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MEASUREMENT OF MAGNETIC CHARACTERISTICS ALONG ARBITRARY DIRECTIONS OF GRAIN-ORIENTED SILICON STEEL UP TO HIGH FLUX DENSITIES

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***Abstract* - A new technique for measuring B-H curves of grain-oriented silicon steel along arbitrary directions has been developed. As the control of waveform is not necessary in the new technique, it is possible to measure B-H curves up to high flux densities which are required for calculating flux distribution using the finite element method.**

1. INTRODUCTION

The flux distributions in transformer cores made of grain-oriented silicon steel have been analyzed using only B-H curves in the rolling and transverse directions[1]. But the magnetic characteristic along the magnetic hard axis cannot be represented by this method as shown in Section 2. Therefore, the flux densities at corners of transformer cores calculated by using the conventional method, for example, become unacceptably high[2]. It is necessary to measure precisely the B-H curves along arbitrary directions up to high flux densities, in order to analyze the flux distribution accurately.

It was difficult, however, to measure such B-H curves by the conventional measuring methods[3-8], because of the spread of flux from the specimen and the distortion of flux waveforms.

In this paper, the magnetic circuit of the measuring equipment is improved. A new method of excitation without waveform control is conceived. As an example, the B-H curves of highly grain-oriented silicon steel are measured up to high flux densities.

2. PROBLEMS OF CONVENTIONAL MODELLING METHOD OF ANISOTROPIC MAGNETIC CHARACTERISTICS

The magnetic field strengths, H_R and H_T, in the rolling (R) and transverse (T) directions are functions of flux densities, B_R and B_T, in the respective directions as shown in (1).

$$\left.\begin{array}{l} H_R = f_R\,(B_R,B_T) \\ H_T = f_T\,(B_R,B_T) \end{array}\right\} \quad (1)$$

In the conventional method[1], (2) has been used instead of (1).

$$\left.\begin{array}{l} H_R = f_R^*(B_R) \\ H_T = f_T^*(B_T) \end{array}\right\} \quad (2)$$

Fig.1 shows equi-H curves obtained from above equations. The solid lines are obtained from (2). The angle θ_2 shows the easiest direction of magnetization at the magnetic field strength of 2H. But the magnetic easiest direction should be the rolling direction (θ_2=0). The dashed lines are obtained from (1). In this case, the easiest and hard axes are the R- and θ_2'(≒50°)-directions and these dashed lines denote

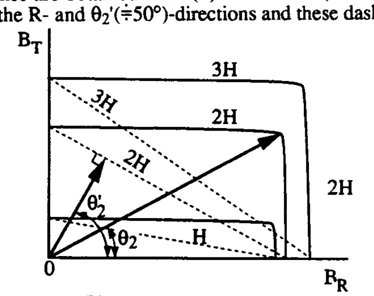

Fig.1 B_R- B_T curves.

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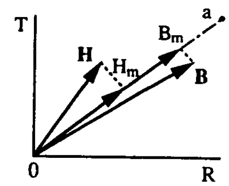


Fig.2 Directions of **B** and **H**.

denote the magnetic anisotropy exactly. That is the reason why we need B-H curves along arbitrary directions.

In the conventional measurement using a single sheet tester[9] in which the specimen is cut in arbitrary directions deviated from the rolling direction, the flux density B_m measured by the B-coil and the magnetic field strength H_m measured by the H-coil are not equal to $|\mathbf{B}|$ and $|\mathbf{H}|$ as shown in Fig.2. Because the directions of **B** and **H** are not coinside with the longitudinal direction $\overline{0a}$ of the specimen due to the demagnetizing fields of magnetic poles which occur at the edge of the specimen. Therefore, equipment should be developed to measure precisely B-H curves in arbitrary directions.

3. IMPROVEMENT OF MEASURING EQUIPMENT

Fig.3 shows the overview of our measuring equipment. The double (upper and lower) yokes are used so that the flux distribution in the specimen becomes symmetrical. The two magnetic circuits are separated from each other in order to avoid the mutual influence. The positions of the exciting windings should be as near as possible to the specimen in order to avoid leakage flux. A fairly large square specimen (150×150 mm) is used to avoid the effect of domain size.

The laminated auxiliary yokes ① and the auxiliary yokes ② made of single sheet are used so that the flux does not spread from the specimen as shown in Fig.4. The single sheet yokes ② are butt-jointed to the specimen as shown in Fig.4 in order to make a small gap to restrain the flux Φ_2 which tends to spread from the specimen, and not to increase VA so much. The single sheet yokes ② are

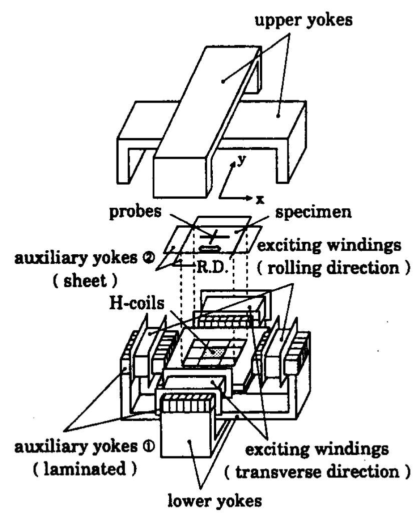


Fig.3 Measuring equipment.

