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On the homogeneity and isotropy of non-grain oriented electrical steel sheets for the modeling of basic magnetic properties from microstructure and texture

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Laminations of non-grain oriented (NO) electrical steel grades for magnetic cores of electrical machines should feature homogenous magnetic properties within the entire sheet plane. Basic empirical models have been introduced to estimate and correlate magnetic properties with microstructural material parameters. In these considerations the steel sheets are generally considered to be homogenous, i.e., orientation dependence and variations across the sheet thickness are often disregarded. Whether or not, these simplifications are justified and how grain size and texture are described most suitable for correlations with magnetic properties, is the focus of this paper discussing four industrial NO steel grades.

Index Terms—**Anisotropy, homogeneity, magnetic texture, non-grain oriented electrical steel.**

I. Introduction

Electromagnetic properties of non-grain oriented (NO) electrical steel directly stem from elemental material properties. Characteristic magnetic values such as permeability, coercivity, losses or saturation polarization depend on, e.g., alloying content, grain size or crystal orientation. Subject of various research is the modeling of distinct characteristic magnetic values from empirical correlations between, for example, Si-equivalent, grain size or texture factors with losses or saturation magnetization [1-3]. However, these empirical correlation equations require explicit values that accurately describe the microstructure and texture. Thus, two main factors become of significant importance; isotropy and homogeneity.

Even though NO electrical steel refers to the non-grain oriented modification of these materials and, thus, indicates isotropic behavior and statistically distributed crystal orientations, distinct deviations from these ideal properties can be observed. Due to the production and processing NO steel actually has a magnetic texture that is not random and as a result anisotropic magnetic properties. For thin sheets the magnetic texture is usually measured on the surface of the samples. Grain size is usually obtained from cross-sectional sample preparation and the grains are assumed to be spherical. Thus, a mean grain size is determined to describe the microstructure. However, in order to obtain credible values of elemental material properties which affect the magnetic properties, the homogeneity and anisotropy of NO steel needs to be considered. In this paper the anisotropy and homogeneity is studied on different industrial materials. Microstructure and texture are evaluated and correlated to the magnetic properties. The results are examined regarding the respective effect of microstructure and texture on existing modeling approaches. The mechanical stress state of industrial grades due to the rolling process can also affect the magnetic properties and anisotropy of the steel sheets. However, the focus of this research is a study on the sensitivity of existing models to homogeneity of microstructure and texture.

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II. Experimental

In total seven different industrial NO electrical steels were studied for this work. Results for four characteristic examples corresponding to a M400-50A, two M330-50A from different manufacturers, and a M270-50A are displayed in this paper to represent inhomogeneous grades as well as homogeneous grades and changes for equivalent grades of different manufacturers. For texture and microstructure measurements, samples were prepared in different layers of the rolling direction (RD), transverse direction (TD) sheet plane, as depicted in Fig. 1. In Fig. 1, the definition of 0 % refers to the surface of the sample, whereas 25 % and 50 % mark ¼ and ½ of the sheet thickness d_{sheet}. This is sufficient due to the symmetry plane of the sheet along half of the thickness and was tested exemplarily.

For texture measurements an X-ray goniometer is used. The sample size for the measurements is 100 mm^2 which corresponds to several thousand grains depending on grainsize and grainsize variation. Previous studies on numerous industrials as well as experimentally produced NO showed that variations on different samples of the same batch are slight to negligible. However, unlikely batch variations cannot be ruled out completely.

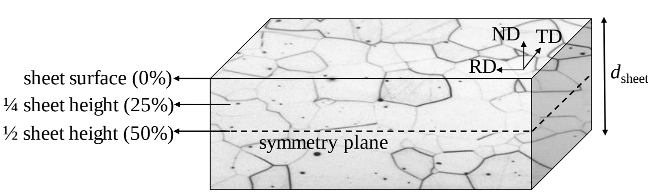

Fig. 1. Schematic illustration of sample preparation for microstructure and texture measurements along different layers of the RD-TD plane.

