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Research article

Interrelation of mechanical properties and magneto-mechanical coupling of non-oriented electrical steel

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ABSTRACT

The magnetic properties of non-oriented iron–silicon electrical steel grades are generally the target properties for their application in commercial speed-variable electric drives. Due to high rotor speed and the resulting mechanical stress, a compromise between magnetic properties and mechanical strength with respect to the dimensions of the rotor topologies has to be found during the design of the electrical motor. What is typically neglected in this consideration is the magneto-elastic coupling, i.e., the change of magnetic properties as a result of induced mechanical stress. In this paper, general interdependencies between the magnetic and mechanical properties with the magneto-elastic sensitivity of seven industrial iron–silicon electrical steel grades is studied in order to improve the best possible material choice speed-variable drives with a high power density.

1. Introduction

Non-grain oriented (NO) electrical steel is used to guide the magnetic flux in electrical machines. The actual energy conversion from electrical to mechanical energy takes place in the air gap between the fixed stator and the rotatable rotor. The flux density in the air gap is proportional to the machine torque and the magnetizing frequency is proportional to the motor speed. As a result of the ongoing efforts to increase the efficiency of and power density of electric drives, motor speed is generally increasing and mechanical properties of NO become more become a decisive factor in the design of electrical machines. This is due to the high centrifugal forces and resulting stress on the filigree parts of the rotor geometries [1,2].

The magnetic characterization of electrical steels is performed, according to international standards, as for example IEC-60404 on sheet materials. The problem with this standardized procedure is that it is performed under the premise of gentle sample preparation on relatively large samples. A significant problem with this characterization occurs, as the magnetic properties are very sensitive to mechanical stress [3,4]. Mechanical stress is inevitably induced in NO during the processing from the steel sheet to a motor core as depicted in Fig. 1. The materials are cut [5–7], stacked [8–10], pressed into a housing [11,12] and assembled. Residual stress and deformations are therefore present in the NO laminations of the motor. During the operation further thermal stress is induced as well as centrifugal forces due to rotation. Thus, the initially characterized magnetic properties of the steel sheet do not necessarily represent actual magnetic properties within the final application. The centrifugal forces also directly affect the rotor design and material choice due to mechanical constraints. Narrow flux bridges and barriers have to be designed which withstand the centrifugal load (Fig. 2) by either increasing their width or utilizing a higher strength material.

The magneto-elastic sensitivity, i.e. magnetic deterioration due to induced mechanical stress, is an important factor that should be considered in the material selection especially for high-speed applications. As machine calculation tools, which are vital during the machine design process, are usually not able to consider and represent the magneto-mechanical behavior, the knowledge of general interdependencies between magnetic and mechanic properties can help the material choice process additionally to magnetic field simulations.

The magneto-mechanical characteristics as well as the mechanical properties are related to fundamental structural material properties such as grain size, thickness and alloying elements. In order to enable an efficient design of electrical machines, the interdependencies of the magneto-mechanical coupling must be understood. In this paper interdependencies between magnetic, mechanical and material properties, i.e., grain size, alloying, texture with the magneto-mechanical sensitivity are studied to identify general relations for iron–silicon electrical steels for series produced electric drives for e-mobility or industrial applications, such as servo motors.

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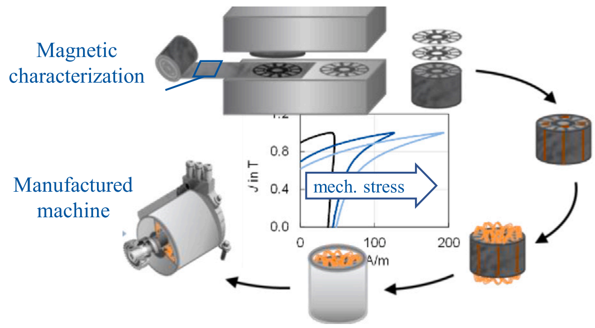

Fig. 1. Processing steps from electrical steel sheet to an electric motor.

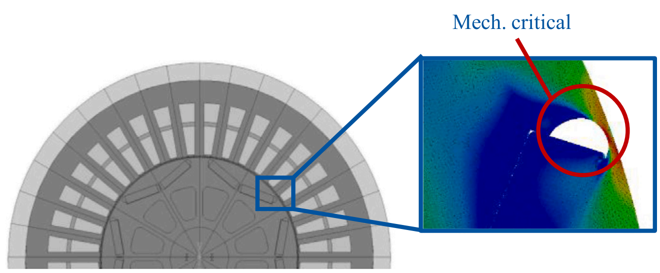

Fig. 2. Example of the influence of centrifugal forces on rotor bridges with depiction of van Mises stress.

