Experiment 12

Hysteresis loop for a ferromagnetic material (M-B curve)

Apparatus:
Two solenoid coils, S and C, ferromagnetic specimen rod, reversible key (R), ammeter, magnetometer, battery, rheostat and transformer.
Purpose of experiment:
i) To study the magnetization (M) of a ferromagnetic material due to an applied magnetic field B and to plot the hysteresis (M vs. B) curve. ii) To calculate the retentivity and coercivity of the material.
Basic methodology:
A ferromagnetic rod is magnetized by placing it in the magnetic field of a solenoid. The magnetized rod causes a deflection (θ) in a magnetometer. The deflection θ is recorded as the current in the solenoid (I) is varied over a range of positive and negative values.

I Theory

The atomic motions in materials bequeath them with magnetic properties: when placed in an external magnetic field, they respond by aligning themselves in such a way as to reduce the net energy of the system.

A ferromagnet is a material in which the atoms behave like magnetic dipoles produced by the spins of unpaired electrons. The energy of the interaction is governed by quantum mechanics, and it turns out that this energy is lowered, even in the absence of an external field, if neighbouring electron spins are aligned parallel to each other. However in a large sample, domains form in the interior of the material within which the dipoles align in a given direction but the domains themselves are randomly oriented. (Figure 1). Thus the bulk material is generally unmagnetized.

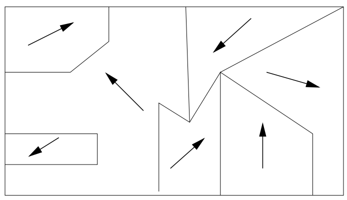

Figure 1: Ferromagnetic Domains

In the presence of an external magnetic field, the different domain moments tend to align, producing a net magnetization in the direction of the applied magnetic field.

The magnetization M, defined as the magnetic dipole moment per unit volume, can be measured by observing the magnetic field produced by the magnetized material. A solenoid produces a fairly strong and uniform magnetic field within it, which is generally used to magnetize a ferromagnetic sample

The magnetic field of a solenoid at a point well inside it, on the axis, is

$$B = \mu_0 n I, \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7}\mathrm{Nm^2/A^2}$ is the magnetic permeability of vacuum, n is the number of turns per unit length of the solenoidal coil and I is the current in the solenoid. The specimen in the form of a cylindrical rod of length l and cross section α, placed along the axis of the solenoid, acquires a magnetization M along its axis. The magnetic dipole moment m of the rod is then

$$m = M(l\alpha). \tag{2}$$

The magnetic field produced by the rod at a point along the axis a distance r from the center of the rod is given by

$$B_M = \frac{\mu_0}{4\pi}\frac{2mr}{\left(r^2 - \frac{l^2}{4}\right)^2}. \tag{3}$$

Now the total magnetic field at that point is a combination of this field, the field of the solenoid and the Earth's magnetic field. In our setup, we will offset the magnetic field of the solenoid using a compensating coil. The apparatus is aligned such that the axis of the rod is perpendicular to the horizontal component of the Earths magnetic field, B_E,which is along South-North direction. A magnetometer needle at r aligns along the resultant magnetic field making an angle θ with B_E as shown in Fig. 2. Clearly,

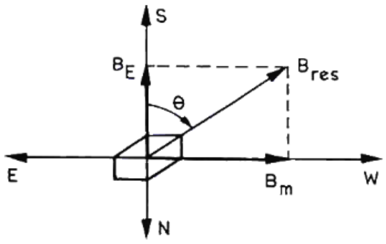

Figure 2: Directions of the magnetic fields

$$\tan\theta = B_M/B_E \implies B_M = B_E \tan\theta. \tag{4}$$

Using Eqs. (2), (3) and (4) we can write

$$M = \frac{4\pi}{\mu_0\alpha(2l)}\frac{(r^2 - l^2/4)^2}{r}B_E\tan\theta. \tag{5}$$

Thus, $M \propto \tan\theta$. Also, the magnetizing field $B \propto I$, the current in the solenoid.

To obtain the relationship between M and B one can observe the $\tan\theta$ *vs* I plot.

