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Measurement of Magnetic Properties of Grain-Oriented Electrical Steel Sheet Using 2D Single Sheet Tester

Abstract*. We have already reported the accuracy of measurement of 2D magnetic properties of non-oriented electrical steel sheet using a novel SST. In this paper, magnetic properties under alternating and rotating magnetic flux of grain-oriented sheet are measured. The accuracy of measurement in the case of grain-oriented sheet is examined by comparing the measured results using 2D-SST with those using an ordinary SST under alternating flux excitation. The effect of positioning error of orthogonal B and H coils on measurement accuracy is also discussed.*

Streszczenie. *Oceniono dokładność badania blachy zorientowanej przy wykorzystaniu testera 2D SST. W celu oceny niepewności wyniki porównano z rezultatami otrzymanymi przy wykorzystaniu konwencjonalnego testera SST. Przedyskutowano problem błędu pozycjonowania czujników. (**Pomiary właściwości magnetycznych blachy zorientowanej przy użyciu testera 2D SST**)*

Keywords: grain-oriented electrical steel sheet, alternating magnetic flux, rotating magnetic flux, two-dimensional magnetic properties.
Słowa kluczowe: blacha zorientowana, tester SST.

Introduction

Recently, a miniature and efficient magnetic device is required. When it is miniaturized, the magnetic flux density of the magnetic circuit becomes high. Therefore, a precise measurement at high flux density of electrical steel sheet that is a main material of magnetic device is important. Generally, the magnetic properties are measured by using a single sheet tester (SST), but it can only measure magnetic properties in one direction. In order to analyze magnetic characteristics of magnetic devices, it is necessary to accurately measure magnetic properties of electrical steel sheet in arbitrary directions [1]. We have already developed a novel 2D-SST and reported the accuracy of measurement of 2D magnetic properties of non-oriented electrical steel sheet [2].

In this paper, magnetic properties of grain-oriented electrical steel sheet under alternating magnetic flux and rotating magnetic flux are measured using our system. The accuracy of measurement is also examined.

2D-SST (2 dimensional single sheet tester)

Fig.1 shows the measuring equipment. The exciting coils for rolling direction (RD) are covered by those for transverse direction (TD). The dimension of a square specimen used for measurement is 150mm×150mm. Two kinds of specimens, grain-oriented electrical sheet, 30G130, and highly grain-oriented one, 30P100, are measured. The flux density under alternating and rotating flux excitation is increased until 1.8T. By exciting the specimen in the diagonal direction, the uniformity of magnetic field distribution near the center is improved [2]. It is verified that the magnetic field is uniform within 2% deviation in 20mm×20mm area at the center of specimen.

The flux density in the specimen is measured using the so-called modified probe method [3]. Pin holes are made in the insulating coating on the specimen by a needle with 20mm distance. Then, the electrically conductive adhesive is put with lead-out wires into the pin holes as shown in Fig.2. The lead-out wires are twisted in order to avoid inductive pick up. The same lead-out wires are put on other side. Both lead-out wires form a B-coil. The orthogonal H coils is made of 1mm thick plate. Each H coil has 400 turns and has been wound with ϕ0.03mm polyester copper wire. Two H coils [4] are installed on the specimen, as shown in Fig.3.

Investigation of measurement accuracy of 2D-SST

In order to examine the accuracy of 2D-SST in measuring magnetic properties of grain-oriented electrical steel sheet, the measured results using 2D-SST and the ordinary 60mm width SST are compared. Magnetic properties are measured by using 2D-SST under alternating magnetic flux excitation. Magnetic properties in the rolling direction (RD, θ_B =0deg.) and transverse direction (TD, θ_B =90deg.) are measured. Rectangular specimens (60mm×240mm) which are parallel to RD and TD directions are prepared for 60mm width SST. The specimen is processed by wire cut. The 2 H-coils method is used in 60mm width SST. The frequency was 50Hz and 30Hz, and the eddy current loss (W_e) and the hysteresis loss (W_h) are separated by the two frequency method using the measured results at 30Hz and 50Hz.

