Magnetic Hysteresis Loop

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Abstract
The purpose of our experiment was to determine the magnetic properties of four metallic materials by studying hysteresis and to classify them depending on their measured properties. We classified three of the materials as ferromagnets and the fourth as a diamagnet given its linear magnetization curve. It was found that nickel had the most magnetization, followed by iron, and tin as diamagnetic material.

1 Introduction

The phenomenon of magnetism was first observed from magnetite which is a naturally occurring magnetized piece of iron ore. It was later found that all matter is magnetic, but some materials can be highly magnetic depending on their atomic structure. Some of these materials are required for the manufacturing of important equipment such as transformers, relays, magnetic recording devices, permanent magnets, inductance cores, and more. Therefore, it is important to determine the magnetic properties of different materials not only for their practical use in our society but to have a better understanding of the forces in nature. In the late 19th century physicist James Ewing used the term hysteresis to describe the behaviour of magnetic materials. Today, hysteresis is the most common way to represent the bulk magnetic properties of materials by plotting the magnetic induction for various magnetic field strengths. In this experiment we utilize a hysteresis loop tracer to obtain a hysteresis representation for different materials to determine their magnetic properties and classify them as ferromagnets.

2 Experimental Theory

A magnet is a piece of material that has its atoms ordered in a way that it exhibits the properties of magnetism. In 1915, Albert Einstein and W. J. Hass demonstrated that magnetism was a result of the alignments of the electron's orbital magnetic moment and spin magnetic moment. The magnet's magnetic moment is a vector that characterizes the overall magnetic properties of the magnet. In most objects, the electrons spin in random directions generating individual magnetic fields. When these electrons spin in opposite directions, their magnetic fields cancel making the material not highly magnetic. However, if the electrons spin in the same direction and are aligned then a net magnetic effect is observed giving high magnetization. The *magnetization* of a magnetized material is the local value of its magnetic moment per unit volume.

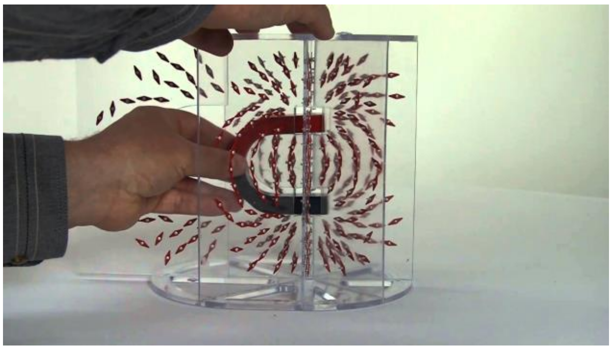

Figure 1. Example of the magnetic field generated by a magnet. The direction of the magnetic moment points from south to north pole.

The direction in which the magnetic fields of the atoms are aligned determines the net direction of the material's magnetic field ***(Fig.1)***. For a bar magnet, the direction of the magnetic moment points from the magnet's south pole to its north pole, and the magnitude relates to how strong and how far apart the poles are. Furthermore, when a magnet is in an external magnetic field it is subject to a torque which tends to orient the magnetic moment parallel to the field in an amount proportional to the magnetic moment and the external field. Therefore, the phenomenon of hysteresis in ferromagnetic materials is the result of rotation of magnetization and changes in size or number of magnetic domains.

3 Properties of Ferromagnets

There are several properties that characterize ferromagnets from other types of magnetic materials. The classifications for magnets are diamagnets, paramagnets, ferromagnets, ferrimagnets, antiferromagnets, helimagnets, and metamagnets. For paramagnets and diamagnets a linear magnetization curve can be observed hence there is no hysteresis loop. However, for ferromagnet materials nonlinear curves can be observed forming a hysteresis loop ***(Fig.2)***. These materials have the strongest form of magnetism and are used for the creation of permanent magnets since they can be magnetized by an external magnetic field and remain magnetized after the field is removed.

