Invited paper

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Measurement of vector magnetic property under stress along arbitrary direction in non-oriented electrical steel sheet

***Abstract**. Electrical steel sheet in electrical machines is magnetized under alternating and rotating magnetic flux. The vector of magnetic flux density B and magnetic field strength H are not parallel because B lags H temporally. It is well known that the magnetic property of the electrical steel sheet is strongly affected by mechanical stress. Therefore, it is important to clarify the relationships between the magnetic property and the mechanical stress. In this paper, we examine the vector magnetic properties under the alternating and rotating magnetic flux conditions by applying the mechanical stress at the arbitrary direction.*

***Streszczenie.** W artykule zaprezentowano badania wektora właściwości magnetycznych blachy niezorientowanej poddanej naprężeniom w dowolnym kierunku. Blachy były magnesowane zarówno w jednej osi jak i rotacyjne. (**Pomiary wektora właściwości magnetycznych blachy niezorientowanej poddanej naprężeniu w dowolnym kierunku**)*

Keywords: vector magnetic property, mechanical stress, arbitrary direction, magnetic power loss.
Słowa kluczowe: magnesowanie osiowe, magnesowanie rotacyjne, wpływ naprężeń..

Introduction

Developing electrical machines, which have high power and efficiency requires effective utilization of magnetic materials. The electrical steel sheet in the actual rotating machines is magnetized under alternating and rotating magnetic flux conditions [1]. In addition, the magnetic properties of the electrical steel sheet are strongly affected by mechanical stress. Therefore, it is important to know the magnetic properties under various stress and magnetic flux conditions in order to utilize for designing the electrical machine.

Various authors have studied the effect of the stress on the magnetic property in the electrical steel sheet [2-5]. However, it is difficult to evaluate the relationships between the stress and the magnetic property under the alternating and rotating magnetic flux condition by using the conventional method in detail. Therefore, we developed new magnetic measurement system under the stress in order to clarify the relationships between the vector magnetic property and mechanical stress. In general, the magnetic flux density vector and the magnetic field strength vector are defined as the vector quantities and the property considering the magnitude and direction of the vector is called the vector magnetic property [6].

This paper presents the influence of the mechanical stress on the vector magnetic property in the non-oriented electrical steel sheet. In addition, we tried to measure the vector magnetic property by applying the mechanical stress along arbitrary direction.

Measurement System

Fig 1 shows the system for the vector magnetic property measurement under mechanical stress. A cross-shaped specimen is used in the measurement. The four arms of the specimen are fixed and an external mechanical load is applied along the *x* and *y* direction. The vector magnetic property under the alternating and rotating magnetic flux conditions is evaluated after applying the load force. The magnetic flux density and magnetic field strength vector are measured with the B-coils and H-coils. Fig. 2 shows the shape and dimensions of the cross-shaped specimen. The specimen is cut from a non-oriented electrical steel sheet. Several slits are made in the specimen in order to apply uniform stress in the measuring region. The slits are cut with a wire electric discharge machine. Thee cross-shaped specimen is set in the sample holder to protect from buckling under the compressive stress.

