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Effect of magnetic anisotropy on Villari Effect in non-oriented FeSi electrical steel

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Abstract. The Villari Effect (inverse magnetostrictive effect), which describes the sensitivity of magnetic properties of ferromagnetic materials to mechanical stress is pivotal for actual operational characteristics of electrical machines. In rotating electrical machines mechanical stress is inevitable. It is inherent in processed parts from processing and manufacturing as well as induced by operation of the machine (e.g. centrifugal force). Consequently, magnetic behavior of non-oriented (NO) electrical steel (ES) needs to be characterized not only in its unstressed state as determined by standardized testing, but also considered with regard to its stress dependency. Due to non-uniform distributions of crystallographic orientations within the material, interdependencies between stress and occurring anisotropies have to be identified in order to explain magnetic properties in the entire sheet plane of NO laminations. In this paper the effect of tensile and compressive stress on the magnetic properties of a conventional 2.4 wt% Si electrical steel is studied. Particular attention is paid to the comparison between different directions of applied mechanical stress with respect to the rolling direction. Therewith, the initial anisotropy and interrelating effects due to mechanical stress are evaluated.

Keywords: Electrical steel, hysteresis, mechanical stress, plastic deformation

1. Introduction and motivation

Non-oriented electrical steel (NO ES) sheets are cut, stacked, welded or interlocked and in a final step assembled in order to build, e.g., the magnetic core of rotating electrical machines. Each of these processing steps invariably induces residual stress both at the macroscopic and microscopic scale [1–3]. Residual stress is complemented by externally applied stress during the operation of the rotating electrical machines such as local magnetic forces or centrifugal forces. Due to the intrinsic magneto-elastic coupling, this stress causes a change of the magnetic properties of NO ES [4,5]. As a result, the performance of the rotating electrical machine is altered.

In order to study the magneto-mechanical coupling, mechanical stress is induced in measurement samples by externally applied forces. Various results show that compressive stress is more detrimental than tensile stress [4,6]. Small tensile stress might even have beneficial effect on the magnetic properties in form of an improved magnetization and lower loss [6,7]. Tensile stress above yield strength however, is solely detrimental [8,9]. Although their classification indicates NO ES to be magnetically isotropic, they exhibit, due to the rolling process, preferred grain orientations that lead to anisotropy in both, the magnetic and mechanical behavior [10]. Due to this anisotropy the magneto-elastic coupling is dependent on the spatial direction of the applied field and applied stress relative to the grain orientations [11].

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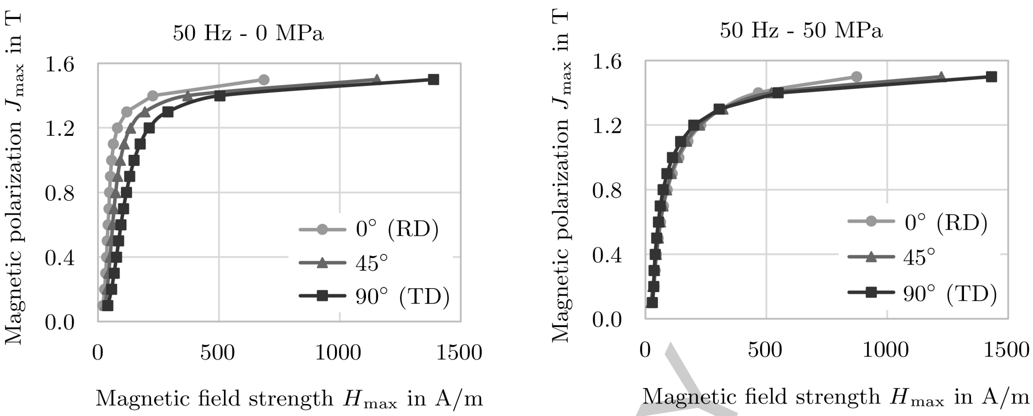

Fig. 1. Magnetization curves at 50 Hz in 0°, 45° and 90° relative to RD for unstressed samples and samples loaded with 50 MPa tensile stress.

Main challenge is the direct correlation of experimentally obtained results in the entire sheet plane, for different stress states. On that account, this paper evaluates the crystallographic texture and considers the magnetic anisotropy when investigating the stress dependence of the magnetic properties of NO ES.

