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MECHANICAL STRESS-DEPENDENCY OF IRON LOSSES IN NON-ORIENTED ELECTRICAL STEEL SHEETS

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***Abstract* - Mechanical loads of diverse origin alter the magnetic properties of the core material of electrical machines during operation and, as a result, magnetic flux path and iron losses. For example, centrifugal forces on the rotor, stresses due to shrink fitting or electromagnetic forces are potential causes of internal mechanical stresses. In this paper, a single sheet tester equipped with a hydraulic pressure cylinder is used to characterize the variation of hysteresis loop shapes and losses of electrical steel sheets loaded by tensile stresses. Based on these measured data, the mechanical stress-dependency of the iron loss model parameters is studied.**

I. INTRODUCTION

The magnetic properties of non-oriented (NO) electrical steels are prone to mechanical stresses, i.e., residual, external or thermal ones. In rotating electrical machines, mechanical stresses are ubiquitous and are of diverse origin such as, e.g., material processing, machine construction and operation conditions. As a result, the efficiency of the machine and specific losses are largely altered by the different states of mechanical stress.

In order to improve rotating electrical machines in terms of energy efficiency and operation characteristics, the interdependence of mechanical stresses and magnetic properties deterioration needs to be investigated and understood. Within the last decades, many researchers have worked on the magneto-elastic coupling being closely related to magnetostriction [1] and its consequences for the magnetic properties of electrical steel sheets [2]. In electrical machines, the knowledge about the behaviour of specific iron losses dependent on the mechanical stress $p_{\text{iron}}(B, f, \sigma)$ in the post processing part of machine design is necessary [3].

This paper discusses the effect of applied tensile stress on the static and dynamic loss components. Based on these measured data, the mechanical stress-dependency of iron loss modelling parameters is studied.

II. IRON LOSS MODEL

The IEM-formula for iron losses [4] describes the iron loss behaviour with the following equation:

$$\begin{aligned} p_{\text{iron}} &= p_{\text{Hys}} + p_{\text{Cl}} + p_{\text{Nl}} + p_{\text{Ex}} \\ &= a_1 B^{\alpha+\beta B} f + a_2 B^2 f^2 + a_2 a_3 B^{2+a_4} f^2 + a_5 B^{1.5} f^{1.5}, \end{aligned} \quad (1)$$

where $a_1..a_5$ are the parameters for hysteresis, classical, non-linear or excess losses, respectively. B represents the magnetic flux density and f its frequency. In contrast to [4], here, the hysteresis loss description is extended to account for the fact that the full polarization dependence of hysteresis cannot be described by a single power function representation. Splitting the equation into a static and dynamic component and adding the stress-dependency, (1) becomes:

$$p_{\text{static}}(B, f, \sigma) = p_{\text{Hys}}(B, f, \sigma) = a_1(\sigma) B^{\alpha(\sigma)+\beta(\sigma)B} f \quad (2)$$

and

$$p_{\text{dynamic}}(B, f, \sigma) = p_{\text{Cl}}(B, f) + p_{\text{Nl}}(B, f, \sigma) + p_{\text{Ex}}(B, f, \sigma). \quad (3)$$

The material specific parameters $a_1(\sigma)$, $\alpha(\sigma)$ and $\beta(\sigma)$ represent the hysteresis loss component or static loss component, respectively, and are determined from parameter fitting using the DC energy measurement results.

The classical loss component parameter is assumed to be independent on the mechanical stress for loads below yield strength and is solely described by material properties [3].

In this paper, only the static loss component consisting of the hysteresis loss component and the dynamic loss component which includes the classic, excess and non-linear loss component are studied.

III. MEASUREMENT

A. Experimental setup

A single sheet tester (SST) equipped with a hydraulic pressure cylinder can load specimens of electrical steel sheet with a maximum force of $F = \pm 5\,\text{kN}$ homogeneously.

The SST is incorporated into a computer-aided setup in accordance with the international standard IEC 60404-3. The samples are characterized using controlled sinusoidal magnetic flux density with a form factor error of less than 1% in the frequency range from quasi-static to $1000\,\text{Hz}$.

Each sample has a length of $l = 600\,\text{mm}$, a width of $w = 100\,\text{mm}$ and a thickness of $t = 0.35\,\text{mm}$. Stress and magnetic flux are applied collinear (uni-axial loading). Only specimens in rolling direction are used.

B. Results of mechanical measurement

The changes in magnetic properties loaded by stress within the elastic area of the material are studied. This is proofed by measuring the strain of an additional sample of the same material while applying a mechanical stress without a magnetic field. The strain is measured by a strain gauge adhered to the centre of one specimen. The result shows an elastic behaviour in the applied stress region with a determined Young's modulus of $E = 174\,\text{GPa}$.