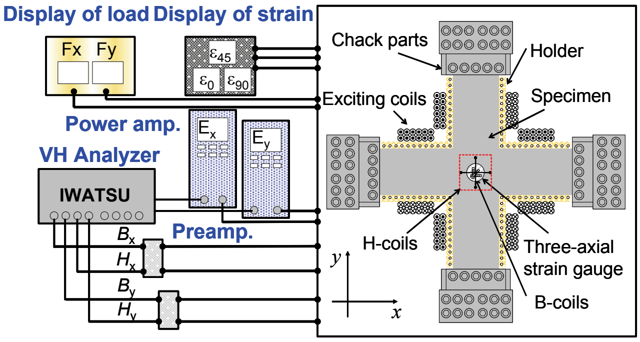

Fig.1. Measurement system

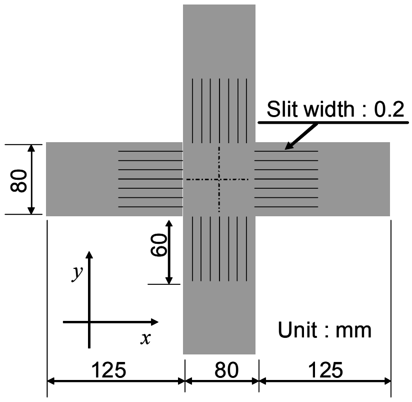

Fig.2. Cross-shaped specimen

Measurement Method of Stress

Fig. 3 shows the three-axial strain gauge. A three-axial strain gauge is used to measure three strain components ε_0, ε_{45} and ε_{90}. The strain gauge is attached the center of the specimen. After measuring the three strain components, the stress components are calculated from the Hooke's law under plate stress condition with the following equations

$$\sigma_x = \frac{1}{1-\nu^2}\left(\varepsilon_0 + \nu\varepsilon_{90}\right) \tag{1}$$

$$\sigma_y = \frac{1}{1-\nu^2}\left(\varepsilon_{90} + \nu\varepsilon_0\right) \tag{2}$$

$$\tau_{xy} = \frac{E}{2\left(1+\nu\right)}\left(2\varepsilon_{45} - \varepsilon_0 - \varepsilon_{90}\right) \tag{3}$$

where: σ_x and σ_y – the stress of *x* and *y* components, τ_{xy} – the shearing stress, *E* – the Poisson's ratio and ν – the

Young's modulus, respectively. The each stress components differ by rotating the coordinate since the stress components are defined as tensile quantity. Therefore, we evaluate the principal stress from the each stress components. The components of principal stress are given by the following equations

$$\sigma_1 = \sigma_x \cos^2\theta_\sigma + 2\tau_{xy}\cos\theta_\sigma \sin\theta_\sigma + \sigma_y \sin^2\theta_\sigma \tag{4}$$

$$\sigma_2 = \sigma_x \sin^2\theta_\sigma - 2\tau_{xy}\cos\theta_\sigma \sin\theta_\sigma + \sigma_y \cos^2\theta_\sigma \tag{5}$$

$$\theta_\sigma = \frac{1}{2}\tan^{-1}\frac{2\tau_{xy}}{\sigma_x - \sigma_y} \tag{6}$$

where: σ_1 and σ_2 – the strength of the principal stress and θ_σ – the angle of stress. The angle of stress is defined as the direction of the applied stress from the rolling direction.

