CONTINUOUS LOCAL MATERIAL MODEL FOR THE MECHANICAL STRESS-DEPENDENCY OF MAGNETIC PROPERTIES IN NON-ORIENTED ELECTRICAL STEEL

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Abstract – **Magnetic properties of electrical steel are affected by mechanical stress. In electrical machines, influences due to manufacturing and assembling and due to operation cause a mechanical stress distribution inside the steel lamination. This stress distribution and its consequences for the magnetic properties must be considered when designing electrical machines. In this paper, an approach for modelling stress-dependent magnetic material properties such as magnetic flux density using a continuous local material model is presented.**

I. INTRODUCTION

In electric machines, mechanical stress of diverse origins is imposed into the electrical steel lamination. Origins are manufacturing of the steel sheet (e. g. coiling) and laminations (e. g. cutting, stamping), motor assembly (e.g. shrinking) or due to operation (e. g. centrifugal forces inside rotors). Considering the magneto-elastic effect, the mechanical stress distribution influences the magnetic behaviour of the steel lamination. To obtain a deeper understanding of the altered magnetic flux path or iron losses due to imposed mechanical stress, material models are required describing the stress-dependent material behaviour.

One focus of recent research is set to the stress-dependency iron losses in electrical machines [1], whereas approaches for the stress-dependent magnetisation curve can be found in [2] and [3]. Although these models lead to good results in an approximation of the stress-dependent behaviour, they need many parameters extracted from measurements. These models do not provide a recursive description to obtain the local mechanical stress distribution inside the material.

In this paper, a continuous local material model describing the stress-dependency of the magnetisation curve is derived from a continuous local material model considering effects of the cutting process. This model can provide the local mechanical stress distribution using the example of a cutting procedure.

II. LOCAL MAGNETIC MATERIAL MODEL

The continuous material model in [4] leads to a description of the magnetic flux density degradation due to cutting processes dependent on distance to cut edge:

$$B(y,H) = \mu_0 H\left[\mu_\mathrm{r}(y=0,H) - \Delta\mu_\mathrm{cut}(H)F\left(y\right)\right], \qquad (1)$$

where B is the magnetic flux density, H the magnetic field strength, μ_r the magnetic permeability, y is the distance to the cut edge, $\Delta\mu_\mathrm{Cut}$ the magnetic permeability drop at the cut edge and $F\left(y\right) = \frac{2}{b}\int_0^{\min\left(\delta/\frac{b}{2}\right)} \eta\left(y,\delta,a\right)\,\mathrm{d}y$ the integral value of the local deterioration profile. The influence depth of the degraded zone is assigned by δ, while a is a compression factor.

This model is now adapted for magnetic flux density degradation due to mechanical stress:

$$B(\sigma,H) = \mu_0 H\left[\mu_\mathrm{r}(\sigma=0,H) - \Delta\mu_\sigma(H)F\left(\sigma\right)\right], \qquad (2)$$

where σ is the mechanical stress. $\Delta\mu_\sigma$ reflects the degradation of the magnetic permeability and F is a function describing the influence of the mechanical stress on the magnetizability of the material. Both, the model parameter $\Delta\mu_\sigma$ and F, are identified on measurements using the following dependency:

$$\Delta\mu_\sigma\left(H\right) = \frac{\mu_\mathrm{r}\left(\sigma=0,H\right) - \mu_\mathrm{r}\left(\sigma,H\right)}{F\left(\sigma\right)} = \text{const.}\ \forall\ \sigma\,. \qquad (3)$$

III. MECHANICAL STRESS DISTRIBUTION

Considering a two-dimensional sample (Figure 1) with the length l and height h subject to a global force in x-direction F_x acting on cross section A, external ($\bar{\sigma}$) and local (σ) mechanical stresses at position (x,y) can be defined:

$$\begin{aligned} &\bar{\sigma}_\mathrm{x}(y) = \frac{F_\mathrm{x}}{A}, \\ &\sigma_\mathrm{x}(x, y=\text{const.}) = \text{const.}, \qquad (4) \\ &\sigma_\mathrm{y}(x,y) = 0. \end{aligned}$$

Here, it is assumed that the local stress distribution has only an x-component and varies in y-direction. Shear stress

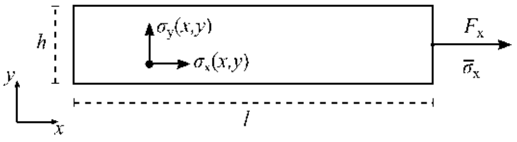

Fig. 1. Two-dimensional sample with local and global mechanical stress distribution.

