

MAGNETIZATION AND MEASUREMENT OF HIGH ENERGY PERMANENT MAGNET MATERIALS

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Abstract

Modern magnetic materials, such as samarium-cobalt and neodymium-iron-boron, are magnetically much stronger than older magnet materials. This allows significantly smaller and lighter magnets to be used in applications such as actuators and motors. The properties of these materials are such that they cause problems for magnetization and measurement. Full magnetization of these materials requires high magnetic fields and measurement in a closed magnetic circuit using an electromagnet is difficult. This paper reports work in progress at NPL to investigate the magnetizing fields and measurement techniques necessary for appraisal of the properties of these increasingly common materials.

Introduction

Permanent magnets are materials which once magnetized remain magnetized under most conditions. They are widely used in many products such as vehicles, audio systems and computers where they perform a variety of functions. Modern high energy magnetic materials, such as samarium-cobalt and neodymium-iron-boron, are magnetically much stronger than older magnet materials such as AlNiCo, which allows components to be made smaller, lighter, more efficient and more powerful.

Full magnetization of these materials requires very high applied magnetic field strengths. To achieve this magnetic field strength expensive superconducting magnets must be used. It may be possible to magnetize the magnets to within a few percent of the maximum value using conventional and much cheaper, methods such as pulse magnetizers.

These materials pose particular measurement problems because of their high intrinsic coercivity (H_{ci} in Figure 2) and the "squareness" of the hysteresis curve. The high intrinsic coercivity can mean that the poles of an electromagnet are saturated by the magnetic field strength required to measure the demagnetization curve. There are grades of these materials for which the magnetic field strength required to measure intrinsic coercivity is impossible to achieve in a conventional electromagnet closed circuit.

Measurement of permanent magnet materials

The measurement of magnet properties of materials are dealt with in the BS6404 series of British standards. BS6404:Part 5:1995 [1] deals with the measurement of magnetically hard materials in a closed magnetic circuit using an electromagnet. The electromagnet method used at NPL conforms to this standard.

Many characteristics of a permanent magnet can be obtained from a graph of the relationship between the magnetic flux density, B , and the magnetic field strength, H , as shown in Figure 1. This curve, known as the B - H curve, or hysteresis loop, describes the cycling of a magnet in a closed magnetic circuit between the poles of an electromagnet. A Hall effect meter is used to measure the magnetic field strength, H , and the flux density, B , is measured using a search coil and voltage integrator.