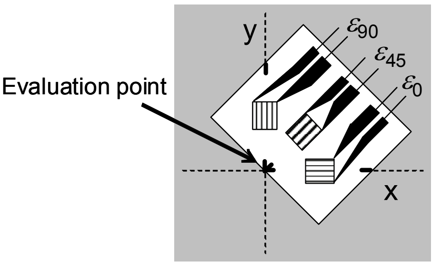

Fig.3 Three-axial strain gauge

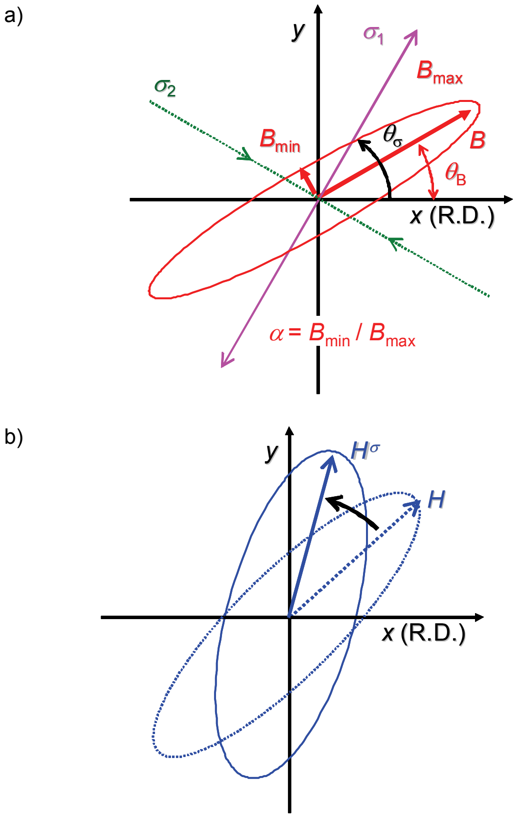

Fig.4. Parameters of stress and vector magnetic property: a) Condition of σ and ***B***, b) ***H*** before and after applying mechanical stress

Evaluation of Vector Magnetic Property under Stress

Fig. 4 shows the parameters of the mechanical stress and vector magnetic property. The magnetic properties, which are not only the magnetic flux density but also the magnetic field strength is effected due to the mechanical stress. The magnetic flux density vector and the mechanical stress are controlled. The conditions of the magnetic flux density vector are defined by three parameters. They are the maximum magnetic flux density B_{max}, the inclination angle θ_B and the axis ratio α. The inclination angle is defined as the angle between the rolling direction and the direction of the magnetic flux density vector. The axis ratio is the ratio of the magnitude of the minimum magnetic flux density to that of the maximum magnetic flux density. In addition, the stress condition is defined by three parameters too. $\boldsymbol{H}^\sigma$ is defined as ***H*** with the mechanical stress as shown in Fig. 4b).

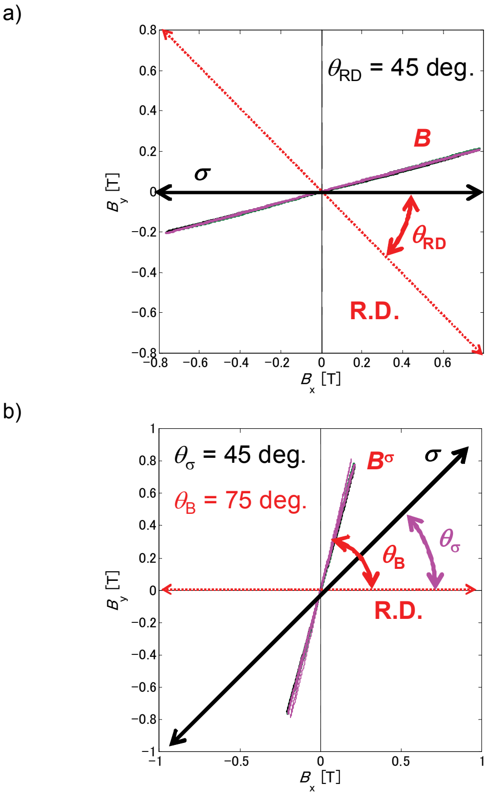

Fig.5. Comparison of σ and ***B*** before and after rotating coordinate: a) Before rotating coordinate, b) After rotating coordinate

Samples various cut out angle θ_{RD} from the rolling direction are used in the measurement. θ_{RD} is 0, 15, 30, 45, 60, 75 deg. Fig. 5 shows an example of the measured ***B*** and σ. Measured σ, ***B*** and ***H*** are rotated by the coordinate transformation in order to match the rolling direction in the *x* direction. The coordinate transformation of ***B*** and ***H*** is calculated by the following equations

$$\begin{Bmatrix} B_x^\sigma \\ B_y^\sigma \end{Bmatrix} = \begin{bmatrix} \cos\theta_{RD} & -\sin\theta_{RD} \\ \sin\theta_{RD} & \cos\theta_{RD} \end{bmatrix} \begin{Bmatrix} B_x^{RD} \\ B_y^{RD} \end{Bmatrix} \tag{7}$$