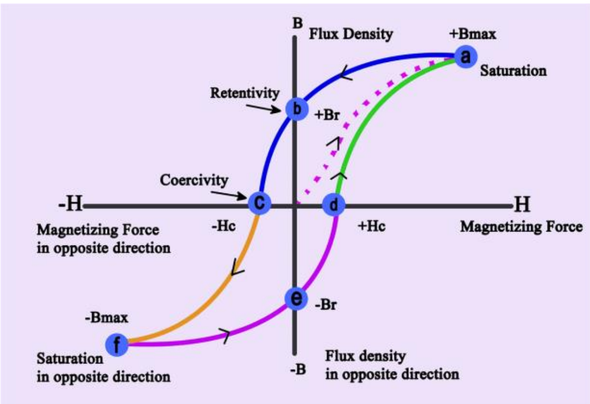

Figure 2. Example of a hysteresis loop displaying the properties of a ferromagnetic material.

Some of the properties of ferromagnets include coercivity, retentivity, permeability, susceptibility, and saturation magnetization. From these properties we are most interested in magnetic *saturation* which is a condition representing all the magnetic dipoles in a material being aligned in the direction of an applied field. If this external magnetic field is increased indefinitely then the magnetization eventually reaches saturation ***(Fig. 2)***. Another important property is the *coercivity* which corresponds to the magnetic field needed to reduce the magnetization of the material to zero from saturation. The *retentivity* is the most characteristic property of ferromagnets since it corresponds to the ability of the material to retain magnetization even after the external field is removed. Retention of magnetization distinguishes ferromagnets from paramagnets which although acquire a magnetic moment, cannot maintain the magnetization after the field is removed. Another property is the permeability being a measure of the ability of a material to support the formation of a magnetic field within itself. The last studied property is the susceptibility which describes if a material is attracted to a magnetic field or repelled form it.

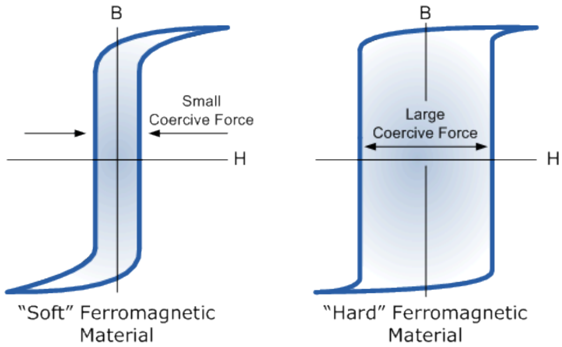

Figure 3. Hysteresis loop comparison between hard and soft ferromagnetic materials.

Ferromagnets are divided into magnetically soft materials, which can be magnetized but do not tend to stay magnetized, and magnetically hard materials, which do. As an example, soft iron has a much higher saturation while hard iron has a much higher retentivity as well as coercivity. From these properties we can conclude that permanent magnets need high retentivity and coercivity in order to retain magnetization ***(Fig.3)***. Furthermore, magnetic recording materials have some common characteristics with permanent magnets in that to be useful they need to have a relatively high retentivity and a sufficiently high coercivity to prevent unanticipated demagnetization resulting in the loss of information sorted on the magnetic tape of a disk.

4 Equipment & Procedure

The experiment objective was to calculate the magnetic properties of four given metallic materials by hysteresis and based on these calculations determine if the materials were ferromagnetic. To obtain a visual of the hysteresis loops for each of the given samples ***(Fig.5)*** we utilized the Scientific Equipment Hysteresis Loop Tracer ***(Fig4)***. The equipment generated a magnetic field in a pickup coil where the samples were placed and allowed us to change various parameters such as phase, demagnetization, H. balance, area ratio, and strength of the magnetic field.

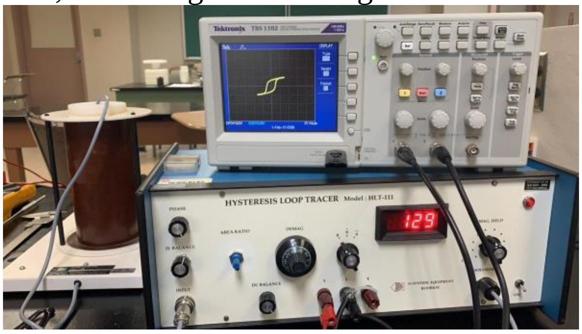

Figure 4. Hysteresis loop comparison between hard and soft ferromagnetic materials.