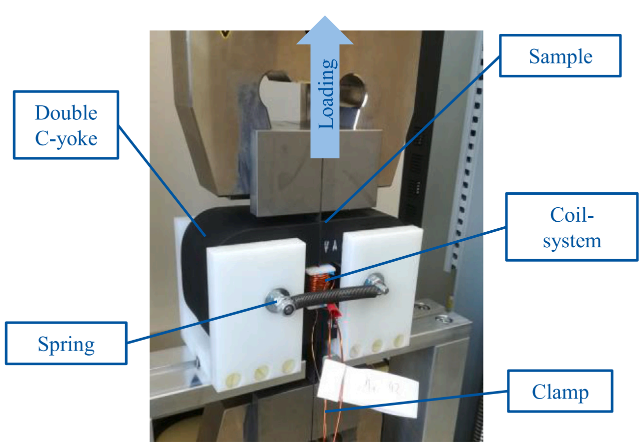

Fig. 3. Experimental setup to measure the magneto-mechanical properties under tensile loading.

2. Measurements and methods

The magnetic measurements in this study are conducted with an experimental setup of the combination of a *Brockhaus Measurements* MPG200 system and a *Zwick/Roell* (Z020/TN Pro Line) universal tensile testing machine. The electrical steel sheet samples have a size of 60 mm in width and 300 mm in length. Samples are clamped in the testing machine, as depicted in Fig. 3 and stressed with various tensile loadings. A primary induction winding and secondary coil of 18 windings each is placed around the sample. A high permeable double C-yoke with 60 mm length closes the magnetic flux. Due to the setup, applied magnetic field and stress are collinear. Samples are measured under an alternating, sinusoidal magnetic flux density with magnetizing frequencies of 50 Hz to 800 Hz. This frequency range is usually covered in data sheets provided by manufacturers and measurements are easy to obtain. Maximum induction at 800 Hz however, was limited to 1.4 T. The studied frequencies, polarizations and applied external tensile stresses are displayed in Table 1.

Table 1
Overview of the magnetic measurements.

Samples	Seven industrial NO
Polarization J_{max}	0.3 T to 1.6 T in 0.1 T -steps
Frequency f	50 Hz, 100 Hz, 200 Hz, 400 Hz, 800 Hz
Mech. stress $\sigma_{mech.}$	0 MPa, 50 MPa, 100 MPa, 200 MPa 300 MPa, 400 MPa

Table 2
Nominal thickness d_{sheet}, chemical composition, mean grain diameter d_{GS} and A-parameter [13] in RD of the studied materials.

	Grade	d_{sheet} mm	Si wt.%	Al wt.%	d_{GS} µm	A
NO1	M270-50A	0.48	2.9	1.1	73	25.9
NO2	M330-35A	0.35	2.6	0.4	105	32.2
NO3	NO30	0.30	3.6	1.1	88	29.9
NO4	NO30	0.31	2.9	1.5	98	29.8
NO5	NO23	0.23	3.6	1.2	116	29.8
NO6	NO23	0.24	3.6	0.9	110	28.5
NO7	NO20	0.21	3.6	0.6	97	29.4

Table 3
Summary of the mechanical properties of the studied NO grades.

	Grade	$R_{p\ 0.2}$ MPa	R_m MPa	A_g %
NO1	M270-50A	433	548	16.1
NO2	M330-35A	363	464	17.7
NO3	NO30	414	523	13.1
NO4	NO30	417	522	12.7
NO5	NO23	415	503	12.1
NO6	NO23	421	533	12.8
NO7	NO20	334	412	12.3

The seven studied materials are all conventional, industrial NO electrical steels with a sheet thickness between 0.5 mm and 0.2 mm and a silicon content above 2.5 wt.%. The samples for the magnetic measurements were cut with a guillotine parallel to the rolling direction (RD) of the steel sheet. This cutting methods is comparable to industrial punching used almost exclusively for the series production of commercial electric drives. For the characterization of the materials, various material science methods have been performed. The chemical composition was obtained by spark spectrometry. The grain size d_{GS} is determined with the line intercept method on optical surface micrographs in the middle of the sheet plane. For each material, at least 300 mean grain diameters are evaluated. The texture is quantified by means of the so-called A-parameter [13], which describes the orientation of easy magnetization axes within the sheet plane. A low value indicates an alignment in the magnetization direction. The parameter is calculated from an orientation distribution function (ODF) which was measured by X-ray diffraction (XRD). A summary of the measured sheet thickness, mean grain diameter, alloying content of Silicon and Aluminum and the A-parameter is presented in Table 2. The mechanical properties were measured on a standardized sample geometry for mechanical testing according to EN 10002 - Computer controlled tensile testing. The results of the measurements are displayed in Table 3