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From the ODF measurements the *A*-parameter is calculated according to the parameter introduced by Kestens et al [3,4]. The parameter describes the mean angle of all crystallographic orientations of a sample between easy magnetization axes, i.e. cube edges in body centered cubic iron and the magnetization angle, so that small values indicate easy magnetization [5-7]. The layered samples are then etched and observed under a light optical microscope. The determination of grain size is performed analogous to the line intercept method and carried out along the RD and TD direction. For the magnetic characterization a 120 mm x 120 mm Single-Sheet-Tester (SST) is used. For all materials square samples along RD and TD direction are measured. Due to the uniaxial flux in this setup, some samples are cut in 5° steps between RD and TD to determine magnetic properties in the further orientations of the sheet plane. An overview on the experimental procedures is given in Tab. 1.

Tab. 1. Experimental procedures performed on the respective materials.

Material	Micro-structure in layers	Texture in layers	SST in RD & TD	SST in 5° angles
M400-50A	yes	yes	yes	-
M330-50A(I)	yes	yes	yes	yes
M330-50A(II)	yes	yes	yes	yes
M270-50A	yes	yes	yes	yes

III. Results and Discussion

A. Microstructure and texture

For all materials under study, the microstructure varies along the sheet thickness. However, Fig. 2 shows, some materials exhibit rather evenly distributed grain sizes with small variations in different layers, for example the M400-50A, as seen in Fig. 2 a). Whereas, other materials, for example the M330-50A (I) shown in Fig. 2 b) and the M270-50A (Fig. 2 c)) show large differences of grains near the surface when compared with grains in the middle of the sheet. For the M330-50A (I) grains on the surface are in average half the size of grains in the middle of the sheet. For the M270-50A grains on the surface are slightly larger than in the center.

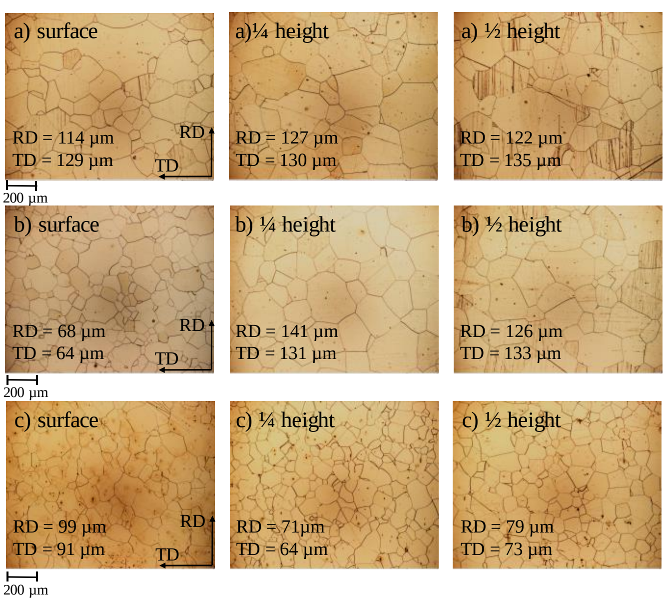
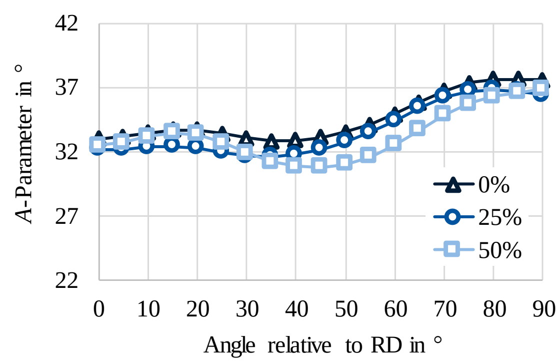


Fig. 2. Light optical microscopy of microstructure for industrial steel grades a) M400-50A, b) M330-50A(I) and c) M270-50A.

The anisotropy concerning RD and TD is less distinct. Thus, the grains are rather spherical in shape. However, differences of 5 % - 10 % are observed, with some materials having larger grains in RD and some in TD. In order to prevent statistical errors, various images per layer and material were evaluated.

