Effects of Multi-Axial Mechanical Stress on Loss Characteristics of Electrical Steel Sheets and Interior Permanent Magnet Machines

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In this paper, we investigate the effects of multi-axial mechanical stress on eddy current and hysteresis losses in electrical steel sheets used for rotating machines. First, the variation of these losses with the multi-axial stress is confirmed by material experiments. From the results, appropriate and useful mechanical-electromagnetic modeling for loss analysis of rotating machines is discussed. Finally, the proposed modeling is applied to the combined electromagnetic field and stress analyses of an interior permanent magnet machine to reveal the effects of multi-axial stress on the rotor core loss, which is directly related to the thermal demagnetization of permanent magnets. It is clarified that both the hysteresis loss and the eddy current loss including excess loss depend on the multi-axial stress. As a consequence, the rotor core loss of interior permanent magnet machine increases by the stress caused by centrifugal force.

***Index Terms*—Permanent magnet machines, losses, stress, finite element methods.**

I. INTRODUCTION

It is well known that the mechanical compressive stress often causes an increase in core loss of rotating machines. The most famous effect is the increase in core loss at stator yokes by shrink fitting of housings. In this case, the directions of both the major component of principal stress and the magnetic field at the yoke are nearly in circumferential direction. Therefore, this core-loss increase is often estimated by the material experiments, in which a uniaxial stress is imposed along the flux direction.

On the other hand, large tensile stress is often generated at the rotor cores of interior permanent magnet synchronous machines (IPMSMs) according to the centrifugal forces worked on magnets and cores [1]. In the rotor of this motor, the direction of the flux considerably varies with position in the core. As a consequence, the direction of the magnetic field is not always parallel to the stress, rather in right angle to the stress in some cases. Therefore, the investigation of the effects of multi-axial stress on the core loss should be needed for the accurate estimation of rotor core loss, which is directly related to the thermal demagnetization of PMs.

The effect of the multi-axial stress on the total core loss in electrical steel sheets has been investigated in reference [2]. However, the effects on each loss component, i. e., the eddy current and hysteresis losses, have not been clarified yet. The detailed variation of these losses with the multi-axial stress should be clarified for the development of loss calculation method for rotating machines because the ratio of these losses to the total core loss considerably varies with machine operating conditions.

From these viewpoints, in this paper, the variation of these losses with the multi-axial stress is confirmed by material experiments. Then, appropriate and useful mechanical-electromagnetic modeling for loss analysis of rotating machines is discussed. Finally, the proposed modeling is applied to the combined electromagnetic field and stress analyses of an interior permanent magnet machine to reveal the effects of multi-axial stress on the rotor core loss.

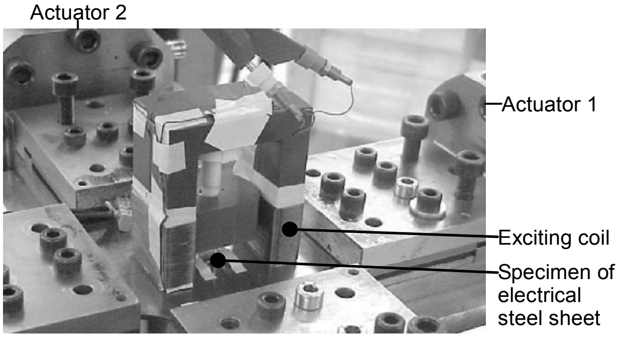
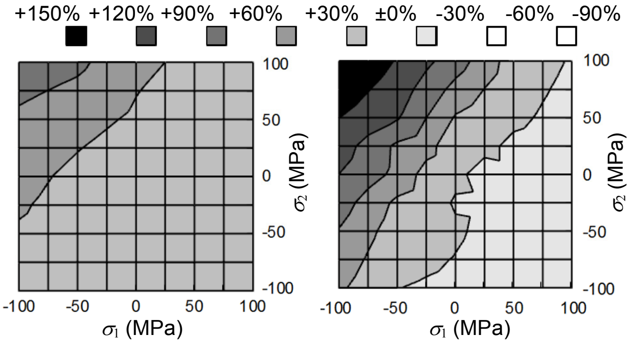


Fig. 1. Experimental system for effect of multi-axial stress[2].



