Introduction to Magnetizing and Measuring Equipment

Some of the most frequently asked questions regarding magnetic materials are:

1. Where can I get equipment to magnetize my magnets?
2. How much magnetizing force does it take to fully magnetize them?
3. How can I tell if they are fully magnetized (saturated)?
4. Who makes equipment for measuring magnets and magnetic assemblies?

Equipment Suppliers
Until a few years ago, to get information on equipment we relied upon trade journals, Thomas Register and networking within the industry. Now we do internet searches, but still rely upon networking for recommendations as internet searches are cluttered with non-relevant links.

To be sure of getting the most suitable equipment, you should have the following information available when contacting a supplier.

- The type of material to be magnetized. If possible, provide a second quadrant hysteresis curve of the material.
- How the magnet is to be used: open circuit or with pole pieces.
- Required magnetizing pattern: axial or radial alignment; single pole or multiple poles; allowable neutral region between adjacent poles; will the useful flux be on the inside or the outside of a ring magnet; are the magnets to magnetized prior to or after assembly; etc.
- Drawings of the magnet and magnetic circuit will assist in communications with the equipment supplier.

The suppliers will work with you to determine what equipment and fixtures are required for your needs. Your application will indicate whether a stock unit is suitable or if a custom-manufactured fixture is needed.

Required Magnetizing Force
To reach the maximum energy output of the magnet and for maximum magnetic stability, magnets should be saturated, that is fully magnetized even though the magnet may be later thermally stabilized or calibrated using a "knockdown" (reverse) field.

The magnetizing force required to saturate a magnet depends on the intrinsic coercivity of the magnetic material and to a lesser extent, physical characteristics of the magnet and components to which it may be fastened during magnetizing. The general rule is that to saturate a magnet, one must apply a peak field of between 2 and 2.5 times the intrinsic coercivity. For example, a magnet with an H_{cJ} of 20,000 oersteds (1590 kA/m) will require at least 40,000 oersteds (3180 kA/m) to saturate.

Isotropic materials reach 98 percent of peak output with a higher field requirement of 2.5 to 3 times H_{cJ}. This is due to magnetizing domains that are not aligned with the applied field. The magnitude of the applied field in the orientation of the domain is equal to the peak field times the cosine of the angle between field alignment and domain alignment. For example 35,000 oersteds (2785 kA/m) will reach 97% of full magnetization for most isotropic bonded neo magnets, but a field of 65,000 oersteds (5170 kA/m) is required to reach 99% of saturation.

In the case of magnets attached to electrically conductive components, eddy currents are generated in the material and these currents set up a reverse magnetic field during the magnetizing pulse. This may prevent the magnetizing flux from fully penetrating the conductive material, perhaps even the magnet, during the short pulse duration and it reduces the field the magnet sees. Sometimes the direction of the flux in the magnet and surrounding material is affected. In these cases, it is necessary for the equipment manufacturer to adjust the LC (inductance capacitance ratio) of the magnetizing circuit to extend the magnetizing pulse width, increase the peak field (which also increases pulse width) or modify the magnetizing fixture to redirect the flux. Both a large peak pulse and extended pulse generate more heat which slows the production magnetizing rate. So an engineered compromise should be reached.

Approximate required peak magnetizing fields for various magnet types to reach at least 98% of maximum output are listed here. These fields are general and affected by the power source, fixture design, the LC circuit (capacitors plus magnetizing coil), etc.

Material	Magnetizing Field Strength	
	Oersted min. - max.	kA/m min. - max.
Alnico all grades, cast and sintered	3000 - 8000	240 - 635
Ferrite (Ceramic) sintered and bonded	6000 - 12000	475 - 955
SmCo 1:5 sintered	25000 - 35000	1990 - 2785
SmCo 2:17 sintered and bonded	40000 - 55000	3185 - 4375
SmCo 2:17 low HcJ bonded grade	35000 - 45000	2785 - 3580
SmFeN bonded	35000 - 55000	2785 - 4375

Determining if Magnets are Fully Magnetized

Three key figures of merit will be discussed:

- B_r (residual induction) representing magnetic strength – how strong the magnet is
- $(BH)_{max}$ (maximum energy product) representing the potential energy for interaction within a magnetic circuit such as in a motor
- H_{cJ} (intrinsic coercivity) which is a measure of a magnet's resistance to demagnetization

Let's start with a brief introduction to the hysteresis loop of magnetic materials. This "loop" is a graph of the relationship of an externally applied magnetic field on a magnetic material – a "magnet". The horizontal axis represents the magnitude of the applied field; the vertical axis represents the magnitude of the induced field (induction). It is called a "hysteresis" loop because the induction lags behind the applied field – as we'll see shortly.

The loop described above is called the "normal" loop. The measured induction is a sum of the applied field and the field contributed by the magnet. If the applied field is separately measured, it can be subtracted from the combined (normal) loop values to create a loop representing just the magnetic field contributed by the magnet. This loop is called the intrinsic loop.