The hysteresis loop tracer was calibrated following the example from the instruction manual in which they changed the parameters of the tracer until obtaining a horizontal straight line with an empty pickup coil. Once calibrated, a sample was placed in the pickup coil and the parameters were changed until obtaining a satisfying hysteresis loop. The parameters were not changed for any of the other samples for the representations to be accurate in relation to each other and the data consistent with the visuals. However, in our first try the parameters were changed for every sample and the hysteresis loops were not accurate with the calculations of the magnetic properties. The Tektronix Imaging Console Oscilloscope ***(Fig. 4)*** displayed a graph of the magnetic flux in relation to the magnetic force using data from the loop tracer. Distinct graphs were obtained corresponding to the hysteresis loops of each of the samples in different magnetic field strengths. The data was saved in a USB flash drive and the graphs for the hysteresis loops were recreated using Microsoft Excel.

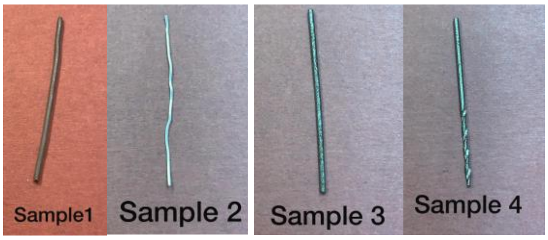

Figure 5. Images and identifications of the given materials.

5 Data & Results

From the obtained hysteresis loops of the four samples at 211G ***(Fig. 6)*** we determined which of them were ferromagnets firstly by visual examination. The samples 1 (blue), 3 (grey), and 4 (yellow) were ferromagnetic

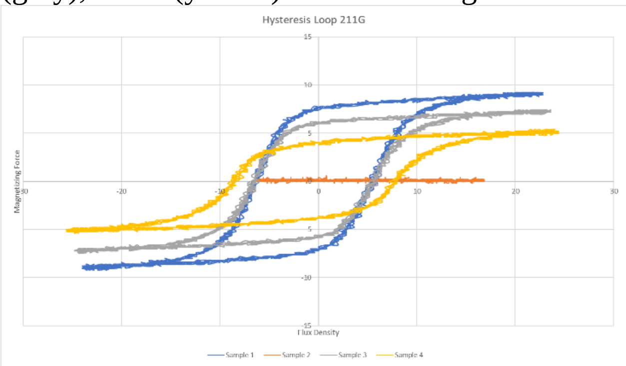

Figure 6. Graph displaying the hysteresis loops of the four samples at 211G.

while sample 2 (orange) was diamagnetic given its linear magnetization. Furthermore, we physically tested for the retentivity of the materials and sample 2 did not stayed magnetized neither was it attracted to a magnet ***(Fig.7)***. It was known that the materials were nickel, soft and hard iron, and one unknown material that appeared to be tin. To properly identify them we calculated the coercivity, retentivity, and saturation properties utilizing the formulas provided in the instruction manual and data from the obtained hysteresis loops.

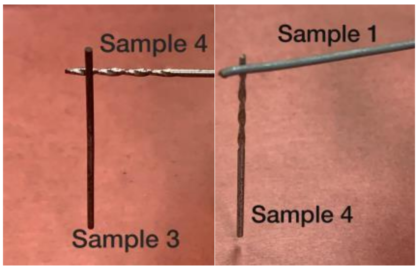

Figure 7. Retentivity test for samples 1, 2, and 3. The materials remained magnetized outside of the magnetic field.

The needed formulas for calculating the magnetic properties of the coercivity, saturation, and retentivity of the materials were

$$H = \frac{G_0 e_x}{\frac{A_S}{A_C} - N}, \qquad \textbf{\textit{(1)}}$$

$$\mu_s = \frac{G_0 \mu_0 g_x (e_y)_s}{g_y\left(\frac{A_S}{A_C} - N\right) 4\pi}, \qquad \textbf{\textit{(2)}}$$

$$\mu_r = \frac{G_0 \mu_0 g_x (e_y)_r}{g_y \left(\frac{A_S}{A_C} - N\right) 4\pi} . \qquad (3)$$

Some of the variables in the above equations were constant. The variables μ_0 and g_y were equal to one and the demagnetization N was of 0.0029 as in the instruction manual. To calculate G_0 we used the formula H_a / e_x, where H_a is the applied magnetic field and e_x the loop width in volts. However, when multiplying G_0 by e_x in formula ***(1)*** we multiplied G_0 by one half of e_x as done in the instruction manual. The value of A_s corresponds to the area of a sample which we calculated from measuring its diameter and A_c corresponds to the area of the pickup coil having a value of 8.09mm. The area ratio was calculated from these values and multiplied by a factor of six alike the demagnetization N which was also multiplied by a factor of 0.4. These multiplication factors changed the form of the hysteresis loop and we tried to make it as similar as possible to the one displayed in the instruction manual. The variable g_x was equal to 100 from the manual and $(e_y)_s$ corresponds to one half the tip to tip height of the hysteresis loop while $(e_y)_r$ corresponds to two times the intercept on the y-axis. Once we calculated the necessary parameters, we obtained values for the three magnetic properties using formulas ***(1), (2), (3)*** for the coercivity, saturation, and retentivity respectively. The following table ***(Table 1)*** summarizes the data for each of the samples.

