The Magnetization Process - Hysteresis

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The way in which a piece of magnetic material behaves when in a changing magnetic field tells a great deal about its properties. The magnetic properties of any material are essentially a superposition of the magnetic properties of a larger number of magnetic regions called "domains". A domain is a region in a magnetic material where the elementary atomic magnetic moments point in the same direction. Between domains are transition regions called "domain walls" in which the atomic magnetic moments change directions from one orientation to another.

Suppose we put a piece of iron in a long coil where the field produced by the coil, H_{app} is uniform. With no field in the coil, the iron breaks up into many alternating domains with equal volumes of up and down domains. If we apply a current to the coil, the domain walls will start to respond as soon as the field exceeds some minimum strength called the coercive field. If we make a graph of the net magnetization of the iron, M, (on the vertical axis) as a function of the field intensity, H, produced by the current in the coil, we obtain a curve such as that shown in Fig. 1.

As the current in the coil (and its magnetic field) increase, the up domains grow larger and larger as the down domains decrease and the net magnetization increases. At some field level all of the down domains have been eliminated, and the material is said to be **saturated**. We designate the field H_{sat}. Fields above H_{sat} no longer change the net magnetization. This is just what we should expect. When all the magnetic moments are lined up with the field, the net magnetization cannot increase further, no matter how much current is applied.

If we now decrease the current, the net magnetization will decrease as well, but it does not begin to decrease until the external field, H_{app} is somewhat below the saturation level. Then, down domains appear, gradually grow and the net magnetization decreases. Notice that the graph does not retrace the same curve. Even when the current is back to zero, there is usually some magnetization left. This is called the **remanent magnetization**.

Increasing the current again, but in the opposite direction gives us an opposite field, - H_{app}. The magnetization continues to decrease and when H_{app} becomes equal to -H_C , the coercive field, the magnetization reaches zero again. Further increasing of the negative field causes the magnetization to increase in the opposite direction until the sample is again saturated when the field reaches -H_{sat} . On decreasing the strength of - H_{app}, the negative field, up domains reappear, and eventually at H_C the net magnetization is brought back to zero.

If we continuously change the current back and forth, that is, if we applied alternating current to the coil, a loop is traced out.

One of the outstanding features of this curve is that there is a difference in the path of the magnetization for increasing and decreasing field. This is called **hysteresis** and the curve is called a **hysteresis loop**. Hysteresis is seen in many other physical systems. For instance, suppose we had a block of wood resting on a horizontal sheet of sandpaper and held in a certain position by springs. If we plotted the position of the block against an applied force that went alternately positive and negative, the plot would look very much like the magnetic hysteresis loop, except that it would not show saturation. In both the mechanical and the magnetic cases, as you go around the hysteresis loop energy is dissipated. It turns out that the area of the loop is directly proportional to the energy dissipated and therefore, to the coercive field. In transformer applications it is desirable to minimize the magnetic energy losses. Thus, one looks for magnetic materials with the smallest H_C .
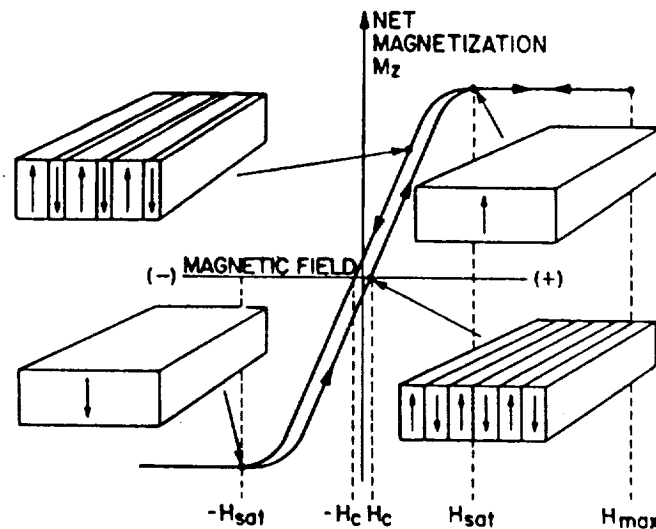

Fig. 1- Sketch of a magnetic hysteresis loop and the corresponding domain structures of a plate with easy axis perpendicular to the surface.

