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Effect of elastic and plastic tensile mechanical loading on the magnetic properties of NGO electrical steel

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ABSTRACT

The magnetic properties of non-grain-oriented (NGO) electrical steels are highly susceptible to mechanical stresses, i.e., residual, external or thermal ones. For rotating electrical machines, mechanical stresses are inevitable and originate from different sources, e.g., material processing, machine manufacturing and operating conditions. The efficiency and specific losses are largely altered by different mechanical stress states. In this paper the effect of tensile stresses and plastic deformations on the magnetic properties of a 2.9 wt% Si electrical steel are studied. Particular attention is paid to the effect of magnetic anisotropy, i.e., the influence of the direction of applied mechanical stress with respect to the rolling direction. Due to mechanical stress, the induced anisotropy has to be evaluated as it is related to the stress-dependent magnetostriction constant and the grain alignment.

1. Introduction

Isotropic magnetic properties are expedient for non-grain-oriented (NGO) electrical steels. Low losses and improved magnetizability in any spatial direction characterize best suited materials. The tailored magnetic properties of the raw material are affected decisively by mechanical stresses of diverse origin. In particular, mechanical stresses induced during material processing, i.e., sheet metal blanking, stacking or shrinking, alter the magnetic properties of the core detrimentally. For improvement of 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. The detrimental effect of mechanical stresses on ironloss and magnetizability requires, in particular, an in-depth study.

The final product of the conventionally used, fully finished material, has a fixed microstructure, magneto-crystalline texture and specific magnetic properties which have been adjusted through hot band annealing, cold rolling and final annealing of thin steel strip. However, material processing, such as shear cutting, stacking, welding or final assembly affects the magnetic properties drastically [1,2]. Various research papers elaborate the severe effect of different cutting techniques, e.g., CO_2 laser, Nd:YAG laser, electrical discharge machining (EDM), water-jet or shear cutting [3–5]. According to [6] the dominant effect for the deterioration of magnetic properties are residual stresses induced by mechanical processing. When constructing the machine, stresses are inevitable and therefore need to be accounted for. In order to not only to characterize the effect of specific processes on a certain material, the general effects on the material need to be studied to find general correlations and enable understanding of all mechanical processing.

This paper particularly focuses on the effect of plastic deformation on the magnetic properties of a high silicon electrical steel and the differentiation regarding the effect of elastic tensile stresses. When studying non-grain-oriented (NGO) electrical steels, it is crucial to consider different spatial directions because in rotating electrical machines a homogeneous and isotropic magnetic field in all rotation directions is necessary to ensure consistent behavior at all times, in every planar direction. Therefore, each experiment is performed in rolling direction (RD) as well as transversal direction (TD) to enable a comparison and to ensure comprehensible considerations.

2. Experimental procedure

The investigated material is a commercially available fully finished and isolated grade, classified as M270-50A, with 2.9 wt% silicon content and 0.5 mm sheet thickness. Experiments on elastic tensile stresses are performed on a 100 mm by 600 mm single sheet tester (SST) equipped with a tensile and compression unit. The test bench is incorporated into a computer-aided setup according to the international standard IEC 60404-3 and the non-

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Table 1
Tensile mechanical stresses σ and resulting strain ε in RD and TD.

	$R_{p\ 0.2}$	470 MPa	500 MPa	530 MPa	R_m
RD	433 MPa	4.5 %	6.5 %	12.5 %	548 MPa
TD	460 MPa	2.5%	4.5%	7.5%	580 MPa

grain-oriented (NGO) electrical steel sample is characterized with the help of controlled sinusoidal magnetic flux density with a form factor error of less than 1% in the frequency range from quasi-static to 1000 Hz. Forces up to 5 kN can be impressed. Samples in rolling and transverse direction are tested because the magnetic flux is parallel to the direction of mechanical loading.

In order to study the magnetic property deterioration within the plastic region, three samples for both distinct spatial directions (RD and TD) are exposed to different mechanical loadings above yield strength using a universal test machine. These plastically deformed samples are subsequently characterized magnetically on a 120 mm by 120 mm SST. In order to ensure a good comparison of results obtained in RD and TD, comparisons are conducted at equal stress levels instead of using equal strain or elongation. Plastic deformations are characterized conventionally by the resulting strain or elongation. However, externally applied mechanical stresses result in different strains because of the anisotropic mechanical behavior in different spatial directions. In Table 1 the resulting stress and strain relations for the plastically deformed samples are displayed.

