MAGNETIC TESTING OF BONDED MAGNETS

S. R. TROUT
Spontaneous Materials
12348 Melrose Circle, Fishers, IN 46038, USA
E-mail: strout@ieee.org

Many techniques exist to characterize the magnetic properties of bonded magnets. We will review the common and not so common techniques in use, with emphasis on the advantages and disadvantages of each one, and some advice on the best method for many common situations.

Introduction

Everyone knows what a good magnet is; we just cannot agree on the measurement to prove it. Much of the problem stems from our point of view. To the researcher, a vibrating sample magnetometer (VSM) curve showing high H_{ci} and determining the Curie temperature may tell the story. To a powder producer, the same VSM is now used to confirm B_r, $(BH)_{max}$ and H_{ci}. To a magnet maker, the curve from a hysteresisgraph, after the magnet is saturated in a pulsed field, may be the test of choice. To a motor manufacturer, the voltage generated by spinning the magnets mounted on a rotor is the defining test. We are all correct and just as equally biased. Something akin to the Tower of Babel takes place when we gather to discuss magnetic measurements.

Common Techniques

Vibrating Sample Magnetometer

The vibrating sample magnetometer (VSM) was invented by Simon Foner [1]. The magnetic moment of the sample is detected by pickup coils near the vibrating sample in an adjustable applied magnetic field. The field may be produced by an electromagnet, superconducting magnet, or Bitter magnet. A system using an electromagnet is shown in figure 1.

Figure 1. A VSM (Photo courtesy of Lake Shore Cryotronics, Inc.)

The VSM is extremely sensitive, suitable for small or weakly magnetic samples, either solid or powder. It is the primary test method for powders. The temperature may be varied from absolute zero to well above the Curie temperature, with little difficulty. The moment is usually calibrated with a Ni standard, taking $4\pi M_s$=6115 Gauss at 10,000 Oe and 20 °C. [2]

Because this is an open circuit measurement, a correction for self-demagnetization is required. [3] Often cubes or spheres are used for solid samples, since they have well-defined self-demagnetization factors. The correction for powders is more problematic, with no ideal solution. Selecting an arbitrary correction factor and using it consistently may be the only practical solution.

With a superconducting or Bitter magnet, the VSM can measure the entire hysteresis loop, even for rare earth magnets with high H_{ci}. However, electromagnets are more commonly used, with a typical maximum field of less than 20 kOe. As a result, some samples will not be fully saturated, except externally by a pulse magnetizer, and H_{ci} may not be measured.

The test is usually a destructive measurement when performed on a magnet, because the sample must be cut from a larger piece. Results may not be representative of the whole magnet, just the actual sample.

Powder samples may be quite small, less than a gram. There may be sampling difficulties here, too. While powder measurements with the VSM are a good indicator, predicting the final properties of the magnet are not as accurate as they might appear, due in part to the difficulties in correcting powders for self-demagnetization.

Advantages

- Sensitive and accurate
- Easy to vary temperature
- Nearly full second quadrant curve
- Suitable for powder samples

Disadvantages

- Sample weight and density must be known
- Self-demagnetization correction required
- Limited field; often can't saturate or measure H_{ci}
- Usually destructive

Hysteresisgraph

In a hysteresisgraph, a sample of uniform cross-section is clamped between the faces of an electromagnet. (See figure 2.) Magnetic induction, B, is measured, either by a coil surrounding the sample, or by a small coil embedded in the pole piece. (See figure 3.) The latter is the more versatile approach.

Figure 2. A hysteresisgraph (Photo courtesy of Walker Scientific, Inc.)

Figure 3. A pole cap, showing embedded pole coils (Photo courtesy of Magnet Physik Dr. Steingroever GmbH)

The hysteresisgraph is suitable for samples with a constant cross-section and thickness, i.e. flat pieces, and is almost always destructive, since the sample is cut from the magnet. The sample may not be representative of the whole magnet. The test is not suitable for powders.

The magnetization is calculated by B – H and calibrated with a Ni standard, like the VSM.

Measurements from of -40 to 200 °C are practical, but require a special fixture.

Generally the fixture allows only one specific size sample to be tested, e.g. a one cm cube.

The hysteresisgraph is a closed circuit measurement, the only one commonly used for permanent magnets. No demagnetization correction is required.

The hysteresisgraph offers a bit more magnetic field, compared to a VSM with an electromagnet, because the gap in the hysteresisgraph is essentially zero. However, the field is not enough to saturate most rare earth magnets, which are usually saturated first with a pulse magnetizer. Often the field is sufficient to obtain H_{ci}.