2. Methods

In this paper a study on the effect of homogeneously distributed stress on the electromagnetic properties of a conventional, fully finished, uncoated 2.4 wt% FeSi with a sheet thickness of 0.5 mm is presented. Experiments are performed in different angles relative to the rolling direction, i.e., 0° (rolling direction (RD)), 45° (diagonal) as well as 90° (transversal direction (TD)). In order to understand and quantify effects of mechanical stress on the magnetic properties of NO ES tensile stress up to tensile strength and small compressive stress are studied. Experiments are performed on a 100 mm × 500 mm single sheet tester (SST), equipped with a tensile and compression hydraulic loading unit. This setup enables the application of mechanical stress collinear (uniaxial loading) to the magnetic flux up to a maximum force of 5 kN. Samples are excited by a sinusoidal alternating magnetic flux density.

3. Results and discussion

3.1. Interdependence of elastic tensile stress and magnetic anisotropy

Results show that the interdependence of magnetic anisotropy and elastic tensile stress is distinct. Figure 1 shows magnetization curves at 50 Hz in the unstressed state for samples in 0°, 45° and 90° relative to RD. For all $J_{\max}$ = const. each $H_{0^\circ} < H_{45^\circ} < H_{90^\circ}$. These unstressed magnetization curves relate to standardized testing methods (i.e., Epstein, SST) of the same material. Furthermore, they correlate with their crystallographic texture represented by their A-Parameter [12]. When exposed to an uniaxial tensile stress of 50 MPa collinear to the magnetic field a homogenization of the curves can be observed in form of a decrease of the directional dependance, i.e., decrease of anisotropy. Especially at low and medium polarizations the overall behavior is less anisotropic. However, magnetization curves cross at different polarization, e.g., at $J_{\max} = 0.5$ T, $H_{90^\circ} < H_{0^\circ} < H_{45^\circ}$, whereas at $J_{\max} = 1.5$ T, $H_{0^\circ} < H_{45^\circ} < H_{90^\circ}$.

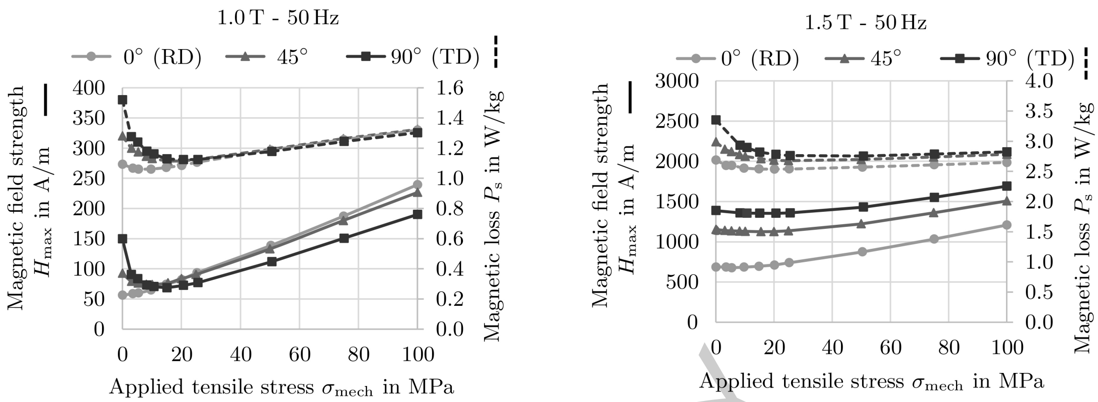

Fig. 2. Magnetization and magnetic loss at 50 Hz and two polarizations 1.0 T and 1.5 T in 0°, 45° and 90° relative to RD with increasing tensile stress up to 100 MPa.

Thus, a polarization dependence has to be considered for investigations. For the following considerations nominal points of 1.0 T at 50 Hz or 100 Hz are evaluated in order to ensure comparability.

