Magnetic Material Deterioration of Non-Oriented Electrical Steels as a Result of Plastic Deformation Considering Residual Stress Distribution

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For the application in the magnetic core of an electrical machine, electrical steel is cut, packaged, and fixed. The processes induce plastic deformation as well as residual stress. As a result, the magnetic material properties are deteriorated. Most of the effects act local, e.g., in the vicinity of the cut edge or welding line. In order to model the change in local magnetic properties, the effect mechanisms of plastic and elastic stress have to be understood and quantified. In this paper, rectangular samples of a conventional non-oriented 2.4 wt% FeSi with 0.35 mm thickness are stressed uniaxially beyond the elastic limit and characterized during loading, after deformation, and during reloading. A homogeneous stress distribution across the cross section is targeted by the experimental setup to enable a correlation between the global magnetic properties and mechanical finite-element simulations of the stress. As a result, separate physical effects, e.g., dislocation formation, global stress distribution, and residual stress after dislocation formation, on magnetic property change are analyzed. This knowledge is essential to understand the complex effects of processing on the local magnetic properties of rotors and stators in electrical machines.

Index Terms— **Electrical steel, plastic deformation, residual stress, soft magnetic properties.**

I. Introduction

DUE to the magnetoelastic coupling, the magnetic properties of electrical steel are sensitive to mechanical stress [1]. The phenomenological study of the effect of global stress and strain on the magnetic properties of electrical steel has been the subject of various studies [2]–[4]. A subsequent study on the fundamental relations beyond the general description of the effects is crucial for all sides of questions concerning the application of electrical steel in electromagnetic energy converters. Processing and manufacturing of magnetic cores lead to complex stress and strain distributions within the material [5]–[7]. The stress covers different spatial length scales, i.e., residual stress within and between grains, local stress variations over several grains, and global residual stress. The residual stress interacts with elastic stress due to magnetic and external forces during the operation, i.e., centrifugal forces acting on the rotor of a rotating machine. To account for the alteration of magnetization and loss due to mechanical stress in actual electrical machines, the basic relations have to be understood. A comprehensive description, a characterization of the magneto-elastic-plastic coupling is still missing in the scientific literature. With a profound knowledge of the interrelations, improved material modeling, and therefore, enhanced simulation of electromagnetic energy converters, such as electric motors or generators, can be enabled.

This paper aims at the identification of the effect of plastic deformation and concurrent impact of elastic residual stress in this context. Previous research indicated that the magnetic deterioration through plastic deformation is caused mainly by elastic stress and not by the mechanism of dislocation formation [8], [9]. On the other hand, research suggests that global residual stress is not the main cause for the deterioration of magnetic properties [10]. This paper contributes to the magneto-elastic-plastic coupling. In contrast to complex processing impacts, for example, cut-edge effects, this paper is performed on rectangular samples with a defined uniaxial tensile mechanical loading. Specimen loading results in a homogenous stress state and is carried out up above yield strength, where the samples are plastically deformed. However, maximum loading is below tensile strength to avoid necking. The results of the experiments by reloading the material samples allow consideration of different contributions of dislocations and internal stress. Furthermore, mechanical finite-element (FE) simulations are conducted to evaluate the residual stress distribution in detail and relate the magnetic deterioration to the mean components of the residual stress.

II. Experiment

The study is performed on samples of a conventional 0.35 mm, 2.4 wt% FeSi electrical steel, with samples prepared in rolling direction (RD) and transverse direction (TD). A single-sheet tester with a 5 kN loading unit by Brockhaus measurement systems is used to do the experiments. Magnetic field and applied loading are uniaxial and collinear. Samples are excited by a sinusoidal alternating magnetic flux density at frequencies of 100 and 400 Hz. Due to the quantity of results, the focus of this paper is placed on a detailed evaluation of the 100 Hz measurements, because they provide a compromise between different loss contributions, i.e., hysteresis and eddy current losses. To account for reproducibility and relative measurement errors, different samples in both

