10. Magnetic Hysteresis

10.1. Purpose

1. To determine the hysteresis curves for a ferromagnetic material.

10.2. Variables and Relationships Used to Denote Magnetism

B, M and H are used to denote magnetic properties and are defined as follows. The term magnetic field is used for two different vector fields, denoted $\vec{B}$ and $\vec{H}$.

- $\vec{B}$ is magnetic flux density in tesla and is also known as the magnetic field measured. 1 tesla = (newton × second)/(coulomb × meter).
- $\vec{H}$ is magnetizing force measured in ampere-turns. It is also called the magnetic field. Outside a material, $\vec{B}$ and $\vec{H}$ are indistinguishable, differing only in a multiplicative constant.
- $\vec{M}$ is magnetization in amperes per meter, and is the magnetic moment per unit volume V: $\vec{M} = \frac{N}{V}\vec{m}$ where N is the number of magnetic moments in the sample. $\vec{M}$ represents how strongly a material is magnetized and only exists inside a material.
- μ is the magnetic permeability of a material and is the ratio $\frac{B}{H}$.

Much care must be taken when using formulas involving these three quantities as one has to consider if you are inside a ferromagnetic, diamagnetic or paramagnetic material, or outside the material in question. In addition, different disciplines (physicists, electrical engineers, electronics engineers) use the terms differently.

10.3. Introduction

Hysteresis occurs in a system that exhibits path dependence. Unlike systems which don't show hysteresis, it is not possible to predict the future state or output based solely on the input. For a system with hysteresis more information is required:

1. the present input
2. the path by which the present state was attained.

In other words, where the system is going to be next depends on how it arrived at its present state. Hysteresis is also defined as a phenomenon in which two physical quantities are related in a way where whether one quantity is increasing or decreasing in relation to the other affects the relationship.

A few types of hysteresis exist such as elastic hysteresis: a rubber band stretching and contracting. The repeated measurement of stress against strain, where the stress first increases and then decreases, will produce a graph for some specimens that has the shape of a closed loop. The loop is called the hysteresis cycle. A thermostat control circuit also utilizes hysteresis. Its output state (furnace on or off) cannot be determined by its input (the present room temperature) alone. One must know if the present temperature was arrived at by increasing or decreasing temperature. This relates to the requirement of dead-band, whereby the cut-out and turn-on temperatures must be different. Electric hysteresis is a third example and there are others.

Ferromagnetic materials exhibit hysteresis when subjected to an external magnetic field. This property is extremely useful and is the physical basis of binary, permanent memory on magnetic media such as hard-drives and other media, and has many other applications.

Magnetically hard materials can be permanently magnetized by a strong magnetic field. Steel and special alloys such as Alcomax, Alnico, and Ticonal, which contain various amounts of aluminum, nickel, cobalt, and copper, are used to make permanent magnets. The strongest permanent magnets are ceramic, made under high pressure and at high temperature from powders of various metal oxides.

Iron is an example of a natural hard magnetic material. Its magnetic properties are due to its atomic structure. The unpaired electrons in the outer orbit of an iron atom produce a strong magnetic field. In a magnetized piece of iron millions of individual iron atoms, called a domain, are aligned in the same direction. The domains have a north and a south pole.

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10.4. Theory and Equipment

When a ferromagnetic substance like iron is situated in a magnetic field, it becomes magnetized. The magnetization $\vec{M}$ is defined as the magnetic moment per unit volume of the material and it varies in a complicated way with the strength of the magnetic field in the which the sample is placed. This experiment will investigate the relationship between $\vec{M}$ and the field intensity $\vec{H}$ causing the magnetization.

A typical magnetic hysteresis curve is shown in figure 10.1 with important characteristics labeled. A hysteresis loop is typically constructed by graphing the magnetization $\vec{B}$ (assumed to be proportional to $\vec{M}$) of the material as a function of the magnetizing force $\vec{H}$. The magnetizing field is generated by passing a controllable current through a long solenoid containing the sample. The sample's magnetization is measured by a magnetic compass's deflection. *Apparatus setup involves insuring that the compass deflection is sensitive the the sample's field only, and insensitive to the solenoid's field.* The apparatus is configured to measure the horizontal component of the sample's field $\vec{M_{Sh}}$ via the external field $\vec{B_{Sh}}$ that the samples magnetization produces.

