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Iron loss components dependent on mechanical compressive and tensile stress in non-oriented electrical steel

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Abstract. Mechanical stress of diverse origin alters the magnetic properties of the core material of electrical machines during operation and, as a result, the magnetic flux path and particularly iron loss. In this paper, based on mechanical stress-dependent magnetic characterisation of non-oriented electrical steel sheet, the behaviour of the specific iron loss and its components are determined and modelled for compressive and tensile stress using stress-dependent iron loss seperation. An approach is presented to model the hysteresis loss component without dc measurements. Here, the focus is set on high frequencies and magnetic flux densities. As a result, a high sensitivity of the components particularly to mechanical compressive stress can be observed and modelled.

Keywords: Iron loss in electrical machines, parameter seperation, magnetomechanical effect

1. Introduction

The magnetic properties of non-oriented (NO) electrical steels are sensitive to mechanical stress and load which have a residual, external or thermal origin. In rotating electrical machines, mechanical tensile and compressive stress is caused by material processing, machine construction and operation conditions and can be found within the stator core as well as within the rotor core lamination.

The efficiency and specific loss of the machine are largely altered by mechanical stress. In this study, the examined correlation of mechanical stress and strain with magnetic properties leads to a detailed magnetic characterisation of mechanically-stressed soft magnetic material specimens which directly relate to actual characteristics of electrical steel laminations in electrical machines. Concurrent with several developments concerning improved power density and performance of these applications, the focus is put to magnetic flux densities and higher frequencies up to 10 kHz. Particular attention has to be given on compressive stress which mostly appears inside the stator yoke due to the shrink fitting process. In contrast, tensile stress occurs inside the rotor core caused by high centrifugel forces during operation.

To determine the electrical machine's efficiency, knowledge about the behaviour of the specific iron loss dependent on magnetic flux density, frequency and mechanical stress within the post processing part of

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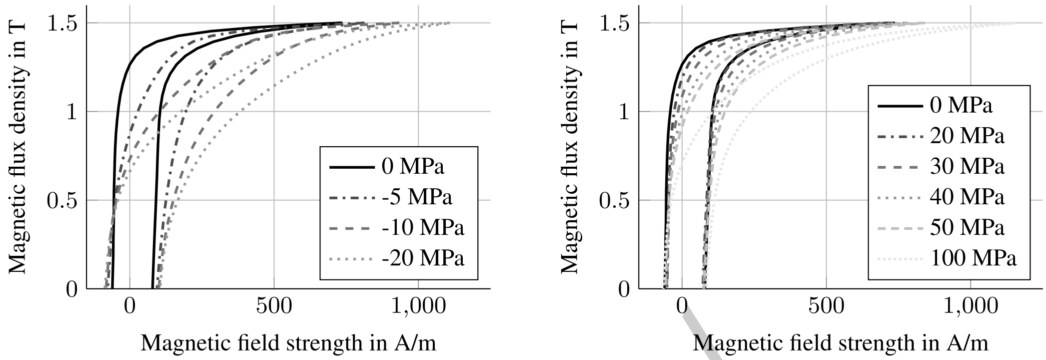

Fig. 1. Measured hysteresis curves for compressive stress (left) and tensile stress (right) at f =50 Hz, B_{max} = 1. 5 T in RD.

machine design is required. In [1], the stress-dependency of iron loss parameters for hysteresis, classical and excess loss components dependent on compressive and tensile stress are studied. A phenomenological description for the three parameters subjected to compressive stress is given. As a conclusion, it is shown that the hysteresis and excess loss component behave similar when subjected to a mechanical stress within the elastic region. In [2], the influence of mechanical stress on the excess loss component is analysed by focussing on the mechanical stress-dependency of intrinsic material parameters. Studies in [3] result in a polynomial description of the stress-dependent hysteresis loss parameter with focus on mechanical compressive stress. In [4], a model is provided which describes the iron loss components for tensile stress within the elastic region. The authors in [5] study the iron loss components for elastic and plastic tensile stress by giving a description for static and dynamic iron loss parts.

This paper discusses the effect of applied mechanical stress within the range of −20 MPa to 100 MPa on the iron loss components. In contrast to the mentioned studies above, a stress-dependent non-linear loss component is added to consider the non-linear behaviour of the magnetisation curve for high magnetic flux densities as well as a description for both mechanical compressive and tensile stress within the elastic region.