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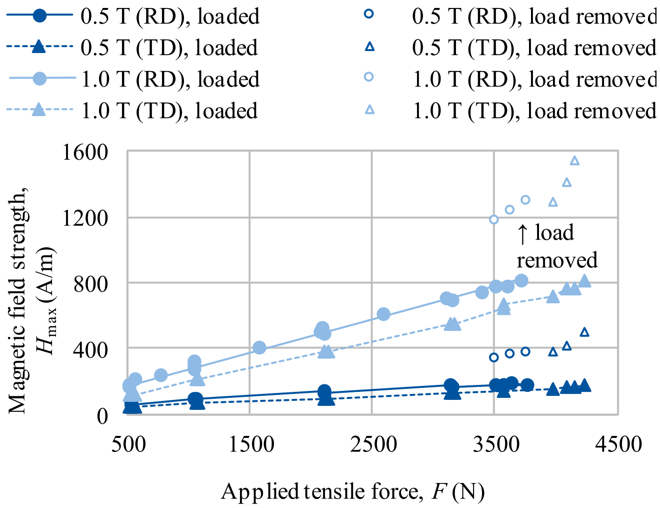

Fig. 1. Magnetic field strength $H_{\max}$ to reach 0.5 and 1 T at 100 Hz at different external loadings (filled markers) and after removal of external loading (empty markers) for three samples each with different maximum loadings in RD and TD.

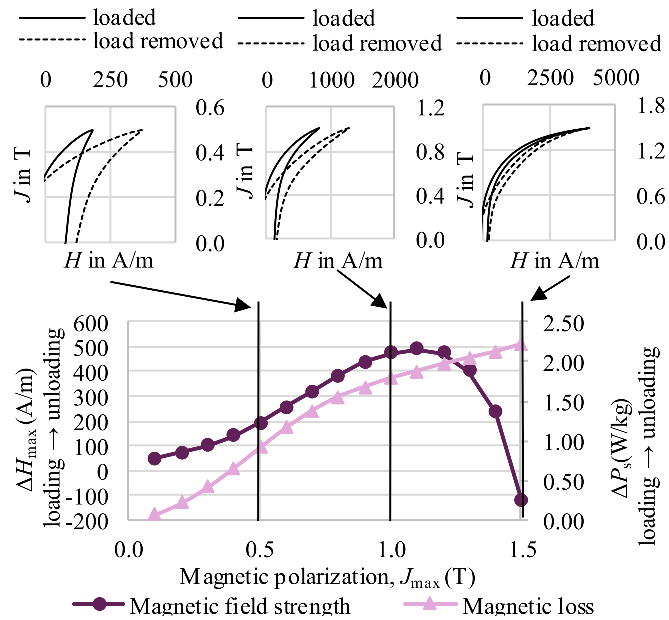

Fig. 2. Magnetic property deterioration of required magnetic field $\Delta H_{\max}$ and magnetic loss ΔP_s at 100 Hz at an external loading of 400 MPa and after removal of external loading with J–H-hysteresis curves at 0.5, 1, and 1.5 T.

RD and TD directions are stressed. The magnetic properties are characterized during the initial deformation process at several distinct loadings, and then again at reloading.

In order to determine the global mechanical stress state within the samples, the tensile test is rebuilt using a mechanical FE simulation with the Abaqus/CAE 6.12-3 software. The electrical steels' mechanical properties are modelled with a Hill yield criterion, enabling the anisotropic mechanical behavior in RD and TD to be taken into account. Stress and strain values discussed within this paper are calculated as mean value over the magnetic measurement area.

III. Results and Discussion

A. Magnetic Deterioration After Plastic Deformation

In [10]—[12], it has been observed that the magnetic properties of uniaxially stressed electrical steel samples are drastically deteriorated after plastic deformation. In general, magnetic loss required field for fixed polarizations and coercive field are increased, whereas remanent polarization and permeability are decreased. In Fig. 1, the required magnetic field strength to reach 0.5 and 1 T at 100 Hz is depicted in a loading range between 500 and 4500 N. The relation between external loading and required magnetic field strength to reach the two polarizations shows a linear dependence in this range for both samples in RD (circular markers) and TD (triangular markers). There is no indication of change of property, when the yield strength is exceeded. These results are concurrent with results obtained in [8] and [11] for coercivity and maximum permeability and indicate that the formation of dislocations does not primarily cause the strong deterioration. Residual stress is, therefore, considered to be an important factor, which at this point, tends to be contrary to the results of [10]. The additional results of the FE simulations and the experiments with reloading in Sections II and III can, however, be connected to either observation.