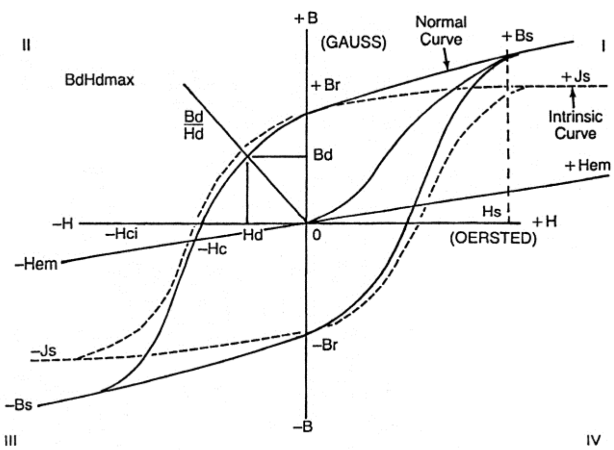

Figure 1. Normal and intrinsic hysteresis loop showing all four quadrants and indicating many key figures of merit. See text for explanation of terminology.

In soft magnetic materials, where there is a very small difference between normal and intrinsic properties, typically all that is presented is the normal loop. This tradition carried over to alnico permanent magnets even though some grades of alnico (especially grades 8 and 9) have substantially different loops. All of the permanent magnets starting with ferrite (ceramic) magnets in the 1950s and continuing with SmCo, NdFeB (neo magnets), and SmFeN are shown with both the normal and intrinsic loops in product catalogs and engineering data.

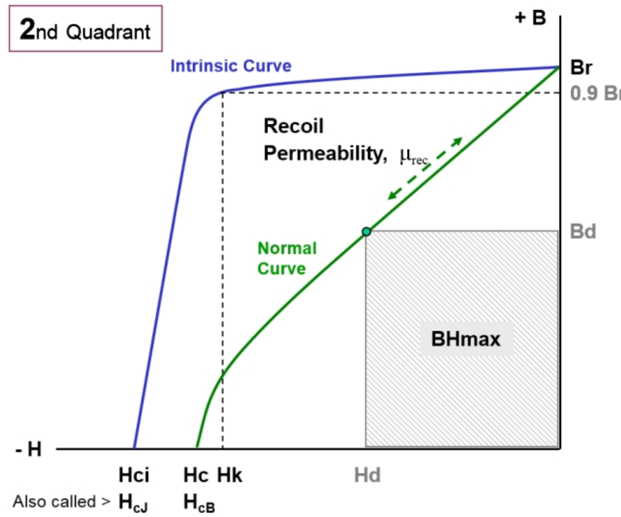

Figure 2. Second quadrant showing both normal and intrinsic hysteresis curves and key figures of merit. Abbreviations for the key values of coercivity have changed over several decades and alternate abbreviations are offered.

The value of **H** at H_{cB} is equal to the corresponding value of **B** on the intrinsic curve (the intersection of a vertical line drawn from H_{cB} up to the intrinsic curve). This means that the demagnetizing field is exactly as strong as the field from the magnet, cancelling each other so there is no net external field. However, the magnet is not "demagnetized".

The value of **H** at H_{cJ} is adequately strong that approximately half the magnetic domains have been reversed causing the magnet to become demagnetized. The interpretation of hysteresis is that it takes the negatively applied field to bring the magnet back to a neutral (demagnetized) state – the magnet lags the application of external field.

The values of **H** in the second quadrant are negative values, but are frequently shown without the "-" (negative) sign. And the values of coercivity are universally reported as positive values in catalogs and literature. When a value of H_{cJ} is shown in a catalog as 35,000 oersteds (2785 kA/m) what we really mean is -35,000 oersteds (-2785 kA/m). But it is the magnitude that is important and we tend to keep presentations as simple as possible.

Measuring Magnets

There are several methods for measuring (quantifying) the magnetic field associated with permanent magnets. Any device that is used to measure magnetic field strength is called a magnetometer. While a full explanation of each type is beyond the scope of a **TECH**Note, a brief description of each will be given along with references.

Measurement of the hysteresis loop is performed using one of four techniques (devices):

1. Hysteresigraph: measurements are made in closed circuit.
2. VSM: measurements are made in (near) open circuit requiring a correction for self-demagnetizing stress
3. SQUID Magnetometer: Measurements are made in a superconducting coil arrangement permitting application of very high magnetizing and demagnetizing fields.
4. Pulse Field Magnetometer: Magnets are measured in open circuit using pulse magnetizing and knock-down fields. Like the SQUID, very high fields can be applied permitting both magnetization in situ as well as providing demagnetizing curves for materials with coercivities above the saturation of pole pieces used in a hysteresigraph.

