Study and Measurement of Magnetic Hysteresis Loop

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Magnetism is a basic kind of property for substances. In physics, several different types of magnetism are distinguished. Ferromagnetism is the strongest type and the common phenomena of magnetism in magnets we encountered in the modern world are attributed to it.[1]In fact, only a few substances are ferromagnetic like iron, cobalt ,nickel and their alloys. Ferromagnetism is vital in technology, and is the basis for all electrical and electronic devices such as electromagnets, motors, generators, transformers, tape recorders, and hard disks. Moreover, Ferromagnetism is the kernel to produce the permanent magnets by applying an external magnetic field to magnetize the chosen material and removing it.

1. Introduction

Nowadays, “Magnetic Recording” is a great important way for us to store a lot of data and provides us with rewritable information. It’s widely used in storage devices for computers, mobile phones as well as other electronic devices and many areas such as medicine and financial technology. “Magnetic Recording” depends on the magnetic materials and the principle of that is the common phenomenon of ferromagnet, called “Magnetic Hysteresis”.

Before talking about “Magnetic Hysteresis”, we should know the fundamental mechanism of ferromagnet first.Ferromagnetism can be viewed as the behavior of the whole magnetic dipoles in ferromagnets that all point in the same direction. However, there are some differences between the paramagnetism and the ferromagnetism.

In a ferromagnet, each dipole “like” to point in the same direction as its neighbors, which we called is domain. Each domain contains billions of dipoles lined up with the same direction, but domains themselves are randomly oriented. [2] Especially, magnetic domains aren’t found in paramagnetic and diamagnetic materials, whose dipoles align in response to an external field but do not spontaneously align, that is ,domains only exist in ferromagnetic, ferrimagnetic and antiferromagnetic materials. Hence, we are able to talk about what is the “Magnetic Hysteresis”.

When there is no external magnetic field applying on ferromagnets ,they won’t show any magnetization due to randomly oriented domains. Yet ,once we apply an external magnetic field on them, then domains in the ferromagnets will gradually rotate to be aligned with the direction of external magnetic field. Moreover, the magnetization would remain partially after removing the external magnetic field as a result of the friction between domains. Then we say that the ferromagnet had been magnetized, and would stay magnetized indefinitely for the remain domains which are roughly pointing the same direction.

The relationship between the external magnetic field applied on the sample “H” and the magnetic field generated by the magnetized sample “B” is not linear in ferromagnets.

If a magnet is demagnetized and the relationship between H and B is plotted for increasing levels of field strength, B follows initial magnetization curve. The curve increases rapidly at first and then approaches an asymptote called “Magnetic Saturation”(owing to the number of magnetic domains in ferromagnets are fixed).

If the magnetic field is now reduced, B follows a different curve. At zero field strength, the magnetization is offset from the origin by an amount called the Remanence or Residual Magnetism. If the B-H relationship is plotted for all strengths of applied magnetic field, then the result is the “Magnetic Hysteresis Loop”, shown as Fig .1[3]:

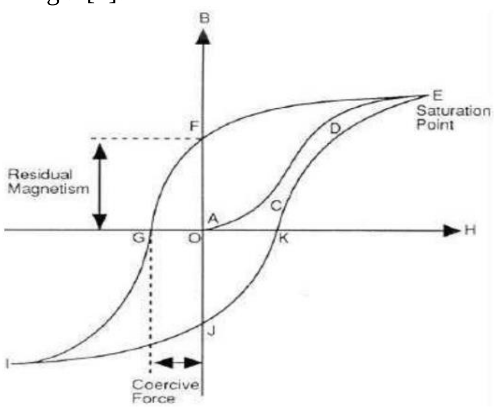

Fig.1:Magnetic hysteresis loop

2. Method

In the experiment, we used the following equipment: the solenoid for magnetizing other objects, the coil for cancelling the magnetic field generated by the solenoid, the DC supplier, the Deflection Magnetometer, the demagnetization instrument and the samples of iron, steel, nickel and the mu-metal(alloy).

This experiment consisted of three sections, for the first part was to set up apparatus.

We need to adjust the distance between the solenoid and the Deflection Magnetometer and connect the coil with the coil in series. Then given the current about 2A to observe whether the magnetic needle rotated. If not,and it implied that the horizontal component of magnetic field generated by the solenoid had been just cancelled by the magnetic field produced by the coil, which was totally what we wanted.

In addition, the only thing we should noticed was that the magnitude of the angle about the rotating magnetic needle shouldn't be over 60 degree. If so, we must increase the distance between the solenoid and the Deflection Magnetometer to decrease the magnetic force.

The second part was to measure the rotated angle with the varying current. The most important thing we should do was that demagnetizing the sample. Next, we connected the DC supplier, the solenoid, and the coil in series. Turn off the bottom represented the current and not turn off the bottom represented voltage. Then we could start the measurement.

We inserted the demagnetized sample into the solenoid and give 0.1A current. Record the rotated angle when the current was steady and then keep increasing the current as well as record the rotated angles until the rotated angle didn't increase, which showed that the sample had reached the state, "Magnetic Saturation".

