2. Theory

A. Hysteresis Phenomenon of Ferromagnetic Material

The magnetization process of ferromagnetic materials is so complex that normally it is studied by measuring the relationship of magnetic field strength H versus magnetic induction intensity B of the magnetization field.

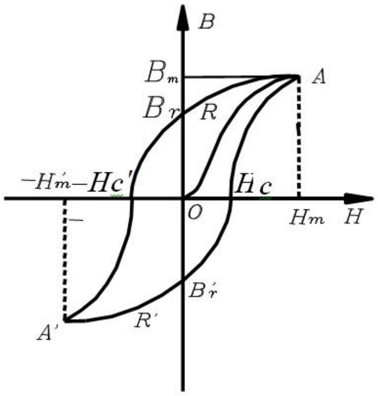

Figure 1 Hysteresis loop and magnetization curve

As shown in Figure 1, if there is no magnetization field in a ferromagnetic material, both H and B are zero, corresponding to the coordinate origin O in the B-H graph. As the magnetic field strength H, increases, the magnetic induction intensity B also increases, but not linearly with H. When H increases to a certain value, B no longer increases or increases very slowly indicating that the magnetization of the material has reached saturation. H_m and B_m are the saturated magnetic field strength and induction intensity, respectively, as shown by point A in Figure 1.

If H is gradually reduced to zero, B decreases accordingly. However, the trajectory of the H-B curve does not follow the original curve (AO) to return to point O; instead it follows another curve AR to reach to point B_r suggesting residual magnetism still remained in the ferromagnetic material even when H drops to zero. However, if magnetic field H is reversed and gradually increased until $H=-H_m$, the curve reaches point A' (reversal saturation point). Now reduce the magnetization field back to $H=0$ and then change magnetic field H to positive while gradually increasing to saturation (H_m). Curve $A'R'A$ that is symmetric with ARA' should be achieved. The closed loop from point A via ARA', $A'R'A$ back to point A is called the magnetic hysteresis loop of a ferromagnetic substance (saturated magnetic hysteresis). The intersection points of the curve with H axis, H_0 and H'_0, are called the coercivity, while the intersection points on B axis, B_r and B'_r, are known as the residual magnetic induction intensity.

B. Measurement of Hysteresis Loop and Magnetization Curve

To measure the hysteresis loop and magnetization curve, a set of magnetization coil is usually wound onto a sample under test that is made of ferromagnetic material, opened with a uniform and narrow gap. Initially, a maximum magnetization current I_m should be supplied to conduct "magnetic exercise" to the sample by repeatedly reversing the current I_m many times. Then the magnetization current I_k is reduced step by step while measuring the corresponding magnetic induction intensity B_k at the central area of the gap using a digital Teslameter to get a hysteresis loop, as shown in Figure 2. By connecting all the vertexes of these hysteresis loops as well as the coordinate origin, the generated curve is called the basic magnetization curve of the sample.

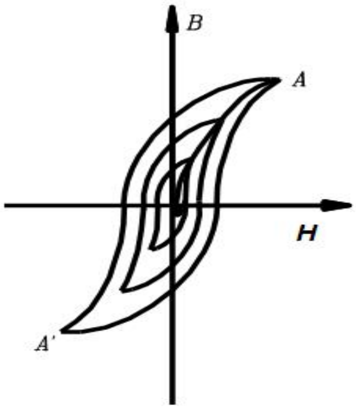

Figure 2 Basic magnetization curve

Requirements for the measurement of magnetization curve and hysteresis loops are:

a) The measurement should start from the original state (H=0, B=0), and hence the sample needs to be demagnetized to eliminate residual magnetism prior to measurement.
b) To get a symmetrical and stable hysteresis loop, sample must be repeatedly magnetized, i.e. "magnetic exercise". This can be done by keeping the highest magnetization current (the maximum current for the present loop) while reversing current flow many times.

For a ring-type sample, if the magnetization current in the coil is I, the magnetic field strength H of the magnetization field is:

$$H = NI / \bar{\ell} \tag{1}$$

where N is the turns of the magnetization coil, and $\bar{l}$ is the average magnetic path length of the sample. The unit of H is A/m.

To measure the magnetic induction intensity B in the sample, a narrow gap is opened in the sample that is in the magnetic path. Empirically, if the section dimensions of the sample in both length and width directions and the average magnetic path length are much larger than the gap width, e.g. 8-10 times, a large region in the gap is guaranteed to have a uniform magnetic field. Under such case, the measured magnetic induction intensity B can accurately represent the true magnetic field in the middle region of the sample.

C. Correction of Gap Influence

For a ring-type sample, if the average magnetic path length is $\bar{\ell}$, the gap width is l_g, the turns of the magnetization coil are N, and magnetization current is I, then we have:

$$H\bar{\ell} + H_g \ell_g = NI \tag{2}$$

where H_g is the magnetic field strength in the gap.

In general, the two magnetic induction intensities, i.e. in the core (B) and in the gap (B_g), are different. However, in the case of a narrow gap, the dimensions of the core cross-section and the average magnetic path length are much larger than the gap, so we have:

$$B_g \cdot S_g = BS \tag{3}$$

where S_g and S are the cross-sections of the gap and the core, respectively. Under these given conditions, $S_g \approx S$, so $B=B_g$. Therefore, the measured magnetic induction intensity B_g in the gap is equal to B in the core. Also, in the gap,

$$B_g = \mu_0 \mu_r H_g \tag{4}$$

where μ_0 is the permeability in vacuum, and μ_r is the relative magnetic permeability. In the gap, $\mu_r=1$, so $H_g=B/\mu_0$. Thus, the magnetic field strength H and the magnetic induction intensity B in the core, and the ampere-turn number NI meet the following equation:

$$H\bar{\ell} + B\ell_g / \mu_0 = NI \tag{5}$$

The sample under test should be made to satisfy $H\bar{\ell} >> B\ell_g / \mu_0$, so $H \approx NI$. If this condition cannot be met, Eq. (5) can be used to correct the H value in magnetization curve measurement.