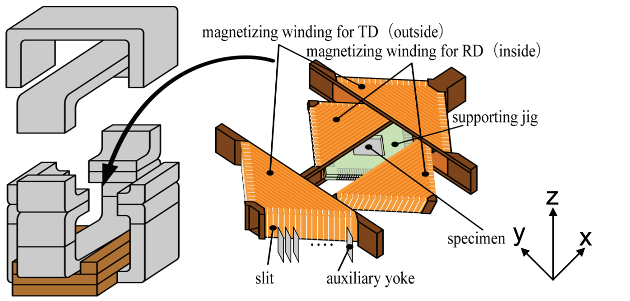
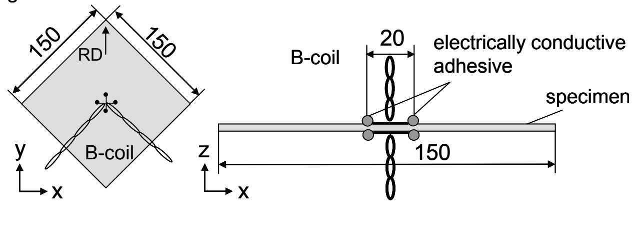
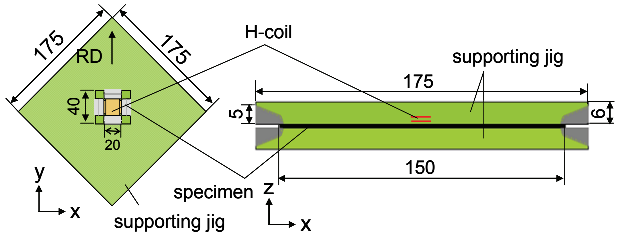


Fig.1. 2D-SST.



(a) upper view (b) side view
Fig.2. B-coils and those setting position.

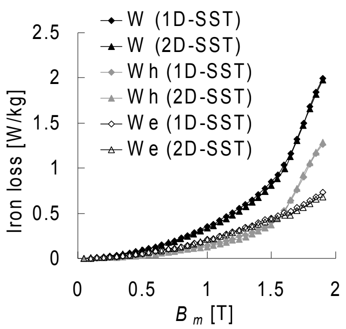


(a) upper view (b) side view

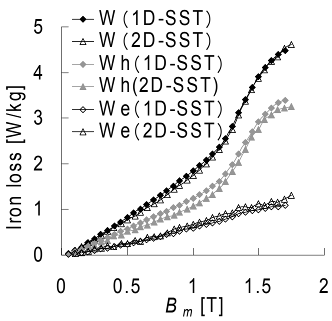
Fig.3. H-coils and those setting position.

Measured results of θ_B =0deg., 90deg. of 30G130 are shown in Fig.4. The whole iron loss (W), the eddy current loss (W_e) and the hysteresis loss (W_h) measured using 2D-SST are almost agree with those of 60mm width SST. But, there is some discrepancy in W_e and W_h at θ_B =90deg. between 2D-SST and 60mm width SST. This may be due to the fact that the effect of stress, which is remained in the specimen, cannot be neglected [5], because the width (=60mm) of specimen is not sufficiently large. Therefore, it is considered that the accuracy of 2D-SST is similar to that of 60mm width SST.

In order to examin the effect of grain on the measured iron losses in three kinds of small areas (20mm×20mm), namely, area A (center of 60mm×240mm specimen), area B (-20mm apart from the center in the longitudinal direction), area C (+20mm apart from the center), the iron losses are measured using 60mm width SST. The H coils with 20mm×20mm and 60mm×120mm measurement areas is used. The B coil with 20mm width, prepared using the modified probe, is put on the specimen in each area. The measured iron losses are shown in Table 1. The discrepancy between measurements is within 10%. Therefore, it can be understood that magnetic properties of the grain-oriented electrical steel sheet can be measured in the measurement area of 20mm×20mm, because the grain size is of the order of mm.



(a) θ_B =0deg.



(b) θ_B =90deg.

Fig.4. Comparison of iron loss of 1D-SST and 2D-SST (50Hz, 30G130).

Table 1. Iron loss measured at various areas (50Hz, 30G130).