HYSTERESIS

Ferromagnetic materials are non-linear, in that the magnetization produced is not proportional to the magnetizing field. Moreover, when the applied field is gradually removed, the material does not return to its original unmagnetized state. Some magnetization is residual. This phenomenon is known as *'hysteresis'*. A typical M *vs* B curve is shown in Figure 3. As the applied field is increased, domains with magnetization along the direction of the applied field grow in size and the magnetization increases rapidly. For stronger fields, whole domains that are not aligned along the field, change their orientation and finally, all the internal spins are oriented parallel to the applied field. The magnetization has now reached saturation (point b) and further increase in B will not increase M.

As the applied field is reduced, the magnetization curve traces a different path upto zero applied field (point c) where the magnetization has a residual value. In order to remove this magnetization the applied field is increased in the reverse direction (upto point d). further increase in reverse field magnetizes the sample in the opposite direction in a symmetric way and the sample reaches saturation (point e). The loop is completed on decreasing the reverse field and then increasing through zero in the opposite direction. Note that the $\tan\theta$ *vs* I curve is also similar.

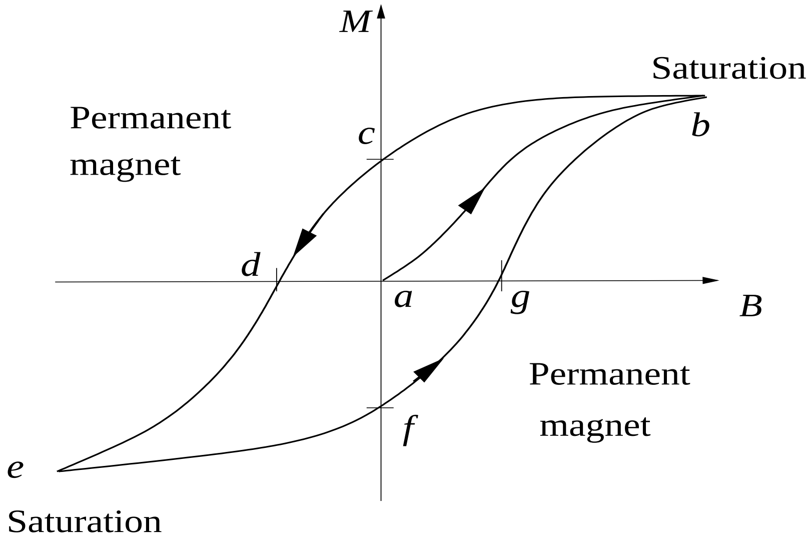

Figure 3: Hysteresis loop for a ferromagnet

Retentivity and Coercivity

Retentivity (M_0) is the residual magnetization in the sample when the applied field is zero.

$$M_0 = \frac{4\pi}{\mu_0 \alpha 2l} \frac{(r^2 - l^2/4)^2}{r} B_E \tan\theta_0 \tag{6}$$

where $\tan\theta_0 = \frac{|c|+|f|}{2}$, points c and f referring to the $\tan\theta$ *vs* I hysteresis curve.

Coercivity (B_0) is the external field required to reduce the magnetization in the sample to zero.

$$B_0 = \mu_0 n I_0 \tag{7}$$

where $I_0 = \frac{|d|+|g|}{2}$, d and g refer to points on the hysteresis curve.