2. Measurements

A single sheet tester (SST) equipped with a hydraulic pressure cylinder can load specimens of electrical steel sheet with a maximum force of ±5 kN homogeneously. The SST is incorporated into a computer-aided set-up in accordance with the international standard IEC 60404-3 [6]. The samples of the material M400-50A are characterised using analogue-controlled sinusoidal magnetic flux density in the frequency range from 10 Hz to 400 Hz. Each sample has a length of 600 mm, a width of 100 mm and a nominal thickness of 0.5 mm. Mechanical load and magnetic flux are applied collinear (uni-axial loading). Specimens in rolling (RD) and transverse (TD) direction are studied.

Figure 1 depicts the measured hysteresis curves for a specimen subjected to compressive and tensile stress at the operating point of 1.5 T and 50 Hz. Compared to tensile stress, compressive stress has a higher impact on the shear behaviour of the hysteresis curves. A mechanical compressive stress of −20 MPa causes a wider shear of the hystersis curves than a mechanical tensile stress of 100 MPa. This stronger impact of the negative effect of compressive stress compared to tensile stress is also observed in [1] and [7]. Compressive stress is understood to be solely detrimental for the magnetic properties of electrical steel, whereas tensile stress yields in a more complex effect. The phenomenological response of the hysteresis curve as a result of applied, unidirectional tensile stress depends on the magnetostriction of the material [8]. In theory, the magnetisation is increased by tension for materials with positive magnetostriction. The opposite reaction, i.e., a decrease of magnetisation occurs with negative magnetostriction [8]. For the material under study however, a Villari-reversal can be observed, which means that with increasing tension, first, a improvement of magnetic properties, i.e., smaller hysteresis area, occurs for stress up to 20 MPa. Then, for higher stress, a shearing of the hysteresis curve results in a deterioration of magnetic properties, i.e., decrease of magnetisation and increase of loss.

3. Model

3.1. Description of stress-dependent iron loss

The current semi-physical approach for modelling iron loss leads to a good prediction for high magnetic flux densities and frequencies [9]. Adding stress-dependency to the existing iron loss model which consist of a hysteresis loss component p_{hys}, a classic (FOUCAULT) loss component p_{cl}, an excess loss component p_{exc} and a non-linear loss component p_{nl}, the equation becomes:

$$p_{\text{tot}}(\sigma) = p_{\text{static}} + p_{\text{dynamic}}, \tag{1}$$

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

$$p_{\text{dynamic}}(\sigma) = p_{\text{cl}} + p_{\text{nl}} + p_{\text{exc}} = a_2 B^2 f^2 + a_2 a_3(\sigma) B^{2+a_4(\sigma)} f^2 + a_5(\sigma) B^{1.5} f^{1.5}, \tag{3}$$

where $a_1 \ldots a_5$ and α, β are the stress-dependent iron loss parameters, B the flux density and f the frequency. The parameters are determined for each stress stage, using the following calculation steps.

3.2. Determination of iron loss components

The classic loss component is independent on mechanical stress. Parameter a_2 is determined by [10]:

$$a_2 = \frac{\pi^2 d^2}{6\rho\rho_{\text{e}}} = 1.356e \cdot 10^{-4}. \tag{4}$$

d is the thickness of the material, $\rho = 7700 \frac{\text{kg}}{\text{m}^3}$ its density and ρ_{e} = 59. 8 μΩ the specific electric resistivity. In measurements, it is validated that the specific electric resistivity does not change for zero stress and different tensile stress values, which is also described in literature [11].

For this study, the low frequency measurements are used to determine hysteresis and excess loss component. The hysteresis energy has to be equal for the measured frequencies f_1 and f_2:

$$\frac{p_{\text{hys}}(f_1, B)}{f_1} \stackrel{!}{=} \frac{p_{\text{hys}}(f_2, B)}{f_2}. \tag{5}$$

The non-linear loss component p_{nl} can be neglected for low frequencies, so (5) becomes:

$$\frac{p_{\text{tot}}(f_1, B) - p_{\text{cl}}(f_1, B) - p_{\text{exc}}(f_1, B)}{f_1} = \frac{p_{\text{tot}}(f_2, B) - p_{\text{cl}}(f_2, B) - p_{\text{exc}}(f_2, B)}{f_2}. \tag{6}$$