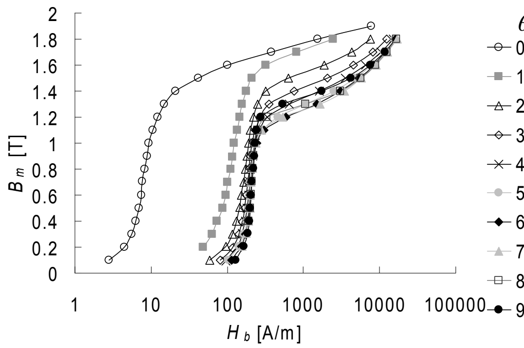
B_m [T]	iron loss [W/kg]		
	area A	area B	area C
0.5	0.898	0.840	0.823
1.0	1.853	1.835	1.805
1.5	4.017	3.92	3.914

Magnetic properties under alternating magnetic flux

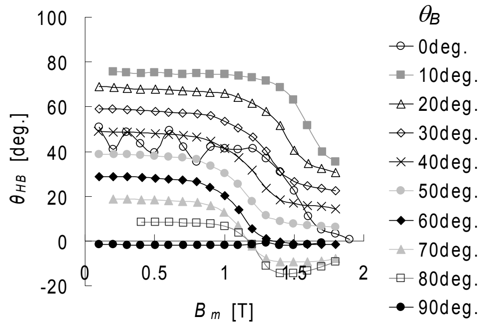
The magnetic properties of the grain-oriented electrical steel sheet (grade: 30G130) in each direction (zero to 90 deg. with 10 deg. step from the rolling direction) is measured under an alternating flux excitation. The measurement frequency is 50Hz.

Fig.5 shows the measured B_m-H_b curve, angle θ_{HB} and iron loss W. H_b is the magnetic field strength when the magnetic flux density becomes a maximum. B_m is the maximum flux density. θ_{HB} is the phase angle of H waveform which is measured from the B waveform. The magnetic field strength H_b becomes the largest when θ_B is equal to around 60 deg. and 70 deg. for the same flux density as shown in Fig.5 (a). This may be due to the fact that the structure of magnetic domain changes around those direction θ_B. Main magnetization process at low magnetic flux density is due to the moving of the magnetic domain wall. Then, the magnetic field strength H_b at low flux density become a maximum at 90 deg. due to the uniaxial magnetic anisotropy. On the contrary, the magnetization process at high magnetic flux density is changed due to the rotation of magnetic domain. The magnetic anisotropy induced at the grain boundary influences at high magnetic flux density [6].

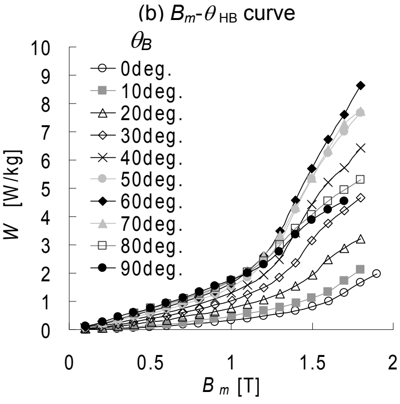
H vector is usually exceeds B vector. This means that θ_{HB} is usually positive. However, θ_{HB} is positive, for example, in the cases of θ_B =70 and 80deg. at high flux density as shown in Fig.5(b). The iron loss becomes the largest at around θ_B =60deg. at high magnetic flux density as shown in Fig.5 (c).



(a) B_m-H_b curve



(b) B_m-θ_{HB} curve



(c) W -B_m curve

Fig.5. Magnetic properties in arbitrary directions (50Hz, 30G130).

Magnetic properties under rotating magnetic flux

It is confirmed that the measured magnetic properties under rotating magnetic flux excitation have errors due to the angle error between two orthogonal coils of B and H coils [7]. Therefore, the measured result of rotational iron loss under clockwise (CW) excitation is different from that under counter clockwise (CCW) excitation especially at high flux density. The iron loss can be obtained as an average of the losses under CW rotating flux and that under CCW rotating flux. Because, the rotational iron loss under CW excitation should be equal to that under CCW excitation. In order to check the angle error θ_b of two orthogonal coils used for B coil shown in Fig.6, the coordinates of pin holes made on the surface of the specimen are measured using a microscope. The measured angle of B coil was θ_b=0.23deg.