3. Results and discussion

This section is divided into two parts. At first, the results of the metrological characterization under tensile mechanical loading, i.e., elastic and plastic deformations, are introduced. Both the change of hysteresis loop shapes and, by way of example, the variation of the required magnetic field to reach 1.0 T at 100 Hz as well as the corresponding coercive field in RD and TD are discussed. In the second part, the measured data is processed in order to divide the iron losses into static and dynamic loss components. Thereby, a deeper insight into the effect of mechanical stress on the intricate coupling of hysteresis and macroscopic eddy currents is gained.

3.1. *Influence of elastic and plastic deformations on magnetic properties*

In Fig. 1 the influence of elastic and plastic deformations resulting from tensile loading on the hysteresis loop shape at 100 Hz and 1.0 T are depicted. The tensile loading varies from 10 to 530 MPa, i.e., both in the elastic and plastic range. In general, it is apparent that elastic as well as plastic deformations affect the shape of the hysteresis loops and as a result the extrinsic magnetic properties, such as coercivity H_c, remanence J_r, and the magnetizability. Particularly, the plastically deformed samples show a strong shearing of the hysteresis loops in RD as well as TD. The resulting shape of the hysteresis loop becomes more S-shaped compared to the rather square hysteresis loop of unloaded samples. The magnetic field strength required to obtain a specific polarization increases drastically, for instance, in RD from under 500 A/m to over 1000 A/m , in TD to over 2000 A/m. This increase is accompanied by an increase of coercivity and a decrease of remanence polarization. The extrinsic properties, coercivity and remanence, relate to the size and shape of the hysteresis loop and thereby affect specific losses extensively.

Fig. 2 shows the detailed course of coercivity and

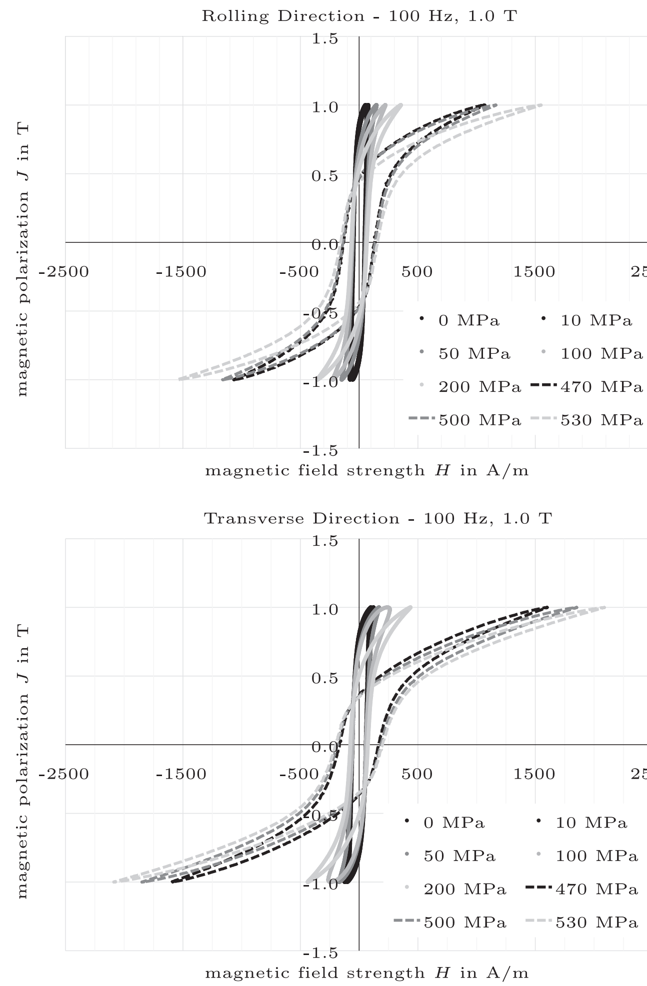

Fig. 1. Hysteresis loops at 100 Hz and 1.0 T of elastically and plastically deformed samples for uni-axial tensile stress and magnetic flux density in RD and TD .

magnetization field strength required to reach 1.0 T at 100 Hz under tensile loading. A distinct gap between elastically and plastically deformed samples is evident in both figures. In TD the shearing of the hysteresis loops is more pronounced and the losses increase intensively with increasing stress.

Samples under elastic loading generally experience analogous tendencies as plastically deformed samples. A shearing of the hysteresis loops to higher magnetization field strengths and coercivities can be observed, accompanied by a concurrent decrease of remanence. The deterioration of these properties is less pronounced over the entire elastic tensile stress spectrum compared to the small range between 470 MPa and 530 MPa and the resulting plastic deformation. Even though a shearing of the hysteresis loops occurs, the slopes are steeper compared to the plastically deformed samples. In the range starting from 50 MPa up to yield strength, a linear relationship of coercivity as well as magnetization field strength with tensile stress can be observed.

