Improvements of single sheet testers for measurement of 2-D magnetic properties up to high flux density

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Abstract — **Due to structural limitation, the currently proposed apparatus based on a single sheet tester (SST) cannot measure magnetic properties along arbitrary directions (so-called 2-D magnetic properties) of silicon steel at high flux densities. In this paper, significant improvements are carried out on magnetizing windings and auxiliary yokes of a double-excitation type of SST. Furthermore, crosswise overlapped H-coils are introduced so that even an ordinary single-excitation type of SST can be applicable to the measurements of 2-D properties. It is demonstrated that 2-D magnetization property up to 1.9 T can be measured by using the newly developed SST's.**

Index Terms — **Crosswise overlapped H-coils, magnetic anisotropy, permeability tensor, silicon steel, single sheet tester, 2-D magnetic properties**

I. INTRODUCTION

When magnetic anisotropy of silicon steel is investigated, measurement of 2-D magnetic properties is required. Various single sheet testers (SST's) have already been proposed [1]-[4]. However, the 2-D properties at high flux densities cannot be measured by using those SST's due to structural limitation on magnetizing windings. In order to overcome this difficulty, a new type of SST is developed. It has crosswise overlapped magnetizing windings and nearly completely closed magnetic paths are realized in both the rolling direction (RD) and the transverse direction (TD). Furthermore, an ordinary SST for the measurement of 1-D properties is improved by introducing crosswise overlapped H-coils. Then, it can also be used to measure the 2-D properties.

In this paper, the constructions and principles of newly proposed 2-D SST's are described, and the 2-D magnetization properties measured under various flux conditions are illustrated. Furthermore, results obtained by both SST's are compared to validate themselves.

II. SINGLE SHEET TESTERS FOR MEASUREMENT OF 2-D MAGNETIC PROPERTIES

Two different types of SST are newly developed based on entirely different concepts.

A) Double-Excitation Type (DET)

Figure 1 shows the schematic structure of an SST having two magnetizing windings for RD and TD. In order to separate magnetic circuits for RD and TD, vertical double-yoke type is adopted for each circuit [4]. As a specimen, a square single sheet of 150 mm×150 mm is required. Rotating flux condition as well as alternating one in arbitrary directions can be satisfied, because the amplitude and direction of flux density can be controlled by using two windings. Remarkable structural features are the crosswise overlapped windings and various auxiliary yokes shown in Fig. 2, which are prepared to compose nearly completely closed magnetic paths in both RD and TD.

As shown in Fig. 1, the winding for TD is set inside that for RD to increase the maximum flux density. The number of turns of each winding is 440 (8 layers). Conductor with rectangular cross section of 3 mm×1 mm is used to keep slits for auxiliary yokes. The maximum magnetic field strength which can be generated is about 32 kA/m.

As shown in Fig. 2, some sheets (JIS 35P125, JIS: Japanese Industrial Standards) in laminated yokes (35A270) are inserted into the windings through slits. The laminated yokes are connected to main yokes (30G150). Another sheet yoke is butt-lapped on each side of specimen to keep the flux distribution in the specimen uniform [4]. Two kinds of sheet

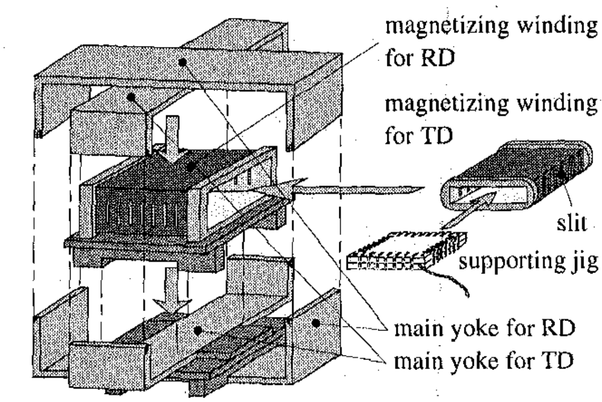

Fig. 1. Schematic structure of double-excitation type of 2-D SST (DET).