3. Results and discussion

The aim of this study is to assess, if the magneto-elastic sensitivity correlates with any of the material parameters or mechanical properties, which then allows the formulation of general relations for iron–silicon NO. Thereby, an estimation for the application in electric drives can be enabled without the need for a thorough magneto-mechanical characterization, which is time consuming and requires advanced experimental setups. As the electrical steel is supposed to withstand plastic deformation, the loadings in this study are in the range up to yield strength.

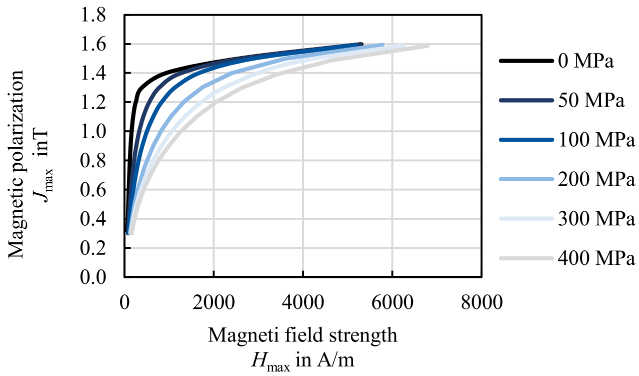

Fig. 4. Magnetization curves for NO4 at 50 Hz and various tensile loadings.

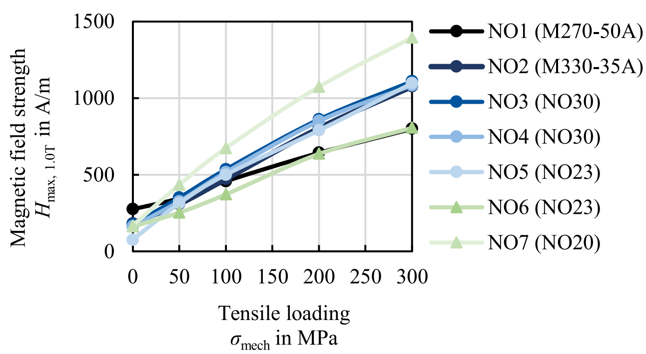

Fig. 5. Magnetic field strength at 1.0 T and 50 Hz for all studied materials at various tensile loadings.

The general effect that occurs as a result of stress is a shearing of the hysteresis curve with an increase of coercive field strength, loss and magnetic field strength and decrease of permeability and remanent polarization. The effect is more pronounced with compressive than with tensile strength [3,14]. Depending on the induction and applied tensile strength, an improvement of magnetization behavior can occur that is related to the material's magnetostriction and the effect of the Villari-reversal as well as possible remaining compressive stress in RD due to the steel strip production. At increasing stress, the magnetic properties deteriorate vastly. The effect is more pronounced at medium polarizations as this is the region of domain wall movement, which is impeded by stress, as can be seen in Fig. 4 on the example of NO4. The saturation behavior is mostly determined by the chemical composition so that the effect of stress is less pronounced at high polarizations. In Fig. 5 the required magnetic field at 1.0 T is depicted for all studied materials.

For the evaluation of the magneto-elastic sensitivity, a value δH_{mech} was defined. As the deterioration behavior in the elastic region is almost linear up to yield strength with the exception of small tensile loadings, a linear regression has been approximated between 50 MPa and 300 MPa. The linear regression can be described as follows:

$$H_{max\ 1.0\ T,\ 50\ MPa}(\sigma_{mech}) = H_{max\ 1.0\ T,\ 50\ MPa} + m \cdot \sigma_x, \tag{1}$$

with σ_x being the mechanical load increase relative to the 50 MPa value and m being the slope of the regression, e.g., δH_{mech}, which describes the magneto-elastic sensitivity of the material. In Fig. 5 it can be seen, that the sensitivity varies for the materials. NO1 for example has the relatively worst magnetization behavior in the unloaded state, whereas NO5 has the easiest magnetization behavior. This makes sense, looking at Table 2 and the grain sizes. NO1 has the smallest grain size and thus, more grain boundaries that impede free domain wall movements. NO5 on the other hand the largest grain sizes and subsequent free an easy