In contrast, the effect of small mechanical stresses on the magnetic properties of the studied material is a notable exception of the uniform behavior in RD and TD. As shown in Fig. 2, samples in TD under small tensile loading exhibit an improvement of their magnetic properties with a minimum of coercivity and magnetization field strength around 10 MPa. In RD the magnetization field strength increases continuously, but still a mild decrease of coercivity at 2 MPa can be distinguished.

The overall observations show a severe effect of elastic and plastic deformations on the magnetic properties. However, the

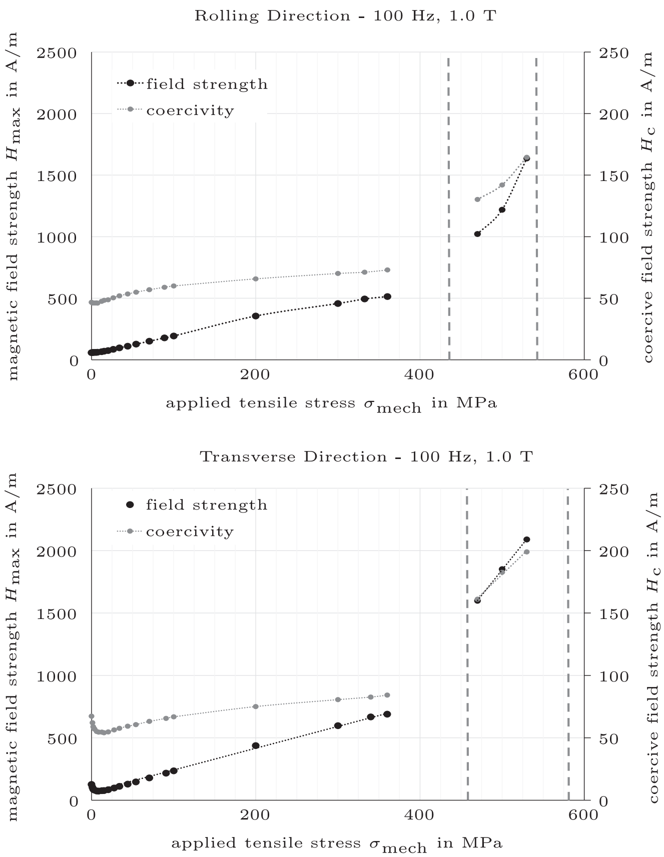

Fig. 2. Coercivity and required magnetic field strength to reach 1.0 T at 100 Hz opposed to uni-axial tensile stress and magnetic flux density. Dashed lines represent the tensile and yield strength for the respective direction: $R_{p\ 0.2\ (RD)}$ =433 MPa, $R_{p\ 0.2\ (TD)}$=460 MPa, $R_{m\ (RD)}$=548 MPa, $R_{m\ (TD)}$=580 MPa.

results illustrate a strong difference between the effect of elastic stresses and plastic deformations. Even small plastic deformations lead to a significant increase of required magnetization field strength and coercivity, which is much larger than the linear relations within the elastic region indicate.

A possible and apparent explanation for the differences in the magnetic behavior during elastic and plastic deformations are the different deformation mechanisms. Within the elastic region, mechanical stresses up to yield strength cause homogeneous elongation across the entire specimen by deviating atoms of the crystal lattice from their equilibrium position. After having removed the mechanical load, the initial state is restored [7]. As a result of elastic deformation, domain structures are reorganized to minimize the magnetic free energy [8]. The sign of the magnetostriction constant and the stress tensor determine the effect on the magnetic properties. Magnetization collinear to the stress direction increases if the two terms 'magnetostriction constant' and 'stress tensor' have the same sign [9]. However, the magnetostrictive behavior of a polycrystal is complex and cannot be simplified easily. The sign of the magnetostriction depends, for example on magnetization, alloying content or crystal orientation [10]. Thus, the distribution of crystal orientations within the sheet plane, i.e., the magneto-crystalline texture is a crucial factor for anisotropic behavior under tensile loading. The occurrence of two stages within the elastic region could be due to micro-yielding [11,12]. Micro-yielding describes the generation of dislocations in the area of grain boundaries below the macroscopic elastic limit. However, an in-depth study of this behavior is necessary to further investigate this effect.