Magnetic materials in which the domain walls move very easily, and which therefore have low coercivity, low remanence, and very narrow hysteresis loops, are called **soft magnetic materials**. The use of the adjective "soft" arose because these tend to be mechanically soft and easily deformable. An iron nail which has a relatively thin hysteresis loop will bend. Over the decades there has been a great sustained effort to improve the magnetic properties of this class of materials.

At the other extreme are magnetic materials which we want to stay magnetized, so called permanent magnets. These we want to have as large a magnetic moment as possible, and when magnetized, to retain that moment even when exposed to moderate magnetic fields. These are called **hard magnetic materials**. These materials have high coercivity and remanence and thus wide hystersis loops. Typically they are mechanically hard, often exceedingly brittle. A permanent magnet made of Alnico will break quite easily. Hard magnetic materials can be prepared by introducing non-magnetic impurities which hinder the motion of domain walls. Another way to make a hard magnetic material is to divide it into particles so small that a domain wall will not fit within the particle. If there can be no domain wall, the magnetization cannot reverse by the domain wall mechanism we have described. Only when we apply a field which exceeds the anisotropy will the magnetization flip over. Thus a further requirement is for a large anisotropy. The magnetic recording materials used in tapes and credit cards have been developed using this approach.

The achievement of good hard magnetic materials also has important economic consequences. Very recently the discovery of greatly improved hard magnetic materials has revolutionized the design of small permanent magnet motors. The development of materials is a vital part of the ongoing improvements in magnetic recording on which the technology of our society is evermore dependent.

An apparatus and activity which show hysteresis in materials in a qualitative manner have been developed. The activity and construction notes follow.

The hysteresis loops introduced above constitute a tremendously valuable tool in characterizing magnetic materials. In transformers and motors the magnetization is swept through a hysteresis loop 60 times every second. Each time some of the electrical energy is converted to heat. If the coercive force is large, the hysteresis loop is fat. Consider a practical application of this principle. A material with a large coercive force in addition to the eddy current losses, would cause a motor to become very hot. Materials with a large coercive force, require large expensive motors. On the other hand if the domain walls move in very small fields, i.e., if H_c is tiny, motors can be smaller and less electrical energy is wasted in heating up the atmosphere.

Construction Notes: Hysteresis

1. You can build a stand for the coils using one foot of 1x3 pine, two 3 - 1/2 inch pieces of 2x2 pine, and a 3 - 1/2 inch piece of 1x2 pine.