$$\begin{Bmatrix} H_x^\sigma \\ H_y^\sigma \end{Bmatrix} = \begin{bmatrix} \cos\theta_{RD} & -\sin\theta_{RD} \\ \sin\theta_{RD} & \cos\theta_{RD} \end{bmatrix} \begin{Bmatrix} H_x^{RD} \\ H_y^{RD} \end{Bmatrix} \tag{8}$$

where: B_x^σ and B_y^σ – magnetic flux density vector after rotating coordinate, B_x^{RD} and B_y^{RD} – magnetic flux density vector before rotating coordinate, H_x^σ and H_y^σ – magnetic field strength vector after rotating coordinate and H_x^{RD} and H_y^{RD} – magnetic field strength vector before rotating coordinate, respectively. Fig. 5 b) shows ***B*** and σ after rotating coordinate. It is possible to evaluate the vector magnetic property under the mechanical stress along the arbitrary direction by using each specimen.

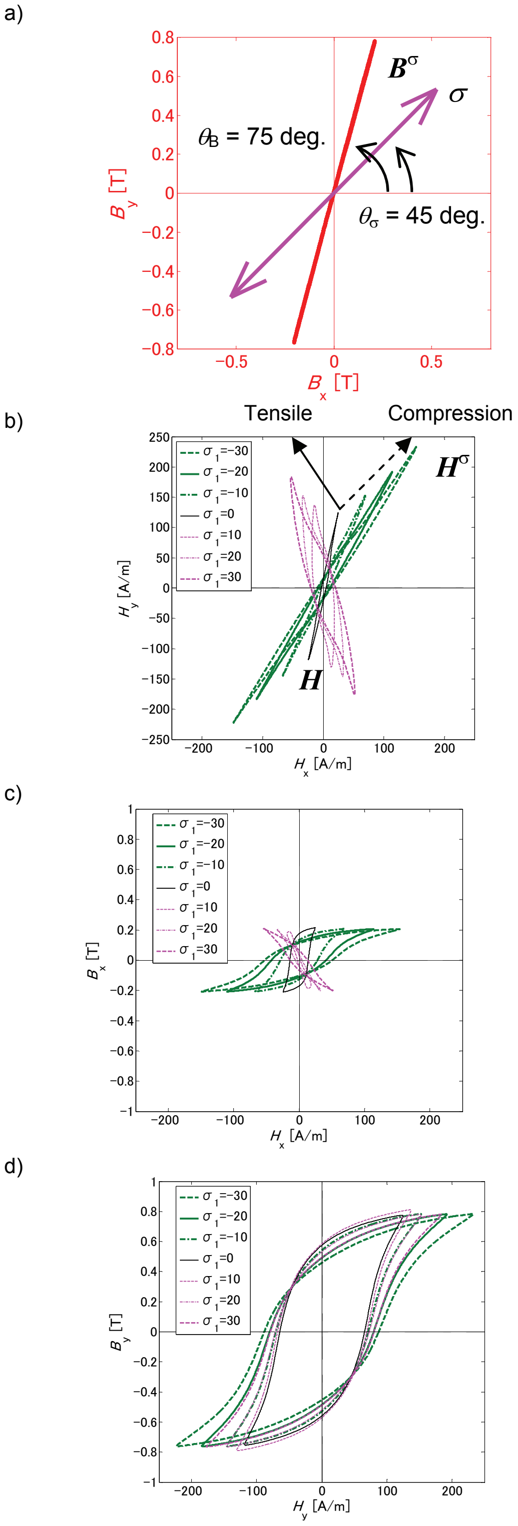

Fig.6. Vector magnetic property depending on the amplitude of stress: a) σ and $\boldsymbol{B}^\sigma$, b) $\boldsymbol{H}$ and $\boldsymbol{H}^\sigma$, c) B_x - H_x, d) B_y – H_y