Above the macroscopic elastic limit, during the plastic deformation stage, deformation occurs as a result of dislocation movement by crystallographic slipping [13]. Dislocation interactions lead to strain hardening during this stage. With increasing strain, the resistance against deformation increases and leads to the typical form of the stress-strain curve. Ashby [14] established the concept of geometrically-necessary dislocations (GND) and statistically-stored dislocations (SSD) in polycrystalline materials and differentiated the impact of stored dislocations on the strain behavior. In single crystals, as in multiphase alloys and polycrystals, dislocations occur accumulated randomly and are called SSD because of the unpredictability of their accumulation. Clusters of dislocations impede the movement of free dislocations and thereby obstruct further deformation. So-called GND are inevitable in order to ensure a compatible deformation in polycrystals. During the tensile loading of a polycrystalline material, each grain experiences a different strain depending on its orientation and constraints inflicted by its neighboring grains. Ashby concluded that arrays of GND and SSD have short-range interactions with moving dislocations and obstruct their movement. However, also they are sources of long-range internal stresses. These long-range stress fields form within the first few percent of the straining. According to Ashby, there is evidence that these long-range stress fields control the hardening during small plastic strains. For exceeding strains, the contribution of the long-range stress fields of GND remains constant whereas short-range interactions between moving dislocations increase as a result of the steadily increasing density of GND [14]. It is likely that magnetic deterioration within the plastic deformation stage results from the mutual concurrence of both effects. Other studies show that dislocations hinder domain wall movement in general; they act as pinning points and reduce the mean free path of domain wall displacement and increase the magnetization field strength and coercivity [11,15]. Another cause for material deterioration is related to long-range internal stresses [11]. The sudden jump of magnetic properties (Fig. 2) above the macroscopic elastic limit is a result of long-range stress fields which are the predominant factor for the beginning of plastic deformation. According to [14], the contribution of these long-range stress fields remains constant for increasing strains after its initial impact during the first few percent of strain. However, dislocation density increases during higher strains, because an increasing amount of dislocations is stored as GND and new dislocations have to be generated to allow further plastic deformation. In addition, free dislocations are obstructed in their movement by the increasing clusters of GND. These dislocation interactions lead to the disproportional increase in the slope of magnetic property changes for higher plastic deformation.

Supplemental use of other non destructive testing methods like Magnetic Barkhausen noise (MBN) detection or Kerr microscopy could deliver closer inside to the micromagnetic stress sensitivity of further studies. Application of tensile stress can lead to subtle changes in MBN energy which can be correlated to different microstructural causes [12,16]. According to [12] changes were attributed to combined effects of changes in magnetic domain size, increasing numbers of 180° domain wall movements, dislocation formations as well as simultaneous activations of magnetic domains, which thereby characterize the stress dependent micromagnetic processes during the elastic and plastic deformation stage. An additional further approach to evaluate the varying behavior, with focus on the magnetostrictive impact in the different spatial directions is to correlate global magnetostriction in RD and TD directions with the occurrence of [100] and [111] oriented grains, i.e., a detailed evaluation of crystallographic texture.

3.2. Influence of elastic and plastic deformations on iron-loss

In accordance to the results presented so far, the iron losses

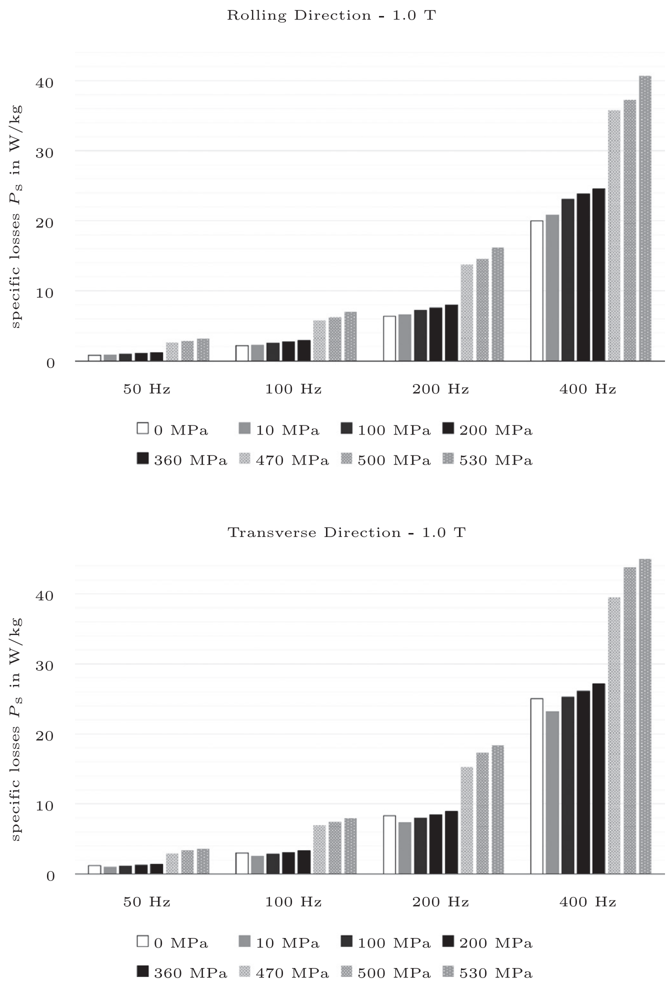

Fig. 3. Specific losses at 1.0 T and different frequencies with applied uni-axial tensile stress. From the unloaded state (white coloring) under increasing tensile stress in the elastic region (uniform coloring) and plastic region (patterned coloring).