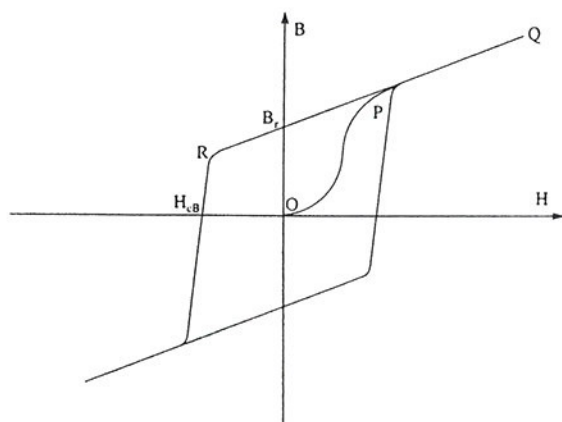


Figure 1 - Schematic B Hysteresis Curve

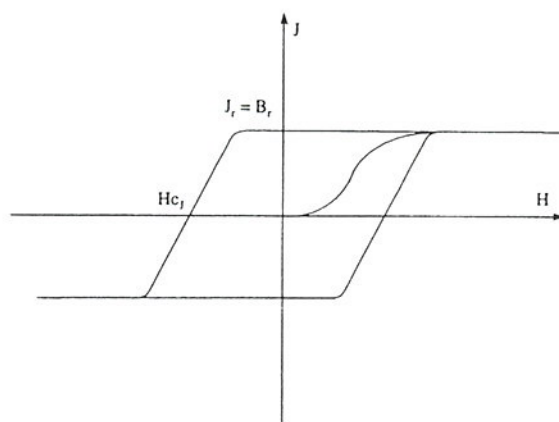


Figure 2 - Schematic J Hysteresis Curve

Figures 1 and 2 show typical hysteresis curves for an anisotropy controlled magnet. As the demagnetized sample is subjected to a steadily increasing magnetic field strength, the flux density in the magnet increases and the curve follows the line OPQ, as shown in Figure 1, until the magnet reaches saturation. As the applied field is reduced the flux density in the magnet decreases more slowly. This is an example of magnetic hysteresis and when the applied field strength is reduced to zero the flux density falls to a value B_r , known as the remanent magnetic flux density, which is the remanent magnetization of the magnet. The magnetic field is reversed and increased, causing the magnetic flux density to fall to zero at a negative value of magnetic field strength, H_{cB} , the coercive magnetic field strength. The applied field continues to be increased until the magnet is saturated in the opposite direction. It is then reduced to zero, reversed and increased to complete the curve. Point R on the curve is the point where the product of B and H is a maximum, this gives the maximum energy density, $(BH)_{max}$, which is a measure of the strength of the magnet.

An alternative approach is to measure the magnetic polarization, J, using a search coil where two sets of windings are arranged to cancel out the flux due to the applied magnetic field, leaving only that intrinsic to the permanent magnet. This is shown in Figure 2 and allows the intrinsic coercivity H_{cJ} , to be measured which is a more useful measure of the properties of the material. The intrinsic coercivity and saturation magnetization of the magnet can be obtained from the graph of magnetic polarization, J, against magnetic field strength, H, or by calculation from a graph of B against H as:-

$$B = \mu_0 H + J \quad (1)$$

The second quadrant of either curve is known as the demagnetizing curve and the important properties of a magnet can be found in this region. It is the region of the graph in which permanent magnets are generally used, and the point on this curve where the magnet operates, the working point, depends on the geometry of the magnetic circuit. If the magnet has been previously magnetized outside of the electromagnet, it is usual only to measure the demagnetization curve.

The electromagnet method can only be used to characterise a limited range of the properties of high energy permanent magnet materials. For many of these materials the intrinsic coercivity is much greater than the magnetic field strength that can be achieved in an electromagnet and so other techniques need to be explored to establish the value of H_{cJ} . For accurate measurement of magnetic materials using the electromagnet technique, the magnetic field must be uniform across the gap in the electromagnet. With high intrinsic coercivity materials the electromagnet poles will become magnetically saturated, causing the field strength in the magnet to be less than that measured by the magnetic field sensor [2]. Further, as the poles approach saturation their incremental magnetic permeability also decreases, and they

become unable to carry all of the flux from the magnet. The electromagnet ceases to be an effective closed magnetic circuit and additional errors are introduced.

These materials have a high rate of change of J with H when passing through the intrinsic coercivity. To ensure an accurate measurement the applied field needs to be increased sufficiently slowly that the instrumentation can follow the rapid change in J .

Most permanent magnet materials are anisotropic, and have a preferred axis of magnetization. If this axis is not aligned with the axis of the magnet, errors are introduced into the measurement of J , B and H . This both reduces the repeatability of the measurement and restricts the accuracy with which the material properties can be characterised.

The use of Helmholtz coils as a search coil allows measurements to be made which can provide valuable information about a magnetic material. The change in flux detected when a magnet is rotated within a Helmholtz coil system is a direct measurement of the magnetic moment of the magnet. Knowledge of the magnetic moment allows the J working point to be calculated using the magnet volume and from the J working point the demagnetizing factor can then be calculated using the J demagnetizing curve.

Measurement of high intrinsic coercivity magnets may be possible using the high magnetic fields available from superconducting magnets. New techniques are being developed to produce accurate and traceable measurements under these conditions and initial results will be reported at the conference.

Magnetization of permanent magnet materials

Modern permanent magnet materials are hard to saturate and frequently need to be magnetized using powerful pulse magnetizers or superconducting magnets. A magnetizing field strength of between 3 and 5 times the coercivity is required to magnetize the older types of magnetic materials such as AlNiCo and SmCo_5 [3]. When magnetizing in a pulse magnetizer or superconducting magnet, extra magnetizing field strength must be provided to overcome the self-demagnetizing field of the magnet. The self demagnetizing effect on magnets with a length to diameter ratio of 1 is such that the applied magnetic field strength will need to be approximately 0.4 MA m^{-1} greater than that required for a closed circuit magnetization [4]. The maximum intrinsic coercivity in a commercially-available NdFeB magnet is 3.3 MA m^{-1} , which would lead to a magnetizing field of greater than 16 MA m^{-1} .