2. Drill a 3/4 inch hole in the center of the piece of 1x2, one inch from one end as shown. Then cut the piece of 1x2 lengthwise down the center.
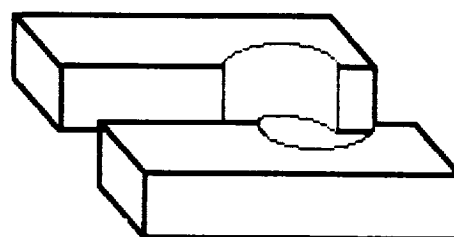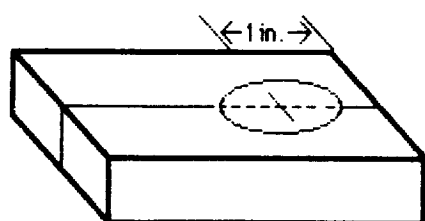
3. Drill three sets of two 5/16 inch holes on the 1x4 three inches from one end and one inch in from the edge as indicated below. Use a 1/2 inch bit to countersink these six holes to a depth of 1/2 inch. This is necessary so that the binding post will fit. Drill another 5/16 inch hole on the center of the 1x3 board.
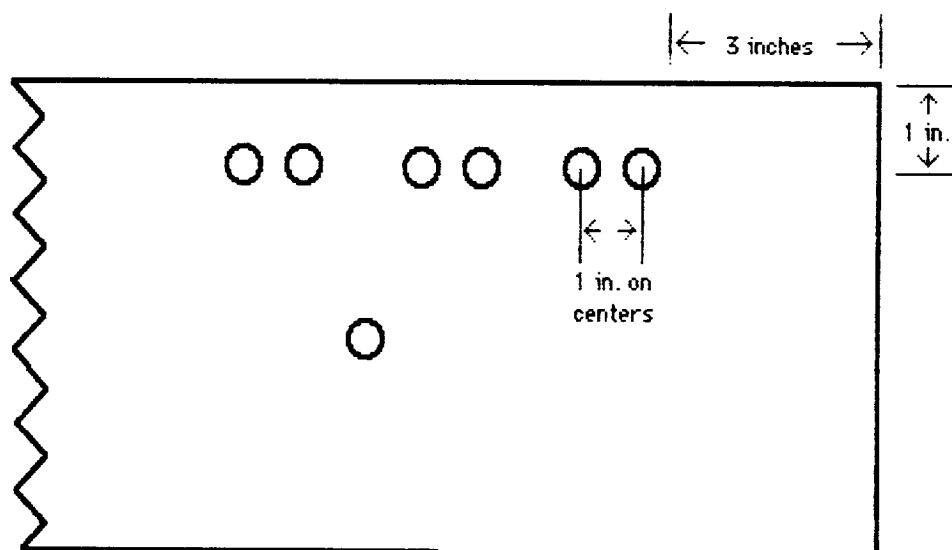

4. Now glue the two pieces of 2x2 on the bottom ends and the two pieces with the half circles and the top ends. The completed stand should look like this:
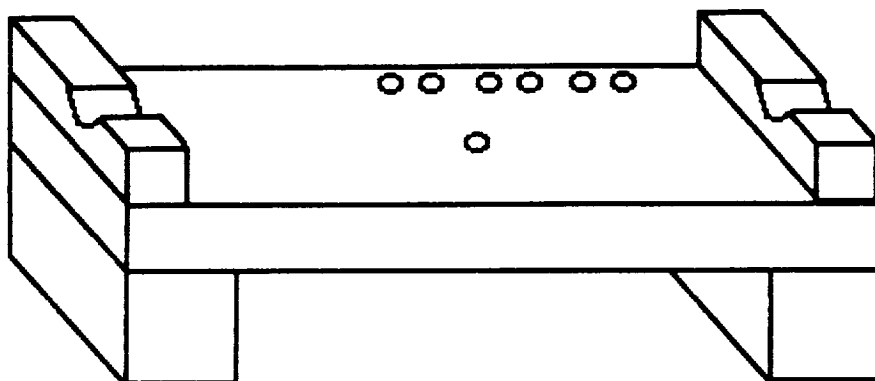
5. Take one foot of 3/4 inch outside diameter tubing. Leaving about 1 - 1/2 feet of loose wire and starting one inch in from the left hand end, wind about 300 turns clockwise of #28 enameled magnet wire. After this leave a one inch length of straight wire. Hold it in place with a piece of tape and then wind 300 turns counterclockwise, continuing to move to the right end of the tube as shown below. Leave another 1 - 1/2 feet of loose wire on this end. Hold the turns in place with tape.

6. Take six inches of one inch inside diameter tubing. Leaving 1 - 1/2 feet of wire loose on each end, wind about 275 turns clockwise on this tube. Hold the turns in place with tape.
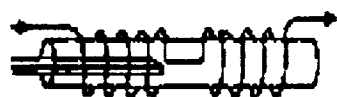
SMALLER TUBE
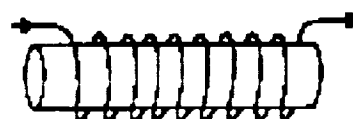
LARGER TUBE

7. Now slide the larger diameter tube over the smaller, covering the coils. Label all four wires as to which coil they are from: the outer , larger diameter, coil or the inner, smaller diameter, coil. Thread all four ends through the hole on the middle of the stand.

