnetic field, Hem, to zero (the induction in the sample is at Br), instead of reversing the field we introduce an air gap between the magnet and the electromagnetic pole, the magnet will produce somewhat less external flux below Br to some Bd_1, Bd_2, Bd_3, etc. value as shown in Figure 9.
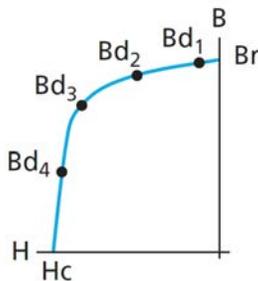

Figure 9: Bd (flux density) versus air gap size.

The flux density in the magnet will be reduced because the flux in the magnet is no longer passing straight through the magnet from end-to-end via a steel flux path but is "leaking" back around the magnet itself. Because this leakage of flux is in the opposite direction to the internal magnet flux, it has a demagnetizing influence on the magnet. As the air gap in the circuit increases, the leakage flux becomes greater. As a result, the net external magnet

flux is decreased. The values of Bd_1, Bd2, etc. are indicated along the normal curve and represent operating points on this curve. How far down the demagnetization curve these operating points lie depends upon the magnet length to air gap ratio – in free space (open circuit conditions), strictly upon the geometry of the magnet.
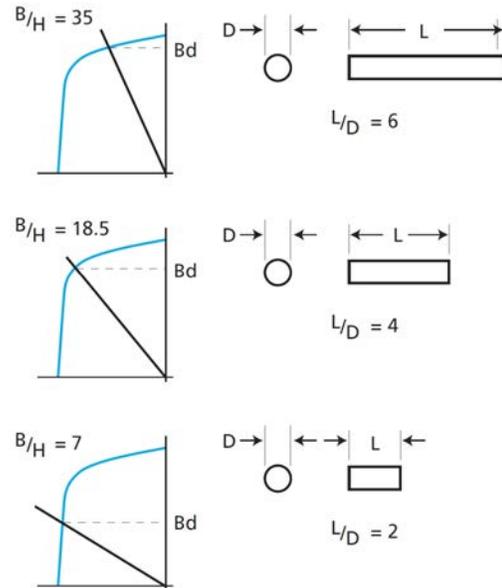

Figure 10: Open circuit conditions.

When the magnet is removed completely from the electromagnet, the flux density in the magnet will drop to its open circuit flux density. As shown by Figure 10, the open circuit flux density is dependent upon the geometry of the magnet which can be equated to an operating slope, B/H, or permeance coefficient. For a given magnet geometry the flux density, Bd, will fall along the B/H operating slope and its actual value will depend upon where the demagnetization curve crosses the B/H slope.
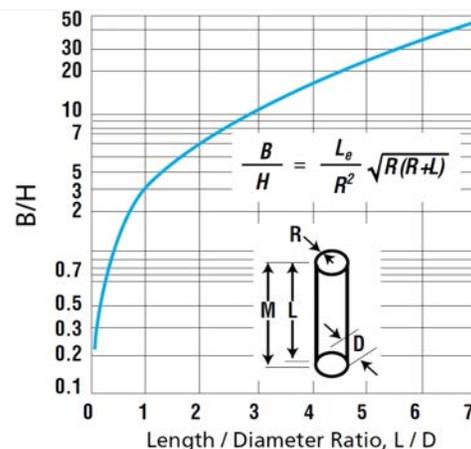

Figure 11: Permeance coefficient, Pc or B/H for axially magnetized cylinders of ferrite or rare earth magnets.
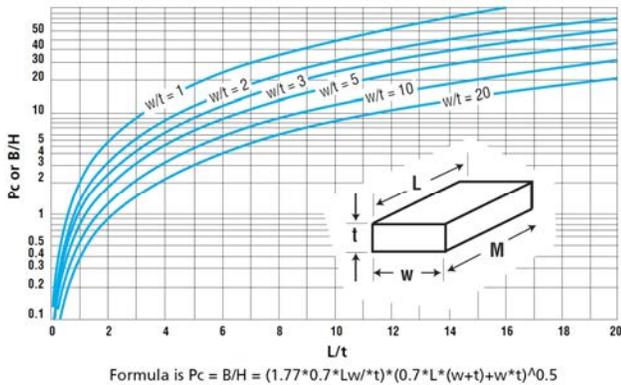
Formula is Pc = B/H = (1.77*0.7*Lw/*t)*(0.7*L*(w+t)+w*t)^0.5

Figure 12: Permeance coefficient, Pc or B/H for rectangles of Alnico magnets.