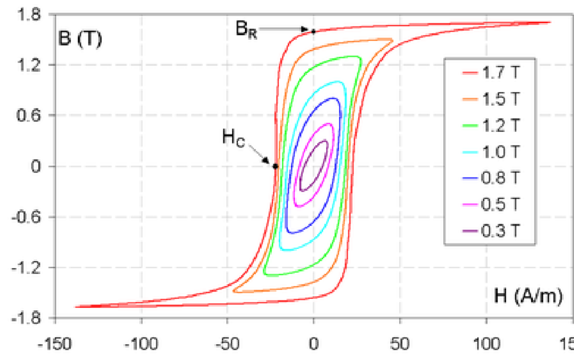
Figure 10.2 shows the apparatus. A sample is placed in the vertical coil "A". Coil "C" (also known as the compensating coil) is used to cancel the horizontal component of coil A's field $\vec{H_h}$. Thus with no sample present, the compass deflection will be minimal or zero. Once current is applied to coil A, the sample will become magnetized and a horizontal component $\vec{B}_{Sh}$ (due to $\vec{M_{Sh}}$ existing now) begins to deflect the compass. The compass and apparatus are aligned in such a way that $\vec{B}_{Sh}$ is perpendicular to the horizontal component of the earth's field $\vec{B_{Eh}}$ as shown in figure 10.3. The compass's magnet will point along the vector formed by $\vec{B_{Eh}} + \vec{B_{Sh}}$. The needle of the compass is mounted 90° to the compass magnet. The earth's field will be running in south-north direction and the apparatus oriented so that the sample's field will be running in a east-west direction. As $\vec{B}_{Sh}$ increases (due to the sample's $\vec{M_{Sh}}$ increasing), the compass magnet will move more and more into alignment with $\vec{B}_{Sh}$.

The following discussion assumes $\vec{M_{Sh}}$ (the magnetization of the sample) is proportional to the external field $\vec{B_{Sh}}$ produced by the source. The strength of the horizontal components of the two fields $\vec{B}_{Sh}$ and B_{Eh} are related by

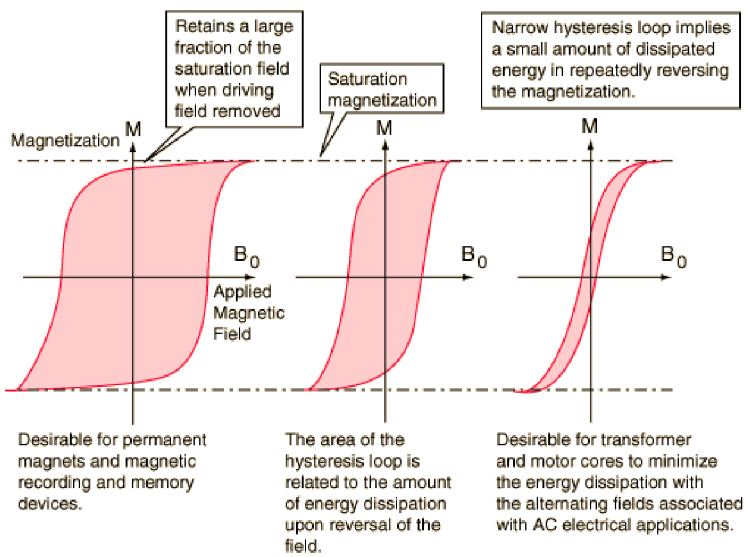
$$B_{Sh} = B_{Eh} \tan\theta$$

Since the magnetization of the sample is proportional to $\vec{B}_{Sh}$ and B_{Eh} is a constant,

$$M = k \tan\theta$$



(a) Hysteresis curves for various values (0.3T to 1.7T) of sinusoidally varying Magnetizing Force $\vec{H}$. BR denotes remanence and HC is the coercivity.



