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DEVELOPMENT OF SYSTEM FOR VECTOR MAGNETIC PROPERTY MEASUREMENT UNDER STRESS

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It is important to know magnetic property of electrical steel sheet under various magnetic flux and mechanical stress conditions. In this paper, we presented a new system developed for measuring vector magnetic properties under the mechanical stress. The vector magnetic properties were measured under a set of amplitudes of the mechanical stress. As the results, it was made clear that the vector magnetic property is obtained due to the mechanical stress.

Keywords: mechanical stress, principal stress, rotating magnetic flux condition, vector magnetic property

1 INTRODUCTION

Electrical steel sheets in rotating machines are magnetized under alternating and rotating magnetic flux conditions[1]. In such conditions the vector of magnetic flux density B and magnetic field intensity H are not parallel because B lags H temporally. In general, B and H are defined as the vector quantity and the property considering the magnitude and direction of B and H is called the vector magnetic property [2].

It is well known that the magnetic property of the electrical steel sheet is strongly affected by mechanical stress. For example, magnetic properties deteriorate due to stress conditions by riveting and welding during manufacturing process, punching and shearing in cutting process of the electrical steel sheets [3-4]. Therefore, it is important to clarify the relationships between the magnetic property and the mechanical stress. Various authors have studied the effect of the stress on the magnetic property [5-7]. However it is difficult to evaluate the relationships between the mechanical stress and the magnetic properties under arbitrary alternating and rotating magnetic flux conditions.

In this paper, we present a new measurement system developed in order to examine the relationships between the vector magnetic property and the mechanical stress. The vector magnetic properties of a non-oriented electrical steel sheet under the rotating magnetic flux condition are measured by applying the mechanical stress.

2 MEASUREMENT SYSTEM

Figure 1 shows the shape and dimensions of the cross-shaped specimen. The cross-shaped specimen is cut out from a non-oriented electrical steel sheet. The slits in the specimen are made in order to obtain uniform stress distribution in the measuring region.

Figure 2 shows a system for the vector magnetic property measurement under the stress. The cross-shaped specimen is set in the sample holder in order to protect compression buckling. The four arms of the specimen are fixed and the outside load are applied along the rolling direction and transverse direction. In this system, it is possible to measure the vector magnetic properties under the various magnetic flux conditions after applying the load force along x and y direction.

3 METHOD OF STRESS EVALUATION

The strain components ε_0, ε_{45} and ε_{90} are measured with the three-axial strain gauge. The stress components are calculated from the Hooke's law under plane stress assumption. Following is the definition of the Hooke's law under the plane stress assumption,

$$\begin{aligned} \sigma_x &= \frac{1}{1-\nu^2}\left(\varepsilon_0 + \nu\varepsilon_{90}\right), \\ \sigma_y &= \frac{1}{1-\nu^2}\left(\varepsilon_{90} + \nu\varepsilon_0\right), \\ \tau_{xy} &= \frac{E}{2\left(1+\nu\right)}\left(2\varepsilon_{45} - \varepsilon_0 - \varepsilon_{90}\right), \end{aligned} \tag{1}$$

where, σ_x and σ_y are the stress of x and y components, τ_{xy} is the shearing stress, respectively. The principal stress is calculated by the following equations,

$$\begin{aligned} \sigma_1 &= \sigma_x \cos^2\theta_\sigma + 2\tau_{xy}\cos\theta_\sigma \sin\theta_\sigma + \sigma_y \sin^2\theta_\sigma, \\ \sigma_2 &= \sigma_x \sin^2\theta_\sigma - 2\tau_{xy}\cos\theta_\sigma \sin\theta_\sigma + \sigma_x \cos^2\theta_\sigma, \\ \theta_\sigma &= \frac{1}{2}\tan^{-1}\frac{2\tau_{xy}}{\sigma_x - \sigma_y}. \end{aligned} \tag{2}$$

Where, σ_1 and σ_2 are the amplitudes of the principal stress components and θ_σ is the angle of the principal stress. When τ_{xy} is equal to 0 MPa, the direction of σ_x and σ_y agrees with the direction of σ_1 and σ_2.

