3. Theory

1) Magnetization law of ferromagnetic materials

The phenomenon of generating a new magnetic field by applying an external magnetic field to a material is called magnetism. The magnetism of materials can be classified into three types, anti-magnetism (diamagnetism), para-magnetism, and ferromagnetism. Materials that can be magnetized are called magnetic media. In ferromagnetic material, there exists a strong inter-coupling effect among adjacent electrons. In the absence of an external magnetic field, their spin magnetic moments can be spontaneously arranged in order within a tiny region to form spontaneously magnetized small regions, known as magnetic domains. In an un-magnetized material, although each magnetic domain has magnetism, the whole material does not show net magnetism as each magnetic domain has random magnetization direction and the vast average is zero. A structural diagram of poly-crystalline magnetic domains is shown in Figure 2 (a).

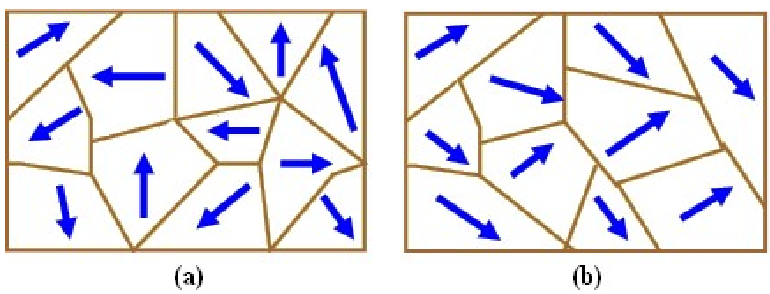

Figure 2 Poly-crystalline magnetic domains (a) before and (b) after magnetization

When the ferromagnetic material is placed in an external magnetic field, these small magnetic domains tend to rotate to follow the direction of the external field by varying their volumes. At this moment, the ferromagnetic material shows macro magnetism. This effect increases with an increase in the intensity of the external magnetic field, until all magnetic domains are arranged along the external magnetic field. At this moment, the magnetization of the material reaches saturation. Figure 2 (b) displays the arrangement of polycrystalline magnetic domains after magnetization.

Because the magnetic moment in each domain is arranged in order, the material shows strong magnetism. This is the reason why the magnetism of ferromagnetic materials is much stronger than that of paramagnetic materials. Doping and internal stress inside the material prevent these magnetic domains from recovering to their original states after the external magnetic field is withdrawn. This is the main cause for hysteresis phenomenon. Ferromagnetism is inseparable with magnetic domain structures. If a ferromagnetic material is impacted by strong vibrations or heated to a high temperature, its magnetic domains collapse. At this moment, a series of ferromagnetic properties (such as high magnetic permeability and hysteresis) which are related to magnetic domains disappear. All ferromagnetic materials have such a critical temperature. When the applied temperature is higher than this critical temperature, their ferromagnetism disappears and the materials become para-magnetism. This critical temperature is called Curie point of ferromagnetic materials.

In various magnetic media, the most important material is represented by iron kind of strong-magnetic substances. Except for iron, general transition metals (such as cobalt and nickel) and lanthanides such as dysprosium and holmium have ferromagnetism. However, most commonly used ferromagnetic materials are alloys of iron and other metallic or non-metallic components, and some iron oxides (ferrites). Ferrites have characteristics of high resistivity and low Eddy current losses, and are suitable for use at high frequency. The main constituent of one kind of soft ferrites is Fe_2O_3. Its general formula can be expressed as $MO \cdot Fe_2O_3$ (spinel-type ferrite), where M is the 2^+ metal element whose spontaneous magnetization is sub-ferrimagnetism. Currently, magnet core materials are mainly ferrites with Ni-Zn centers.

Magnetization law of magnetic media is described by magnetic induction *B*, magnetization *M* and magnetic field strength *H*. They satisfy the following relations:

$$\mathrm{B} = \mu_0(\mathrm{H}+\mathrm{M}) = (\chi_m + 1)\mu_0\mathrm{H} = \mu_r\mu_0\mathrm{H} = \mu\mathrm{H} \tag{1}$$

where $\mu_0=4\pi\times10^{-7}$ *H*/m is the vacuum permeability, x_m is the magnetic susceptibility, μ_r is the relative permeability (a dimensionless coefficient), and μ is the absolute permeability. For paramagnetic media, $x_m>0$, μ is slightly larger than 1; for diamagnetic media, $x_m<0$ and in general their absolute values are between $10^{-4} \sim 10^{-5}$, μ is slightly less than 1; for ferromagnetic media, $x_m>>1$, so $\mu_r>>1$.

For isotropic non-ferromagnetic media, there exists a linear relationship between *H* and *B*, i.e. $B=\mu H$; while for ferromagnetic media, there has a complex non-linear relationship among μ, *B* and *H*. Under normal conditions, spontaneous magnetization exists in ferromagnetic materials, and the lower the temperature is, the greater the spontaneous magnetization will be.

A typical magnetization curve (*B-H* curve) is shown in Figure 3, which reflects the common characteristics of magnetic susceptibility of ferromagnetic materials, i.e. at the beginning, *B* increases slowly as *H* increases when μ is relatively small; then *B* increases sharply as *H* increases and μ also increases rapidly; finally *B* tends to saturate as *H* increases, at this time, μ reaches the maximum value and then decreases quickly. Figure 4 indicates that magnetic permeability μ is a function of magnetic field *H*.