In Fig. 2 magnetization and magnetic loss at two polarizations are shown for increasing tensile stress from 0 MPa to 100 MPa. As previously stated, the distinct anisotropy in the unstressed state as well as a homogenization with increasing elastic tensile stress for medium polarizations can be observed. For magnetization, i.e., required magnetic field strength to induce 1.0 T at 50 Hz, as well as magnetic loss a two staged behavior can be observed. In the first stage anisotropy is especially pronounced and results in a different behavior for orientations of 0° and 90° relative to RD. The magnetization for samples stressed in RD progressively increases with increasing stress. In TD a strong decrease in required magnetization occurs up to approximately 15 MPa, followed by a mild increase for larger stress. Samples stressed in 45° relative to RD exhibit a behavior between these extremes, with an initial decrease of magnetization smaller when compared with 90° samples. The course of the magnetic loss with increasing tensile stress shows analogous tendencies with only the difference that in 0° orientation a slight decrease of loss occurs. The second stage however, is uniform for all orientations for both losses and magnetization. Here, a sharp linear relation between magnetic properties and increasing tensile stress is shown. At higher polarizations these two stages can also be observed. However, they are far less pronounced. Additionally the anisotropy, especially in magnetization is still striking, even at 100 MPa. A beneficial effect on magnetic loss occurs even at high polarizations. Also noticeable is the beneficial magnetization for TD at 1.0 T and stress over 15 MPa compared with RD and 45° resulting from a crossing of magnetization curves. This effect is polarization dependent and not occurring at high polarizations because the initial order of magnetization curves from the unstressed state is restored.

Evaluation of J-H-hysteresis curves at 1.0 T as shown in Fig. 3, enables a closer look on a number of magnetic properties, e.g., $H_{\max}$, J_{r}, H_{c}, μ_{r}. Uniaxial tensile stress either causes a shearing of curves or a steepening towards an upright position. In RD and stress of 50 MPa and 100 MPa a sole shearing with increase of field strength and coercivity occurs while remanence and permeability decrease. A sole shearing also occurs in 45° orientation. But in TD the 50 MPa curve exhibits a steepening of the curve before shearing with increasing stress. The results presented so far can also be summarized when looking at the magnetic loss, Table 1. For the unstressed state the magnetic loss shows a high anisotropy, whereas loss in RD is smaller compared with 45° and TD. With increased tensile loading resulting in 50 MPa and 100 MPa stressed samples, the magnetic anisotropy decreases. For RD a sole increase in losses is observed, whereas for 45° and TD a decrease of loss for 50 MPa is followed by an increase