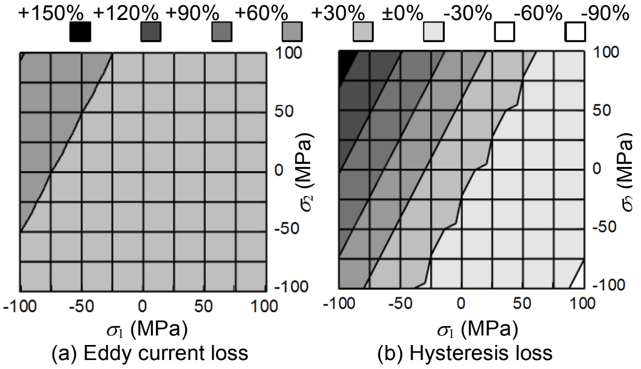
(a) Eddy current loss (b) Hysteresis loss

Fig. 2 . Measured variation in losses with multi-axial stress.

II. BASIC EXPERIMENTS FOR MULTI-AXIAL STRESS EFFECTS

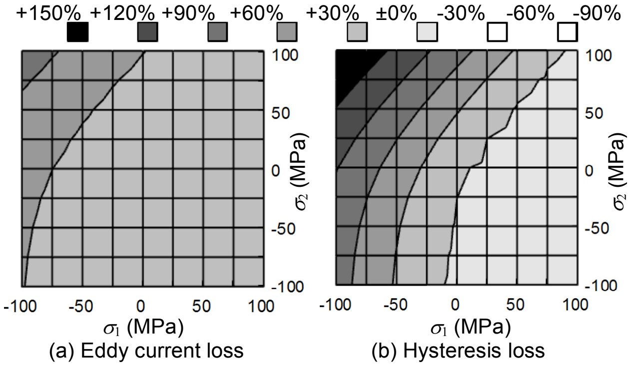
Fig. 1 shows the experimental system used in [2], in which arbitrary 2-axial stress can be imposed on the specimen of an electrical steel sheet by the actuators noted 1 and 2. The magnetic field is applied along the direction of the force produced by actuator 1. The specimen is an electrical steel sheet with 3% silicon.

The hysteresis loss and the eddy current loss including the excess loss are separated from the measured total core losses at 50 Hz and 200 Hz. Fig. 2 shows the results. It is revealed that both the eddy current and hysteresis losses are affected by multi-axial stress. These losses become maximum when the compressive (minus) σ_1 and tensile (plus) σ_2 are imposed.



(a) Eddy current loss (b) Hysteresis loss

Fig. 3. Calculated losses by $W(\sigma_1,0)$ and σ_{eq} by (1)



(a) Eddy current loss (b) Hysteresis loss

Fig. 4. Calculated losses by $W(\sigma_1,0)$ and σ_{ea}^C by (2).

III. EQUIVALENT STRESS FOR LOSS CALCULATION

The experiments explained in the previous section cannot be always carried out for many kinds of electrical steel sheets. To obtain the approximated multi-axial stress effects, the single axial equivalent stress σ_{eq} has been proposed.

In reference [3], following expression was derived under the assumption that a same magneto-elastic energy leads to a same characteristics of the magnetic materials:

$$\sigma_{eq} = \frac{3}{2}\vec{h}.\mathbf{s}.\vec{h} \tag{1}$$

where $\vec{h}$ is the unit vector along the magnetic field direction, $\mathbf{s}$ is the deviatoric part of the stress tensor expressed by σ_1 and σ_2. It is assumed that the variation in core loss with single σ_{eq} along the magnetic field direction is identical to that with multi-axial σ_1 and σ_2. Therefore, the effect of the multi-axial stress can be estimated only by (1) and the experiment, in which a uniaxial stress is simply imposed along the flux direction.