Figure 3 shows the principal stress with and without control. At first, the outside load F_x at x direction is applied to be parallel along the rolling direction. The principal stress at x and y direction occurs due to the increase of F_x as shown in Fig. 3(a). Fig. 3(b) shows the principal stress with the control. The direction of the principal stress becomes parallel to the rolling direction.

Figure 4 shows an evaluation method of the vector magnetic properties with and without mechanical stress. At first, the vector magnetic property is measured without mechanical stress.

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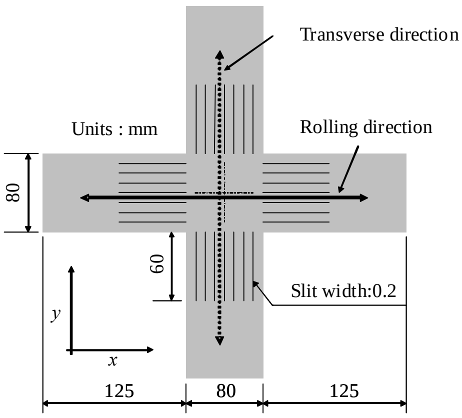

Fig. 1. Cross-shaped specimen.

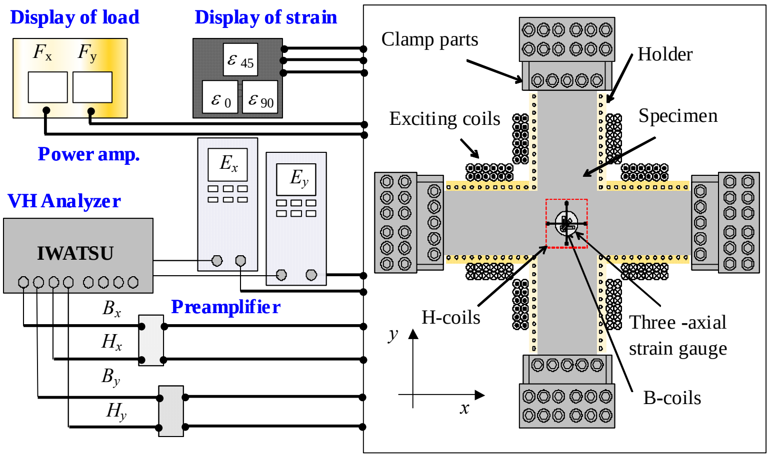

Fig. 2. Measurement system for vector magnetic property under stress conditions

The vector of magnetic flux is controlled to trace the pure circle in the rotating magnetic flux conditions. The maximum magnetic flux density $B_{\max}$ is 1.0 T. The mechanical stress with σ_1 = +20 MPa, σ_2 = 0 MPa and θ_σ = 0 deg. is applied along the rolling direction as shown in Fig. 4 (b).

It is possible to control the principal stress by adjusting the outside load in x and y axis.

4 EVALUATION METHOD OF VECTOR MAGNETIC PROPERTIES UNDER STRESS

The amplitude and direction of the principal stress are controlled by adjusting the outside load in x and y axes. After that, the vector magnetic properties are measured after applying the mechanical stress. $\boldsymbol{H}^\sigma$ is defined as the vector of the magnetic field intensity after applying the mechanical stress. The locus of $\boldsymbol{H}^\sigma$ differs in comparison with $\boldsymbol{H}$ without the mechanical stress. It is possible to measure the vector magnetic property with and without the mechanical stress with the developed system.

