Stress vector magnetic property measurement system

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The development of high-efficiency, low-loss motors is required for industrial and automotive applications. We propose that motors with high efficiency and low loss can be developed by controlling the vector magnetic properties of non-oriented electrical steel sheets by applying stress. Therefore, it is necessary to examine not only the magnitude of the magnetic field strength but also the spatial phase difference between the $B$ and $H$ vectors under stress. In this paper, we present a measurement system that we developed to clarify the relationship between stress and vector magnetic properties.

Key words: non-oriented electrical steel sheet, stress, vector magnetic property, tension, compression

1 Introduction

The development of high-efficiency, low-loss motors is required for industrial and automotive applications. Non-oriented electrical steel sheets are used as core materials in various motors. We propose that motors with high efficiency and low loss can be developed by controlling the vector magnetic properties of such steel sheets by applying stress [1-3]. Therefore, we developed a measurement system to clarify the relationship between the vector magnetic properties and stress. In particular, it is necessary to examine not only the magnitude of the magnetic flux density and the magnetic field strength but also the spatial phase difference between the $B$ and $H$ vectors under stress conditions. This paper presents the measurement method, setup and some results for the proposed measurement system.

2 Measurement system

Figure 1 shows the dimensions and shape of the experimental sample. In this figure, an angle of 0° represents the rolling direction during sheet fabrication. The specimen used in our measurements was cut from a Japanese Industry Standard 35A440 non-oriented electrical steel sheet.

Figure 2 shows the measurement system. After clamping the edge of the sample, external loads were applied along the directions of 0, 45, 90, and 135°. The stress was evaluated based on the mechanical strain, which was measured using a three-axis strain gauge attached to the center of the specimen. The stress tensor components were then calculated using Hooke’s law under plane stress conditions [4]. The specimen was magnetized from the x and y directions using two excitation coils on the upper and lower yokes after clamping the edges of the eight arms of the sample. The magnetic flux density vector and the magnetic field strength vector were measured using a vector-hysteresis sensor equipped with B needle-probes capable of penetrating the insulating coating of the electrical steel sheet. The magnetic flux density was calculated by measuring the terminal voltage in the B needle-probes, while the magnetic field strength was calculated by measuring the voltage induced in the $H$-coil on the specimen surface. The specimen was placed in a sample holder to prevent compression buckling.

3 Measurement method

The amplitude and angle of the principal stresses $\sigma_1$ and $\sigma_2$ and the shear stress angle $\theta_\sigma$ are calculated according to the following equations

$$\sigma_1 = \sigma_z \cos^2 \theta_\sigma + 2 \tau_{xy} \cos \theta_\sigma \sin \theta_\sigma + \sigma_y \sin^2 \theta_\sigma$$ (1)

$$\sigma_2 = \sigma_z \cos^2 \theta_\sigma - \tau_{xy} \cos \theta_\sigma \sin \theta_\sigma + \sigma_y \sin^2 \theta_\sigma$$ (2)

$$\theta = \frac{1}{2} \tan^{-1} \frac{2 \tau_{xy}}{\sigma_z - \sigma_y}$$ (3)

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where $\sigma_x$ and $\sigma_y$ are components of the stress, respectively, and $\tau_{XY}$ is the shear stress. In this paper, the principal stresses are $\sigma_1 = 30$ MPa and $\sigma_2 = 0$ MPa. The angle $\theta$ is varied from 0 to $135^\circ$ in steps of $45^\circ$.

Figure 3 shows the insulating process for the specimen. The specimen is placed on the sample holder, and the specimen edge is clamped after the excitation yoke is applied to the specimen.
control. The loci of the \( H \) inclination angle \( \theta \) shows the principal stress in this measurement system. Thus, it is possible to control the magnitude and angle of varying the loading angle between 0, 45, 90, and 135°.

The relationship between the stress and strain becomes linear by decreasing the stress during the insulating process. In this measurement system, it is possible to cancel the residual stress. On the other hand, the relationship is nonlinear for a loading force at 45°. In particular, tensile and compressive stresses are mixed when the stress is not controlled. On the other hand, the relationship between the stress and strain becomes linear by varying the loading angle between 0, 45, 90, and 135°.

Thus, it is possible to control the magnitude and angle of the principal stress differed during each process. It was necessary to decrease the stress during the insulating process. The amplitude and angle of the principal stress in order to measure the vector magnetic properties accurately.

Figure 4 shows the measured principal stress in the insulating process. The amplitude and angle of the principal stress differed during each process. It was necessary to decrease the stress during the insulating process. The amplitude and angle of the principal stress during the insulating process. The amplitude and angle of the principal stress differed during each process. It was necessary to decrease the stress during the insulating process. In this process, it is possible to cancel the residual stress. On the other hand, the relationship is nonlinear for a loading force at 45°. In particular, tensile and compressive stresses are mixed when the stress is not controlled. On the other hand, the relationship between the stress and strain becomes linear by varying the loading angle between 0, 45, 90, and 135°.

Thus, it is possible to control the magnitude and angle of the principal stress in this measurement system. Figure 6 shows the \( B \) and \( H \) vectors with and without stress control. The loci of the \( H \) vector differs with and without stress control. Figure 7 shows the magnitude \( |H|_{\text{max}} \) and inclination angle \( \theta_H \) of the \( H \) vector with and without stress control. Both \( |H|_{\text{max}} \) and \( \theta_H \) are seen to be affected before and after controlling the stress. Therefore, it is important to control the amplitude and angle of the stress in order to measure the vector magnetic properties accurately.

\[ W_m = \frac{1}{\mu I} \int_0^T (H_x \frac{\partial B_x}{\partial t} + H_y \frac{\partial B_y}{\partial t}) \, dt \]  

Here \( T \) is the period of the excitation and \( \rho \) is the material density. The value of \( W_m \) differs depending on the value of \( \theta_{BH} \). In particular, when \( \theta_{BH} \) is small, \( W_m \) decreases and increases. In addition, it was clear the \( W_m \) decreases in comparison with the non-stress case by applying the stress.
Fig. 8. Dependence of loci of $B$ and $H$ vectors on stress angle $\theta$, (from left to right, $\theta=0$, 45, 90 and 135°)

Fig. 9. Magnetic power loss $W_m$ depending on $\theta_{BH}$

Thus, it is possible to control the vector magnetic properties and decrease the magnetic power loss of a non-oriented electrical steel sheet by applying stress.

5 Conclusions

The design and method for a stress vector magnetic measurement system is presented. It is possible to control the amplitude and angle of stress by adjusting the external load at 0, 45, 90, and 135° with respect to the rolling direction. The magnitude and inclination angle of the $H$ vector differed with and without stress control. It was necessary to control the amplitude and angle of the stress in order to accurately measure the vector magnetic properties under stress. It was clear that not only the magnitude of the $H$ vector but also the spatial phase difference of the $B$ and $H$ vectors changed when stress was applied. Thus, it is possible to control the vector magnetic properties of non-oriented electrical steel sheets by applying stress.

References


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