In reference [4], the expression (1) was expanded to following one by considering the effect of magnetic domains:

$$\sigma_{eq}^C = \frac{1}{K}\ln\left\{\frac{2\exp(K\vec{h}.\mathbf{s}.\vec{h})}{\exp(K\vec{t}_1.\mathbf{s}.\vec{t}_1)+\exp(K\vec{t}_2.\mathbf{s}.\vec{t}_2)}\right\} \tag{2}$$

where $\vec{t}_1$ and $\vec{t}_2$ are the unit vectors that are perpendicular to the magnetic field, K is the factor that expresses the effect of magnetic domains. The relationship between (1) and (2) can be expressed as follows:

$$\sigma_{eq} = \lim_{K\to 0}\sigma_{eq}^C \tag{3}$$

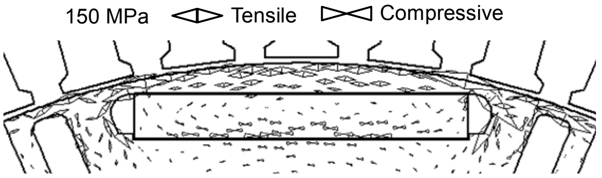


Fig. 5. Rotor stress distribution in IPMSM (10000 r/min)

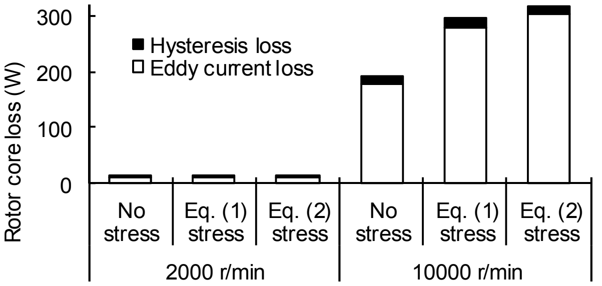


Fig. 6. Calculated rotor core loss of IPMSM at no load.

This can be easily proved only by mathematics.

Figs. 3 and 4 show the calculated variation in the losses only from the measured loss $W(\sigma_1,0)$ by single axial σ_1 and the equivalent stresses. It is confirmed that these results well express the measured eddy current and hysteresis losses in Fig. 2. In detail, the result by (1) slightly underestimates the effect of σ_2 as compared with that by (2).

IV. APPLICATION TO IPMSM

The above-mentioned equivalent stresses are applied to the combined electromagnetic field and stress analyses [1] for rotor core loss calculation of a 100 kW class IPMSM. In the analyses, the loss is calculated by following expression:

$$w_c = \sum_{k=1}^{2}\left\{C_e\left(\sigma_{eq,k}, B_{\max,k}\right)w_{e,k,\sigma 0} + C_h\left(\sigma_{eq,k}, B_{\max,k}\right)w_{h,k,\sigma 0}\right\} \tag{4}$$

where C_e and C_h are the increase ratios of eddy current and hysteresis losses that are obtained by the core material experiments with single σ_1, respectively; $\sigma_{eq,1}$ and $\sigma_{eq,2}$ are the equivalent stresses for $\vec{h}$ =(1,0) and $\vec{h}$ =(0,1), respectively; $B_{\max,1}$ and $B_{\max,2}$ are the amplitude of flux-density components along the principal axes, respectively; $w_{e,k,\sigma 0}$ and $w_{h,k,\sigma 0}$ are the eddy current and hysteresis losses caused by B_k when the mechanical stress is zero.

Fig. 5 shows the result of the stress analysis. Large circumferential tensile stress is observed at the rotor surface. This stress is almost in right angle to the magnetic field direction. Fig. 6 shows the calculated rotor core losses. The effect of the multi-axial stress at high speeds is clarified.

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