The fact that plastic deformation did occur is ensured based on two observations. First, a remaining change of length after the loading is removed, which can be measured for samples that exceeded the yield strength. Second, the magnetic properties show a strong deterioration with removal of the external loading. This strong deterioration at removal of the load is displayed in Fig. 1, where filled markers indicate measurement during loading and empty markers indicate measurements after removal of the external load. The required magnetic field strength for a set polarization has a dependence on the external load. At removal of the external load, the required field increases strongly. Samples that are loaded below the yield strength do not exhibit a remaining property change after removal of the load. The strong deterioration is also observed for other magnetic properties as magnetic loss, permeability, and coercivity, and occurs for samples in RD and TD.

The effect of magnetic property deterioration solely from removal of external loading above yield strength can be quantified by the following equations:

$$\Delta H_{\max} = H_{\max,\,\text{load removed}} - H_{\max,\,\text{loaded}} \tag{1}$$

$$\Delta P_s = P_{s,\,\text{load removed}} - P_{s,\,\text{loaded}}. \tag{2}$$

In Fig. 2, $\Delta H_{\max}$ and ΔP_s as a function of polarization are exemplarily displayed for a sample stressed at 400 MPa in RD. The resulting stress is determined by (3), where the technical strain σ_{mech} is a function of the external loading F and the initial cross section A_{initial}

$$\sigma_{\text{mech}} = \frac{F}{A_{\text{initial}}}. \tag{3}$$

The polarization dependence of $\Delta H_{\max}$ and ΔP_s is notably different. The magnetic loss has a monotonous positive slope with increasing polarization with the highest slope at

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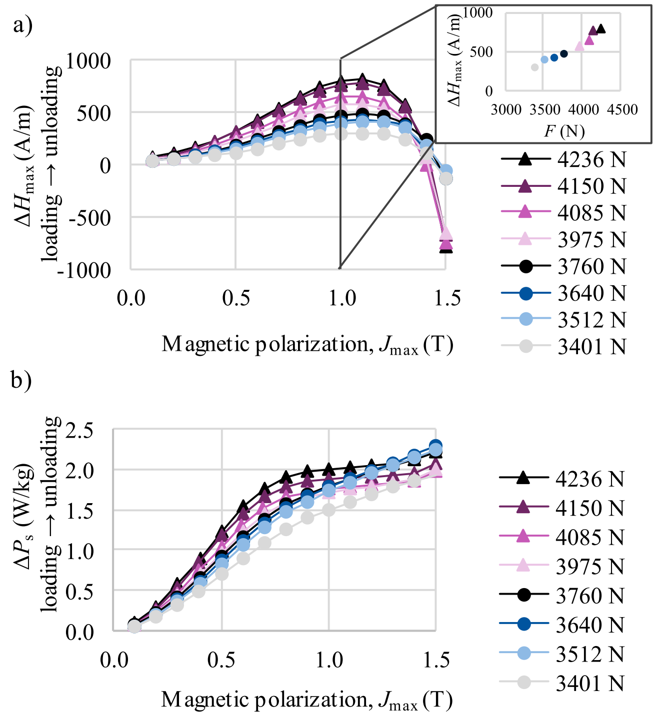

Fig. 3. Magnetic property deterioration of (a) required magnetic field ΔH_{max} and (b) magnetic loss ΔP_s at 100 Hz at various peak loadings in RD (circular markers), TD (triangular markers). Inset: ΔH_{max} over applied force F at 1 T.