(b) Curves for different ferromagnetic materials showing different widths and different remnant fields. Here M is used to denote the sample's field value and B is used to denote the external field.

Figure 10.1.: Hysteresis Curves

Thus M can be determined from measurements of θ and plotting $\tan\theta$ instead of M is sufficient for the hysteresis curve.

In this experiment the magnetizing field H is produced by a coil (turns N and length L) with a current I running through it. For this coil $B = \frac{\mu NI}{L}$. In this case B and H are related by

$$B = \mu H$$

and thus

$$H = \frac{NI}{L}$$

Since N and L are constants, H can be calculated from measurements of I. So it is also sufficient to plot I instead of H. Thus the hysteresis curves can be produced by plotting $\tan\theta$ as a function of I rather than M as a function of H. The 90° difference between the compass needle direction and θ as defined in figure 10.3 can also be ignored.

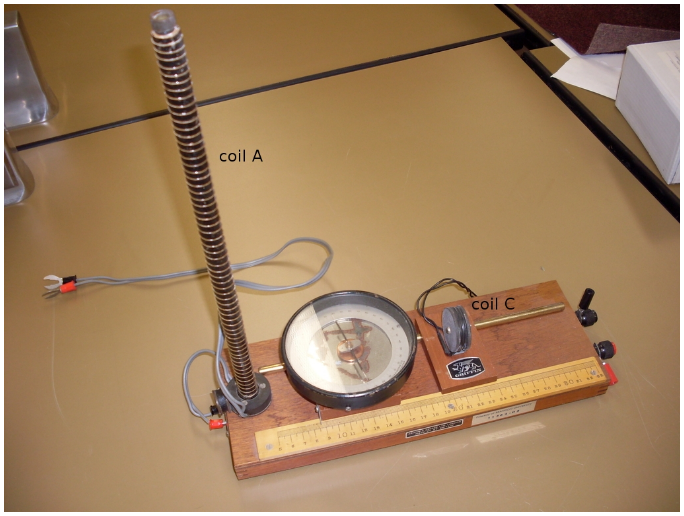


Figure 10.2.: Hysteresis apparatus. The very small coil at the base of the vertical magnetizing coil “A” is not used. It is fed with the unconnected lines in the photo. The compensating coil “C” is to the right of the compass/magnetometer.

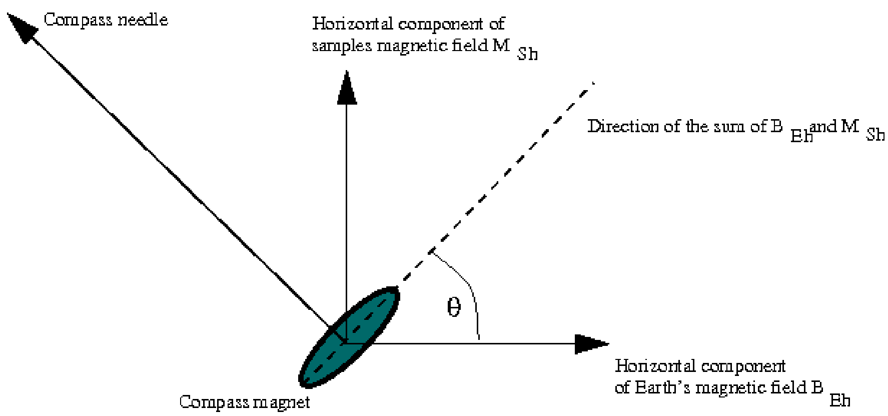


Figure 10.3.: Vectors showing horizontal components of sample and earth fields along with the compass needle direction.

10.5. Domains

Magnetic domains are a region within a magnetic material which has uniform magnetization. Inside any one domain the electron spins of the bound electrons align to produce a magnetic field. These structures exist because their formation reduces the magnetic free energy.

Ferromagnetic materials contain domains. Figure 10.4 shows a photograph of such domains on some polished material. These structures are typically $25\mu m$ to $100\mu m$. Adjacent domains will usually have a net magnetization which is pointing in a different direction. With no external magnetic field H, taken together all these domains cancel each other out as they are oriented randomly.