Advantages

- Almost any thin sample can be measured
- No self-demagnetizing correction required
- Higher maximum field than VSM available
- Nearly full second quadrant curve measured

Disadvantages

- Destructive test
- Slow, due mainly to sample preparation

Helmholtz Coil

Helmholtz coils are a pair of thin, parallel, and identical coils, separated by a distance equal to their radius. (See figure 4.) Ordinarily the coils are used to generate a small but uniform magnetic field near the center of the coils, but in this case they are used as pickup coils.

The measurement is made by saturating the magnet with a pulsed field magnetizer, inserting the sample in the coil with the magnetic axis parallel to the coil axis, zeroing the fluxmeter and extracting the magnet out of the coil. When the volume of the sample is known, the magnetization can be calculated by the following equation

Figure 4. Helmholtz Coils (Photo courtesy of Magnetic Instrumentation, Inc.)

$$4\pi M_0 = \frac{C}{V}\int E dt$$

where the integral is the fluxmeter reading, V is the volume of the sample and C is a coil constant, determined either empirically or by the number of turns and the coil diameter. [4] As shown in figure 5, the magnetization measured is not B_r, but a point on the intrinsic curve to the left of B_r, $4\pi M_o$, (open circuit) which depends on the self-demagnetization factor or loadline of the magnet.

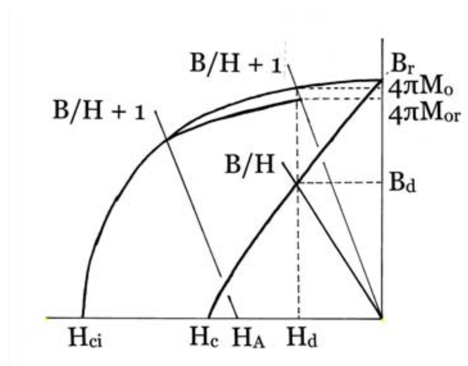

Figure 5. Magnetization measured by Helmholtz coils

Since the test only measures a single point on the curve, there is a risk of not recognizing a magnet with low H_{ci}. Therefore, an adverse field, such as H_A in figure 5, is sometimes applied to the sample via a pulsed magnetizer and the measurement is repeated. The second measurement gives an indication of the magnet's resistance to demagnetization and recoil characteristics, $4\pi M_{or}$ in figure 5.

It is also possible to do this measurement in 3-dimensions, with three orthogonal Helmholtz coils. This would allow one to see orientation or magnetization irregularities.

Advantages

- Fast and easy, production friendly
- One coil can measure many sizes
- Reasonably accurate
- Often non-destructive
- Inexpensive equipment

Disadvantages

- Single point measurement
- Not suitable for multi-pole magnets
- Volume measurement required
- Self-demagnetization correction required

Search Coil

In a search coil measurement, a coil, as shown in figure 6, is placed around a magnet in conjunction with a fluxmeter. The coil should be tight fitting. Extracting the coil from the magnet gives the magnetic induction B, by the equation

$$B = \frac{\Phi}{A}$$

where A is the area of the magnet. Again, this is an open circuit measurement, so the B measured is the induction at the magnet's operating point, B_d in figure 5.

Typically there is a special coil for each magnet size, to keep the area of the coil and the area of the magnet nearly the same.

Figure 6. A search coil (Photo courtesy of Magnet Physik Dr. Steingroever GmbH)

Advantages

- Simple and fast

Disadvantages

- Each magnet size requires its own coil
- Single point measurement

Hall Probe

The Hall probe is one of the most popular ways to test magnets, used along with a Gaussmeter. The sensing element is an InAs chip that generates a voltage proportional to the applied magnetic field. The probe measures the field at a point in space. The sensing axis may be either parallel to the probe axis, called an axial probe, or perpendicular to the probe axis, called a transverse probe. Both types are shown in figure 7.

Figure 7. Axial and transverse Hall probes (Photo courtesy of Hirst Magnetic Instruments, Ltd.)

Typically, the probe is put directly on the face of the magnet or held at some fixed distance. The field measured is related to B_r for magnets with relatively linear B vs. H behavior. However, the main drawback is that the field around a magnet in free space varies rapidly as one moves away from the face of the magnet, as shown in the equation below

$$H(x) = \frac{B_r}{2}\left[\frac{L + x}{\sqrt{R^2 + (L + x)^2}} - \frac{x}{\sqrt{R^2 + x^2}}\right]$$

which describes a disc magnet with radius R, length L and distance away from the magnet face x.