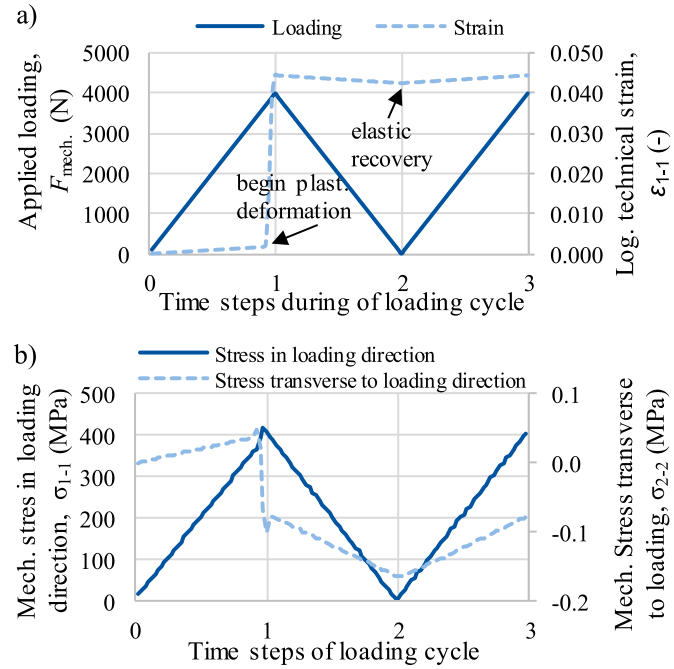

Fig. 4. Simulation of mechanical property evolution during loading cycle in RD. (a) Logarithmic technical strain and applied loading as a function of time steps. (b) Resulting mechanical stress in loading and TD (relative to loading).

about 0.9 T, whereas the required field has a maximum at 1.1 T and even exhibits a negative ΔH at high polarizations. This means that the magnetization is improved at removal of the load as it can be seen in the accompanying J–H-hysteresis curves at 1.5 T. Thus, it can be deduced that the polarization range of 0.8–1.2 T is most sensitive to the effect of magnetic deterioration at removal of external loading considering both magnetization and magnetic loss.

Consistent with the qualitative course described in Fig. 2, i.e., a monotonous positive slope for P_s and first a positive and then negative slope for H_{max}, the observed behavior is distinct for all plastically deformed samples that are tested. Two further observations can be concluded with consideration to all tested samples, namely, a dependence on the value of peak loading and a dependence on the spatial orientation of the samples, i.e., a distinct difference between samples in RD and TD. The dependence on peak loading is displayed in Fig. 3 and pertains samples in both directions. With increasing peak loading ΔH_{max} and ΔP_s increase. The only exception from this behavior is for ΔH_{max} at polarizations over 1.4 T. The spatial orientation affects the curve shape. For samples in TD, an improvement of magnetization at 1.5 T is distinctly more pronounced, so that the required field strength decreases up to 750 A/m at removal of the load. For the magnetic loss, the samples in RD have a more linear dependence compared with samples in TD.

The relations displayed occur at removal of the load. From a metal physics point of view, plastic deformation is driven by dislocation formation and movement. In the case of electrical steel with its polycrystalline composition, the microstructure leads to gradients of plastic deformation within the material. An external stress leads to non-uniform deformation of grains, depending on the orientation and geometrical constraints between neighboring grains [13]. When the yield strength is exceeded, dislocations are formed and move, which leads to a change of shape (elongation) and strain hardening. This, however, occurs already during loading. In Fig. 1, the magnetization behavior is not visibly affected by this process. At removal of the load, however, the magnetic properties deteriorate. This may be caused by residual stress, which has been discussed in some scientific literature [8], [10]. In order to analyze the impact of residual stress, FE simulations and further experiments are performed.

B. Mechanical Simulations of Loading Cycle

In this part, the FE simulations are discussed. In order to investigate the potential role of residual stress, the samples are not only loaded and unloaded, but they are additionally reloaded.

In Fig. 4(a), a description of the loading cycle is displayed by the applied external force F as a function of time steps. During the first step the applied loading increases linear to 4000 N. Because this results in a global stress above yield strength, plastic deformation of the sample occurs. The logarithmic technical strain increases linearly up to tensile strength with a small slope proportional to the elasticity modulus. When plastic deformation starts, indicated by the arrow in Fig. 4(a), the elongation increases until the peak loading of 4000 N is reached. When the external load is removed, the elastic recovery leads only to a small decrease of strain due to the irreversible plastic deformation ($\varepsilon_{1-1} = 4.2\%$).