Measured Results

Fig. 6 shows the vector magnetic property under the alternating magnetic flux condition. The amplitude of the mechanical stress is changed from -30 MPa to +30MPa every 10 MPa. The angle of the stress θ_σ is 45 deg. The magnetic flux vector is controlled B_{max} = 0.8 T and θ_B = 75 deg. The loci of ***H*** incline perpendicular to the direction of the applied stress due to the tensile stress. Meanwhile, the loci of ***H*** incline parallel to the direction of the applied stress due to the compressive stress. The area and inclination of BH loops differ by applying the mechanical stress. Fig. 7 shows the permeability and magnetic power loss depending on the amplitude of the mechanical stress. The relative permeabilities μ_{mx} and μ_{my} of x and y components are calculated by the following eqations

$$\mu_{mx} = \frac{B_{mx}}{\mu_0 H_{mx}} \tag{9}$$

$$\mu_{my} = \frac{B_{my}}{\mu_0 H_{my}} \tag{10}$$

where: H_{mx} and H_{my} are the maximum magnetic field strength 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.

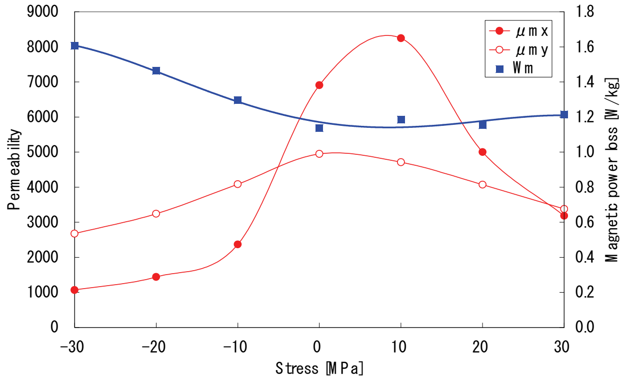

Fig.7. Magnetic property depending on amplitude of mechanical stress

The magnetic power loss W_m is calculated by the following eqation

$$W_m = \frac{1}{\rho T}\int\left(H_x\frac{dB_x}{dt} + H_y\frac{dB_y}{dt}\right)dt \tag{11}$$

where: T – period of excitation wave and ρ – material density, respectively. μ_{mx} increases slightly and decreases rapidly by applying the tensile stress. The value of μ_{mx} decreases by applying the compressive stress. The change of μ_{my} has opposite tendency in comparison with that of μ_{mx}. W_m increases due to increment of the tensile and compressive stress. It was clarified that the magnetic property of x and y components differ due to the mechanical stress.

Fig. 8 shows the vector magnetic property depending on θ_σ. The mechanical stress is applied at σ_1 = -30 MPa, +30 MPa and $\sigma_2 \approx 0$ MPa. The angle of the principal stress is changed from θ_σ = 0 deg. to θ_σ = 90 deg every 15 deg. The magnetic flux condition is controlled at B_{max} = 0.8 T and θ_B = 45 deg. The loci of ***H*** and BH loops of x and y components differ depending on θ_σ. In the case of the tensile stress, the the loci of ***H*** incline gradually toward the transverse direction due to increment of θ_σ as showns in Fig. 8(a). On the othe hand, the values of the parallel magnetic field strength in the direction of the applied stress increses due to the compressive stress as showns in Fig. 8 b). The BH loops of x and y component chage continuously depending on θ_σ. Fig. 9 shows W_m dependin on θ_σ. The values of W_m become a minimum as the direction of the applied stress approachs the direction of ***B***. When the difference between θ_σ and θ_B becomes large, the values of W_m increase due to the tensile stress and decrease due to the compressive stress.