behave analogously to the change of coercivity and magnetization, as depicted in Figs. 2 and 3. In RD specific losses increase with increasing mechanical tensile stress. In TD the beneficial effect of minor stresses can be observed in form of lower specific losses at 10 MPa compared to the unloaded state. The reoccurring of a pronounced step between iron losses in the elastic and plastic stage can also be distinguished. In addition, crucial information about the frequency dependence can be obtained from Fig. 3. The discontinuous behavior between the elastic and plastic stage is evident for all applied frequencies. However, with increasing frequency the relative deterioration between high elastic stresses compared to plastic deformations decreases. Relative increase of iron-loss between 360 MPa and 470 MPa at 50 Hz is more than +50 % compared to the increase of about +30% at 400 Hz in both RD and TD. An unambiguous trend for the relative deterioration decrease with frequency is also observed for the elastic stage.

In order to study the effect of elastic and plastic deformations on the different loss contributions, the phenomenological loss-separation principle [17] is applied, whereby the total power loss P in W/kg is decomposed into the hysteresis loss, P_h, and the dynamic loss. The dynamic loss can be further split-up by statistical methods into the classical loss, P_{cl}, pertaining to a perfectly smooth medium, without domains and the excess loss, P_{exc}, due to space-time correlation effects in the magnetization process.

$$P = \underbrace{P_h}_{\text{static}} + \underbrace{P_{cl} + P_{exc}}_{\text{dynamic}} \tag{1}$$

The static component (hysteresis loss) is related to microscopic short-range eddy currents locally induced due to the broken (jerky) motion of domain walls (Barkhausen effect). The dynamics of this motion is ruled by certain features of the microstructure and it determines the intensity and the distribution of the microscopic currents. Hysteresis loss density does not depend on the geometry of the sample, neither on the frequency of the applied magnetic field (hysteresis is a quasi-static phenomenon), but it depends on the local maxima attained by the field $H(t)$ all through the magnetization history of the sample.

Currents directly induced by the variation of the external magnetic field when the presence of magnetic domains is averaged are the origin of the classical loss component. These depend on the geometry of the sample, the specific electric conductivity and on the rate of variation of the applied field. Enhanced eddy currents in the vicinity of moving domain walls due to space-time correlation are the source of excess loss.

The various origins of the different loss components indicate that applied mechanical stresses primarily affect hysteresis losses due to its strong relation to the material microstructure. Independent of this assumption, a semi-physical parameter identification procedure [18] is followed to identify the different loss components based on DC and AC measured data at each mechanical load level. In contrast to [18], 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:

$$P_h = a_1 B^{\alpha+\beta B} f, \tag{2}$$

where f is the frequency of the magnetic flux density variation, B is the peak value of the magnetic flux density averaged across the lamination. Parameters a_1, α and β are identified for each tensile load level using the method of least squares to minimize the approximation error between DC measured data and the loss prediction according to (2).

Fig. 4 depicts the stress dependence of the three parameters describing the hysteresis loss of the material both for RD and TD in the elastic and plastic range.

The classical loss that is related to the sample thickness d, specific electrical resistivity ρ_e and mass density ρ is calculated a-priori according to (3) [17].

$$P_{cl} = \frac{\pi^2 d^2}{6\rho\rho_e} B^2 f^2 \tag{3}$$

Assuming that the chemical composition is not affected, i.e., constant specific electrical resistivity ρ_e, changes of the classical loss are solely related to geometry variation during elastic and plastic loading.

Excess loss related to the correlation effects leading to enhanced eddy currents around moving domain walls are calculated by

$$P_{exc} = \frac{1}{\rho} 2Bf\left(\sqrt{n_0^2 V_0^2 + 2\pi^2 \sigma G S V_0 B f} - n_0 V_0\right), \tag{4}$$

where n_0 and V_0 are material-dependent microstructural parameters that depend on the magnetic flux density level, S is the cross sectional area of the lamination and G is statistical parameter derived in [17].

