Open Circuit Tests and Their Application

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Abstract

Three types of open circuit measurements are defined and some practical considerations for their use are discussed. The correlation of open circuit test results to the demagnetization curve are also explored.

Introduction

Open circuit testing of a permanent magnet can be defined as a magnetic measurement on just the magnet itself, after saturation, with no return path or externally applied field.

The goal of such a test is to obtain information about the intrinsic properties of the magnet or to estimate the performance of the magnet in its final application.

Hall Effect

A description of the Hall Effect is shown in Figure 1. In the presence of a magnetic field H, and a constant current i, a voltage is generated across the element. The voltage is given by

$$1) \quad e_H = \frac{R_H i}{t} H$$

where t is the thickness of the slab and R_H is a constant of the material. The typical material for the Hall element is InSb, which has an $R_H \approx 10^{-5}$ volt-cm/amp-Oe. Note that in this explanation, H can be replaced by the flux density B, as long as the measurement is made in empty space, where M = 0.

A Hall probe therefore is able to measure the field at a point. The Gaussmeter serves as a source of constant current, voltmeter and usually scales the reading so the voltage can be read directly in units of field or flux density. There are two types of Hall probes. One is axial where the axis of the probe and the axis of field sensitivity are the same. The other is transverse, where the axis of the probe and the axis of field sensitivity are perpendicular.

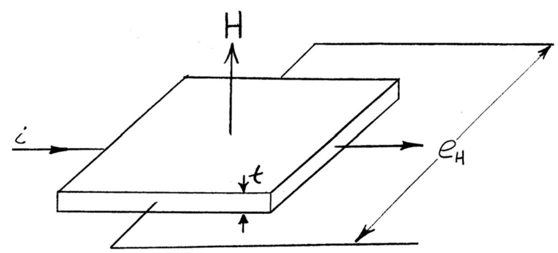

Figure 1. The arrangement of magnetic field, current and voltage in a Hall element. (1)

A typical measurement made by a Hall probe is to measure the flux density at the surface of the magnet. A simple case is that of a disc, for magnets where $B_r \approx H_c$, the maximum flux density is given by

$$2) \quad B = \frac{B_r(\ell / d)}{2\sqrt{(\ell / d)^2 + 1/4}}$$

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where ℓ is the length of the magnet in the magnetic direction and d is its diameter. The actual flux density measured will be slightly lower, since the Hall element is not right at the probe surface.

Hall probes are calibrated by comparison to known fields, usually generated by reference magnets, traceable to the National Bureau of Standards. A calibrated probe itself may have an accuracy of less than 1%, while the accuracy of the measurement may be 2-3%, depending on geometry.

Hall probes are fragile devices because of their small size and electrical connections to the element. It is important that probes be handled carefully and be protected as much as possible.

Hall probes are temperature sensitive. The Hall constant in equation 1 is a function of temperature. For very accurate measurements, control of the temperature or compensation for the variation of R_H with temperature is necessary.
Hall probes are best suited for inspection type testing when it is only necessary to know if the magnets exceed a specified minimum value. However, there are some cases where high accuracy is required and the Hall probe may be the only way to make the measurement. Then a carefully designed experiment is essential.

Search Coil or Extraction Method

A search coil can be used to measure the flux or flux density generated by a magnet in a plane.

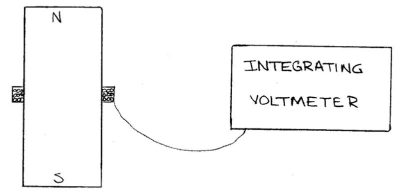

Figure 2. A search coil surrounding a magnet with the signal fed to an integrating voltmeter.

A coil of wire is placed around the neutral axis of the sample, and an integrating voltmeter is connected to the coil and reset to zero. The coil is removed from the magnet and integrated voltage is read. Such a measurement is described by Faraday's Law

$$3)\quad \int V dt = 10^{-8} N\phi$$

where N is the number of turns. For the magnet shown in Figure 2, the flux can be written as,

$$4)\quad \phi = BA = (-H_d + 4\pi M)A$$

where A is the area of the coil and H_d is the demagnetizing field, inside the magnet. The demagnetizing field is proportional to the magnetization, so that

$$5)\quad H_d = N_d M$$

where N_d is the demagnetizing factor, which depends only on the geometry of the sample. Lists of demagnetizing factors are given in the standard reference texts on permanent magnet materials. Equations 3, 4 and 5 can be solved for either the magnetization of the sample or the flux density of the sample,

$$6)\quad 4\pi M = B - H = \frac{10^8}{(1 - N_d/4\pi)NA}\int V dt$$

and

$$7)\quad B = \frac{10^8}{NA}\int V dt$$

The values calculated in equations 6 and 7 are shown as they relate to the demagnetization curve in Figure 3.