The magnetic flux density in TD direction is calibrated as B'_{TD} by using (1).

$$B'_{TD} = \frac{B_{TD} - B_{RD}\sin\theta_b}{\cos\theta_b} \quad (1)$$

where: B_{RD} – magnetic flux density measured by the B coil for RD, B_{TD} – magnetic flux density measured by the B coil for TD, B'_{TD} – calibrated magnetic flux density in TD direction. In the control of flux density waveform, the calibrated B'_{TD} is used.

Fig.7 shows the measured iron loss under circular rotating magnetic flux excitation (α=1) before and after calibration. α is the axis ratio (=B_{min}/B_{max}). The definition of B_{max} and B_{min} is shown in Fig.8. θ is the inclination angle. The frequency is 50Hz. The iron loss under CW excitation is different from that under CCW excitation especially at more than 1.2T. The difference between CW and CCW excitations is reduced at more than 1.5T by the calibration. The figure denotes that even if the angle error is very small (θ_b=0.23deg.), the measured iron loss under CW and CCW excitation is influenced by the error at high magnetic flux density. The average value of CW and CCW excitation before calibration is almost agree with that after calibration.

In order to examine the reproducibility of measurement, the specimen is taken off from the equipment and it was again put on for measurement. Fig.9 is shown results of No.1 and No.2 measurements. The difference between No.1 and No.2 measurements is due to the change of relative position of B coil and H coil after putting on the specimen in 2D-SST. It is impossible to remove the change of relative position perfectly. But the reproducibility can be guaranteed in the rotational iron loss by adopting the average of CW and CCW measurement.

As a result, it is not easy to accurately measure magnetic properties under rotating magnetic flux, because a small error between B and H coils influences measured result under CW and CCW excitation at high magnetic flux density.

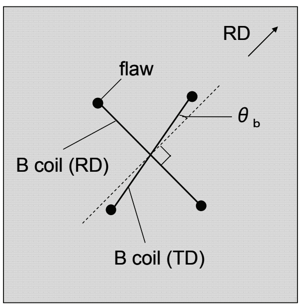


Fig.6. Error of orthogonal B-coils.

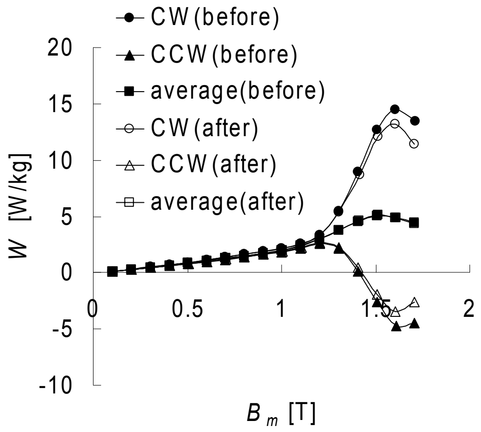


Fig.7. Iron losses under rotating magnetic flux before and after calibration of B-coils (50Hz, 30G130, α=1).

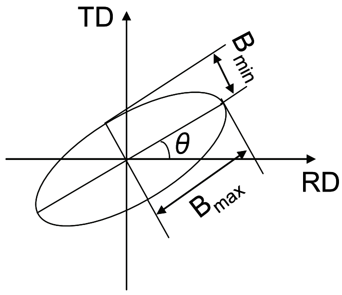


Fig.8. Elliptically rotating magnetic flux.

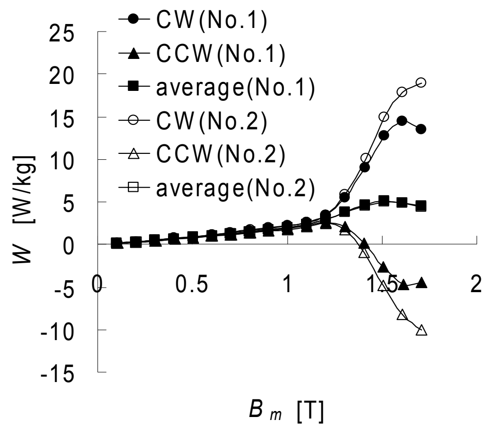
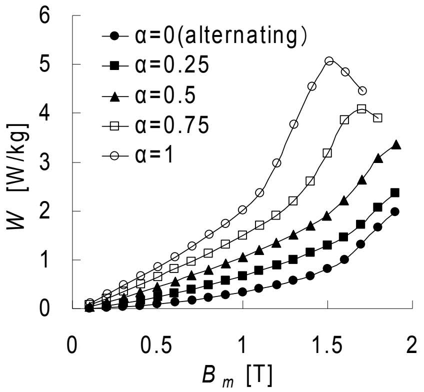


Fig.9. Iron losses under rotating magnetic flux at No.1 and No.2 measurements (50Hz, 30G130, α=1).