Fig. 5 presents the results obtained summing up the three loss contributions as well as their individual share on the overall loss in comparison to the measured data. The relative error increases slightly for high plastic deformations. Fig. 6 shows the respective

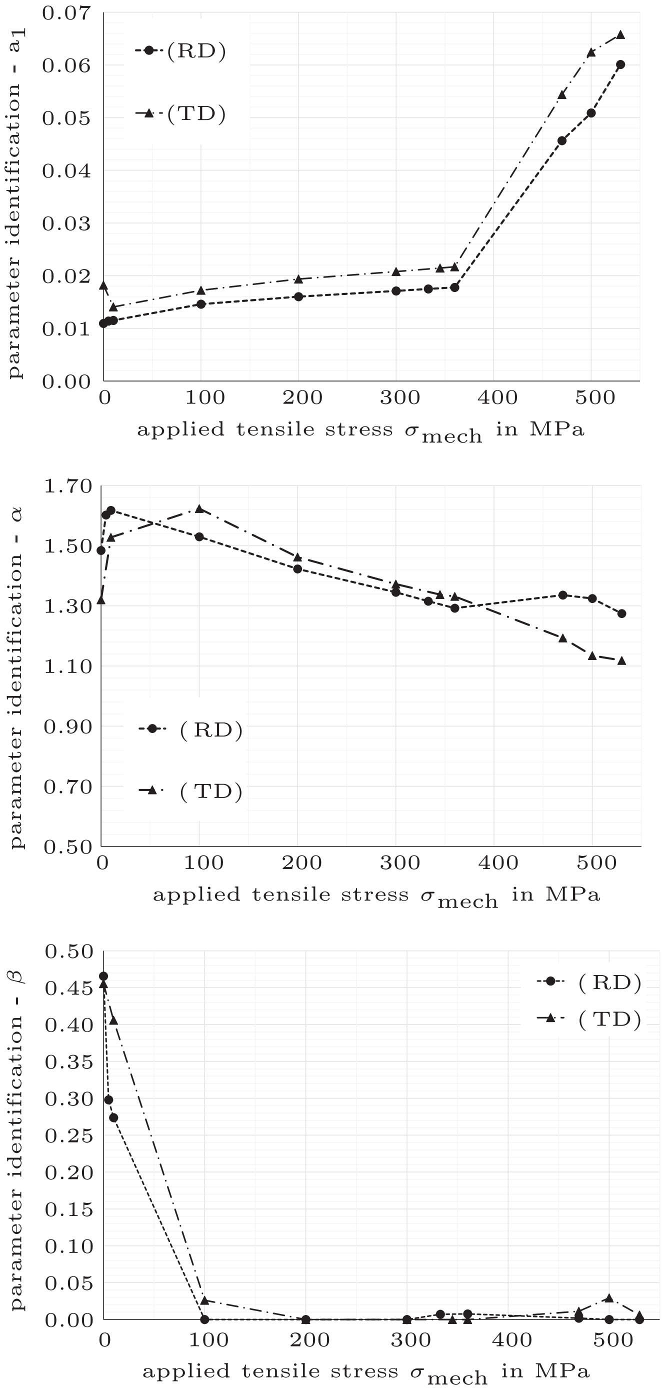

Fig. 4. Tensile stress dependence of static hysteresis loss parameter (2).