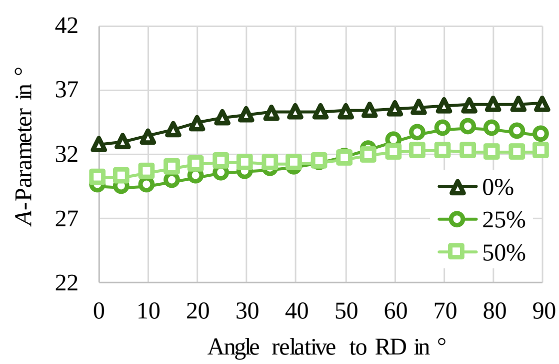
In general, the homogeneity of the microstructure along the sheet thickness can also be obtained from cross-sectional images, under the condition that measurements are evaluated with respect to potential differences across the cross section. Thus, more images are necessary for the line intercept method in order to evaluate a sufficient number of grains. Additionally, the anisotropy can only be evaluated from cross-sectional images, when different images from the ND-RD and ND-TD planes are produced. In order to determine the homogeneity of the microstructure, either method cross-sectional or surface-sample preparation can be used. Nonetheless, both methods are demanding.

a)



	0%	25%	50%
A_{total}	34.6	33.7	33.3

b)



	0%	25%	50%
A_{total}	35.0	31.7	31.5

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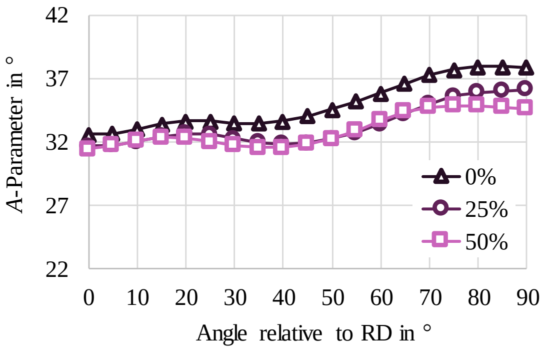
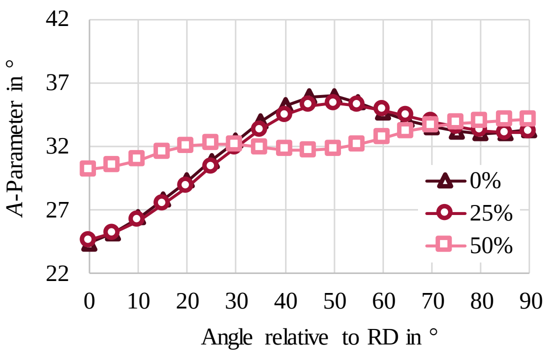
c)



	0%	25%	50%
A_{total}	35.0	33.3	33.0

d)



	0%	25%	50%
A_{total}	32.0	31.8	32.3

Fig. 3. Angular dependence of the *A*-parameter calculated from the ODF and the averaged *A*-parameter A_{total} along the sheet plane between 0° and 90° for a) M400-50A, b) M330-50A(I), c) M330-50A(II) and d) M270-50.

Results indicate that texture also varies along the sheet thickness, i.e., in the different examined layers. In Fig. 3 the *A*-parameter over the range between 0° (RD) and 90° (TD) for different materials is depicted. For all layers the mean angle between the directional vector and easy magnetization axis is smaller in RD when compared with TD. If the *A*-parameter is averaged across the sheet plane it is apparent that A_{total} is considerably dependent on the position of measurement. Considering that texture measurements on very thin sheet are usually done on RD-TD microsections, it is apparent that an evaluation based on surface texture measurements only, is not sufficient. Although, for some materials, for example Fig. 3 a) the texture is very homogenous, for Fig. 3 b) the surface layer has significantly higher values for the *A*-parameter at each angle, which indicates inferior magnetization. For Fig. 3 d) the surface as well as the ¼ height layer exhibit larger values of *A* in 45° to 50° relative to RD. The ideal orientation for NO is a ND-rotated cube fiber and therefore, a value for A_{total} of 22.5. A statistically random texture has an *A*-parameter of approximately 31. Compared to the values for all materials under study it is highlighted that the desired cube texture for NO steel grades is not evident in industrial NO.