Next, we began to decrease the current and did the same as the previous step until the magnitude of the current down to zero. Moreover, we reversed the direction of the current for the coil and the solenoid and repeated the steps(measure the rotated angle with increasing and decreasing the current).

Finally, we reversed the direction of current again and repeat the step until the sample had approached the state, "Magnetic Saturation". At that time, we turned off the current and change samples and did as the whole process.

The third part was to plot the "Magnetic Hysteresis Loop" with the currents versus the corresponding rotated angles represented as the tangent value. Meanwhile, we plotted another "Magnetic Hysteresis Loop" by using the following relation formulas from Fig.2:

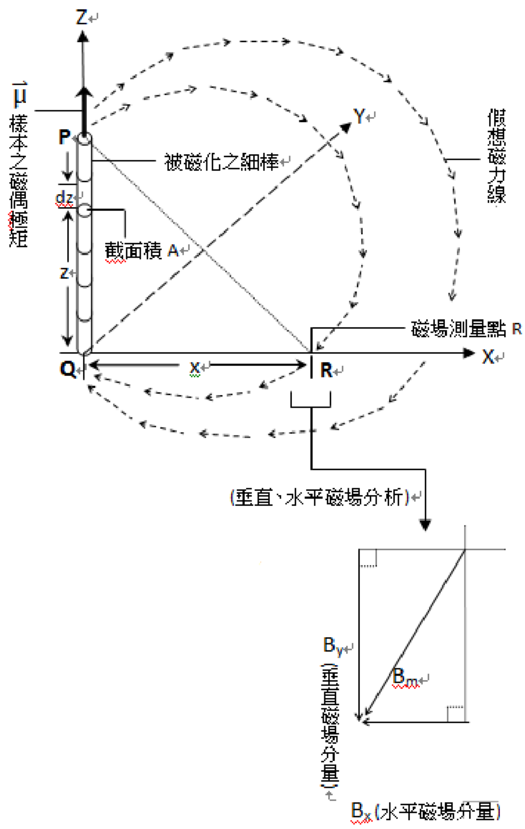

Fig.2: The analysis of the sample in the magnetic field

The magnetic field generated by the magnetic dipole moment of sample(source) was:

$$\mathbf{B} = \frac{\mu_0}{4\pi}\frac{3\boldsymbol{r}(\boldsymbol{r}\cdot\boldsymbol{\mu})-\boldsymbol{\mu}}{r^2} \quad (1)$$

$$\mathrm{r} = \sqrt{(\overline{QR})^2 + z^2}$$

where $\boldsymbol{\mu}$ is the magnetic dipole moment, $\boldsymbol{r}$ is the position vector between the magnetic dipole moment and the measurement point and μ_0 is the vacuum permeability.

Besides, the infinitesimal segment of the sample generated the magnetic field was that:

$$\mathrm{d}\mathbf{B} = \frac{N}{V}A(dz)\frac{3\boldsymbol{r}(\boldsymbol{r}\cdot\boldsymbol{\mu})-\boldsymbol{\mu}}{r^2} \quad (2)$$

where V is the volume of the sample, A is the cross-section area of the sample and N is the number of magnetic dipole moment in sample.

If we integral the x-direction component of the magnetic field along the z-axis:

$$B_x = \int_0^{\overline{PQ}} \left(\frac{N\mu}{V}\right) A \frac{-3\overline{QR}zdz}{r^5}$$
$$= \frac{MA}{(\overline{QR})^2}\left[\frac{(\overline{QR})^3}{((\overline{QR})^2+(\overline{PQ})^2)^{\frac{3}{2}}} - 1\right] \qquad (3)$$

where $\overline{PQ}$ is the length of the sample and M is the number of the magnetic dipole moment per unit volume.

Let's consider the rotated angle of the magnetic needle due to the horizontal component of geomagnetic field B_E and the magnetic field generated by the ferromagnet B_{ex}, which they are orthogonal:

$$tan\varphi = \frac{B_{ex}}{B_E} \qquad (4)$$

Plug (4) into (3),and we will obtain the result:

$$\mathrm{M} = \frac{B_E(\overline{QR})^2}{A\left[1 - \frac{(\overline{QR})^3}{((\overline{QR})^2+(\overline{PQ})^2)^{\frac{3}{2}}}\right]} tan\varphi$$
$$= \alpha tan\varphi \qquad (5)$$

3. Result

As our measurement, we plotted the following graphs corresponding four samples:

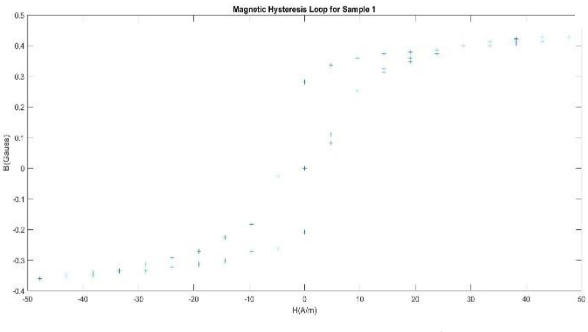

Fig.3:The magnetic hysteresis loop for Sample 1

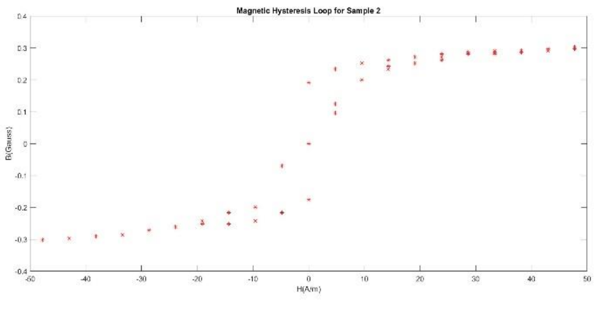

Fig.4:The magnetic hysteresis loop for Sample 2

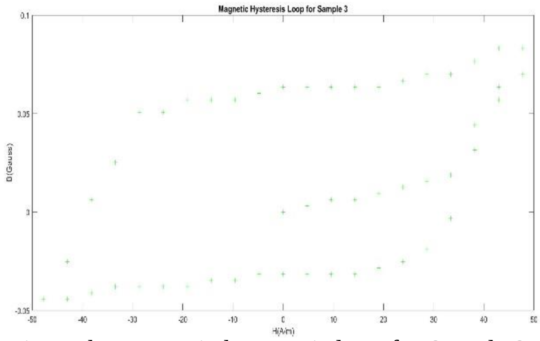

Fig.5:The magnetic hysteresis loop for Sample 3

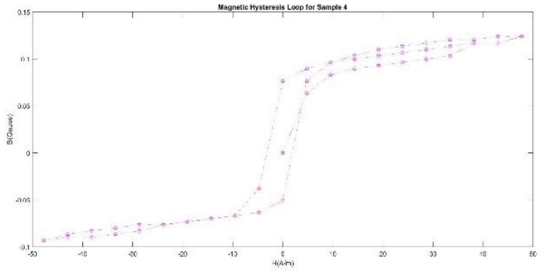

Fig.6:The magnetic hysteresis loop for Sample 4

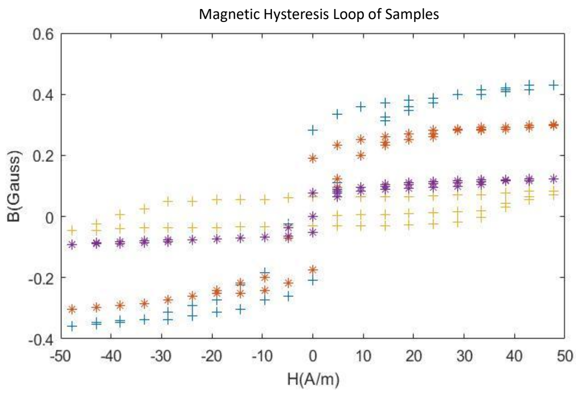

Fig.7:The magnetic hysteresis loop for samples

4.Disscussion

Through Fig.7, we can obviously find that the highest magnetic susceptibility of materials was sample 1, the second of them was sample 2, and the lowest was sample 4. According to table on https://en.wikipedia.org/wiki/Permeability_(electromagnetism) ,we thought that sample 1 was mu-metal which has the highest magnetic susceptibility as well as sample 2 ,3 , and 4 are iron, steel and nickel, respectively.

In the experiment, we found two main problems. The first was that the difficulty in the experiment was to measure the magnetic hysteresis loop for sample 3. Remember we must demagnetize the sample before measurement first, and then we could insert it into the solenoid as well as magnetize the demagnetized sample.

Nonetheless, sample 3 was so sensitive that it had been magnetized by surrounding magnetic fields such as the DC supplier, the laptop or even the smartphones before inserted. Thus, it was quite tough for us to operate the process and plot the Magnetic Hysteresis Loop for sample 3.

The last and the most critical problem was that we had doubt on the “strange” magnetic susceptibility of mu-metal. According to https://en.wikipedia.org/wiki/Mu-metal, we knew that mu-metal is roughly composed of 77% nickel, 16% iron, 5% copper, and 2% chromium or molybdenum. So if it was really true, then how was the magnetic susceptibility of the mu-metal the highest due to the 77% nickel which has the lowest magnetic susceptibility ? Even if the relation between materials of alloy and magnetic susceptibility is “nonlinear”, we just couldn’t understand what happen on it. Hence I thought to understand this phenomenon, the much knowledge like statistic physics or quantum electrodynamics were needed.

Reference

[1] Chikazumi, Sōshin ,*Physics of ferromagnetism*,2nd Ed,translated by C.D. Graham, Jr Oxford: Oxford University Pres

[2] David.J.Griffits,*Introduction to Electrodynamics*,4th Ed,Pearson Education (2013)

[3]Young, Hugh D., *University Physics*, 8th Ed., Addison-Wesley, 1992