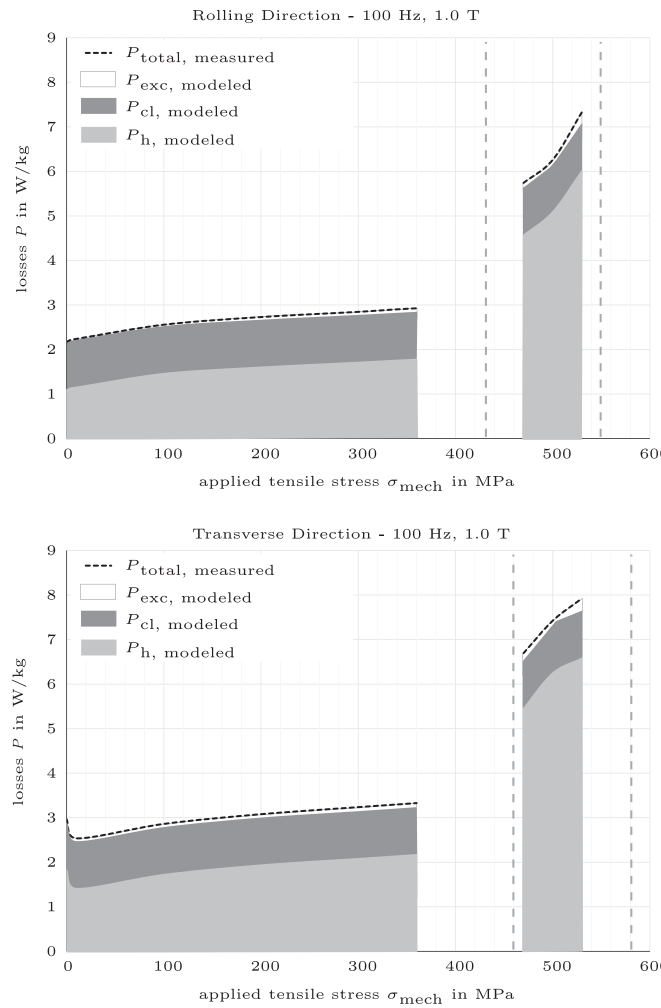

Fig. 5. Results of loss modeling at 1.0 T at 100 Hz opposed to uni-axial tensile stress. Dashed lines represent the tensile and yield strength for the respective direction.

results for a polarization of 1.5 T. Except for the modeling at 470 MPa in RD, the measured and estimated results largely match. In addition, at increasing frequency a relatively small error between measured and estimated losses is still obtained. Results are presented in Fig. 7. In TD an increasing proportion of excess losses can be observed with increasing frequency.

4. Conclusions

The optimization of non-grain-oriented (NGO) in regard to its application in rotating electrical machines, requires comprehensive considerations of spatial variations of magnetic properties in the sheet plane and careful awareness of occurring anisotropic effects. Extensive study on the stress related changes of electromagnetic properties in non-grain-oriented (NGO) electrical steels is thereby, necessary. The presented results of the studied non-grain-oriented (NGO) electrical steel enable elementary correlations between the material, the processing and its application by investigating the general influence of mechanical tensile stresses on the magnetic properties. The extent of their influence depends on the size of the stresses and the excitation para - meters in combination with material characteristics, such as magnetocrystalline anisotropy and different deformation mechanisms in the elastic and plastic stage. However, investigations of stress related changes in magnetic behavior can additionally be used for applications of non-destructive testing (NDT) methods. In-depths understanding enables the detection and evaluation of residual stresses and changes in microstructure, by means of magnetic measurements. This highlights the significance of comprehensive studies on this topic. The resulting impact of tensile stresses on the electromagnetic properties of the investigated material can be concluded as followed.

1. Mechanical tensile loading affects the shape of the hysteresis loop and thereby the extrinsic magnetic properties. With increasing stress hysteresis loops become more sheared and for plastic deformations, exhibit a strong S-shape. With the exception of minor stresses in TD remanence decreases while

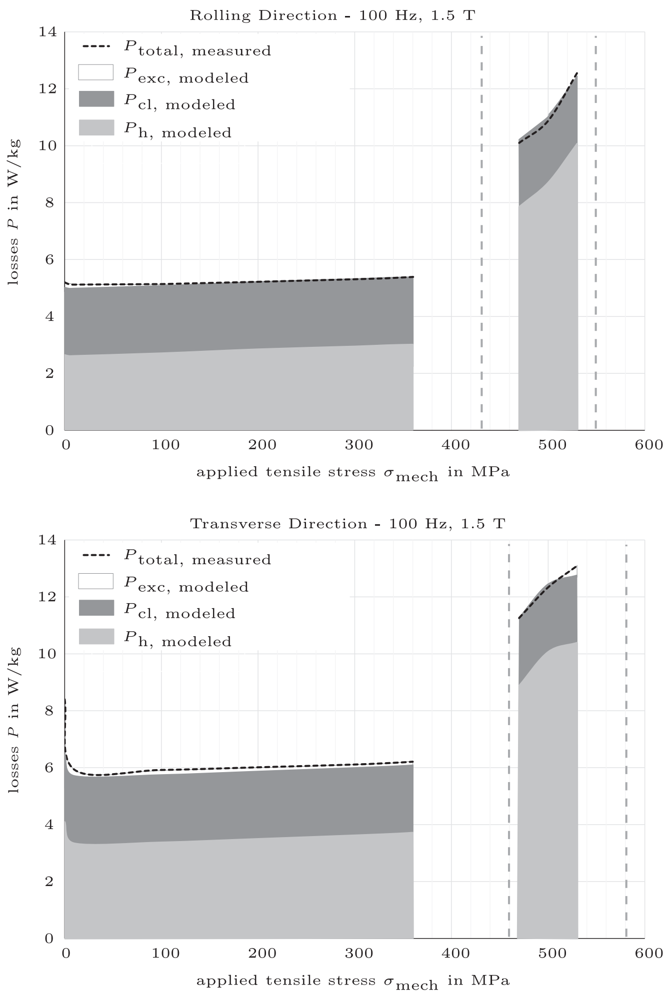

Fig. 6. Results of loss modeling at 1.5 T at 100 Hz opposed to uni-axial tensile stress. Dashed lines represent the tensile and yield strength for the respective direction.