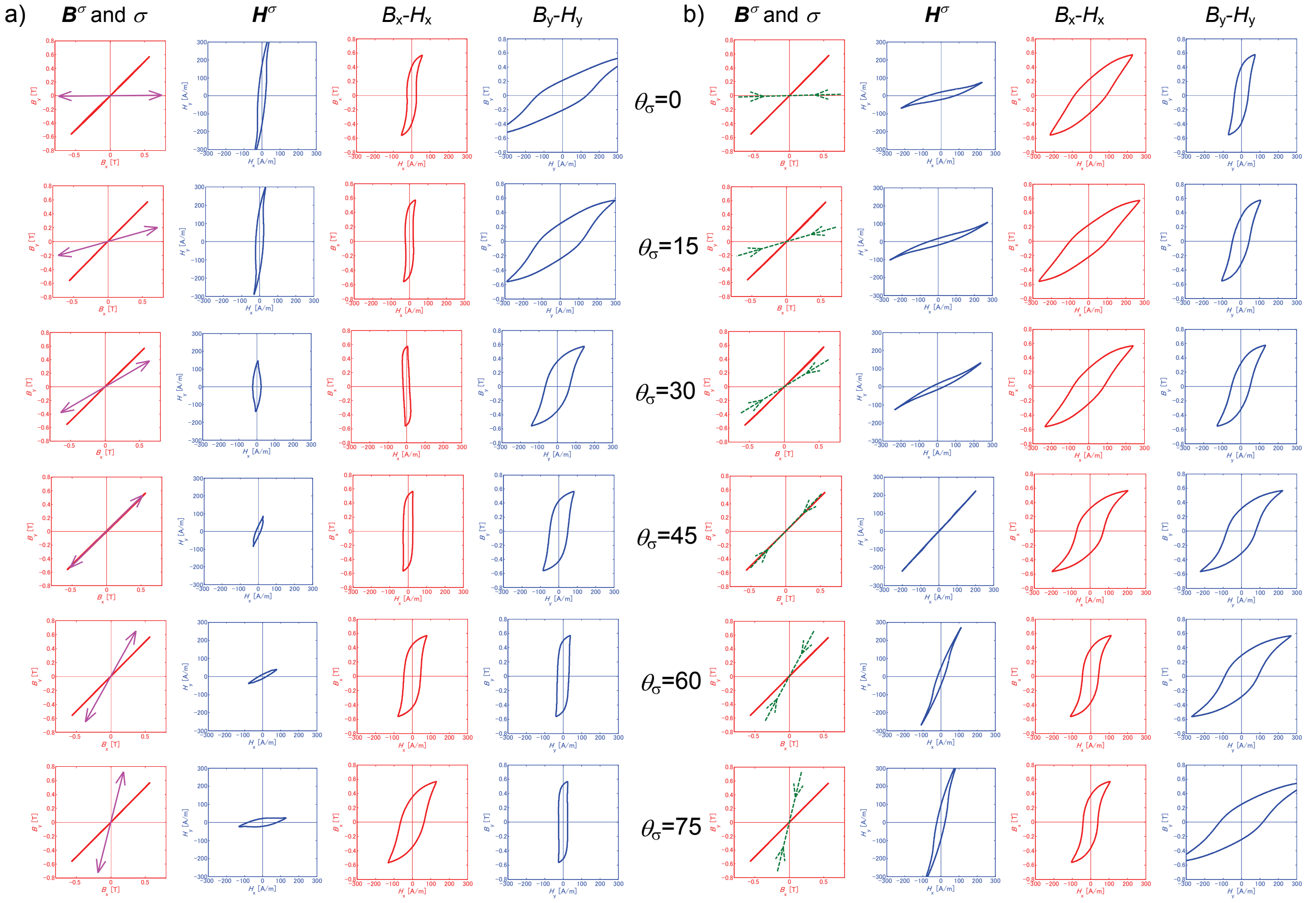

Fig.8. Vector magnetic properties under alternating magnetic flux condition at B_{max} = 0.8T, θ_B = 45 deg. and α = 0: a) σ_1 = +30 MPa, b) σ_1 = -30 MPa