5 MEASUREMENT RESULTS

The vector magnetic properties under the rotating magnetic flux condition and variable stress conditions are measured. Figure 5 shows the loci of $\boldsymbol{H}$ with and without the mechanical stress under the rotating magnetic flux condition at $B_{\max}$ = 1.0 T. The tensile stress and compressive stress are applied along the rolling direction. The loci of $\boldsymbol{H}^\sigma$ with the applied mechanical stress differ in comparison to those of $\boldsymbol{H}$ without the mechanical stress. The value of $\boldsymbol{H}^\sigma$ in x axis decreases due to the tensile stress. However, the value of $\boldsymbol{H}^\sigma$ in y axis increases due to the compressive stress. The change of locus of $\boldsymbol{H}^\sigma$ becomes larger by increasing the mechanical stress. Figure 6 shows the loci of $\boldsymbol{H}$ depending on the magnetic flux density. $B_{\max}$ is varied from 0.6 T to 1.4 T by 0.2 T. The change of the loci of $\boldsymbol{H}^\sigma$ increases due to increment of $B_{\max}$. The loci of $\boldsymbol{H}$ without the mechanical stress at $B_{\max}$ = 1.4 T is changed by the influence of the crystal magnetic anisotropy. In addition, the loci of $\boldsymbol{H}^\sigma$ differ due to the influence of the stress. It is possible to evaluate the magnetic anisotropy due to the stress and crystal.

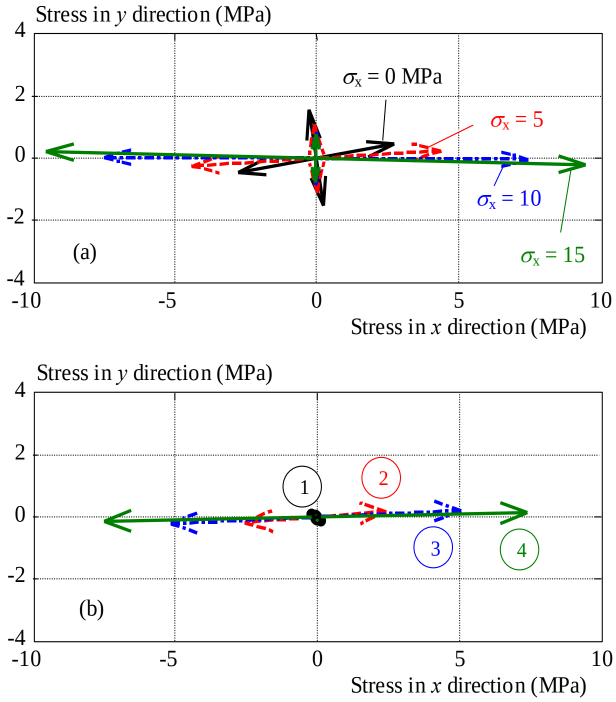

Fig.3. Comparison of amplitude and direction of principal stress: (a) - without and, (b) - with control, where ① σ_1 =-0.1, σ_2 =0.4, θ=0 deg, ② σ_1 =4.9, σ_2 =-0.1, θ=4.3 deg, ③ σ_1=10.1, σ_2= 0, θ=2.6 deg, ④ σ_1=14.7, σ_2=-0.1, θ=1.2 deg

Figure 7 shows the permeability dependent on $B_{\max}$. The maximum permeability μ_{mx} and μ_{my} of x and y components are defined by following equations,

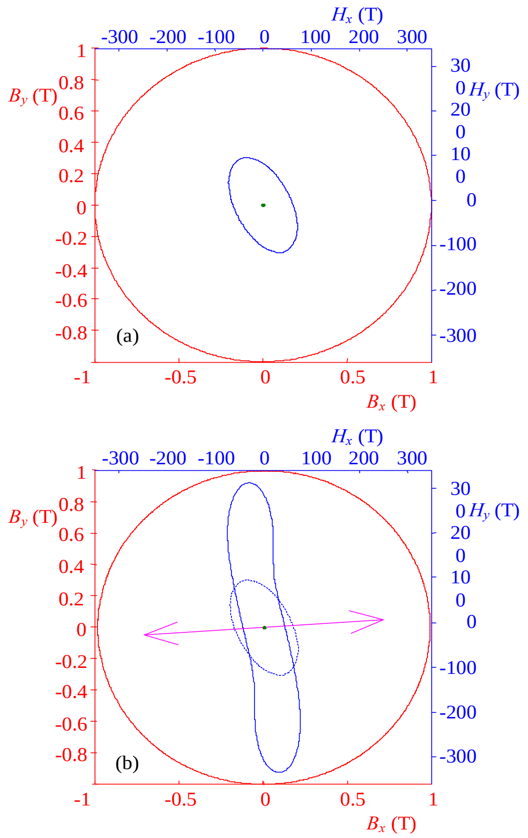

Fig. 4. Evaluation method of vector magnetic property: (a) - without and, (b) - with mechanical stress