The properties of magnet materials have been measured after being magnetized using different magnetizing field strengths and techniques. Figure 3 shows the intrinsic open circuit working point of specimens of different permanent magnet materials after magnetization in a pulse magnetizer at a series of magnetizer settings. The specimens had a length to diameter ratio of 1 and were each pulsed 3 times at each setting and then measured using a Helmholtz coil system.

It can be seen from Figure 3 that different types of high energy magnetic material have different magnetizing characteristics which depend on the mechanism which produces the permanent magnet behaviour. Magnetic materials such as SmCo_5 or the sintered NdFeB magnet shown in Figure 3, have behaviour based on a nucleation mechanism. The grain size of the powder from which the magnet is made is larger than the single magnetic domain size and the domain walls can move freely within the grain allowing magnetization with modest applied fields. The intrinsic coercivity is determined by the grain's resistance to the formation of a reverse domain. This is controlled by the structure at the grain boundaries which provide a strong pinning of the domains and these materials can therefore exhibit intrinsic coercivity larger than the applied field required to magnetize them. Magnets which have a pinning mechanism, such as $\text{Sm}_2\text{Co}_{17}$, have a fine cell structure within the grain, which pins the domain walls. They exhibit a high coercivity but require a much higher applied field to magnetize. The highest energy product NdFeB magnets are based on a large magnetocrystalline anisotropy due to the rare earth. The grain size is around the size of a single magnetic domain and a high applied field is required to align

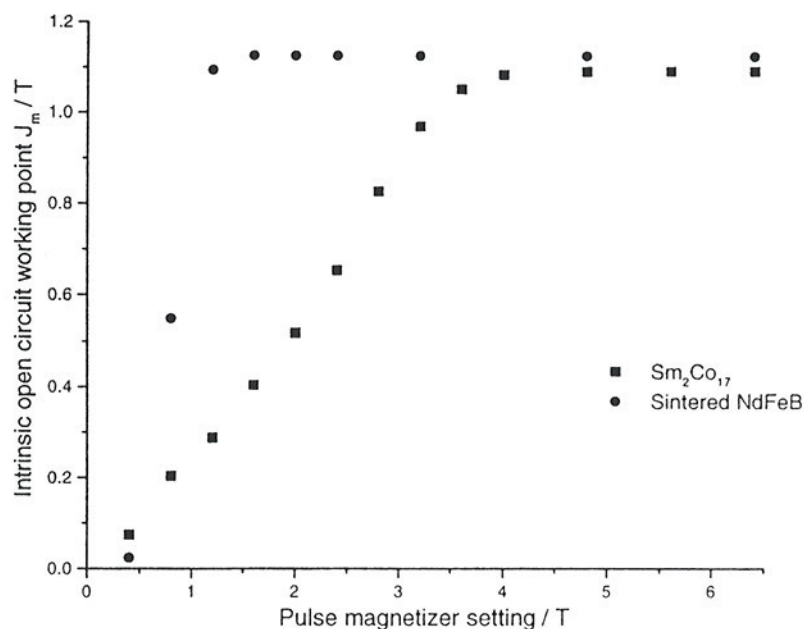


Figure 3 - Intrinsic working point for materials magnetized with different magnetizing field strengths

the grain magnetizations and fully magnetize this material. Further results on the magnetizing characteristics of these materials will be reported at the conference.

Conclusion

The conventional methods of measurement provide limited information on the properties of high energy magnetic materials. Techniques using Helmholtz coils provide valuable information, but new techniques are being developed to measure the intrinsic coercivity of some magnet materials.

The field strength needed to magnetize modern magnet materials is not only related to coercivity, but also depends on the mechanism on which the permanent magnet properties are based. The permanent magnet materials examined so far seem to be close to their optimum properties when magnetized with a field of around 4 MAm⁻¹, a field strength easily obtainable in pulse magnetizers. Work is continuing on materials expected to require higher magnetizing field strengths, and the results will be reported at the conference.

Acknowledgement

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