Permeability is also a function of temperature as shown in Figure 4. When temperature reaches a certain value, a ferromagnetic material changes its magnetic state from ferromagnetism to paramagnetism. The mutation point on the temperature curve is the Curie temperature T_c.

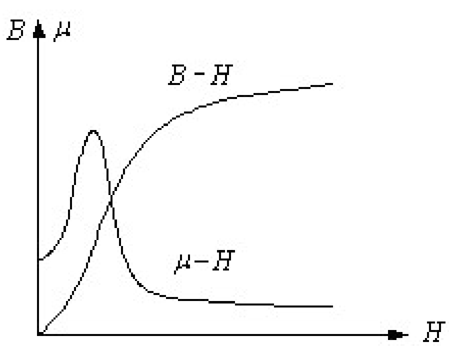

Figure 3 Magnetization curve and μ~H curve

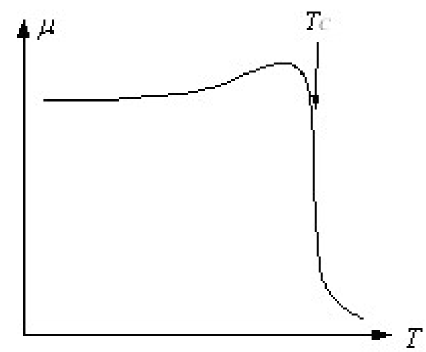

Figure 4 μ~T curve

2) Measurement of Curie temperature using an electrical bridge

Curie temperature of a ferromagnetic material can be measured using an AC electrical bridge. Figure 5 shows the schematic of a basic AC electrical bridge. The four arms of the bridge can be resistances, capacitances or inductances combined in sequence or in parallel. Bridge balancing is to adjust the parameters of the four arms to bring the potential difference between points C and D to be zero. It is:

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4} \tag{2}$$

Now, the modulus and arguments of both sides of the complex equation must equal, yielding

$$\frac{|Z_1|}{|Z_2|} = \frac{|Z_3|}{|Z_4|} \tag{3}$$

$$\varphi_1 + \varphi_4 = \varphi_2 + \varphi_3 \tag{4}$$

It can be seen that both impedance and phase angle must satisfy specific conditions to bring an AC electrical bridge to balance. This is the main difference between AC and DC electrical bridges.

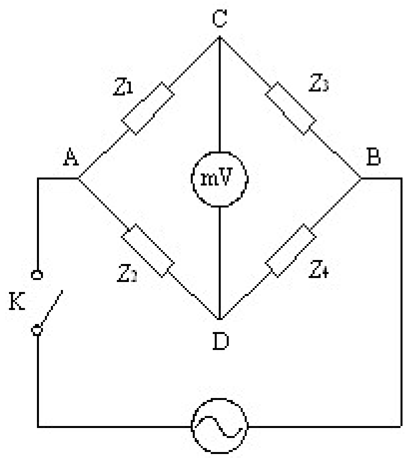

Figure 5 Basic AC electrical bridge

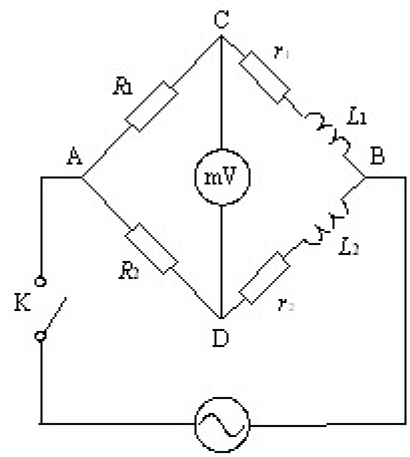

Figure 6 RL AC electrical bridge

This experiment adopts a RL AC bridge, as shown in Figure 6, where the input signal source is provided by a signal generator. An appropriately higher frequency is preferred in experiment. In these figures, *w* is the angular frequency of the input signal, Z_1 and Z_2 are pure resistances, Z_3 and Z_4 are inductances (including the linear resistances r_1 and r_2 of the inductances). The complex impedances are:

$$Z_1 = R_1,\ Z_2 = R_2,\ Z_3 = r_1 + j\omega L_1,\ \ Z_4 = r_2 + j\omega L_2 \tag{5}$$

When the electrical bridge is balanced, we have:

$$R_1(r_2 + j\omega L_2) = R_2(r_1 + j\omega L_1) \tag{6}$$

Let the real part and the virtual part equal, respectively, we get:

$$r_2 = \frac{R_2}{R_1} r_1, \quad L_2 = \frac{R_2}{R_1} L_1 \tag{7}$$

By selecting suitable electric components, the electrical bridge can be balanced in the absence of a ferrite sample in the path. If a ferrite sample is put into one inductance coil, the inductance of the corresponding coil is changed and hence the bridge becomes unbalanced. As temperature reaches a certain value, ferromagnetism of the ferrite sample is changed to paramagnetism. The potential difference between points C and D decreases sharply and tends to zero. Again, the bridge becomes balanced. The temperature of this mutation point corresponds to the Curie temperature.

This experiment is to acquire the relationship curve between the bridge output voltage and the temperature applied to the ferrite sample for the determination of the Curie temperature at the mutation point. As the location of the ferrite sample is not the same as the temperature sensor, there exist errors between the readout and the actual temperature of the sample. For this reason, it is preferred to heat the sample slowly in order to achieve a dynamic temperature balance. The experiment can also explore the influence of heating and cooling rates on experimental accuracy.