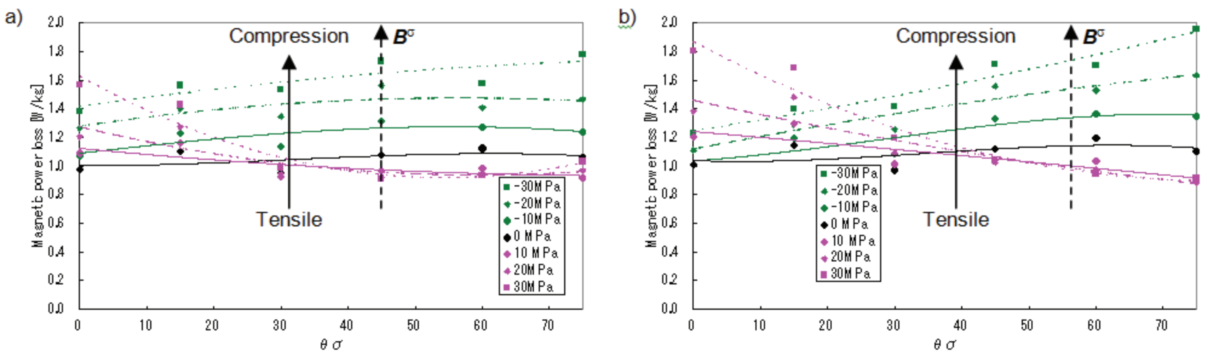

Fig. 9. Magnetic power loss at B_{max} = 0.8T, θ_B = 45 deg. and α = 0 depending on θ_σ: a) θ_B = 45 deg., b) θ_B = 60 deg.

Fig. 10 shows the vector magnetic property under the rotating magnetic flux condition at B_{max} = 0.8 T and α = 1.0. The loci of ***H*** is rotated due to the increment θ_σ. In particllar, the values of ***H*** of the parallel and perpendicular direction to the direction of the applied stress change due to the mechanical stress. The difference of the magnetic anisotropy was obtained by evaluating the vector magnetic property under the rotating magnetic flux conditions.

Fig. 11 shows W_m under the rotating magnetic flux condition depending on θ_σ. The magnetic power loss under the rotating magnetic flux condition hardly changes depending on θ_σ in comparison with that under the alternating magnetic flux condition. It is necessary to investigate the magnetic power loss under the rotating magnetic flux condition in more detail.

From thsese results, the difference of the magnetic power loss was obtained due to not only the amplitude but also the angle of the mechanical stress. It was clarified that the magnetic power loss changes nonlinearity depending on θ_σ.

Conclusion

We developed a new measurement system to clarify the relationships between the mechanical stress and vector magnetic property. The difference of the magnetic field strength vector under alternating and rotating magnetic flux conditions is obtained due to the strength and the direction of the mechanical stress. It was clarified that the magnetic power loss decreases depending on not only tensile stress but also the compressive stress. Therefore, it is possible to improve the magnetic property of the non-oriented electrical steel sheet by controlling the mechanical stress.

