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An Improved Method for Determining the DC Magnetization Curve Using a Ring Specimen

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***Abstract* -- When the dc magnetization curve (B–H) of non-oriented material is measured in a ring specimen, there is an intrinsic error due to the assumption that the mean magnetic path length is equal to the mean geometric path length.**

In this paper, a new method for determining the B–H curve accurately is proposed. The validity of the method is verified by experiments.

I. INTRODUCTION

When the dc magnetization curve (B–H) is measured using a ring specimen, the mean geometric path length L_c is used instead of the mean magnetic path length L_a, because L_a is unknown. Therefore, the B–H curve obtained has an error, and it may be affected by the ratio γ of the outside radius to the inside radius and the shape of the B–H curve of the specimen. The IEC Standard specifies that γ should be less than or equal to 1.1 [1]. But it is difficult to make such a large specimen. If an unannealed specimen with a small width is used, the flux distribution may be affected by the stresses induced due to cutting [2]. Therefore, the specimen must be large and it becomes difficult to handle.

In this paper, the effects of γ and the shape of the B–H curve on the error are discussed, and a new method for determining the B–H curve accurately using a numerical calculation is explained in detail. The effectiveness of the proposed method is also verified by experiments.

II. ERROR OF CONVENTIONAL METHOD

If we want to determine the B–H curve using a ring specimen as shown in Fig.1, the flux density B(R) at a point P on the radius R and the corresponding magnetic field strength H(R) should be measured. Although H(R) can be calculated from Eq.(1),

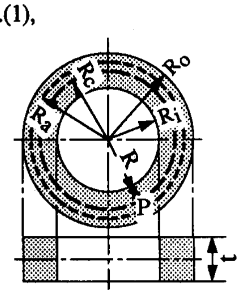

Fig.1 Ring specimen.

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$$H(R) = NI / 2\pi R \tag{1}$$

where NI is the applied magnetomotive force (MMF), B(R) cannot be measured, but the average flux density B_a, can be measured using a search coil, as defined by Eq.(2),

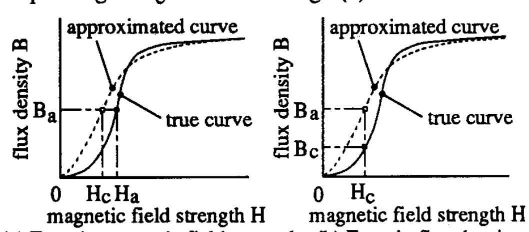
$$B_a = \frac{1}{R_o - R_i} \int_{R_i}^{R_o} B(R)\, dR \tag{2}$$

where R_o and R_i are the outside and inside radii.

There are two kinds of approximation methods for B or H in the conventional method as follows:

1) Instead of the magnetic field strength H_a on the mean magnetic path corresponding to B_a, the magnetic field strength H_c on the center radius $R_c(=(R_i+R_o)/2)$ is used as the approximate magnetic field strength corresponding to B_a as shown in Fig.2(a).

2) Instead of the flux density B_c on the center radius R_c, the flux density B_a is used as the approximate flux density corresponding to H_c as shown in Fig.2(b).



(a) Error in magnetic field strength (b) Error in flux density

Fig.2 Approximation methods for B-H curve.

If the true B–H curve is known beforehand, the error ε_H of the magnetic field strength corresponding to the case *1)* mentioned above, and the error ε_B of the flux density corresponding to the case *2)* which are defined by Eqs.(3) and (4) are calculated as shown in Figs.3(a) and (b).

$$\varepsilon_H = (H_c - H_a) / H_a \times 100\ (\%) \tag{3}$$

$$\varepsilon_B = (B_a - B_c) / B_c \times 100\ (\%) \tag{4}$$

Fig.3 is obtained for the steel (SS400). The errors ε_H and ε_B are affected by the ratio γ which is defined by Eq.(5) and the shape of the B-H curve.

$$\gamma = R_o / R_i \tag{5}$$

III. NEW METHOD FOR DETERMINING THE B–H CURVE

In the newly developed method proposed here, B_c in Fig.2(b) is obtained directly using Eq.(2) in order to eliminate the error of the conventional method. The applicability of the

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method for obtaining H_a in Fig.2(a) is discussed later in this section.

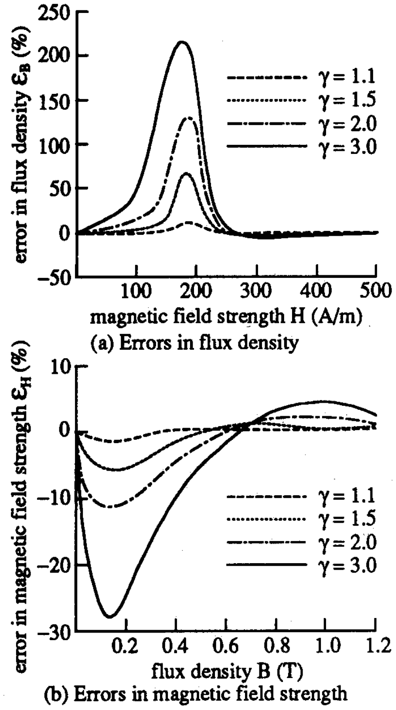


Fig.3 Errors related to conventional method (steel(SS400)).