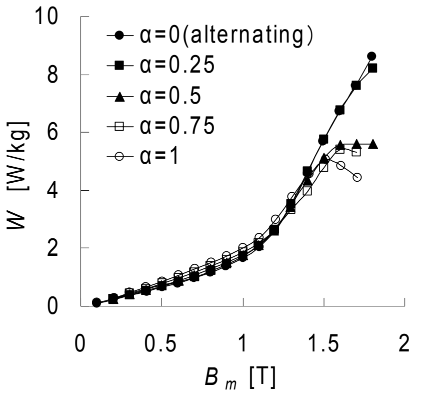
Magnetic properties under elliptically rotating magnetic flux

The effects of axis ratio α, inclination angle θ on iron losses under elliptically rotating magnetic flux excitation are examined. Fig.10 shows measured results at 50Hz. The iron loss W is obtained as an average of the losses under CW and CCW excitation. The iron loss W is increased with the axis ratio α at low magnetic flux density. When α is near to unity, the iron loss is decreased at high magnetic flux density. This is, because the hysteresis loss is decreased under rotating flux at high flux density. When α is large, the flux density, when the iron loss begins to decrease, is reduced. The bigger the inclination angle θ, the smaller the difference in the iron loss by the axis ratio at low magnetic flux density.

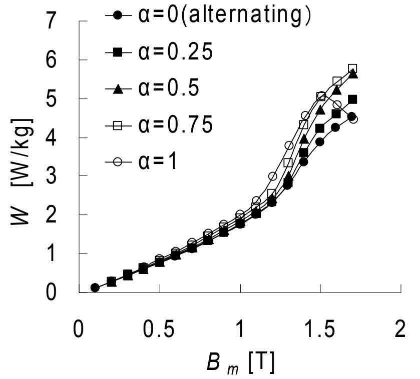
The iron loss at α=1 does not change even if the inclination angle θ is changed, because it is a circle. In the case of θ =0deg.(easy magnetization), the bigger the axis ratio, the bigger the iron loss as shown Fig.10 (a). This is, because the flux density B_{TD} in TD direction is increased with the axis ratio. In the case of θ =60deg.(almost difficult magnetization), the bigger the axis ratio α, the bigger the iron loss W below 1.3T. But, the smaller the axis ratio α, the bigger the iron loss W above 1.3T as shown in Fig.10 (b). This is, because the iron loss W under circular rotating flux (α =1) is smaller than that under alternating flux (α =0) in the direction of difficult magnetization.



(a) θ =0deg.



(b) θ =60deg.

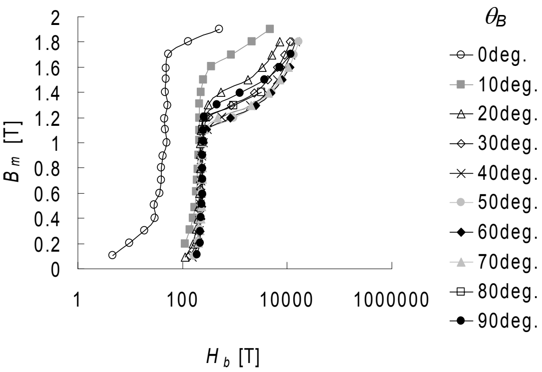


(c) θ =90deg.

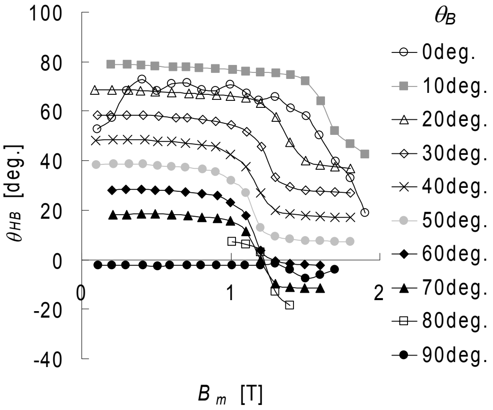
Fig.10. Effect of axis ratio α and inclination angle θ of rotational magnetic flux on resuls of iron losses.