While the measured field clearly relates back to a magnet property, B_r, magnet dimensions and position are critical. Probe construction also needs to be considered in determining distance x. The fragile Hall element is typically buried inside an aluminum tube for protection; often the precise position is not well controlled. Probe placement is a very serious issue with Hall probes.

Advantages

- Fast and easy

Disadvantages

- Easy to misinterpret
- Single point measurement

Fixture Test

The philosophy behind the fixture test is to measure the magnet in approximately the same way that it will be used. In many ways, it gives the best indication if a magnet assembly will behave as expected. Often magnets are glued on a rotor and rotated in the fixture and a generated voltage is measured. (See figure 11.) Besides the magnets, the rotor and geometry can also affect the generated voltage. Relating the generated voltage back to the intrinsic properties of individual magnets is difficult. Any kind of comparison is extremely difficult. Often two identical fixtures are made; one for the magnet supplier, one for the customer. This is the only sure way to obtain comparable results.

Figure 8. A magnetic test fixture (Photo courtesy of Tengam Engineering, Inc.)

Advantages

- Measurement closest to actual usage

Disadvantages

- Difficult to relate back to magnet properties
- Other components affect results, e.g. return path, air gap
- Comparisons impossible without identical fixtures

Less Common Techniques

Pulsed Field Magnetometer

In a pulsed field magnetometer (PFM), a capacitive discharge magnetizer is used to generate a large magnetic field in a solenoid. Fields up to 100 kOe are available for a brief duration. The sample induction is detected by a coil around the sample and the signal is processed by a computer to generate the hysteresis loop. Again, a nickel standard is used for calibration. A typical configuration is shown in figure 9.

This method can measure the entire hysteresis loop very quickly. Measurements can be made from -40 to 200 °C, without too much difficulty. Since this is a dynamic measurement, eddy currents must be considered and an appropriate correction applied. Usually a second copper standard is used for this purpose. A correction for self-demagnetization is also necessary.

Figure 9. A pulsed Field Magnetometer (Photo courtesy of Hirst Magnetic Instruments, Ltd.)

In spite of its speed, this method has been slow to gain acceptance; the main objection is the eddy current correction. However, the PFM has the potential to equal or surpass the VSM and the hysteresisgraph as a method to measure hysteresis loops, especially as high speed data acquisition techniques improve. [5]

Advantages

- Extremely fast
- High magnetic fields, full hysteresis loop
- Suitable for powder samples

Disadvantages

- Eddy current correction required
- Self-demagnetization correction required

Potential coil

The potential coil is a simple way to examine a magnet, in or out of a magnetic circuit. (See figure 10.) The measurement is based on the fact that the sum of the products of field and length around a magnetic circuit is zero, that is

$$\oint H \bullet dl = 0$$

The coil is a long, small diameter solenoid with a length much greater than its diameter. The signal is fed into a fluxmeter. Magnetic flux couples at just one end of the coil. If the coil is moved from one pole of the magnet to the other, as in figure 11, the internal magnetic field H_m is usually measured by

$$P_m = H_m \bullet ds$$

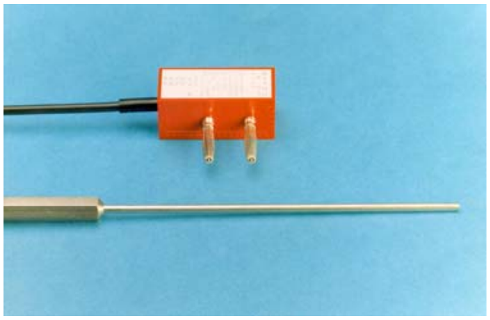

Figure 10. Potential coil (Photo courtesy of Magnet Physik Dr. Steingroever GmbH)

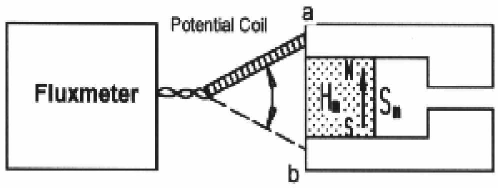

Figure 11. Using the potential coil to measure the internal field of a magnet. When the potential coil is moved from point a to point b, the internal field of the magnet is the potential divided by the magnet length. (Photo courtesy of Magnet Physik Dr. Steingroever GmbH)

In spite of their simplicity, potential coils are not very popular. It may be that the physics is difficult to grasp, making the interpretation difficult.