For simplicity, it is assumed that the B–H curve can be approximated by linear interpolation. Fig.4 shows an example of the B–H curve which is measured by applying four kinds of MMF's. Fig.5 shows the part of B–H curve related to the 2nd MMF. H_{ik}, H_{ck} and H_{ok} are the magnetic field strengths for the k-th MMF on the radii R_i, R_c and R_o respectively. B_{ik}, B_{ck} and B_{ok} are the flux densities corresponding to H_{ik}, H_{ck} and H_{ok}. B(R) is interpolated as follows:

$$B(R) = \frac{H(R) - H_L}{H_U - H_L}(B_U - B_L) + B_L \tag{6}$$

where H_L and H_U are the magnetic field strengths on the lower and upper boundaries for a piecewise linear interpolation.

The last m-th MMF should be chosen to be above the saturation magnetic field strength H_s as shown in Fig.4. This is due to the need to know the flux density B_{im} (This corresponds to B_{i4} in Fig.4) at the end point of the B–H curve in order to interpolate B_{i3} in Fig.4. B_{im} is calculated by the following equation:

$$B_{im} = \mu_0 H_{im} + M_s \tag{7}$$

where μ_0 is the permeability of free space. M_s is the saturation magnetization which is known.

For example, B(R) between B_{c1} and B_{c2} shown in Fig.5 is represented as follows:

$$B(R) = \frac{H(R) - H_{c1}}{H_{c2} - H_{c1}}(B_{c2} - B_{c1}) + B_{c1} \tag{8}$$

As B(R) between B_{o2} and B_{i2} are represented by three lines as shown in Fig.5, the integral in the right-hand side of Eq.(2) is separated into three parts as follows:

$$\int_{R_i}^{R_o} B(R)\,dR = S_\alpha + S_\beta + S_\gamma \tag{9}$$

where S_α, S_β and S_γ are the integrated results, which correspond to the hatched parts ▩, ▧ and ▒ shown in Fig.5 respectively. For example, S_β is calculated from Eqs.(1), (2), (8) and (9) as follows:

$$S_\beta = \frac{NI_2}{2\pi\,(H_{c2} - H_{c1})}\left\{\left(-\ln\frac{H_{c2}}{H_{c1}} + \frac{H_{c2}}{H_{c1}} - 1\right)B_{c1} + \left(\ln\frac{H_{c2}}{H_{c1}} + \frac{H_{c1}}{H_{c2}} - 1\right)B_{c2}\right\} \tag{10}$$

When H_a is chosen as the unknown variable, the radius R_a of the mean magnetic path corresponding to H_a is also unknown. As a result, the equation of H_a like Eq.(10) cannot be obtained. Therefore, H_a is not chosen as the unknown variable.

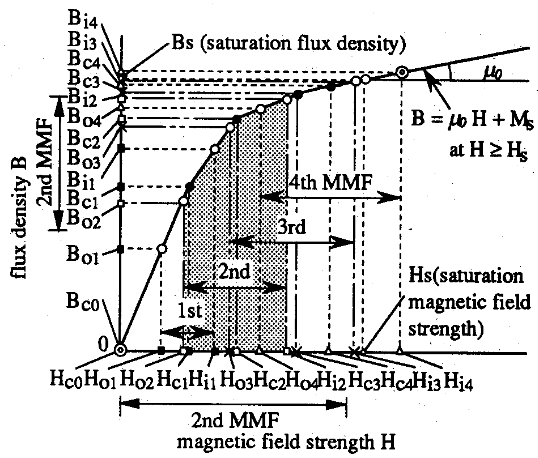


Fig.4 B-H curve measured by applying four excitations (m=4).

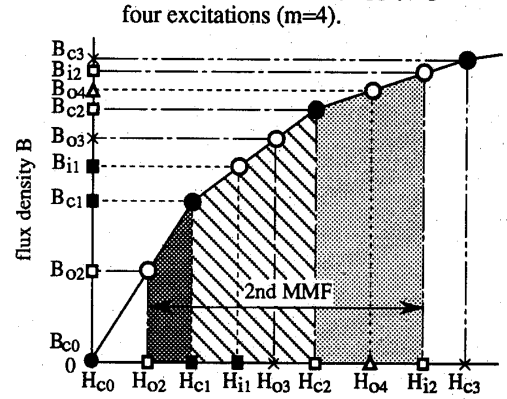


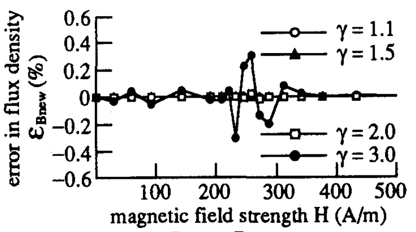
Fig.5 Interpolation of B and H in the case of k=2.