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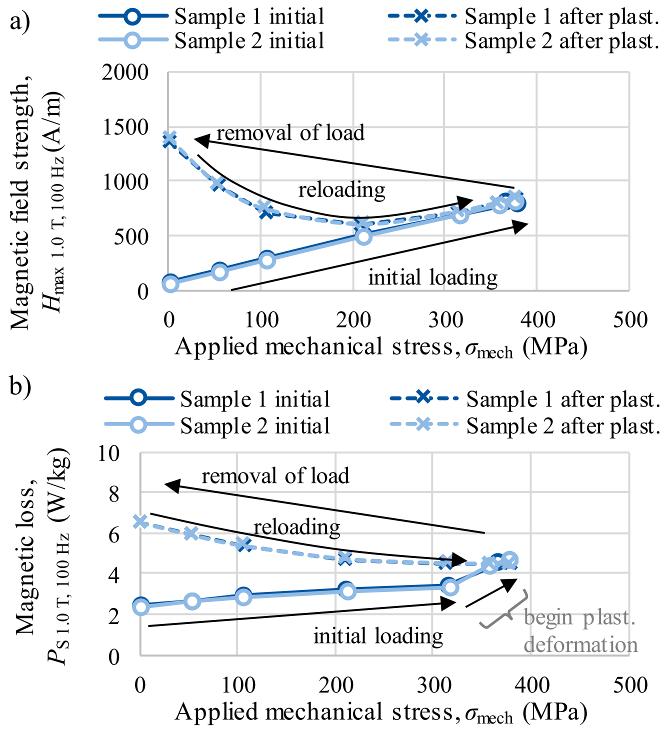

Fig. 5. (a) Magnetic field and (b) magnetic loss at 1 T and 100 Hz as a function of applied mechanical stress in RD for two samples.

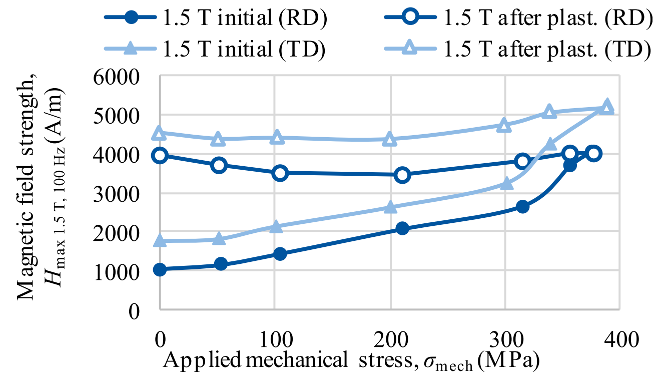

Fig. 6. Effect of applied mechanical stress on required magnetic field at 1.5 T and 100 Hz in RD and TD.

When the external load in time step 2–3 is increased again, the strain increases by the value of the elastic recovery.

In Fig. 4(b), the mechanical stress in RD and TD is displayed. The stress in loading direction is consequently dominant, compared with the stress in transverse to the loading. When the external loading is fully removed at time step 2, no significant amount of residual stress is present in the samples. Consequently, the magnetic deterioration is likely not due to macroscopic compressive stress after loading. This is in accordance with [10], which concludes that the produced residual stress is not responsible for the deterioration. The results of Section I indicate that the creation of pinning sites can not solely be responsible for the magnetic deterioration. Therefore, the magnetic properties at reloading are of great interest to improve the understanding of the occurring effects. In the following, the magnetic property change is studied during the loading cycle according to the FE simulation, i.e., loading, removal of load and reloading.

The behavior of the magnetic field strength during the initial loading is described and discussed in Section I. The results have to be complemented by a closer look on magnetic loss. It has to be noted that the exceedance of the tensile strength is indeed visible with a sudden increase of the slope, as depicted in Fig. 5(b). However, the change of properties during removal of the load is also significant, as already described in Section I.