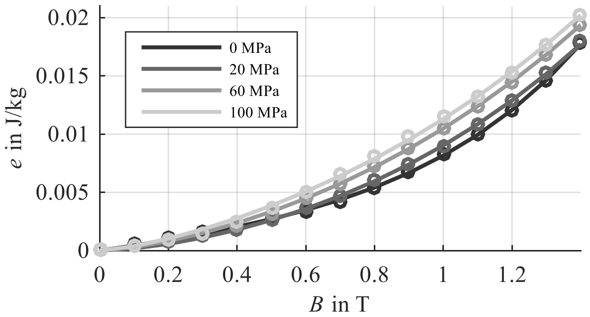

Fig. 1. Measured (circles) and calculated (lines) specific energy losses for different stress levels.

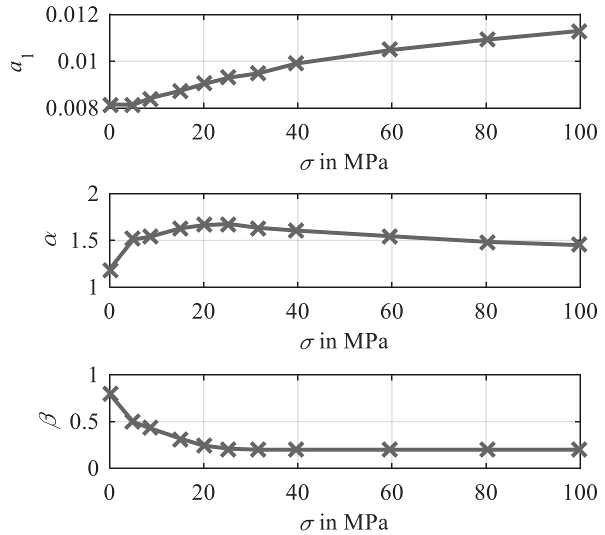

Fig. 2. Parameters of static loss component dependent on mechanical stress.

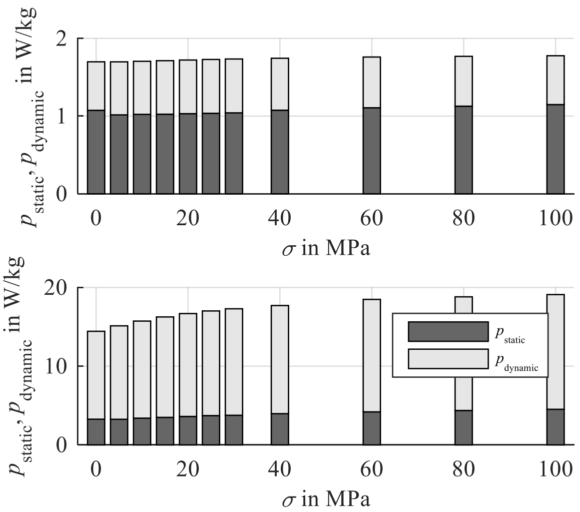

Fig. 3. Proportion of static and dynamic losses of the total losses for $f = 50\,\text{Hz}$, $B = 1.5\,\text{T}$ (upper diagram) and $f = 400\,\text{Hz}$, $B = 1\,\text{T}$ (lower diagram).

C. Results of magnetic measurement

For each stress level, the results of the DC measurement are used to determine the parameters a_1, α and β (Fig. 1). Fig. 2 depicts the trend of the parameters a_1, α and β dependent on the stress level. It is apparent that for small stress values up to approx. $\sigma = 20\,\text{MPa}$, there is the most variation of the parameters. Due to a shear in the hysteresis curves for higher stress values and thus a higher magnetic energy loss, parameter a_1 increases in the complete area. Parameter α rises for small stress values before reaching its peak at approx. $20\,\text{MPa}$. Then, a slight decrease occurs. Parameter β declines before reaching its limitation at approx. $30\,\text{MPa}$.

Fig. 3 shows the proportion of the static loss and dynamic loss component for $f = 50\,\text{Hz}$, $B = 1.5\,\text{T}$ (upper diagram) and for $f = 400\,\text{Hz}$, $B = 1\,\text{T}$ (lower diagram). The dynamic loss component is determined by calculating the difference of measured total losses and static losses for each stress level. Seemingly, for small mechanical stresses up to approx. $20\,\text{MPa}$, the static loss proportion decreases and then starts to increases slightly. For higher frequencies, the same behaviour is observable.

For $f = 50\,\text{Hz}$, the dynamic loss component reaches its maximum proportion at approx. $20\,\text{MPa}$ and then remains almost constant. For $f = 400\,\text{Hz}$, an increase of the dynamic loss component is noticeable before reaching an upper limit for high stress values. Changes of the dynamic loss component are related to changes of the micro- and domain-structure affecting the excess loss component.

IV. CONCLUSIONS

In this paper, the stress-dependency of the static and dynamic iron loss component is studied. The influence of mechanical stress on the iron losses is noticeable. Particularly, for small stress values up to $20\,\text{MPa}$, the most variation in the loss components is observed.

Due to the observed effects, the stress-dependency of magnetic properties in electrical steel sheets cannot be neglected and has to be considered in the electrical machines' design process.

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