By calculating Eq.(2) for all MMF's (four kinds of MMF's in this case) in the same way mentioned above, the following matrix equation, in which the number of equations is equal to the number of the applied MMF's, is finally obtained for the case of Fig.4:

$$\begin{bmatrix} A_{11} & A_{12} & 0 & 0 \\ A_{21} & A_{22} & A_{23} & 0 \\ A_{31} & A_{32} & A_{33} & A_{34} \\ 0 & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{Bmatrix} B_{c1} \\ B_{c2} \\ B_{c3} \\ B_{c4} \end{Bmatrix} = \begin{Bmatrix} B_{a1} \\ B_{a2} \\ B_{a3} \\ B_{a4} \end{Bmatrix} \quad (11)$$

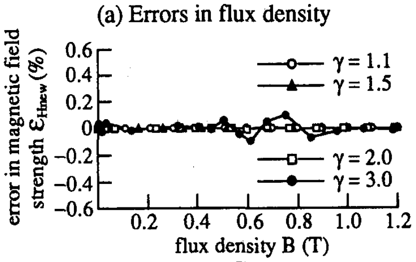
where B_{ak} is the average flux density for the k-th MMF shown in Eq.(2), and this is the known value. A_{kj} is the coefficient of B_{cj} in Eq.(11) for the k-th MMF. When the matrix equation is solved, the unknown variables B_{ck} (k=1,--- ,m) are obtained simultaneously.

Fig.6 shows the errors related to the new method obtained for the steel(SS400). Even in the case of γ=3.00, it is found that the errors of the new method are very small compared with those of the conventional method.



$$\varepsilon_{Bnew} = \frac{B_{new} - B_{true}}{B_{true}} \times 100(\%)$$

(a) Errors in flux density



$$\varepsilon_{Hnew} = \frac{H_{new} - H_{true}}{H_{true}} \times 100(\%)$$

(b) Errors in magnetic field strength

Fig.6 Errors related to new method (steel(SS400)).

IV. EXPERIMENTAL VERIFICATION

A. Preparation of Specimens

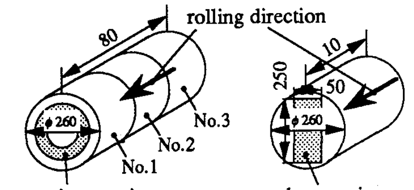
In order to examine the effect of the ratio γ on the accuracy of the estimated B–H curve, three kinds of ring specimens shown in Table 1 are tested. The ratios γ are chosen as 1.10, 1.36 and 3.00 respectively. The specimens are made of carbon steel which has a weak anisotropy. In order to avoid an additional error due to the anisotropy, the specimens are cut from one lot as shown in Fig.7, so that the flux flows perpendicular to the rolling direction. A bar specimen shown in Fig.7(b) is prepared for the permeameter method for measuring the dc magnetic properties of solid steels (Type A in IEC Publication 404-4, N63) [1]. All specimens are annealed for 1.5 hours at about 650°C in nitrogen (N_2). The accurate final reprocessing is done after annealing.

B. Results and Discussion

Fig.8 shows the B–H curves obtained by the proposed method, the conventional method and the permeameter method [1]. In the case of γ=3.00, the error ε_B related to the conventional method was about 40% at H=100(A/m). The value is smaller than that for the case of SS400 shown in Fig.3(a). If the squareness of the B–H curve is near 1.0, the error may be much larger.

Table 1 Ring specimens measured

No.	$\gamma = R_o/R_i$	size (mm)		
		R_i	R_o	t
1	1.10	61.5	67.5	15
2	1.36	16.5	22.5	15
3	3.00	22.5	67.5	15



ring specimen (a) Ring specimen (15mm thick)

bar specimen (b) Bar specimen (5mm thick)

Fig.7 Cutting method of specimens.

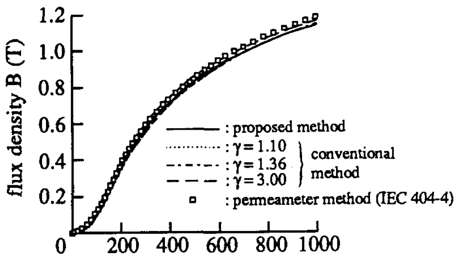


Fig.8 B-H curves obtained by various methods (steel(S25C)).

V. CONCLUSIONS

The effects of the shape of the B–H curve and the ratio of the outside radius to the inside radius on the error of the measured B–H curve are discussed. A new method for determining a dc magnetization curve accurately is proposed. The validity of the proposed method is also verified by experiments.

Experimental investigation should be continued to clarify the error of the conventional method for various kinds of specimen with different curve squareness.

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