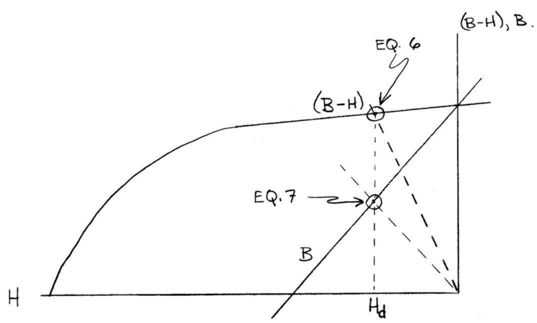

Figure 3. The values of B and (B-H) measured by a search coil.

Throughout the calculation, it has been assumed that the area of the coil and the area of the sample are nearly equal, otherwise an error is induced in the measurement. The resultant measurement will be lower than the true value.

There are some practical factors to be considered when applying this method. First, the length of the coil should be less than one-third the magnet length. This constraint may cause problems with ferrite and rare earth-cobalt magnets. Second, there should be enough turns on the coil to assure good sensitivity. This depends on the magnet, its geometry and the integrating fluxmeter. Third, coil construction is tedious. Usually, many turns (10 to 100) of fine wire (#30 to #50) are wound on a close fitting coil form.

Calibration of the NA of the coil can be determined by calculation or by a reference field. The reference field calibration is more accurate since it compensates for overlapping coils and other winding irregularities.

It is possible to use the search coil for 1% accuracy measurements. It is useful for inspection, although a coil is needed for every magnet cross-section measured. However, this technique is also good over a wide temperature range.

Helmholtz Coil

The term Helmholtz coil is used to describe a pair of pick-up coils that are wound to satisfy the Helmholtz condition. That is, the radius of each coil is equal to their separation.

The signal generated by moving a magnet from position 1 to position 2 in Figure 4 is fed to an integrating voltmeter. The signal is related to the magnetization by,

$$8)\quad 4\pi M = \frac{C}{V_{sample}}\int V dt \text{ (reference 2)}$$

where V_{sample} is the volume of the sample and C is the coil constant. The coil constant is dependent on the coupling of the magnet to the coil in position 1 and position 2, and is determined empirically.

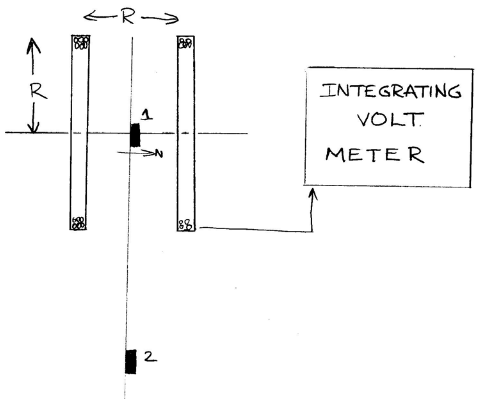

Figure 4. Helmholtz Coil with Integrating Voltmeter. (2)

Calibration of the coil is made by using a reference magnet. This can be any magnet where the demagnetization curve has been measured accurately by another method, e.g. permeagraph or vibrating sample magnetometer, and where the (B-H)/H load line is known. One good material for this reference magnet is $(SmGd)Co_5$ since the measured moment would not depend strongly on temperature. It is also possible to calibrate the coils by using a nickel standard with an external field to saturate the nickel. However, this technique is not simple because of the field required to saturate nickel and the volume over which the field must be applied.

The Helmholtz coil is a very good technique for rapid measurements or relative measurements between magnets of the same size. The technique is valid for irregularly shaped magnets or other geometries which cannot be handled by the two preceding methods. Usually only one Helmholtz coil is necessary for all measurements in a laboratory or factory.

In practice, there are two constraints on a Helmholtz coil. First, all magnet dimensions should be less than 1/5 of the coil diameter. Second, the coils are sensitive to noise. They should be placed away from charged magnets and sources of electrical noise.

Conclusion

Three methods for open circuit measurements, as well as their uses and constraints have been outlined. Of all magnetic testing methods, open circuit testing is the easiest to perform and the easiest to misinterpret. It is always essential to be aware of how the measured quantities relate to the demagnetizing curve and to the information desired. This is particularly true when different materials with varying H_{ci} values are tested.

References

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2. D. L. Martin and M. G. Benz, IEEE Transactions on Magnetics 8 (1972) 35.

Biography

S. R. Trout (strout@ieee.org) spent his professional life in the permanent magnet and rare earth industries. Early in 2001, he launched a consultancy called Spontaneous Materials devoted to finding practical solutions to 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.