II Setup and Procedure

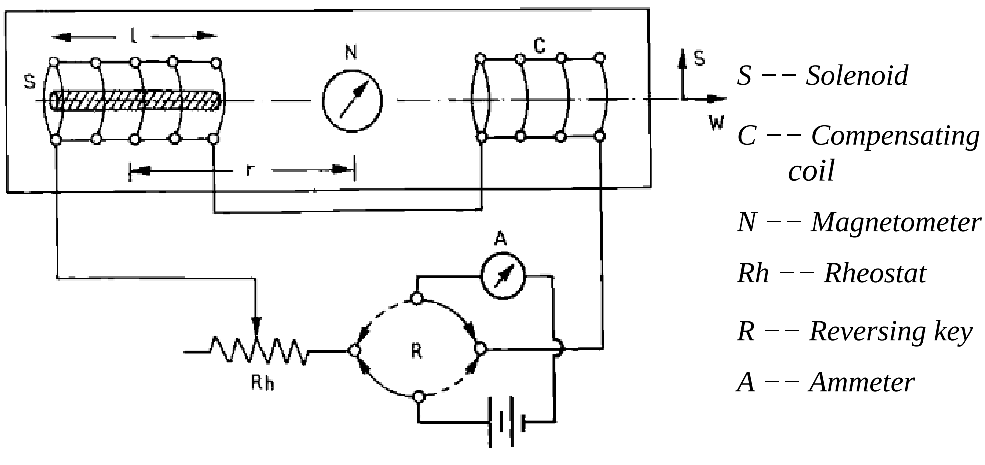

Figure 4: Circuit Diagram

1. Connect the circuit according to the figure above.

2. Alignment of apparatus:
   Rotate the dial of the magnetometer until the $0 - 0$ position is aligned with the axis of the solenoid. Rotate the wooden arm containing the solenoid, magnetometer and compensating coil, until the magnetic pointer coincides with the $0 - 0$ position. In this position the wooden arm is along the E–W direction. The horizontal component of the Earths magnetic field B_E (along S-N direction) is then perpendicular to the wooden arm.

3. Demagnetization of specimen rod: Connect the circuit according to Figure 5. Set the AC

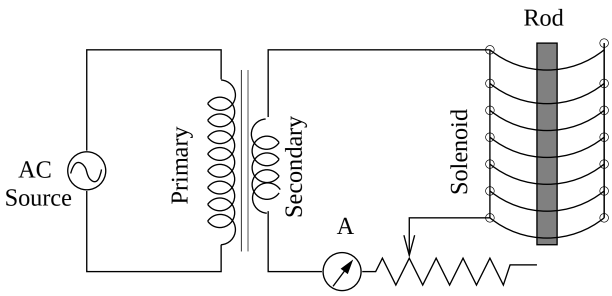

Figure 5: Demagnetizing Circuit

   current to maximum. Now gradually reduce the current to zero using the rheostat.

4. Positioning of the Compensating Coil:
   Pass current (say 1A) through the coils S & C. Vary the position of C along the wooden arm until the deflection of the needle is zero. The magnetic field of solenoid S is now nullified (at the position of the magnetometer) by the magnetic field of C.

5. Begin Measurement:

   (a) To begin with, the current in the solenoid should be switched off.

   (b) Insert specimen rod so that its leading tip is at the edge of the solenoid.
   Note: There should be no deflection of the needle at this point. If deflection is observed repeat step 3 for demagnetizing rod.

   (c) Keep the rheostat position at maximum resistance.

   (d) Switch on the current.
   Caution: From now on, strictly follow the current variation sequence. Do not *change or back-track—this will lead to incorrect results.*

   (e) Vary the current using the rheostat from 0A. Note the deflections θ_1 and θ_2 of the two ends of the magnetometer needle. Change the current in steps of 0.1A and note the deflections for each setting of current. Continue until saturation is reached.
   Caution: To get strictly zero current you will have to switch off the battery.

   (f) Reverse the position of the reversible key R and repeat the measurements, varying the current in the reverse direction 0A to maximum current (saturation) and back, to 0A.

   (g) Reverse the position of the key R again, and repeat, varying the current now from 0A to the maximum.

6. Plot a graph of I *vs* $\tan\theta$, where θ is the average of θ_1 and θ_2.

III Exercises and Questions

1. Define paramagnetic, diamagnetic & ferromagnetic substances. Give one example of each.

2. Why is the M vs. B curve called the hysteresis curve?

3. Derive equation (6).

4. What is the need to align the solenoid along the E-W direction?

5. Will the hysteresis curve be different if this alignment were not done? If yes, why?

6. How does the demagnetization setup demagnetize the rod?

7. It is said that dropping the specimen rod on a hard surface also serves to remove any small residual magnetization. Is this true? If so give reasons.

8. Draw a small figure showing how the hysteresis curve would develop over many cycles of the current.

9. How would the retentivity and coercivity change with temperature? Do you think they should depend in the geometry of the sample?

10. Identify the main sources of error in your experiment.

References

1. *Fundamentals of Physics*, D. Halliday, R. Resnick and J. Walker, John Wiley & Sons, New York, 2001.

2. *Physics*, M. Alonso and E.J. Finn, Addison-Wesley 1992.

3. *Introduction to Electrodynamics*, D.J. Griffiths, PHI, 1998.