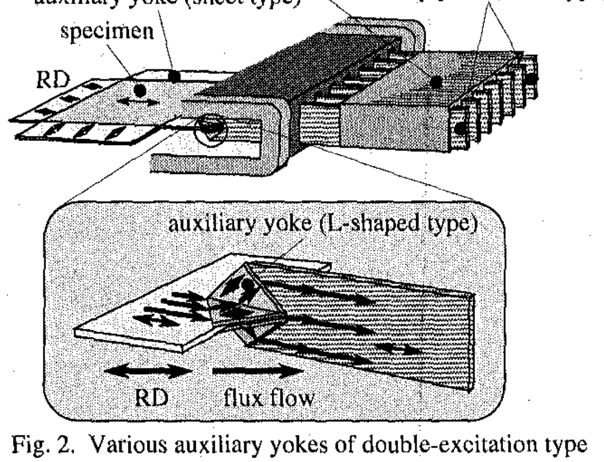

Fig. 2. Various auxiliary yokes of double-excitation type of 2-D SST (DET).

Manuscript received March 5, 1999.
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yokes are connected by L-shaped yokes (23P100) to get smooth flux flow as shown in Fig. 2. In order to set up SST easily, L-shaped yokes are adhered to a supporting jig shown in Fig. 1. All auxiliary yokes are annealed after cutting and bending.

The flux density B is detected in 40 mm×40 mm region at the center of specimen by using probes [5] equivalent to single-turn search coils, which are put on the specimen and require no hole. The magnetic field strength H is detected in 40 mm×30 mm region by using the double H-coils. In each H-coil, the number of turns for RD is 3000 and 750 for TD. The reason why the number of turns for RD is larger than that for TD is that H in RD is less than H in TD.

B) Single-Excitation Type (SET)

Figure 3 shows the strip specimen and a part of yoke of single-excitation type of 2-D SST. The horizontal double-yoke type is adopted. Unlike an ordinary SST to measure 1-D properties, crosswise overlapped H-coils shown in Fig. 4(b) are introduced. Several strip specimens are necessary, of which the cutting directions are different from RD. It is required that the flux should flow along the cutting direction so that B can be detected by using an ordinary B-coil shown in Fig. 4(a). When this requirement is satisfied, the components of $\boldsymbol{B}$ in RD and TD can be calculated accurately. Due to this requirement, it is very difficult to measure 2-D properties near RD. Because of the single excitation, measurements are limited under the alternating flux condition. In constructing this type, it is enough to replace only H-coils in an ordinary SST. This is a big advantage of SET compared with DET.

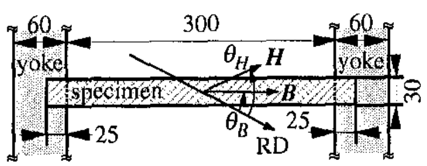
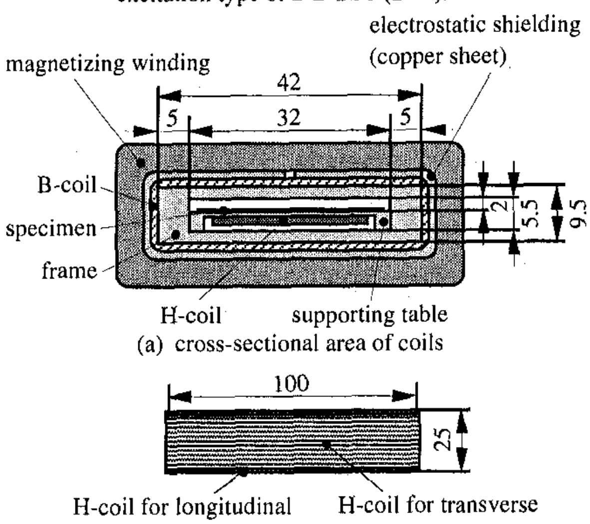


Fig. 3. Strip specimen and a part of yoke of single-excitation type of 2-D SST (SET).



(a) cross-sectional area of coils

(b) H-coil

Fig. 4. Configuration of coils of single-excitation type of 2-D SST (SET).