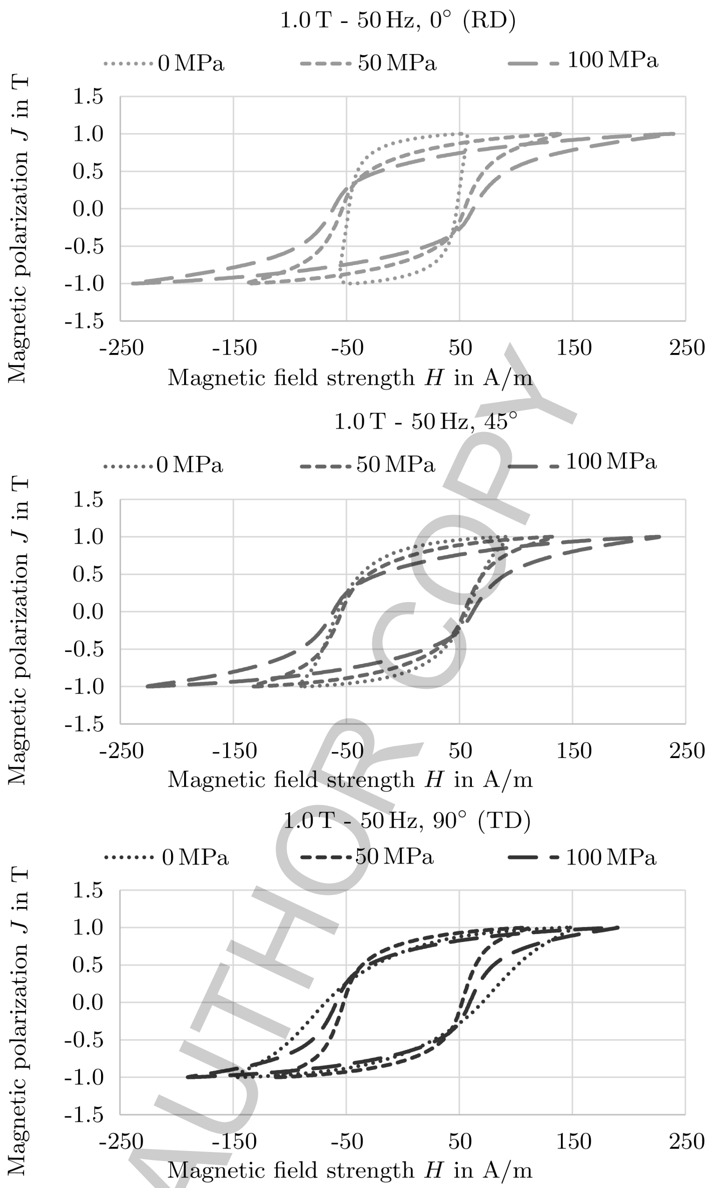

Fig. 3. J-H-hysteresis loops at 50 Hz and 1.0 T in 0°, 45° and 90° relative to RD for unstressed samples, 50 MPa and 100 MPa tensile loading.

of loss for 100 MPa. This change in behavior relates to the steepening and shearing of the hysteresis curves (Villari-reversal). This Villari-reversal is also represented in the respective magnetization curves. In RD an increase of stress leads to a consecutive flattening of the curve, whereas 45° and 90° samples first exhibit a more parallel shifting of the magnetization curve towards better magnetization. Then, at a specific load, the Villari-reversal occurs with a flattening of the magnetization curve and a deterioration of magnetic properties.

The apparent, distinct interrelation of magnetic anisotropy in the unstressed state and mechanical stress dependency for NO ES needs to be studied further. Within the elastic region uniaxial tensile stress

Table 1
Magnetic loss P_s at 50 Hz, 1.0 T

	0 MPa	50 MPa	100 MPa
0° (RD)	1.09 W/kg	$\uparrow$ 1.19 W/kg	$\uparrow$ 1.32 W/kg
45°	1.28 W/kg	$\downarrow$ 1.19 W/kg	$\uparrow$ 1.32 W/kg
90° (TD)	1.52 W/kg	$\downarrow$ 1.18 W/kg	$\uparrow$ 1.30 W/kg

results in an elastic distortion of the crystal lattice within the polycrystal [13]. Although microplasticity can occur in certain regions even before reaching the yield strength [14], it is unlikely that the observed effects are caused by microyielding, because the mechanical stress is still relatively small (up to 100 MPa). Also, effects are reproducible with the same samples, showing the exact same behavior. Therefore, a sole elastic behavior can be assumed. One probable explanation for the observed effects can be magnetostrictive differences and changes due to the polycrystalline character of the samples. Body-centered cubic iron has different magnetostriction along $< 100 >$ and $< 111 >$ axis, λ_{111} is negative, whereas λ_{100} is positive [15]. For unidirectional tension material with positive magnetostriction expands when magnetized, leading to a steepening of the magnetization curve. For negative magnetostriction the effect is reversed, resulting in a decrease of magnetization [16]. Just as the A-Parameter depends on the direction of the magnetization vector, so does the global magnetostriction, because it is a result of the entirety of orientation distributions, i.e., magnetostriction constants along the crystallographic axis. How the global magnetosriction and external load interacts with the elastic deformations and geometric continuity conditions of a polycrystal is relatively unknown. A second factor for the reversing behavior for TD can be the residual stress distribution in the initial state. If compressive stress is distributed along TD a tension could improve the magnetic properties during loading until a neutralization is reached and a deterioration begins just as in RD. However, the annealing treatment after cold rolling should largely eliminate residual stress due to recrystallization and grain growth.

Up to this point, there are no reliable methods available to measure residual stress [17,18]. From texture measurements it is evident that magnetization for the studied material in the unstressed state correlates to its crystallographic texture and thus, does not indicate a strong impact of residual stress. However a study on stress relief annealing for the studied samples can give evidence about the impact of residual stress on the initial magnetic anisotropy and stress dependency. Furthermore, the effect of elastic tensile stress on the crystallographic orientations of the grains and elastic lattice distortion should be further studied, for example with Electron backscatter diffraction (EBSD) under tensile loading as well as magnetostriction measurements in the unstressed state. With these methods, an evaluation of contributions could be possible and enable a identification of the primary factor.