Advantages

- Simple and fast

Disadvantages

- Single point measurement
- Difficult interpretation

Polanzeiger

Polanzeiger is a German word that has crept into the language of magneticians everywhere, meaning polarity indicator. [6]

In the original polanzeiger, shown in figure 12, a diametrically oriented ferrite magnet is free to rotate to indicate the polarity, north or south, of the face of the magnet being tested. In the newer electronic version, seen in figure 13, a Hall element does the sensing and an LED indicates the polarity. Although neither provides any quantitative data, they are useful tools.

Figure 12. A mechanical polanzeiger (Photo courtesy of Thyssen Magnet und Komponententechnik)

Figure 13. An electronic polanzeiger (Photo courtesy of Thyssen Magnet und Komponententechnik)

Magnet Viewer

Also known as "green paper", magnet viewers are another qualitative way to examine permanent magnets. The viewer is a film containing a colloidal suspension of nickel particles in a gelatinous media. The particles are free to rotate, and do when exposed to a magnetic field. A light region is observed at the transition between poles, leaving a dark region everywhere else, as shown in figure 14. [7]

The viewers are ideal for multiple pole magnets, a common application of bonded magnets. It is the best technique for counting poles and for observing the transition between adjacent poles, and is a popular way to gage how well a magnetizing fixture is working. It is also possible to identify if there is a problem with misdirected flux, a particular concern for isotropic magnets as this can lead to unexpected poor performance. [8]

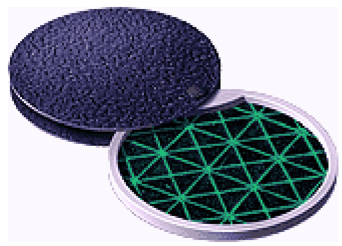

Figure 14. A magnet viewer, the light regions showing the transitions between poles (Photo courtesy Magne-Rite, Inc.)

Discussion

Magnetic measurements are a compromise at best. They may be slow, destructive, inaccurate, misleading and difficult. But we must do them; we make very important decisions based on the information they yield. So, as we develop new projects, it is important to consider what we really need to know about our magnets and to carefully select the best available methods to make the measurements.

While it is difficult to anticipate all situations, Table I is offered as a guide for testing. The techniques are listed in decreasing order of helpfulness for the three common types of samples.

Table I. Preferred test methods, in decreasing preference, for various sample types

Powders	Magnets	Assemblies
VSM	Hysteresisgraph	Fixture Test
PFM	VSM	Hall Probe
	Helmholtz Coil	Potential Coil
	PFM	
	Potential Coil	
	Hall Probe	

Acknowledgement

Thanks to the many suppliers of magnetic measuring equipment who contributed the photographs and very helpful information used in writing this paper.

References

1. Simon Foner, "Versatile and Sensitive Vibrating Sample Magnetometer," Review of Scientific Instruments, 30 (1959) pp. 548-557
2. Magnetic Instrumentation Technote 97-01, www.kjsmagnetics.com/tech.htm
3. B. D. Cullity, Introduction to Magnetic Materials, Addison-Wesley, (1972), pp. 49-61
4. S. R. Trout, "Use of Helmholtz Coils for Magnetic Measurements," IEEE Transactions on Magnetics 24 (1988) 2108, www.spontaneousmaterials.com/Papers/Helmholtz88.pdf
5. John Dudding, Hirst Magnetic Instruments, Ltd., private communication
6. Thyssen Magnet und Komponotenttechnik, Beratgestrasse 36, 44149 Dortmund, Germany, Tel. +49-231-44-22-700, Fax +49-231-44-22-7015, www.tmk-magnetworld.de
7. Magne-Rite, Inc., 17625 East Euclid Street, Spokane, WA 99216, USA, Tel. 1-509-921-6966, Fax 1-509-922-2586, www.magnerite.com
8. S. R. Trout and Yuriy Zhilichev, "Effective Use of Neodymium Iron Boron Magnets, Case Studies," Electric Manufacturing and Coil Winding Conference (1999), www.spontaneousmaterials.com/Papers/CoilWinding1999.pdf

Biography

S. R. Trout spent the last twenty-seven years in the permanent magnet and rare earth industries, successfully solving problems in a wide variety of technical and commercial roles, collaborating with many international luminaries in the process. Early in 2001, he launched a consultancy, Spontaneous Materials (www.spontaneousmaterials.com), devoted to finding practical solutions for client problems with magnetic materials and the rare earths, in a technical, commercial and educational capacity. Dr. Trout is a registered professional engineer, received his B.S. in Physics from Lafayette College and his M.S. and Ph.D. in Metallurgy and Materials Science from the University of Pennsylvania. He is a senior member of the IEEE Magnetics Society.