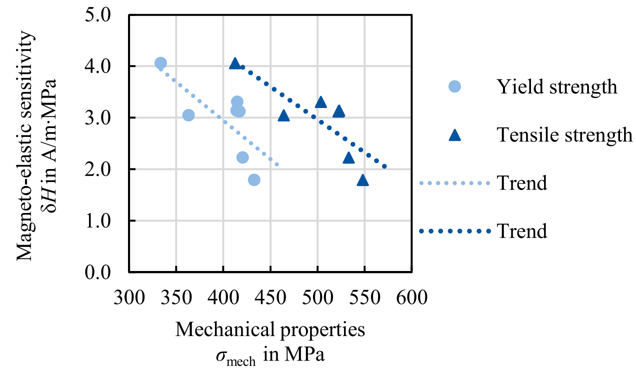

Fig. 6. Magnetic field strength at 1.0 T and 50 Hz for all studied materials at various tensile loadings.

magnetization. The magnetization behavior is strongly changed, by the magneto-elastic coupling as NO1 is the least sensitive to mechanical stress and exhibits the easiest magnetization at 300 MPa along with NO6.

The magneto-elastic sensitivity δH_{mech} has been compared to all characterized material parameters and the mechanical properties of the studied materials to find, if general trends and correlations can be observed. The one that was most pronounced is displayed in Fig. 6. It can be seen that the magneto-elastic sensitivity generally decreases with increasing mechanical strength, i.e., yield as well as tensile strength. The mechanical properties could not directly be linked to specific material parameters as these have a combined influence on the mechanical strength. NO1 with the highest strength has the largest sheet thickness and smallest grains which both increase the strength. A high silicon content also increases the strength, as for example for NO6.

The magneto-elastic sensitivity is evaluated at 1.0 T and 50 Hz. With increasing polarization and frequency, the sensitivity to external mechanical stress decreases. At higher frequencies this is due to the dominating effect of global eddy currents and dynamic processes for the loss and magnetization behavior. At increasing polarization the effect of domain rotation and crystallographic texture as well as saturation becomes more important. Therefore, the evaluation is best performed at excitation, where the effect is most pronounced, which has been displayed in this section.

4. Conclusions

In this study the magneto elastic sensitivity of iron–silicon NO electrical steels has been studied on seven industrial grades. A general trend between the yield and tensile strength and the magneto-elastic sensitivity can be observed, with higher strength leading to smaller magneto-elastic sensitive for the studied NOs at tensile loading. A distinct trend with individual microstructural material parameters could not directly be found as the strength is determined by the interrelation between various factors that, i.e. grain size, silicon content and sheet thickness. The trend for the mechanical properties is however, distinct.

The results show that an initial assessment of magneto-elastic behavior can be obtained by mechanical characteristics, which for machine designers can be of great value. For an electric drive with a high power density and high rotor speeds, a high strength electrical steel is not only beneficial due to the geometric constraints for rotor bridges but also likely is less sensitive to a magnetic deterioration due to external stress based on the results. The magnetic, mechanical and magneto-elastic properties should all be considered for the material selection process, but are in most cases not, as magneto-mechanical sensitivity is usually neglected in magnetic field simulations. However, results on general trends for the magneto-elastic sensitivity as presented in this paper can help during material choice.

The entwined relations between magnetic, microstructural and magneto-mechanical properties can be highlighted by an exemplary recommendation for a traction drive with high rotor speeds, filigree rotor bridges and a high electric frequency. Global eddy currents are usually minimized by using small sheet thicknesses. A relatively small grain size is can be chosen due to the stronger influence of the excess-loss component at medium to high frequencies compared to hysteresis losses. A small grain size usually increases mechanical strength which in turn, is also beneficial for a lower magneto-mechanical sensitivity. With these three material characteristics (mechanical strength, sheet thickness and grain size), a pre-evaluation of possible iron–silicon NO for a deeper study of machine performance can be selected. The actual values of sheet thickness, grain size or Si-content depend on the specific motor design and application parameters. What is yet to be considered are effects of anisotropy or thermal conductivity which affect the machine performance as well.

CRediT authorship contribution statement

N. Leuning: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **B. Schauerte:** Methodology, Data curation, Investigation, Writing – original draft, Writing – review & editing. **K. Hameyer:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Benedikt Schauerte reports was provided by German Research Foundation. Nora Leuning reports a relationship with German Research Foundation that includes: funding grants.

Data availability

Data will be made available on request.