3.2. Interdependence of plastic deformations and magnetic anisotropy

Due to the mechanical anisotropy of the material, key mechanical properties are also dependent on the orientation of the samples. In Fig. 4 magnetization and magnetic loss are plotted as a function of the external tensile force F in N. The application of stress that leads to a plastic deformation, i.e., above yield strength is considered for two states due to the physical effects of plastic deformation. The circles describe the stressed state while loaded. The crosses relate to the state after removal of the load. This means at 0 N external load. However, to highlight their relation to the corresponding plastically stressed state these results are positioned vertically above the maximum load for each deformed sample.

When samples are stressed there is a distinct difference between the effect on magnetic loss and on magnetization. For the magnetization there is no indication of exceedance of yield strength, i.e., elastic

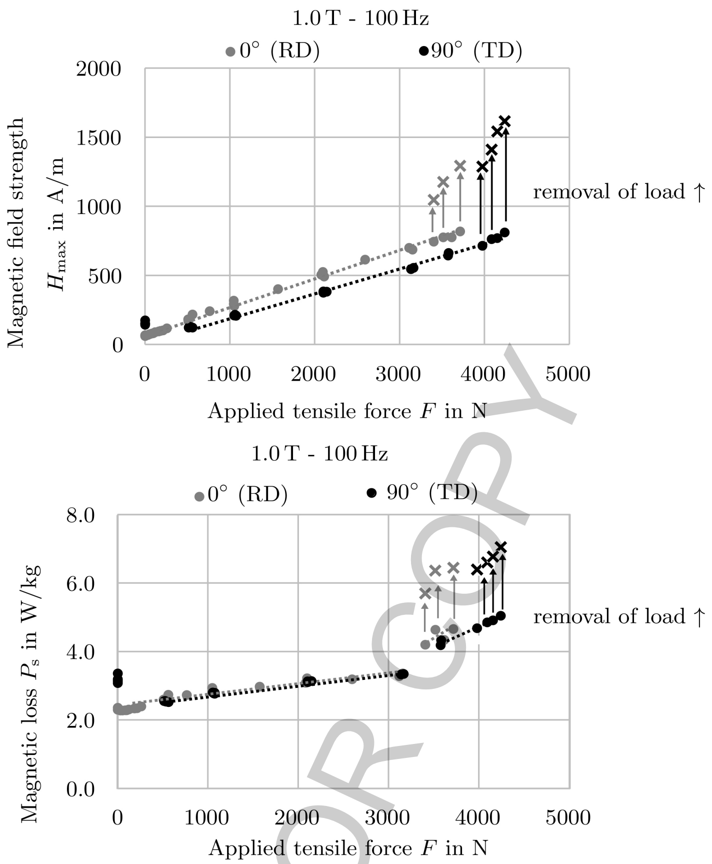

Fig. 4. Magnetization and magnetic loss at 100 Hz and 1.0 T in 0° and 90° relative to RD for increasing tensile force F up to plastic deformation.

limit. The linear relation for required magnetic field strength with increasing tensile loading is still valid. However, for magnetic loss there is an indication of exceedance of yield strength in form of sudden increase of loss. The slope of the curve is not as linear as below yield strength. Plastic deformation is caused by crystallographic slipping and results from dislocation generation and movement [19]. Thus, it can be seen that an increase of dislocation density has a strong effect on loss but a minor effect on magnetization. The generally observed severe deterioration for magnetic properties after plastic deformation [11,20] only occurs after removal of the load. For 1.0 T magnetic loss exhibits an additional increase of about 40% to 50%. Due to the previously identified effect of dislocations as pinning points and their impact on losses, the sudden increase after removal of the load can be attributed to a dispersal of stress that leads to multiaxial stress [21]. The authors of [20] relate the deterioration to long-range internal stress. The overall residual stress state after plastic tensile deformation is globally compressive. By re-applying the corresponding external tensile load to the 0 MPa state (crosses) the stressed state (circles) can be reinstated.