At reloading the magnetic properties, both H_{max} and P_s, gradually approach the value of the loaded state of initial deformation at peak value. This means a steady improvement, i.e., decrease of loss and required field strength with tensile reloading. In Fig. 5(a) and (b), this is displayed for 1 T and 100 Hz. If the sudden increase of loss and magnetic field strength at removal of the external loading can be just removed by a reloading with the same peak value, it can be deduced that local stress distributions that act equivalent to a compressive stress in tensile direction are responsible for the deterioration at load removal. The change in the overall stress state is indicated by remaining compressive stress in σ_{2-2} direction in Fig. 4(b) after unloading. This supports the explanation made in [11]. Several samples have been tested for their behavior at reloading, to test the reproducibility of the effects. Two samples with a small variation of peak load in RD are displayed in the graphs in Fig. 5. In Fig. 6, results are displayed for a higher polarization, along with a sample in TD. In general, the reloading always leads to a restoration of the initially loaded state. For the magnetic field strength, the only notable difference is a visible exceedance of the yield strength at high polarizations. This leads to an improvement at removal of the load, which was already evident from the polarization dependence displayed in Figs. 2 and 3 at 1.5 T. Therefore, reloading leads to a deterioration of properties, i.e., an increase of field to reach the magnetic properties at peak value, supporting the theory that residual stress is largely responsible for the deterioration after plastic deformation.

Makar and Tanner [10] as well as the FE simulations in Section II indicate that the global residual stress as a result of plastic deformation in this range is not responsible for the magnetic deterioration. It is likely that long-range internal stress due to the non-homogenous deformation and intergranular interactions affect the stress distribution [13]. This is not considered in the FE simulation of global residual stress. The contribution of this stress distribution to the magnetic deterioration is not negligibly, especially when modeling methods for the magneto-elastic-coupling are transferred from one process to another. If the impact of plastic deformation and residual stress distribution is different for example with shear and laser cutting, the correlation of residual stress to magnetic properties is likely affected. For shear cutting, an interference of residual stress, as simulated in [14] with the plastically deformed regions, is expected. In contrast, laser cutting shows no significant plastic deformation in the vicinity of the cut edge according to [15], so that the thermally induced residual stress by laser cutting does not interfere with cutting-induced plastic deformation.

IV. Conclusion

In this paper, rectangular samples in two orientations relative to the rolling direction (RD and TD) and with different peak loadings are stressed beyond the elastic limit and magnetically characterized during loading, at removal of the external loading and during reloading. With this approach, the effect of plastic deformation on the magnetic property changes is discussed. In this paper, different contributions of dislocations as the underlying mechanism of deformation and residual stress distribution as a direct consequence of plastic deformation are incorporated in the discussion. Mechanical FE simulations are used to correlate the global residual stress distribution with the elastic residual stress in the deformed samples.

It has been observed that the exceedance of yield strength during loading is visible in magnetic loss and required magnetic field strength for high polarizations by a change of the slope from the otherwise linear dependence. These effects can be correlated with the formation of dislocations and their direct role as pinning sites. For low-to-medium polarizations, the required magnetic field strength shows no such reaction to the plastic deformation.

The magnetic deterioration at the removal of the load is not due to global residual stress according to the FE simulation. This is also in accordance with other scientific references in the literature. However, reloading leads to an improvement of the magnetic properties, which indicates that certain stress distributions are indeed responsible for the deterioration. Both initial loading with the peak value and reloading with the peak value lead to the same magnetic properties. As a consequence, it can be deduced that after removal of the external loading, several local stress distributions are formed which act as a global compressive stress, which can be reversed by a tensile stress of peak value. This is likely caused by stress in the vicinity of the dislocation and, therefore, as a direct result of the deformation structure. These stresses are not incorporated in mechanical FE simulations.

This is valuable information for the coupling of mechanical and magnetic simulations, because it adds another contributing factor to the magnetic deterioration. This also means that the interference of elastic residual stress in plastically deformed material regions can lead to further improvement or deterioration depending on the stress tensor orientation, which should be considered in correlations and quantifications of the effect of plastic deformation.

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