	Sample 1	Sample 2	Sample 3	Sample 4
Sample Area (A_s)	0.9500	0.1960	0.7854	0.2500
Area Ratio * 6	0.7046	0.1454	0.5825	0.1854
Loop Width (V)	11.800	22.800	12.400	16.400
Demagnetization * 0.4	0.0012	0.0012	0.0012	0.0012
Tip-Tip Height (V)	18.2	0.2	14.4	10.2
Y-Intercept (V) * 2	15.2	0.4	12	8
e_x (loop width * 0.50) (V)	5.9	11.4	6.2	8.2
$(e_y)_s$ (tip height * 0.50) (V)	9.1	0.1	7.2	5.1
$(e_y)_r$ (Y-Intercept) (V)	7.6	0.2	6	4
G_0 (G/V)	17.88	9.25	17.02	12.87
Coercivity (1G=1Oe)	*150.00*	*731.28*	*183.45*	*572.93*
Saturation	*1840.76*	*51.05*	*1677.57*	*2835.63*
Retentivity	*1537.34*	*102.09*	*1397.99*	*2224.02*

Table 1. Table displaying the values used to calculate the magnetic properties of the samples using manually selected points from the hysteresis loop.

To determine the loop width, tip-tip height, and intercept, points were selected directly from the graphs. The values for the magnetic properties were calculated only for the magnetic field of strength 211G given that we observed the same loop behaviour for different magnitudes of the field. In ***(Fig. 8)*** we can appreciate the loop for sample 3 getting bigger as we increased the strength of the field. This behaviour was observed for all the samples therefore, we would obtain the same information regardless of the magnetic field strength if we compared all the samples as we did in ***(Fig. 6)***.

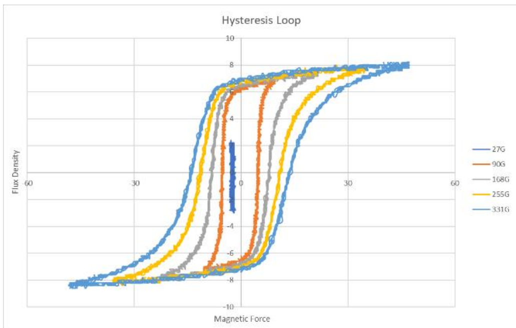

Figure 8. Graph displaying the hysteresis loops for sample 3 in 27G, 90G (orange), 168G, 255G, and 331G.

6 Conclusions

By inspection of the hysteresis loops and analyzing the calculated magnetic properties of the materials we conclude that three of them were ferromagnetic and one of them diamagnetic. This can be confirmed by inspecting ***(Fig. 6)*** and ***(Fig. 7)*** where the three ferromagnetic materials (samples 1, 3, and 4) form a hysteresis loop while the diamagnetic material (sample 2) follows a linear magnetization curve. The calculations for the magnetic properties of the samples in ***(Table 1)*** are consistent with their visual representations. Analyzing the results for the coercivity values of the ferromagnetic materials, sample 4 should have the widest hysteresis loop and this is found to be true and consistent with ***(Fig. 6)***. The second highest coercivity value corresponds to sample 3 followed by sample 1 which values are also consistent with their visual representations. We classify sample 4 as the magnetically hardest material given its high values of coercivity and retentivity followed by sample 3 and sample 1 being the softest having higher saturation and lower coercivity than sample 3. Furthermore, we classify sample 4 as nickel given its distinct hysteresis loop, sample 3 as hard iron, sample 1 as soft iron, and sample 2 as tin which is diamagnetic. From Kale's (2017) table of magnetic properties it seems that nickel has a higher coercivity than iron an is therefore a magnetically harder material as we previously concluded making it sample 4.

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