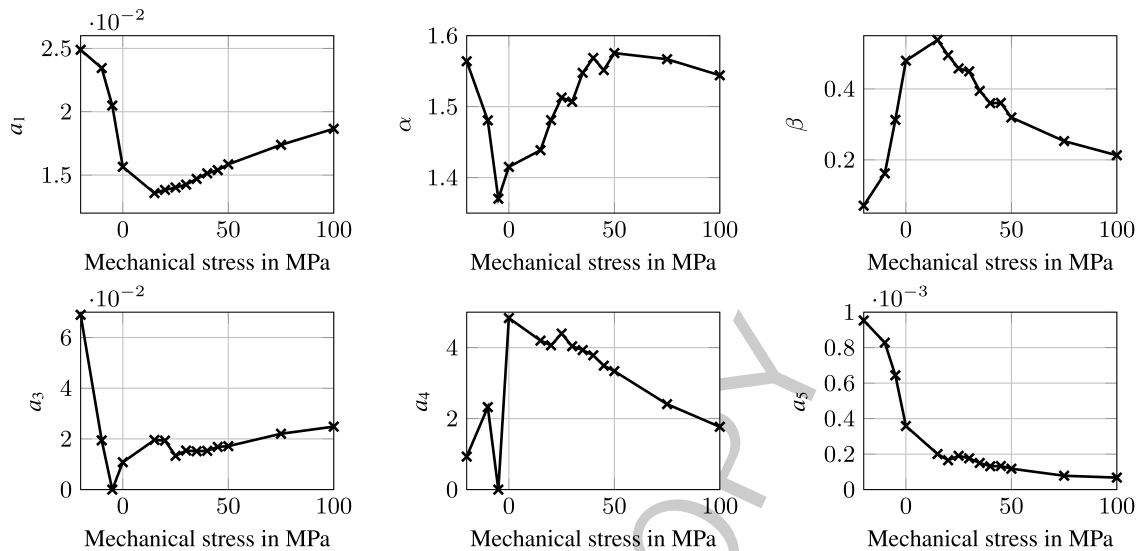

Fig. 2. Stress dependent iron loss parameters.

a_5 can now be evaluated by using the description of the excess loss term in (3):

$$a_5 = \frac{\frac{p_{\text{tot}}(f_2,B)-p_{\text{cl}}(f_2,B)}{f_2} - \frac{p_{\text{tot}}(f_1,B)-p_{\text{cl}}(f_1,B)}{f_1}}{B^{1.5}(f_2^{0.5} - f_1^{0.5})}, \tag{7}$$

with the measured magnetic flux densities B.

The hysteresis loss parameters can now be easily calculated after knowing the excess loss by mathematical fitting of the specific hysteresis energy:

$$\frac{p_{\text{hys}}(B)}{f} = a_1(\sigma)B^{\alpha(\sigma)+\beta(\sigma)B} = \frac{p_{\text{tot}}(f, B) - p_{\text{cl}}(f, B) - p_{\text{exc}}(f, B)}{f}. \tag{8}$$

To account for measured loss at higher magnetic flux densities ($B > 1$ T), a so-called nonlinear or saturation loss component is added which considers the non-linear material behaviour for high frequencies and magnetic flux densities [4]. The non-linear loss parameters are estimated by mathematical parameter identification.

3.3. Stress-dependency of loss components

In Fig. 2, the determined stress-dependent iron loss components are shown. The parameters are determined by the loss seperation methods explained in Section 3.2. Missing values between the measuring points are determined by using a mathematical interpolation.

Obviously, for mechanical stress below 20 MPa, the iron loss coefficients $a_1 \ldots a_5$ are very sensitive to mechanical stress, whereas for mechanical stress larger than 20 MPa, the influence is smaller. Regarding compressive stress, the iron loss and its parameters are saturated for high compressive stress. This behaviour was also observed in previous studies, e.g. in [11]. The discontinuous behaviour of parameters a_3 and a_4 is a result of the parameter determination of the non-linear loss component.