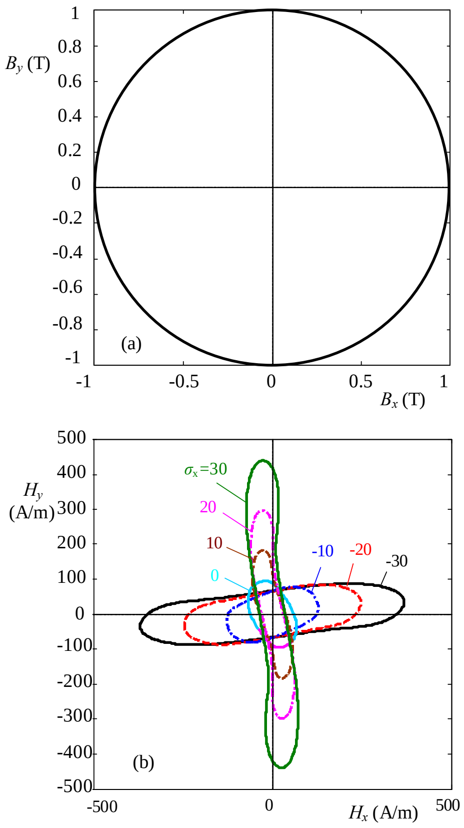

Fig. 5. Loci of ***B*** and ***H***: (a) - without and, (b) - with mechanical stress applied along the rolling direction