Formula is Pc = B/H = (1.77*Lw/*t)*(L*(w+t)+w*t)^0.5

Figure 13: Permeance coefficient, Pc or B/H for rectangles of Ferrite or Rare Earth magnets.
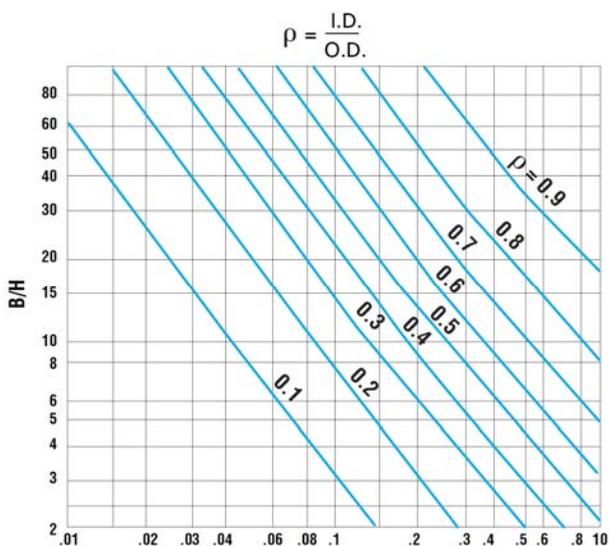

$$\rho = \frac{I.D.}{O.D.}$$

Figure 14: Permeance coefficients for tubular magnets with axial magnetization

Figures 11, 12, 13 and 14 equate the magnet dimensions to the permeance coefficient (Pc, B/H) for three magnet geometries.

All of the previously discussed conditions apply to magnets that operate under static conditions; that is, where there is no external demagnetizing field applied to the magnet and its B/H operating slope remains constant. If an external demagnetizing field is applied to a magnet the flux density in the magnet will decrease as shown in Figure 15.
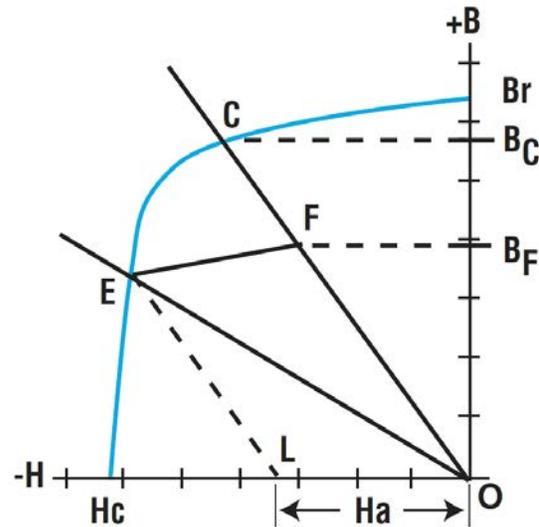

Figure 15: Externally applied field, Ha.

Line OC depicts the operating slope of a magnet in a circuit with some air gap, and Bc represents the flux density in the magnet. If an external field of magnitude, Ha, is applied to the magnet, the flux density of the magnet will decrease to point E. Note that the new operating slope line, LE, is parallel to OFC.

For magnet materials that exhibit a "knee" in the demagnetization curve, when the external demagnetizing field is removed the flux density does not return to point C, but instead will return along a line with the slope of recoil permeability represented by EF. Note that when the external field is removed, the magnet operating slope returns to the original value along line OFC to a new flux density, Bf. (The slope of line EF is referred to as the recoil permeability of the magnet.)

A similar flux loss will occur if the circuit air gap is increased and then decreased, or if the magnet is magnetized outside of the circuit, that is, in an open circuit condition, and then inserted into the circuit.

With materials that exhibit straight line demagnetization (ceramic, Samarium Cobalt or Neodymium Iron Boron), the flux loss associated with magnetizing and handling in the open circuit condition is greatly reduced.

These materials are also more resistant to demagnetization from the presence of reverse fields.

Conclusion

Understanding the fundamentals of magnet operating conditions helps to remove the mystery often associated with these materials.

References

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