sandwiched between laminated yokes ① . If the overlap length between yokes ① and ② is small, the magnetic resistance is increased, and if it is large, the leakage flux is increased. Then, the overlap length between yokes ① and ② is chosen to be 3mm. The laminated auxiliary yokes ① are used to restrain the flux Φ_2 which is perpendicular to the lamination as shown in Fig.4. The functions of the single sheet auxiliary yokes ② are as follows: The magnetic resistance for the main flux Φ_1 is small and that for the flux Φ_2 is large.

In order to determine the sizes of B- and H-coils, the uniformity of the distributions of **B** and **H** vectors in the specimen are measured and calculated. The distributions of **B** and **H** are nearly uniform within 40×40 mm. Therefore, the sizes of the B- and H-coils are determined as shown in Figs.5 and 6. The modified probe method[10] is used for measuring flux density instead of the ordinary search coil in order to avoid the disturbance due to holes, and the so-called "two H-coil method" [9] is adopted in both directions as shown in Fig.5. Both H-coils which measure the magnetic fields in the rolling and transverse directions are wound on the same epoxy glass plate in order to neglect the angle error between the two H-coils as shown in Fig.6.

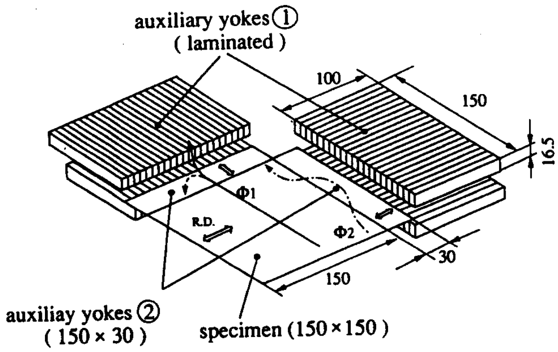


Fig. 4 Role of auxiliary yokes (flux Φ_2 is restrained).

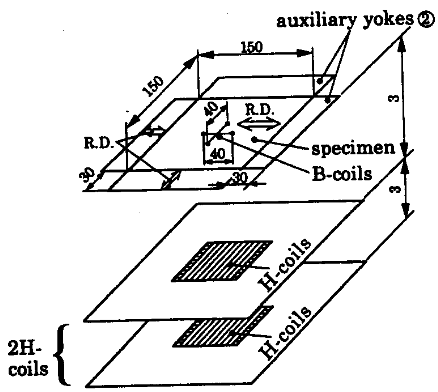


Fig.5 B-and H-coils.

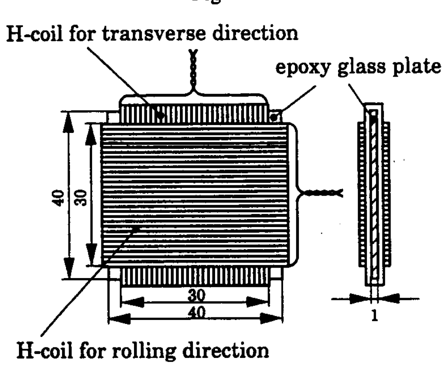


Fig.6 Construction of H-coils.

4. NEW EXCITATION METHOD

In this section, whether the B-H curves can be measured without waveform control is discussed.

Table I denotes the classification of controlling methods of B and H waveforms and the direction of magnetization. Examples of loci of **B** and **H** for each controlling method are shown in Fig.7. θ_B and θ_H are the angles of **B** and **H** vectors measured from the rolling direction. It is impossible to control both **B** and **H** waveforms to be sinusoidal as shown in Table I and Fig.7(a) from the physical point of view. The new exciting method proposed here is the method D in which the waveforms and the directions of excitation are not controlled.

Fig.8 shows an example of the comparison of B-H curves for a 0.3 mm thick highly grain-oriented silicon steel (AISI : M-0H) which are measured by using the new method D and the method B-1, in which the angle θ_B is controlled to 30°. In the example shown in Fig.8, the difference between the two measured curves is within 3% for $|B|>1.0$T. As the differences in other examples are also less than 3%, the new method D is acceptable.