The number of turns of winding is 1465 (5 layers). The maximum H is about 40 kA/m. Conductor with circular cross section of ϕ0.85 mm is used to wind itself densely.

As a yoke, 20 sheets of grain-oriented silicon steel (35G155) are laminated.

A B-coil of 340 turns is wound on a frame for the winding in the range of 200 mm. The longitudinal component of $\boldsymbol{H}$ in 200 mm×25 mm region and its transverse component in 20 mm×200 mm region are detected by using two crosswise overlapped H-coils shown in Fig. 4(b) which are arranged in the longitudinal direction. In each H-coil, the number of turns for the longitudinal direction is 830 and 166 for the transverse direction.

III. Parameters to be Evaluated in 2-D Magnetization Property

When material has the magnetic anisotropy, directions of $\boldsymbol{B}$ and $\boldsymbol{H}$ vectors are different with each other as shown in Fig. 5. A general representation of permeability tensor μ [2], which is very useful to model the anisotropy in magnetic field analysis [6], has been proposed by Enokizono as follows:

$$\mu = \begin{bmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{bmatrix} = \begin{bmatrix} \mu_{eff}\cos\theta_{HB} & \mu_{eff}\sin\theta_{HB} \\ -\mu_{eff}\sin\theta_{HB} & \mu_{eff}\cos\theta_{HB} \end{bmatrix}, \qquad (1)$$

where μ_{eff} is B/H. θ_{HB} is $\theta_H - \theta_B$, and θ_B and θ_H are angles of $\boldsymbol{B}$ and $\boldsymbol{H}$ from RD, respectively.

According to the above expression, diagonal entries of μ_{xx} and μ_{yy} are identical. As concerns nondiagonal entries of μ_{xy} and μ_{yx}, only their signs are opposite. Full tensor expression can be given by using two parameters μ_{eff} and θ_{HB}. In the measurements, H and θ_{HB} versus B are evaluated at various θ_B's under the condition of sinusoidal flux waveforms in RD and TD, which can be obtained by using a digital waveform control [7].

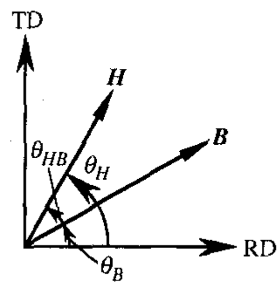


Fig. 5. Parameters to be evaluated in 2-D magnetization property.

IV. Results and Discussion

Figure 6 shows the B-H and B-θ_{HB} curves of grain-oriented silicon steel sheet (JIS 35G165, thickness: 0.35 mm, $W_{17/50}$: ≤1.65 W/kg) measured at 50 Hz under the alternating flux condition by means of DET. It is noted that the material selected is not representative for modern types but is widely used in reactors. $\boldsymbol{H}$ are measured changing B at fixed θ_B. Although B-θ_{HB} curves at θ_B=0 and 90 deg are oscillated due to the measurement error, that is not a problem in the magnetic field analysis, because θ_{HB} can be set at zero essentially at θ_B=0 and 90 deg. It is demonstrated that the 2-D magnetization property up to 1.9 T can be measured by using the proposed SST.

Figure 7 shows the loci of $\boldsymbol{B}$ and $\boldsymbol{H}$ at θ_B=30 deg. It is verified that the alternating flux condition can be satisfied even at high B. Figure 8 shows the loci of $\boldsymbol{B}$ and $\boldsymbol{H}$ under the rotating flux condition. It is understood that elliptic condition as well as circular one can be realized. It is noted that the LEG (Laboratoire d'Electrotechnique de Grenoble) group could measure 2-D properties of a modern type ($W_{17/50}$: ≤ 0.85 W/kg) up to 1.5 T under the circular condition by means of the conventional DET [8].

Figure 9 shows the comparison of the proposed SST's in the B-H and B-θ_{HB} curves under the alternating condition. The slightly large difference is observed in the B-H curve at θ_B=0 deg. In DET, it is very difficult to control the direction of $\boldsymbol{B}$ near RD as shown in Fig. 6(b), because the easy magnetization axis deviates from RD in some degree and its deviation depends on B. Therefore, H at θ_B=0 deg includes the component in TD. The difference is also observed in the B-θ_{HB} curves. This may be resulted from the influence of grain size and sensing area of $\boldsymbol{B}$ which is used for the waveform control. However, it may be concluded that the differences of results measured by means of the proposed SST's are in allowable range.