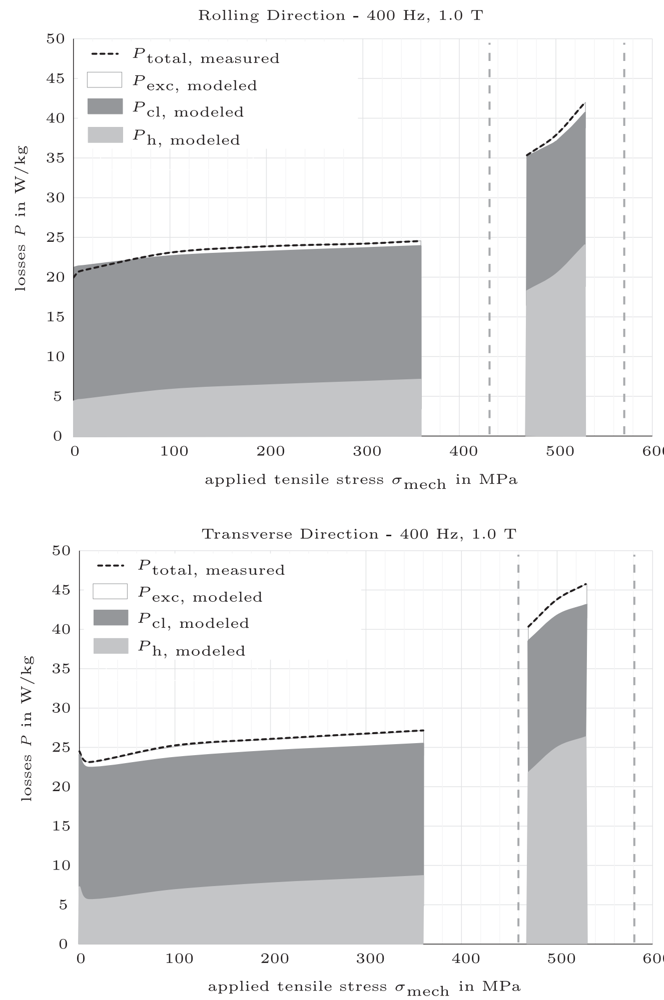

Fig. 7. Results of loss modeling at 1.0 T at 400 Hz opposed to uni-axial tensile stress. Dashed lines represent the tensile and yield strength for the respective direction.

coercivity and magnetization field strength increases. A detrimental effect on the magnetization behavior as well as on the losses could be observed. In the elastic stage deterioration results from reorganization of domain structures dependent on magnetostriction and the stress tensor. The distinct increase in losses of the plastically deformed samples are linked to long-range internal stresses and short-range dislocation interactions as a result of GND and SSD, which are cause for plastic deformation in polycrystals.

2. In addition, it was observed that stresses can be beneficial. This is the case in TD in the elastic range, at stresses smaller than 50 MPa. This unanti-cipated behavior is likely a result of the magneto-crystalline anisotropy. If the external field and the applied stresses are co-linear, a positive magnetostriction constant will ease the magnetization process. For an approximately 3 wt% FeSi a positive magnetostriction constant is found in the [100] direction, while a negative magnetostriction can be found in [111] direction. However, magnetostriction can change its value from positive to negative depending on magnetic field strength. The observed magnetic improvement and its dependence on polarization can be explained by this. However, the complex influence of stresses on the magnetostriction constants and effects of the alignment of grains on global anisotropy require in depth-studies.
3. Detailed investigations on the effect of stresses on iron losses and on static and dynamic loss components, enable further insight to the impact of tensile stress on the electromagnetic properties. Quasi-static and low frequency measurements as well as loss modeling display how stresses primarily affect the hysteresis term. This concords with the theory that hysteresis losses are strongly related to the microstructure contrary to the classical loss component which depends on geometry, electrical resistivity and rate of change of the applied field. The identified causes for the course of magnetic properties in the elastic and plastic stage (1.) and the beneficial effect in TD (2.) can directly be applied to explain the course of the iron losses, because they are proportional to the size of the hysteresis loop. These causes are further, both related to the microstructure. The magneto-crystalline anisotropy, its change as well as the effect of dislocation interactions and internal stresses are directly linked to the structure of the material and thus, primarily affect the hysteresis term of the losses, which can be affirmed from the results. The excess loss term is nearly not evident in the observed cases. Though related to the microstructure and possibly affected by external mechanical stress, it is not possible to identify an impact, because of its small values.

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