5. MEASURED RESULTS

Figs.9 and 10 show the B-H curves obtained for highly grain-oriented silicon steel (AISI: M-0H) of which the thickness is 0.3 mm. In the case of Fig.9, the relationship between the amplitudes $|B|$ and $|H|$ of **B** and **H**, and that between the angle θ_H and $|H|$ are shown. In

Table I Controlling methods of B and H waveforms

		B		*H*	
method		θ_B	waveform	θ_H	waveform
A		cont.	sinu.	cont.	sinu.
B	1	cont.	sinu.	uncont.	uncont.
	2	cont.	uncont.	uncont.	uncont.
C	1	uncont.	uncont.	cont.	sinu.
	2	uncont.	uncont.	cont.	uncont.
D		uncont.	uncont.	uncont.	uncont.

sinu. : sinusoidal, cont. : controlled, uncont. : uncontrolled

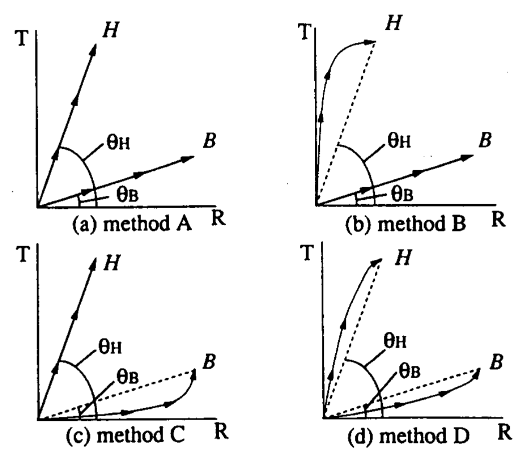


Fig. 7 Loci of flux density and magnetic field strength vectors in various exciting methods.

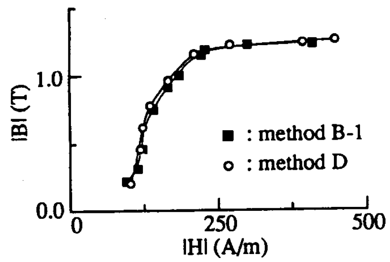
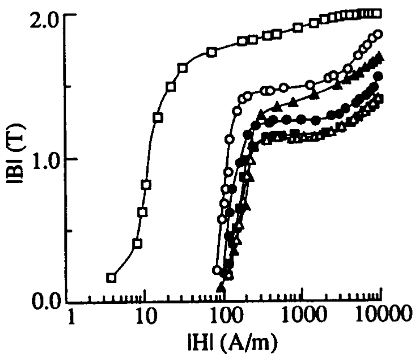
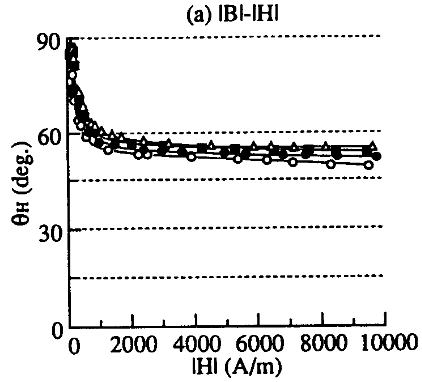


Fig. 8 Comparison of B-H curves (θB=30°, AISI : M-0H).



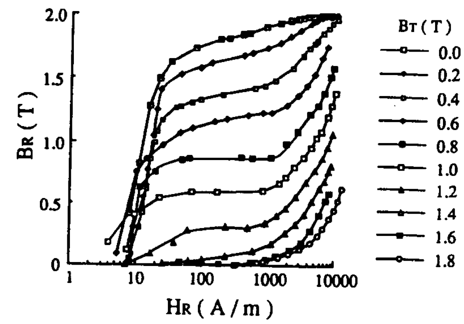
(a) |B|-|H|



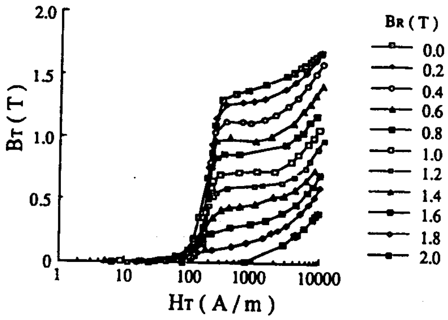
(b) θH-|H|

□: θB = 0 (deg.)   ■: θB = 45 (deg.)
○: θB = 15 (deg.)   △: θB = 60 (deg.)
●: θB = 30 (deg.)   ▲: θB = 90 (deg.)

Fig.9 B-H curves of which the parameters are θB.



(a) rolling direction



(b) transverse direction

Fig.10 B-H curves of which the parameters are B_T and B_R.

the case of Fig.10, the relationship between components B_R and H_R of **B** and **H**, and that between components B_T and H_T are shown. Using the new measuring method, B_R=2.0T and B_T=1.7T can be obtained.

It is important to investigate which representing method for B-H curves is suitable for the numerical analysis. It will be reported in another paper.

6. CONCLUSIONS

It is shown that B-H curves in arbitrary directions can be measured up to high flux densities.

The analysis of flux distribution in cores made of grain-oriented silicon steel using the B-H curves in arbitrary directions, and the comparison with measurements will be reported in another paper[11].The uncertainty of the B and H measurements should be examined systematically in order to obtain accurate results. AC iron losses along arbitrary directions, and B-H curves and iron losses under rotating flux should be investigated in the future.

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