Applying an external magnetic field causes some domains to change their alignment to minimize the total energy. As the external field's strength increases, more domains come into alignment with the applied field as shown in figure 10.5. Once all domains are fully aligned, the sample's magnetization $\vec{M}$ can not be increased and the hysteresis curve reaches saturation.

If the external field is now decreased, the domains begin to lose alignment, but removing the external field entirely from a ferromagnetic material does not cause the sample's magnetization to become zero. A

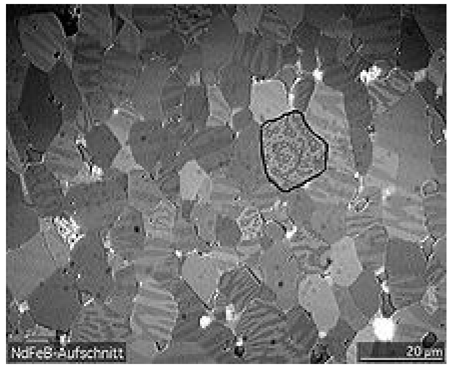


Figure 10.4.: Magnetic domains in NdFeB made visible by contrast with a Kerr microscope.

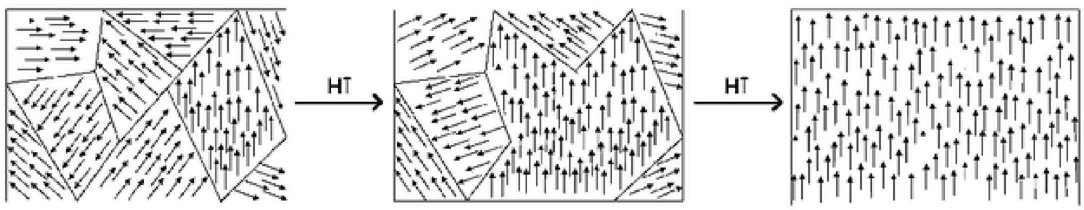


Figure 10.5.: Domains become more aligned with increasing external field.

“remnant” field will remain, and the sample is said to be permanently magnetized. The result is that the domains tend to lag behind in terms of changes to the external field.

If the magnetizing field is reversed and gradually increased, the samples magnetization will decrease due to some domains beginning to reverse their field direction. When the samples magnetism has returned to zero, the value of the external field has reached the “coercivity” for that material. Large and small values of coercivity each have benefits different applications.

10.6. Apparatus

sample wire (hard or soft iron), DC power supply, DMM, reversing switch, 50W rheostat, compass-magnetometer, vertical solenoid and compensating coil (wooden hysteresis apparatus from Griffen).

10.7. Procedure

Note: The small coil at the base of the vertical magnetizing coil is not used. Its connections should be left unused.

1. Connect the apparatus as shown in figure 10.6. Leave the sample out of the vertical coil. Twist the connection lines together which supply current to the apparatus.

2. Align the hysteresis magnetometer board so that the compass pointer (not the compass magnet) point directly toward the solenoid. Then rotate the compass body so that the compass reads zero degrees.