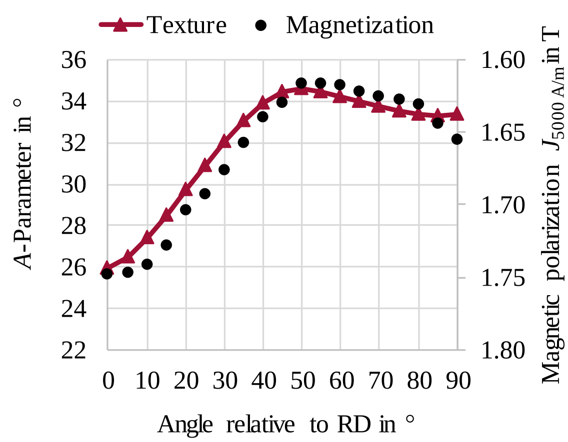
B. Correlations with magnetic measurements

The *A*-parameter describes the mean angle between easy magnetization axis of all orientations from an ODF and the magnetization vector and therefore should correlate with the magnetization behavior [1,5]. In Fig. 4 the magnetization at high field strength, i.e., 5000 A/m and 10000 A/m at 50 Hz is plotted in 5° angles between RD and TD and compared to the calculated *A*-parameter. It is shown that the tendency is in good accordance. The texture however, was weighted from the measurements of the surface, ¼ height and ½ height, according to the following equation:

$$A_{\theta,\mathrm{weighted}} = \frac{(A_{\theta\ 0\%} + 2 \cdot A_{\theta\ 25\%} + A_{\theta\ 50\%})}{4} \quad (1)$$

In this equation θ describes the angle between the magnetization vector and RD. From comparisons between magnetic measurements, texture measurements in different layers and cross-sectional microstructural analysis for different material this weighting ratio was deducted.

a)



b)

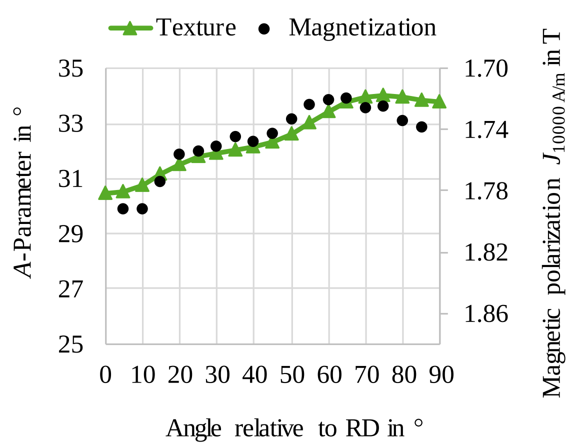


Fig. 4. Correlation between averaged texture and magnetization at high field strengths i.e. 5000 A/m and 10000 A/m at 50 Hz for a) M270-50A, b) M330-50A (I)

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C. Adaption to modeling

As previously shown grain size as well as texture can vary within the cross section of the steel sheets. Different models [1-7], e.g., eq. (2) [4], describe the correlation between magnetic properties and microstructural features. The results of the performed experimental series are applied exemplarily to the following model, so that an analysis of the sensitivity to inhomogeneity and anisotropy can be examined.

$$P_{\mathrm{h}} = (-3.9 \pm 0.8)d + (0.15 \pm 0.04)A - 0.869 \qquad (2)$$

In Tab. 2 calculated and estimated hysteresis losses are compared. The term "standard" in this case refers to the conventional method of microstructural analysis, i.e., texture measurements on the surface of the sample and grain size determination from longitudinal microsections with the assumption of spherical grains.

Tab. 2. Comparison between measurements and calculated P_{h} (2) 0° relative to RD.

	estimated P_{h} in W/kg at 50 Hz	calculated P_{h} in W/kg standard*	calculated P_{h} in W/kg differentiated**
M400-50A	2.21	3.61 64%	3.52 59%
M330-50A(I)	1.75	3.61 107%	3.23 85%
M330-50A(II)	2.01	3.82 90%	3.69 84%
M270-50A	1.55	2.46 58%	2.77 78%

* standard: Texture ($A_{0°}$, $A_{90°}$)measured at sample surface, grain size measured from longitudinal micro sections.
** differentiated with homogeneity and anisotropy: Texture as well as grain size determined from microsections in different layers of RD-TD.