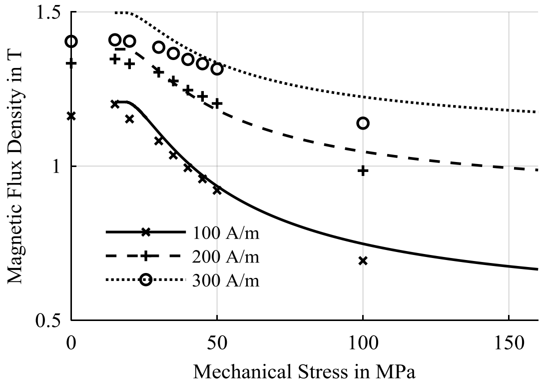

Fig. 2. Modelled magnetic flux density dependent on mechanical stress (lines) compared to measurements (markers) for various magnetic field strengths.

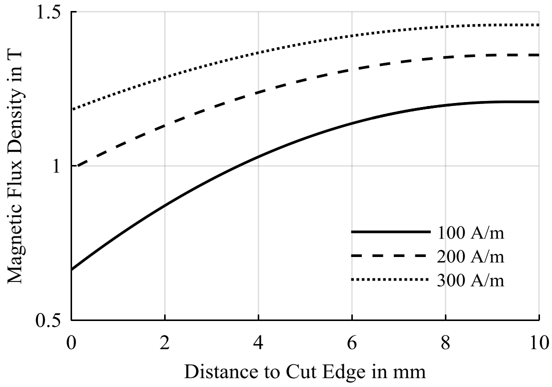

Fig. 3. Modelled magnetic flux density dependent on distance to cut edge for various magnetic field strengths.

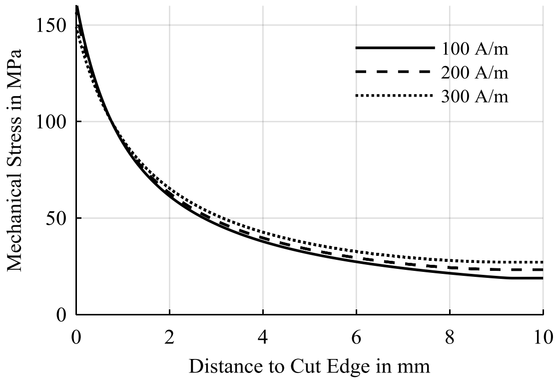

Fig. 4. Resulting mechanical stress distribution dependent on distance to cut edge for various magnetic field strengths.

components are neglected. Therefore, the local mechanical stress can be determined for each *y*-position inside the sample:

$$\sigma = \sigma_{\mathrm{x}}\left(y\right). \tag{5}$$

IV. RESULTS

Measurements of the steel grade M400-50A are used to parametrise the mechanical stress model (2). Resulting local distributions of magnetic flux density are presented for various values of magnetic field strength as function of the mechanical stress in Figure 2. For this study, only tensile stress is applied causing a homogeneous stress distribution inside the specimen. As depicted in Figure 2, mechanical stress causes an increase of magnetic flux density for small mechanical tensile stresses and a constant magnetic field strength. Then, a decreasing behaviour can be observed. An explanation can be found in [1, 5]. The proposed model leads to a good description from 15 MPa to higher mechanical stress. For small mechanical stresses, two values of magnetic flux densities fulfil the criteria (6).

Cutting processing yields a local decrease of magnetic flux density at the cut edge (Figure 3). The results of both models (1) and (2) are used to find a mechanical stress distribution dependent on the distance to cut edge. Therefore, the mechanical stress is searched as a function of distance to cut edge *σ*(*y*) where

$$B\left(y,H\right) \overset{!}{=} B\left(\sigma(y),H\right) \text{ for } H = \text{const.} \tag{6}$$

Figure 4 depicts the resulting mechanical stress distribution dependent on the distance to cut edge. Cutting processes cause high mechanical stress along the cut surface. The mechanical stress decreases quickly before it reaches the penetration depth. Beyond this distance, the mechanical stress distribution stays constant, close to zero.

Discrepancies can be explained by approximation errors for high mechanical stress and high magnetic field strength.

V. CONCLUSIONS

In this study, a model was developed describing the local flux density distribution dependent on mechanical stress. This model is used to find a local mechanical stress distribution due to the cutting process.

In the full paper, the model will be explained in detail and compared to measurement results. Furthermore, the model will be extended for higher mechanical stress up to the yield strength and compressive stress will be added.

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