3. Place one of the samples into the magnetizing coil. Saturate the sample by running the current up to 1.5 to 2 amps.

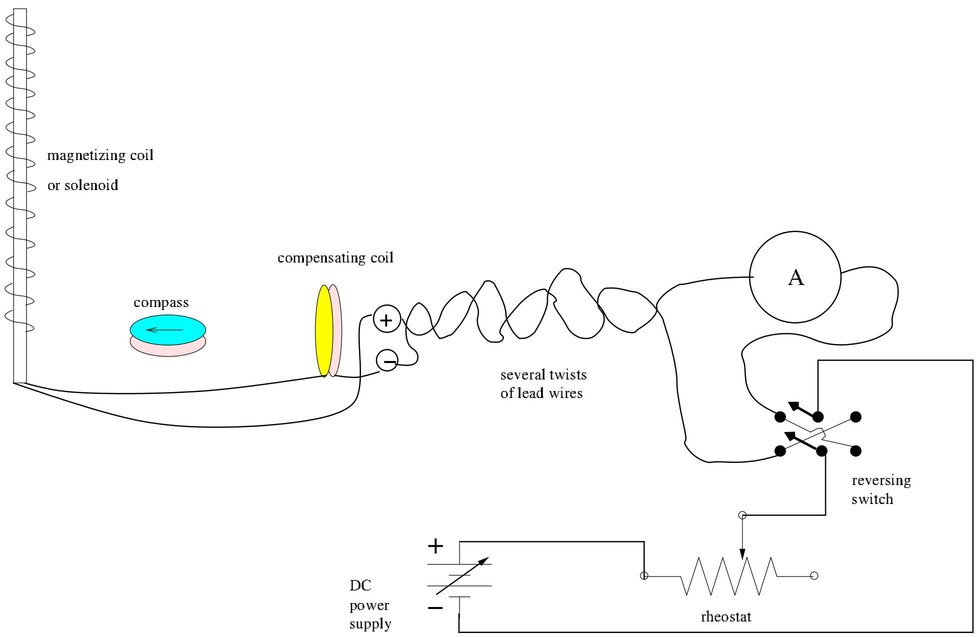


Figure 10.6.: Hysteresis apparatus connection diagram

4. Place the magnetometer (compass) so that the deflection is not greater the $60°$. This is to reduce error in $\tan\theta$. Small errors in θ cause large errors in $\tan\theta$ when $\theta > 60°$.

5. Remove the sample and place it far enough away from the magnetometer that it will not affect the magnetometer deflection.

6. Adjust the current up to $2A$. Position the compensating coil C so that the magnetometer deflection is zero. Use the reversing switch to check that you have zero or minimal deflection for both current directions. Maintain this position for coil C for the rest of the lab.

7. Adjust the current value back to $0A$.

8. Demagnetize the sample using the tape-head demagnetizer. Check that it is demagnetized by placing it back into the vertical coil. The compass should not move more than a few degrees. If it moves a lot and you have demagnetized it again, flip the sample end-for-end and see if the deflection is smaller. Four or five degrees deflection is acceptable.

9. With no sample in the magnetizing coil, practice controlling the current. You want to be able to adjust it reasonably smoothly for you data, that is avoid big jumps in current value. You will have to use the current and/or voltage dials on the supply from some adjustments, but most adjusting will be done with the rheostat. *NB: When increasing the current I during the experiment, DO NOT reduce it until saturation has been reached. You will have to start again.*

10. The metal in the chair frames has been a problem for the compass needle deflection. Moving your chair back from the apparatus is advised.

11. Make the current value zero. Place a demagnetized sample in the vertical coil. In the following steps, the current must not be interrupted except when it is reading 0.0A.

12. Adjust the current up to 0.1A and read the magnetometer deflection. Continue increasing the current in steps of approximately 0.1A (let the data guide you on appropriate current step-size) until the

magnetometer deflection stops changing (around 1.5 to 1 amperes). This indicates saturation has been reached.

13. Do not flip the switch yet. Begin reducing the current by similar sized steps as above until you read zero current, continuing to read the magnetometer deflection.

14. At zero current, reverse the switch. The values of current will now be negative. Repeat steps 11 and 12

15. Once the current is zero again, reverse the switch and take the sample back up to the first saturation value.

16. If time permits, repeat the procedure for a second sample.

10.8. Data and Analysis

Plot a graph of $\tan\theta$ as a function of current I for both samples. Use the same scale for both plots to facilitate comparison. Label the saturation and coercivity values.

10.8.1. Questions

1. Why was it necessary to twist the supply wires together which are feeding the hysteresis apparatus?

2. Why is it necessary to orient the apparatus so that the compass needle pointed directly at the vertical magnetizing coil? What geographical direction is this?

3. If completed, compare the two hysteresis loops. Which sample had the larger coercivity? Which sample had the larger remnant field?

4. Which sample is best suited for an electromagnet and which is best suited for a permanent magnet? Which sample would be best suited for use in a transformer?