8. Tape the ends of the smaller tube into the half circles in the wood on either end of the stand and turn the stand over.

9. Place three sets of binding posts in the six holes and tighten the nuts. Label the three sets of posts as " AC IN ", " X- axis ", and " Y - axis "

10. Identify the two ends of the outer, larger diameter, coil. Solder a one ohm ,three watt resistor to one of these ends. Solder the resistor to one of the binding posts of the set marked " AC IN ". Solder the other end to the other post of this set.

11. Identify one of the ends of the inner, smaller diameter, coil and solder a 100 K ohm resistor to it. Then solder the 100 K ohm resistor to one of the posts labeled " Y - axis ". Solder the other end of the inner coil to the other post of this set. Finally solder a 1 µf capacitor to both posts of this set.

12. Solder a wire from the post that has the one ohm, three watt resistor to one of the posts labeled " X - axis ". Solder another wire from the joint between the one ohm resistor and the end of the outer coil to the other post labeled " X - axis ". Check your circuit with the diagram below
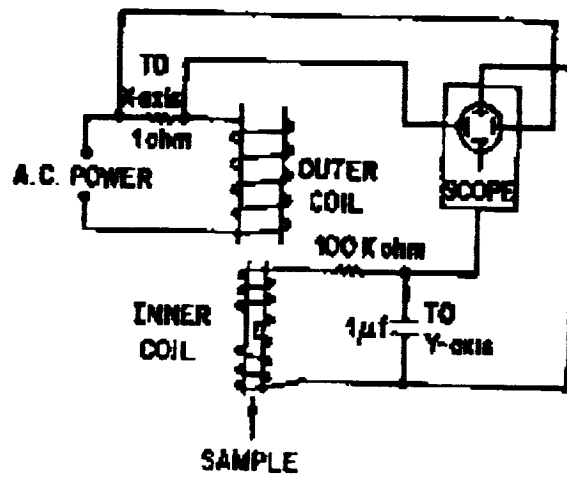
Activity: Hysteresis of Common Magnetic Materials

The way a material is magnetized in the presence of an alternating magnetic field can be displayed on an oscilloscope. The resulting "hysteresis loop" reveals important properties of the material.

You will need: an AC power supply (5 to 10 volts), an oscilloscope, and several samples of different magnetic materials.

1. When current is passed through the outer coil, it acts as the primary of a transformer, producing a magnetic field along the length of the tube. The inner coil acts as the secondary of the transformer and senses the field produced by the primary or drive coil. The two oppositely wound halves of the sense coil give equal and opposite currents which cancel each other perfectly. When a magnetic sample is placed into the tube within the first half of the sense coil, the two output signals of the secondary coil halves no longer cancel and the result depends on the extra field produced by the sample itself.

2. Pass a 60 Hz alternating current (about 0.5 to 1.0 amps) through the outer primary coil using the power supply (or a six volt step-down transformer plugged into a wall socket) with a one ohm resistor in series. The voltage across this series resistor is the X-input to the oscilloscope. It is numerically equal to the current in the coil, which is proportional to the field in the center of the coil. The Y-input to the oscilloscope is the signal from the sense coil attached as shown in the figure. A resistor and capacitor in this sensing circuit are used to filter out extraneous high-frequency signals. On the oscilloscope, set the Y-axis scale to 10 mV/cm and the X-axis scale to 0.2 V/cm.