However, looking at the impact of magnetic anisotropy no distinct changes can be observed. Samples behave analogous despite different orientations. Direct comparison between values in RD and TD is difficult, because of their anisotropic mechanical properties. Thus, same external load or same stress results in different states, because the yield strength and tensile strength for RD are slightly lower when compared with TD.

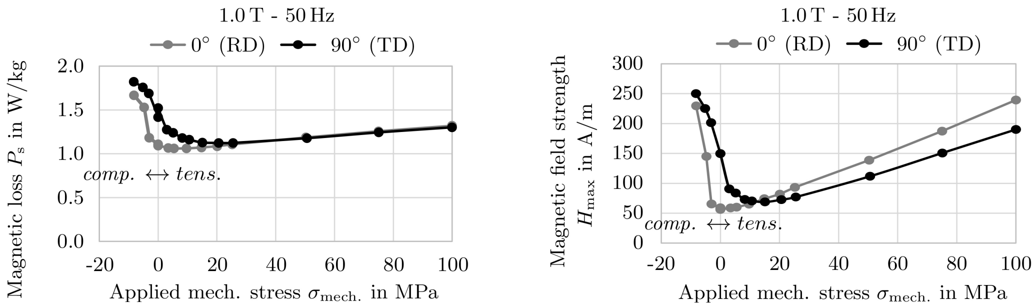

Fig. 5. Magnetic loss and magnetization at 1.0 T and 50 Hz in 0° and 90° relative to RD for tensile (positive) and compressive (negative) stress.

3.3. Interdependence of small compressive stress and magnetic anisotropy

Figure 5 depicts the magnetic properties as a function of tensile and compressive stress. Compressive stress solely deteriorates the magnetic properties in form of a degrading magnetization and increasing loss. Even relatively small compressive stress has a strong impact. 10 MPa compressive stress increases the loss far more than 100 MPa tensile stress. For the magnetization behavior the deterioration for 10 MPa is close to the deterioration at 100 MPa tensile stress. Evaluating the effect of anisotropy it is less distinct compared to tensile stress. RD is better than TD for all applied compressive stress. Due to the measurement setup only small compressive stress could be applied on the cross section of the samples, because of a bending of the sheet samples and thus, a deviation from the uniaxial stress conditions, which are compared.

4. Conclusions

The presented results show that magnetic anisotropy of NO ES has a significant effect on issues regarding mechanical stress. Even though NO ES are supposed to be isotropic they exhibit certain favorable and unfavorable textures, resulting in anisotropic magnetic as well as mechanic properties. Considering its application in magnetic cores of rotating electrical machines, the NO steel sheets are exposed to external forces which induce stress, e.g., from processing, manufacturing and application. Thus, the consideration of mechanical stress dependance is as important as the magnetic characterization during standardized material testing.

The results of Section 3.1 to 3.3 issue a number of effects caused by different deformation mechanisms and are taken into account alongside the magnetic anisotropic behavior. Generally the anisotropy in the unstressed state correlates with the samples' crystallographic texture for high polarizations, i.e., $J_{5000\ \mathrm{A/m}}$. Even if it is more pronounced with elastic tensile loading, anisotropic behavior is also observed for plastic deformations, as well as small compressive stress.

1. Elastic deformation shows a strong interrelation with magnetic anisotropy. A different phenomenology in different sample orientation occurs, resulting in deterioration or improvement of magnetic properties compared to the unstressed state. Additionally, a "homogenizing effect" of elastic tensile stress on magnetization and magnetic loss is observed. The effects are polarization-dependent and especially pronounced at small and medium polarizations.
2. Plastic deformation has a smaller interrelation with magnetic anisotropy, although an anisotropy can still be observed. However, the general behavior for different orientation is analogous.

3. Compressive stress is far more detrimental to magnetic properties than tensile stress. The initial anisotropy is more or less constant during the small compressive stress range studied, with only a very slight homogenization.

A few points in question still remain as to the origin and interrelation of effects leading to the anisotropy and differences in the stress dependance. One key question is whether the crystallographic texture is the primary reason for magnetic anisotropy or if it is additionally affected by residual stress. These points are objective of further research on this topic.

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