Hysteresis losses at 50 Hz are estimated from measurements at 50 Hz minus the classical loss component P_{cl}, calculated by (3)[8] with the specific density ρ and electrical resistivity ρ_{el} as well as frequency f, sheet thickness d_{sheet} and magnetic induction $\hat{B}$.

$$P_{\mathrm{cl}} = \frac{(\pi \cdot f \cdot d_{\mathrm{sheet}} \cdot \hat{B})^2}{6 \cdot \rho \cdot \rho_{\mathrm{el}}} \quad (3)$$

The expected measurement uncertainty on the magnetic loss is below 1.5 % at the considered frequency and flux density. The calculated P_{h} in the third column, i.e., with consideration of homogeneity and anisotropy uses weighted values (eq. 1) of the three layers and considers anisotropy of grain size in RD and TD for A and d of eq. (2). However, the fit is still very poor with a discrepancy of measured and calculated values of far more than 50%. Losses are significantly overestimated for all steel grades under study. The constants are changed in line with the trust region of the parameters according to Kestens and Jacobs [4] to improve the fit. When the constants of eq. 2 are changed from -3.9 to -4.7 and 0.15 to 0.11 the fit improves, especially for the M400-50A and the M270-50A. But for both M330-50A the calculation is still 25 % above the measured values for the standard calculation and between 10 % to 20 % with consideration of homogeneity and anisotropy.
Thus, a new set of constants for eq. (2) is used to improve the calculation of all the four materials. The parameters were selected to ensure a respective error below 10 % for each individual grade and the lowest combined error for all four grades. Furthermore, the model was adjusted to calculate specific losses P_{s} at 50 Hz instead of hysteresis losses P_{h} to converge to standard measurements. Due to the constant sheet thickness of the studied material one set of new factors is sufficient and is shown in eq (4).

$$P_{\mathrm{s}} = (-5.2)d + (0.138)A - 1.0 \quad (4)$$

In the following Tab. 3 the comparison between the newly calculated P_{s} with eq.3 and the measurements of P_{s} are collected. Analogous to Tab. 2 the standard calculations by measurements as well as by differentiated inhomogeneity and grain size anisotropy are collated. The adjustment of the factors has improved the calculations for both the standard and the differentiated case. For latter, the error is less than 10 % for both

Tab. 3. Comparison between measurements and calculated P_{s} from (4) for the studied steel grades with a) in RD and b) in TD.

a) RD

	measured P_{s} in W/kg at 50 Hz	calculated P_{s} in W/kg standard*	**calculated P_{s} in W/kg differentiated** **
M400-50A	2.86	2.92 2.2 %	**2.84** **-0.5%**
M330-50A(I)	2.51	2.90 15.8%	**2.59** **3.1%**
M330-50A(II)	2.82	3.21 13.7%	**3.11** **10.0%**
M270-50A	2.32	1.95 -16.0%	**2.16** **-6.6%**

b) TD

	measured P_{s} in W/kg at 50 Hz	calculated P_{s} in W/kg standard*	**calculated P_{s} in W/kg differentiated** **
M400-50A	3.47	3.55 2.2%	**3.40** **-2.1%**
M330-50A(I)	3.01	3.34 11.0%	**3.06** **1.7%**
M330-50A(II)	3.44	3.94 14.7%	**3.71** **8.0%**
M270-50A	2.98	3.18 6.4%	**3.23** **8.1%**

* standard: Texture ($A_{0°}$, $A_{90°}$)measured at sample surface, grain size measured from longitudinal micro sections.
** differentiated with homogeneity and anisotropy: Texture as well as grain size determined from microsections in different layers of RD-TD.

RD and TD measurements and calculation, as highlighted bold in Table 3. All steel grades under study have a silicon content over 2.4 wt.% Si. The impact of other factors, for example mechanical stress state that can also lead to initial anisotropy was not yet regarded but could pose a further impact on the losses and could be a determining factor for differences besides grain size and texture.

IV. Conclusions

For materials with varying microstructural features across the sheet thickness and along different orientations it is necessary to consider the inhomogeneity, when modeling magnetic properties. The studied industrial grades show distinct differences considering homogeneity and anisotropy with some grades being very isotropic and some being inhomogeneous. Application of the experimental results to the studied model approach highlights the sensitivity of the calculated results to inhomogeneity. Correlations between microstructure, texture and magnetic properties demonstrate that a differentiated consideration leads to good accordance even for inhomogeneous grades with errors between calculations and measurements below 10 %. Thus, an initial evaluation of isotropy is important. However, the model approach needs to be adjusted to the magnetic measurements in terms of parameter identification for the constants of the equations and the methods of weighting the different layers also needs to be studied.

The next step to further improve magnetic modeling is to examine and evaluate the intrinsic factors affecting these constants. In this context, possible impacts of alloying, precipitation state or mechanical stress should be discussed and generally be taken into account to evaluate their impact on possible anisotropy and magnetic losses.

V. Acknowledgements

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