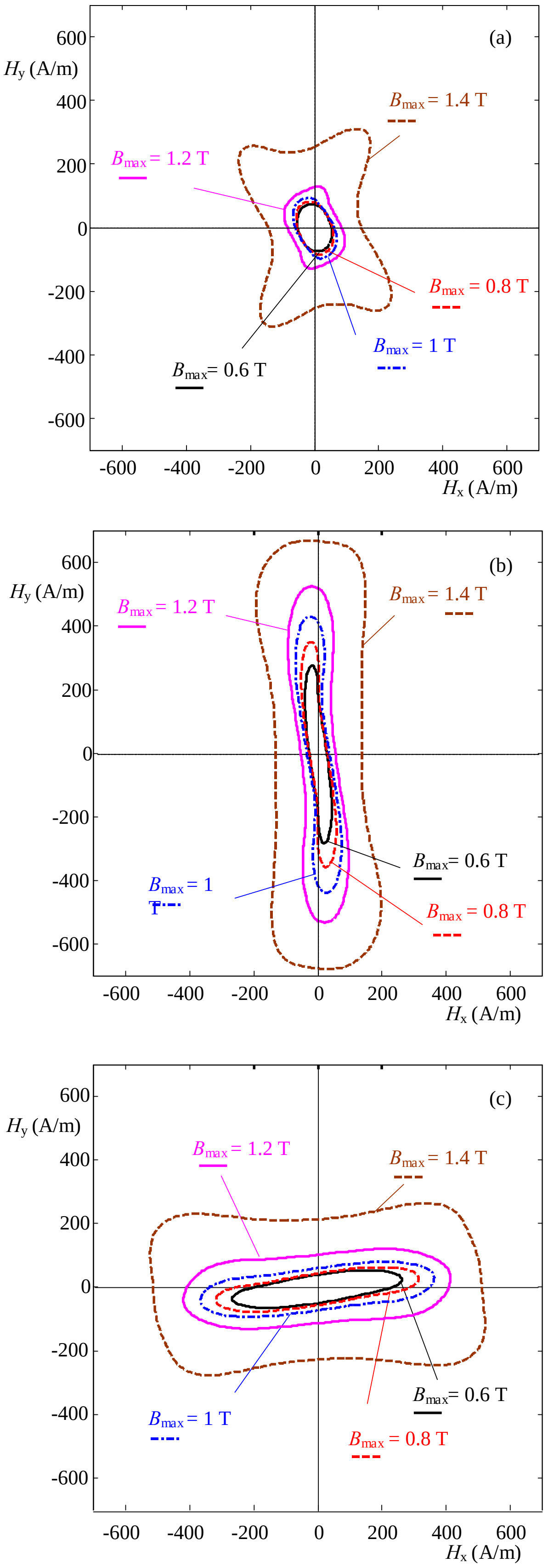

Fig. 6. Comparison of locus of ***B*** and ***H***: (a) – without and, (b), (c) – with mechanical stress depending on magnetic flux density, while $\sigma_y = 0$: (b) – σ_x = 30 MPa, and (c) – σ_x = -30

$$\mu_{mx} = \frac{B_{mx}}{\mu_0 H_{mx}},\qquad \mu_{my} = \frac{B_{mx}}{\mu_0 H_{mx}}. \tag{3}$$

where, H_{mx} and H_{my} are the maximum magnetic field intensity of x and y components, B_{mx} and B_{my} are the maximum magnetic flux density of x and y components and μ_0 is the permeability of free space, respectively. The peak values of μ_{mx} and μ_{my} depend on the applied stress. In the low magnetic flux density level, μ_{mx} increases due to the tensile stress and decreases due to the compressive stress. μ_{my} shows opposite tendency in comparison to μ_{mx}. The permeability decrease by increasing the magnetic flux density since the magnetization process approaches to the saturation.

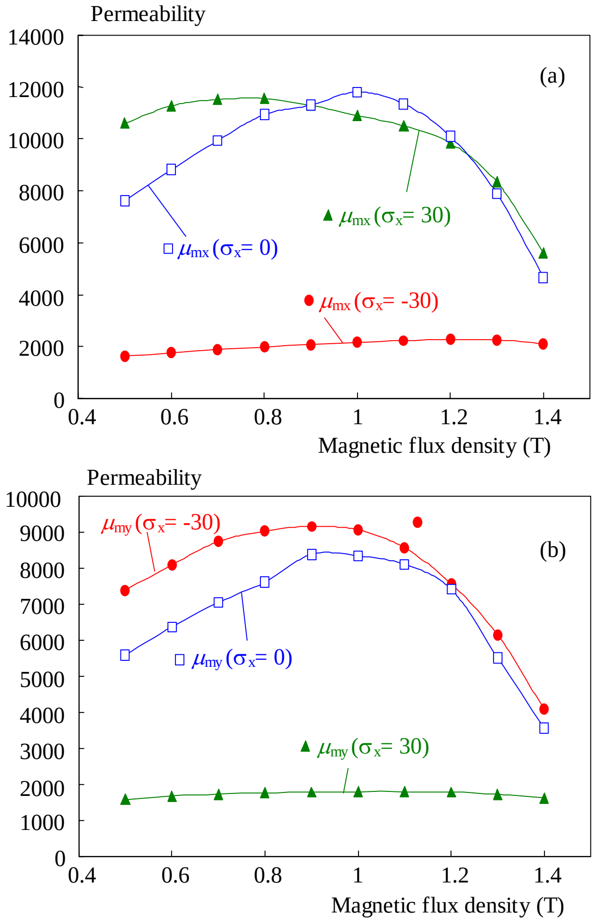

Fig. 7. Permeability depending on magnetic flux density: (a) – x component, (b) – y component

From these results, the loci of H were changed due to the difference of the intensity of the applied mechanical stress. It was made clear that the magnetic properties of each component differ due to the mechanical stress along the rolling direction.

6 CONCLUSIONS

We developed the new measurement system in order to clarify the relationships between the mechanical stress and the vector magnetic properties. As the results, it is possible to control the amplitude and the direction of the principal stress by adjusting the outside load. It was clarified that the vector of magnetic field intensity H is changing due to the induced magnetic anisotropy by the mechanical stress. The developed system is very useful to evaluate the vector magnetic property under the stress conditions. In the future woks, we will measure the vector magnetic properties under the various stress and magnetic flux conditions with the developed system.

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