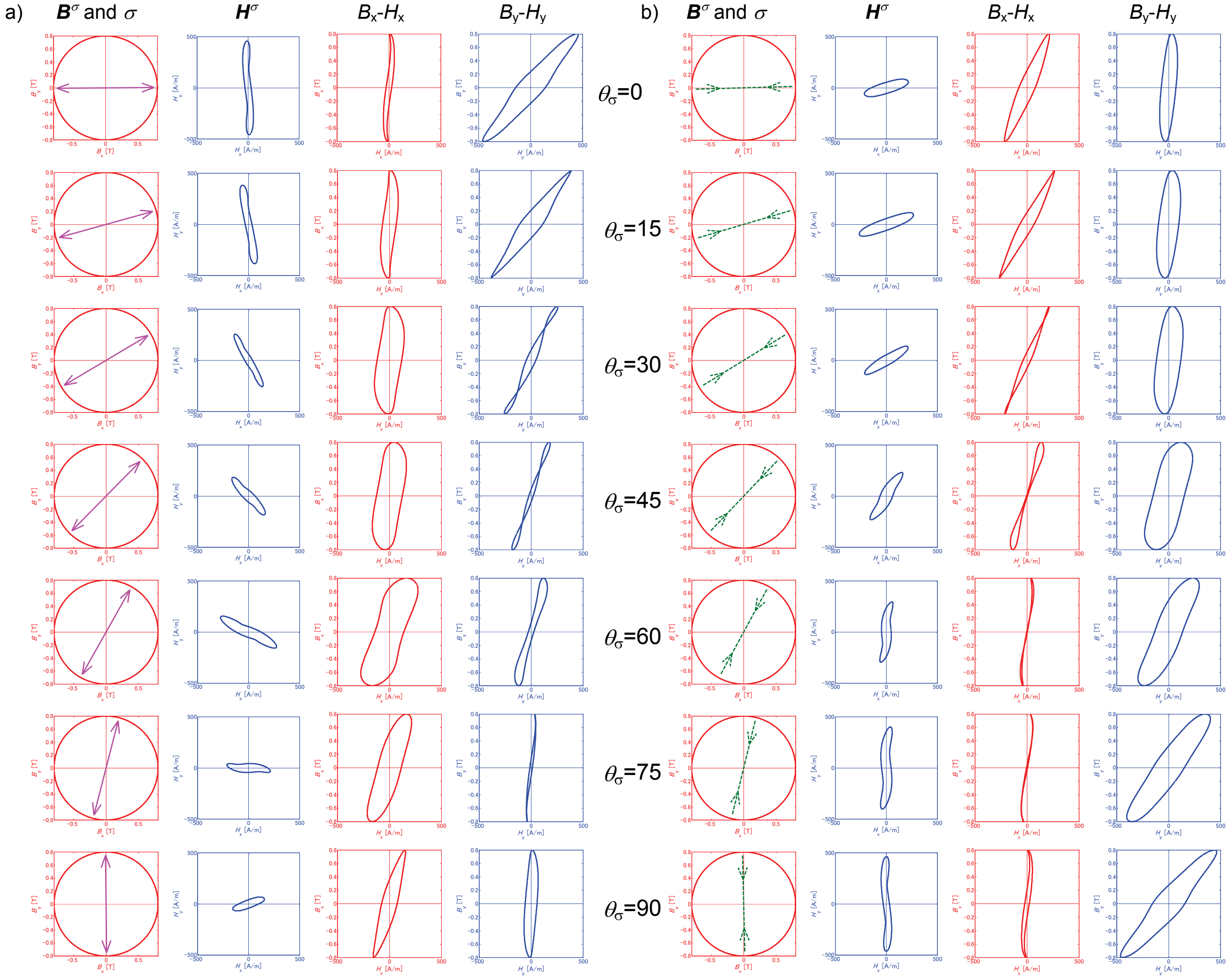

Fig.10. Vector magnetic properties under rotating magnetic flux condition at $B_{\max}$ = 0.8 T and α = 1.0: a) σ_1 = +30 MPa, b) σ_1 = -30 MPa

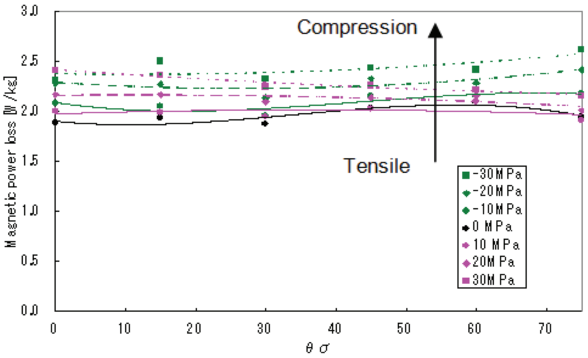

Fig.11. Magnetic power loss at $B_{\max}$ = 0.8 T and α = 1.0 depending on θ_{σ}

In the future works, we will investigate the magnetostriction and magnetic domain wall movement under the stress condition in order to clarify the relationships between the vector magnetic property and stress in more detail.

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