Figure 3. Typical hysteresigraph including a yoke structure, search coils for detecting the magnetic field, fluxmeters and power supply, computer control system and software.

The hysteresigraph sensing elements are ("search") coils, gauss probes and combinations thereof. Test output is one or more quadrants of the 4-quadrant hysteresis loop. For permanent magnets, the 2nd quadrant is most often presented.

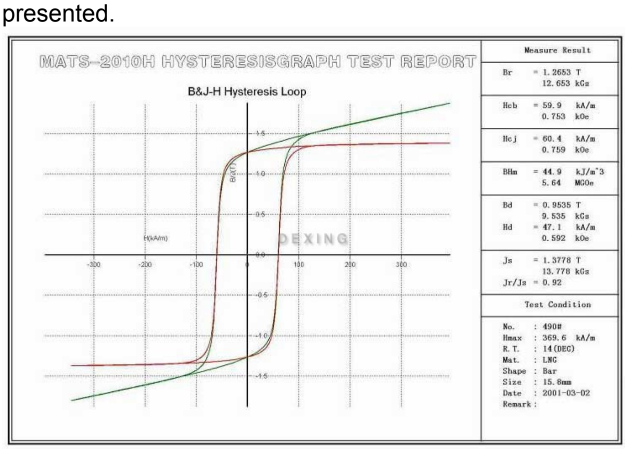

Figure 4. Hysteresigraph output showing all four quadrants. Permanent magnet properties of interest are usually second quadrant while soft magnetic materials are tested for 1st quadrant or for all quadrants.

One of the simplest magnetic measurements is made with a gaussmeter. This is a combination of a Hall probe and an electronic processor to turn the Hall probe signal into a meaningful output in units of gauss or tesla. (10,000 gauss equals 1 tesla). Field strength varies as a function of position relative to a magnet and is sensitive to direction of the magnetic field. That is, the Hall sensing element provides a signal output that is a function of the magnitude of the field strength and the cosine of the angle between the field direction and the direction perpendicular to the face of the Hall sensing chip.

While the measurement is easy, it is also prone to reading variation due to probe position including position error due to sensing chip location within the probe – chip is almost always recessed from the end or face of the probe. Test procedures need to be carefully followed. Correlated test methods between producer and user or between different locations within the same company must be rigorously adhered to.

Gaussmeter and Hall probe — Variety of Hall probes

Figure 5. Gaussmeter and selection of Hall element probes.

Gauss readings can be "mapped" around a magnet or magnetic assembly. This can be done manually by re-positioning the gauss probe or automatically using programmed motive devices to move the probe and magnet relative to each other. This is often called "field mapping".

Magnetic field strength can be measured very accurately with an NMR sensor – nuclear magnetic resonance sensor. However, the sensor and electronics are very expensive and this technique is most appropriate for extremely demanding, precise, and accurate measurements.

Very weak fields, e.g. less than a few gauss, require a device such as a fluxgate magnetometer.

> "A wide variety of sensors is currently available and used to measure magnetic fields. Fluxgate compasses and gradiometers measure the direction and magnitude of magnetic fields. Fluxgates are affordable, rugged and compact with miniaturization recently advancing to the point of complete sensor solutions in the form of IC chips, including examples from both academia and industry. This, plus their typically low power consumption makes them ideal for a variety of sensing applications."[4]

The Helmholtz test is another method that is easy to perform and less sensitive to operator error than a gauss measurement. The Helmholtz coils are a set of two identical circular magnetic coils (solenoids) that are placed symmetrically along a common axis, one on each side of the experimental area, and separated by a distance equal to the radius of the coils. The two coils are connected in series. This geometry creates a region of uniform field input (or output, if a current is fed through the coils).

Magnets are either extracted from a Helmholtz coil set or rotated within it to generate a voltage output. This voltage is accumulated ("integrated") and a total output reading is provided that is a function of the strength and size of the magnet. Several different values can be provided by the equipment including maxwell-turns, webers, volt•seconds, weber•cm, and more.

Figure 6. Arrangement of a Helmholtz coil set mounted horizontally and an integrating fluxmeter.

The Helmholtz coil set works by creating a region of uniform field between the two coils which makes them relatively insensitive to the position of the magnet.

Rotating the magnet in the coil set is equivalent to extracting it, rotating the magnet and re-inserting it between the coils – it doubles the integrated value providing additional resolution of the reading. For calculations, the output is divided by two.

Other methods for measuring magnetic fields include using a search coil plus fluxmeter. When the coil is moved within a magnetic field, it produces output. Alternatively, a magnet can be moved relative to the coil. When the search coil is close-fitting around a magnet, it may be slid from the neutral plane of the magnet and off of the magnet producing an output proportional to the magnetic strength of the magnet. Calculations made dividing the output by the cross-sectional area of the magnet provide a value of "B" at the operating point of the magnet.

Some useful references

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