V. Conclusions

The results obtained are summarized as follows:

(1) Even in the double-excitation type, nearly completely closed paths can be realized in magnetic circuits for both the rolling direction and the transverse direction. Then, the measurable range of flux density is fairly increased under various flux conditions.

(2) In the single-excitation type, the 2-D property under the alternating flux condition can be measured after the fairly simple modification on H-coil in an ordinary SST for the measurement of 1-D property.

(3) 2-D magnetization properties under the alternating flux condition measured by means of both types are in good agreement with each other.

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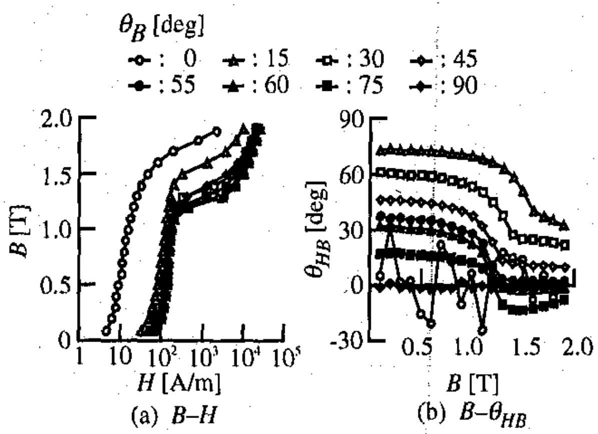

Fig. 6. 2-D magnetization property under alternating flux condition (JIS 35G165, f=50Hz, DET).

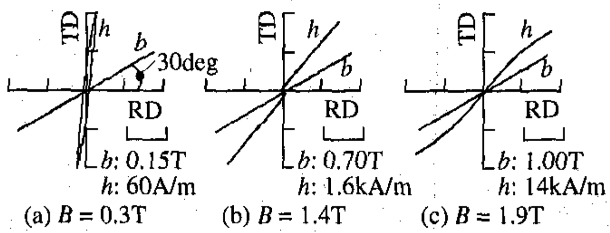

Fig. 7. Loci of flux density and magnetic field strength under alternating flux condition (JIS 35G165, f=50Hz, θ_B = 30deg, DET).

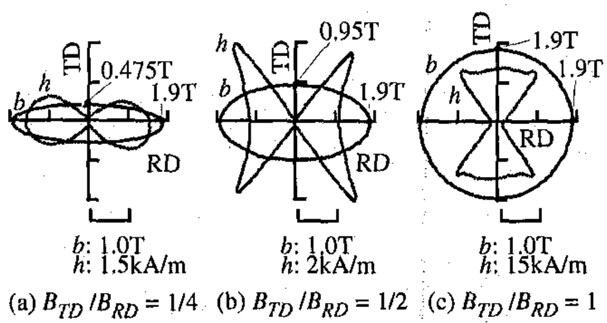

Fig. 8. Loci of flux density and magnetic field strength under rotating flux condition (JIS 35G165, f=50Hz, DET).

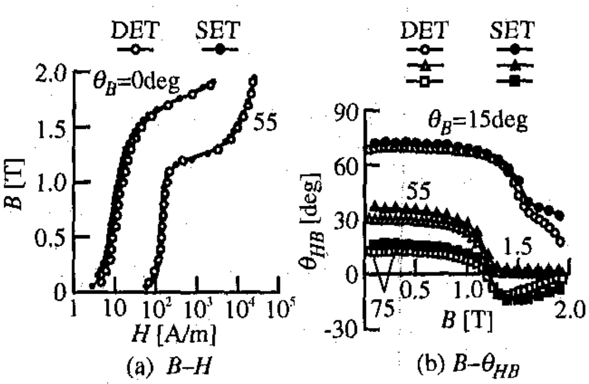

Fig. 9. Comparison between DET and SET of 2-D SST (JIS 35G165, f=50Hz).