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References

[1] A. Belahcen, M.A. Sitnikov, S.A. Galunin, Optimization of a high-speed synchronous reluctance machine's rotor topology, in: 2021 International Conference on Electrotechnical Complexes and Systems, Vol. 1116, ICOECS, IEEE, 2021, pp. 279–284, http://dx.doi.org/10.1109/ICOECS52783.2021.9657390.

[2] M.E. Gerlach, M. Zajonc, B. Ponick, Mechanical stress and deformation in the rotors of a high-speed PMSM and IM, E I Elektrotech. Inform. 138 (2) (2021) 96–109, http://dx.doi.org/10.1007/s00502-021-00866-5.

[3] A.P.S. Baghel, J.B. Blumenfeld, L. Santandrea, G. Krebs, L. Daniel, Effect of mechanical stress on different core loss components along orthogonal directions in electrical steels, Electr. Eng. 101 (3) (2019) 845–853, http://dx.doi.org/10.1007/s00202-019-00827-4.

[4] D. Singh, P. Rasilo, F. Martin, A. Belahcen, A. Arkkio, Effect of mechanical stress on excess loss of electrical steel sheets, IEEE Trans. Magn. 51 (11) (2015) 1–4, http://dx.doi.org/10.1109/TMAG.2015.2449779.

[5] A. Kedous-Lebouc, O. Messal, A. Youmssi, Joint punching and frequency effects on practical magnetic characteristics of electrical steels for high-speed machines, J. Magn. Magn. Mater. 426 (2017) 658–665, http://dx.doi.org/10.1016/j.jmmm.2016.10.150.

[6] H.A. Weiss, N. Leuning, S. Steentjes, K. Hameyer, T. Andorfer, S. Jenner, W. Volk, Influence of shear cutting parameters on the electromagnetic properties of non-oriented electrical steel sheets, J. Magn. Magn. Mater. 421 (2017) 250–259, http://dx.doi.org/10.1016/j.jmmm.2016.08.002.

[7] A. Moses, N. Derebasi, G. Loisos, A. Schoppa, Aspects of the cut-edge effect stress on the power loss and flux density distribution in electrical steel sheets, J. Magn. Magn. Mater. 215–216 (2000) 690–692, http://dx.doi.org/10.1016/S0304-8853(00)00260-2.

[8] T. Albrecht, C. Gürsel, E. Lamprecht, T. Klier, Joining techniques of the rotor segmentation of PM-synchronous machines for hybrid drives, in: 2012 2nd International Electric Drives Production Conference, EDPC, 2012, pp. 1–8, http://dx.doi.org/10.1109/EDPC.2012.6425122.

[9] S. Imamori, S. Aihara, H. Shimoji, A. Kutsukake, K. Hameyer, Evaluation of local magnetic degradation by interlocking electrical steel sheets for an effective modelling of electrical machines, J. Magn. Magn. Mater. 500 (2020) 166372, http://dx.doi.org/10.1016/j.jmmm.2019.166372.

[10] D. Ukwungwu, T. Krichel, B. Schauerte, N. Leuning, S. Olschok, U. Reisgen, K. Hameyer, Electromagnetic assessment of welding processes for packaging of electrical sheets, in: 2020 10th International Electric Drives Production Conference, EDPC, 2020, pp. 1–6, http://dx.doi.org/10.1109/EDPC51184.2020.9388200.

[11] D. Miyagi, N. Maeda, Y. Ozeki, K. Miki, N. Takahashi, Estimation of iron loss in motor core with shrink fitting using FEM analysis, IEEE Trans. Magn. 45 (3) (2009) 1704–1707, http://dx.doi.org/10.1109/TMAG.2009.2012790.

[12] L. Bernard, L. Daniel, Effect of stress on magnetic hysteresis losses in a switched reluctance motor: Application to stator and rotor shrink fitting, IEEE Trans. Magn. 51 (9) (2015) 1–13, http://dx.doi.org/10.1109/TMAG.2015.2435701.

[13] L. Kestens, S. Jacobs, C. Esling, Texture control during the manufacturing of nonoriented electrical steels, Texture, Stress, Microstruct. 2008 (2008) 173083, http://dx.doi.org/10.1155/2008/173083.

[14] N. Leuning, S. Steentjes, H.A. Weiss, W. Volk, K. Hameyer, Magnetic material deterioration of non-oriented electrical steels as a result of plastic deformation considering residual stress distribution, IEEE Trans. Magn. 54 (11) (2018) 1–5, http://dx.doi.org/10.1109/TMAG.2018.2848365.