SAMPLE

SMALLER TUBE

INNER WINDING

LARGER TUBE
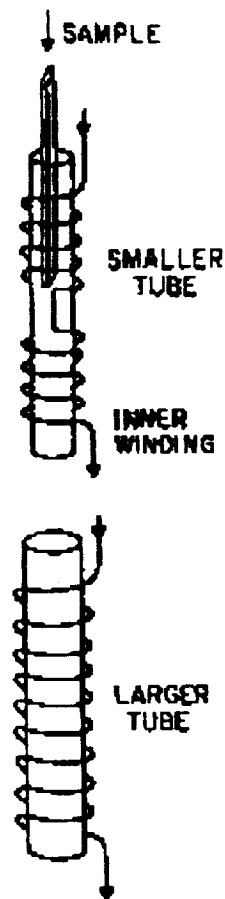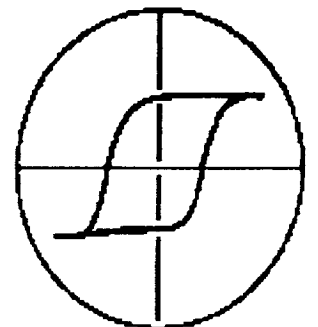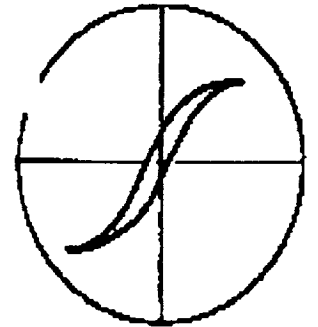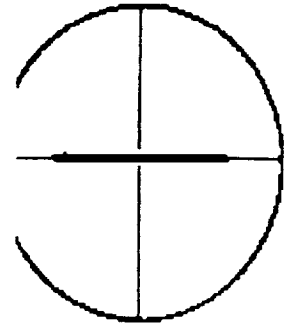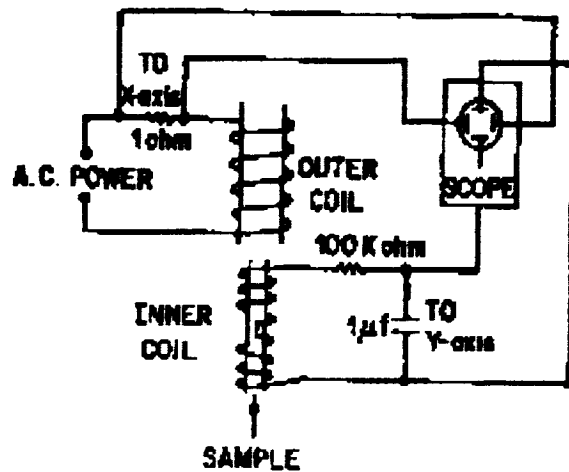
With no sample in the coil, the output should be a horizontal straight line. (If the coils are not well matched, this line will slope up or down. Sliding the outer coil back and forth over the inner coil should result in a better balance and a better horizontal line.)

3. Place various metallic objects into the first half of the sense coil. Non-magnetic samples such as an aluminum nail will have hardly any effect on the output. A hacksaw blade will produce an open hysteresis loop. Paper clips, a screw driver, a coat hanger, transformer core material, will each produce an interesting loop. (Adjust the Y-axis scale to display the best loop for each sample.) Note that some loops are thin and some are wider or square. Using a small piece of silicon iron, or several together, see the difference in the loops when they are magnetized along the rolling direction or perpendicular to it. Try a large iron nail and see the changes produced by flattening it with a hammer and by heating it in a Bunsen burner. Explain the shape of each loop in terms of the motion of domain walls and the rotation of the magnetization within each sample.

4. The magnitude of the applied field can be calculated from the formula:

$$H = (4 \pi N I) / 1000 X l$$

where N = number of turns, I = current in amperes, and l = length of the coil in meters. If the circuit has been designed so that I = 1 amp, N = 1000 turns and l = 12.5 cm, then the field in the center of the coil is

$$H = (4 \times 3.1416 \times 1000 \times 1) / (1000 \times 0.125)$$

$$= 1.005 \text{ amps/meter} = 80 \text{ oersteds}$$

(Remember that the earth's magnetic field is about 1 oersted.)

If the X-axis scale on the oscilloscope is set at 0.2 V/cm, and the voltage across a 1 ohm series resistor is used as the input, each cm on the horizontal axis is equivalent to 16 oersteds. This calibration can be used to estimate the value of the coercive force from the half-width of the hysteresis loop at the X-axis. The Y-axis cannot be easily calibrated, since it depends on the volume of the sample, but the remanent magnetization can be estimated as a fraction of the saturation magnetization for each loop.