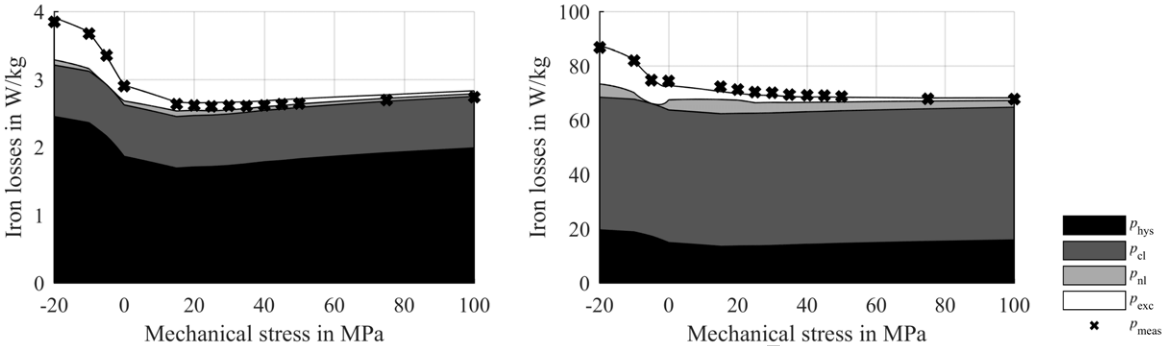

Fig. 3. Measured iron loss and modelled loss components dependent on mechanical stress for f =50 Hz, B =1.5 T (left) and f =400 Hz, B =1.5 T (right) in RD.

4. Results

In Fig. 3, the modelled iron loss components and the measured iron loss are shown for different frequencies. It can be observed that for the shown frequencies (50 Hz and 400 Hz), the modelled iron loss represents the measured loss. Similar results can be observed for other frequencies in the range of 10 Hz to 400 Hz. Small discrepancies are mainly due to the mathematical determination error of hysteresis and excess loss component. However, the presented model enables a good estimation of mechanical stress-dependent iron loss.

As seen in the model and measurement results, the iron loss is strongly deteriorated by mechanical compressive stress. In particular for small compressive stress, a strong increase of iron loss is observed. A large sensitivity of the hysteresis curves (cf. Fig. 1), which means a wide shear due to compressive stress, causes a large hysteresis loss component. The trend shows a saturating behaviour for high compressive stress, which can validated by other studies [12]. The model and measurement results show a loss minimum at small tensile stress. This minimum is frequency-dependent, meaning that for low frequencies, the hysteresis loss component is dominant. As consequence, the tensile-stress induced shear of the hysteresis curve is dominant. This causes a loss minimum for small tensile stress whereas for higher frequencies, the classic loss component becomes dominant, resulting in a smaller influence of the hysteresis loss component for tensile stress. The minimum is due to a Villari reversal, which sees a change of behaviour with increasing uni-directional tensile stress. For small tensile stress, the hysteresis curves steepen, thus less magnetic field strength is required to reach a certain polarisation, while the losses decrease. At a higher mechanical stress level, the curves then shear and the magnetic properties deteriorate. For higher compressive stress, a further shear of the hysteresis curve is not possible, resulting in a saturation of loss for high compressive stress [11]. Regarding the increasing behaviour of the excess loss component for compressive stress, this component is very relevant when compared to tensile stress.

Within the stator yoke of electrical machines, high compressive stress occurs caused by shrink fitting of stator core and housing. As presented in this study, a large deterioration of iron loss for compressive stress, which is caused by a drastic increase of the hysteresis loss component, is shown. As consequence, the iron loss within the stator yoke are increased. Due to high magnetic flux densities and frequencies within the stator lamination core, the influence of mechanical stress on the iron loss cannot be neglected when calculating the machine's efficiency and the local distribution of iron loss.

Mechanical tensile stress mostly occurs within the rotor lamination of the machine. Particular for high-speed electrical machines, high mechanical stress up to the yield strength of the core material is generated by high centrifugal forces. Due to the existence of a loss minimum at small tensile stress and low frequencies, the rotor core loss can be reduced by a smart rotor design.

5. Conclusions

In this study, a model for the mechanical stress-dependency of iron loss components was developed and analysed for mechanical compressive and tensile stress. The model leads to a good estimation of iron loss and allows a study on the loss components for different mechanical stress stages. A strong influence of compressive load on the iron loss is observed, which can be motivated by a drastic increase of hysteresis loss.

Interesting for the design and operation of electrical machines is the strong loss degradation for compressive stress as well as the presence of a loss minimum for small tensile stress at low frequencies, meaning that the existence of stress has essential influence on the efficiency of electrical machines.

The developed model can be implemented to give stress-dependent iron loss and continuative efficiency calculations. Within the machine design, these estimations can be used to develop improved rotor designs and focus on a stress-reduced machine and steel sheet processing. These outcomes will be presented in further studies. Furthermore, an extension of this model will provide more dimensional cases, where mechanical stress and strain are not applied collinear.

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