Measurement of magnetic properties of highly grain-oriented steel sheet

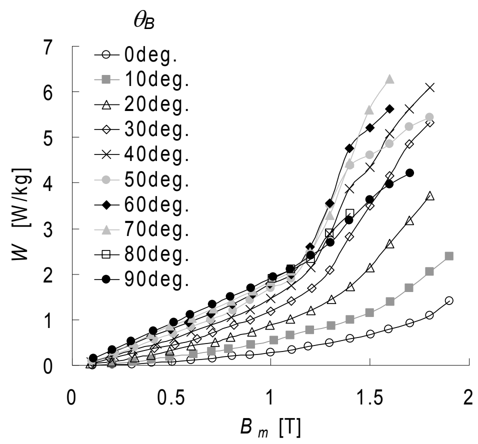
Fig.11 shows the measured B_m-H_b curve, angle θ_{HB} and iron loss W of the highly grain-oriented steel sheet (grade: 30P100) in each direction (zero to 90 deg. with 10 deg. step from the rolling direction under alternating magnetic flux excitation). The measurement frequency is 50Hz. The iron losses of 30P100 in areas A, B and C like the case of Table 1 are also measured. The discrepancy of iron losses between measured results at each area was less than 25%. Therefore, it should be regarded that the measured result of 30P100 in Fig.11 is an example of magnetic properties at a special part (20mm×20mm) of specimen, because the grain size of the highly grain-oriented steel sheet is the order of 10mm. More larger measurement area (uniform magnetic field area) is necessary in order to measure general magnetic properties of highly grain-oriented steel sheet. The tendency of results is almost similar to that of 30G130.



(a) B_m-H_b curve



(b) B_m-θ_{HB} curve



(c) W -B_m curve

Fig.11. Magnetic properties in arbitrary directions (50Hz, 30P100).

Fig.12 shows the measured iron loss W under circular rotating magnetic flux excitation (α =1). The measured result using the 2D-SST is a part (20mm×20mm) of specimen.

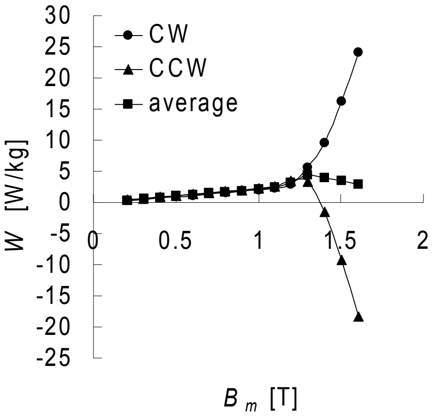


Fig.12. Iron losses under rotating magnetic flux (50Hz, 30P100, α =1).

Summary

The obtained results can be summarized as follows:

(1) The accuracy of 2D-SST in the measurement of grain-oriented electrical steel sheet is examined by comparing with the measured iron losses using 60mm width SST. It is also shown that the magnetic properties of the grain-oriented silicon steel sheet like 30G130 can be measured in the area of 20mm×20mm.

(2) The behaviour of magnetic properties of the grain-oriented electrical steel sheet in each direction (zero to 90deg. with 10deg. step from the rolling direction) under alternating flux excitation is clarified.

(3) A small error between B and H coils influences measured results of iron loss under CW and CCW excitation at high magnetic flux density. The average value of the iron losses under CW and CCW rotating magnetic flux excitation before calibration is almost agree with that after calibration.

(4) In the case of θ =0 deg. (easy magnetization), the bigger the axis ratio α, the bigger the iron loss *W* under elliptically rotating magnetic flux. On the other hand, in the case of θ =60 deg. (almost difficult magnetization), the smaller the axis ratio α, the bigger the iron loss *W* above 1.3T.

(5) An example of magnetic properties of highly grain-oriented steel sheet under alternating flux and rotating flux (α =1) excitation is shown.

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