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Impact of the interaction of material production and mechanical processing on the magnetic properties of non-oriented electrical steel

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Thin laminations of non-grain oriented (NO) electrical steels form the magnetic core of rotating electrical machines. The magnetic properties of these laminations are therefore key elements for the efficiency of electric drives and need to be fully utilized. Ideally, high magnetization and low losses are realized over the entire polarization and frequency spectrum at reasonable production and processing costs. However, such an ideal material does not exist and thus, achievable magnetic properties need to be deduced from the respective application requirements. Parameters of the electrical steel such as lamination thickness, microstructure and texture affect the magnetic properties as well as their polarization and frequency dependence. These structural features represent possibilities to actively alter the magnetic properties, e.g., magnetization curve, magnetic loss or frequency dependence. This paper studies the influence of production and processing on the resulting magnetic properties of a 2.4 wt% Si electrical steel. Aim is to close the gap between production influence on the material properties and its resulting effect on the magnetization curves and losses at different frequencies with a strong focus on occurring interdependencies between production and mechanical processing. The material production is realized on an experimental processing route that comprises the steps of hot rolling, cold rolling, annealing and punching. https://doi.org/10.1063/1.4994143

I. INTRODUCTION

The efficiency and performance of rotating electrical machines are largely determined by the magnetic characteristics of the fully-finished, non-oriented electrical steel sheets used for the magnetic core of the machines. In case of electrical steels with silicon contents above 2 wt% Si the magnetic properties in the final geometry are a result of all preceding production and processing steps, because no austenitic phase transition occurs with this alloying condition. Properties are inherited over the different processing steps[1,2] and thus, a detailed consideration of the consecutive impact on the material has to be established with further consideration of interdependencies, in particular between the annealed sheet material and the mechanical processing.[3] In order to understand the processes, improve the material modeling and finally deduce production strategies

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to improve the magnetic properties of the final laminations, a comprehensive study needs to be performed.

In this paper results of a large-scale laboratory experimental study on the production and processing of nine different material states due to different production routes and further interaction with mechanical cutting are presented. Based on one 2.4 wt% Si alloy, homogeneous hot bands of different thickness are produced. Varying cold-rolling reductions lead to final thicknesses of 0.5 mm and 0.25 mm steel strip, which is annealed at 800 °C to 1200 °C. In immediate proximity to industrial standards cutting experiments are performed on an industrial mechanical single action press with a cutting clearance of 7 %, a fixed cutting speed and a sharp tool.[3] A detailed microstructure and texture analysis of the material states, according to previously established techniques in different layers over the steel cross section, is applied. Thereby, the homogeneity and anisotropy in the microstructure, which can vary significantly for different final states can be accounted for. Subject of this paper is the micro-macro-mapping of magnetic properties and microstructure, texture and mechanical stress due to the production process. In the end, a final evaluation of strong interdependencies and distinguishable tendencies is presented.

II. EXPERIMENTAL

For the presented research, an alloy of 2.4 wt% Si content is used. Framework of the variation of processing routes are two hot strip thicknesses, proceeded by three cold-rolling reductions (CR) to 0.5 mm and 0.25 mm steel strip. Annealing of the cold strips for this study is performed at overall four different annealing temperatures.

Hot strips used in the research were produced on a four-stand semi-continuous hot-rolling mill. Within 9 passes the 64-mm continuously cast thin slab feedstock was hot rolled to 1.0 mm. The hot rolling start temperature was 1180 °C after reheating the thin slab and soaking for 60 minutes at 1220 °C. An exit temperature of 890 °C was achieved and coiling temperature was 800 °C. The thin slab microstructure is characterized by a typical columnar grain structure and grain sizes over 1000 µm. After hot rolling the 1 mm thick hot strip shows a homogeneous microstructure with a grain size of 65 µm. Cold rolling plays an important role on the whole process, because it determines the final thickness and provides the driving force for final annealing. Furthermore, the texture can be improved during cold rolling and might be remained after final annealing. There are two main influencing factors for cold rolling: hot-band textures and cold rolling strategies. That is why two hot-band textures and two height reductions have been chosen. Annealing temperatures were selected in order to provide a wide deviation in microstructure. At the lowest temperature, recrystallization barely takes place while at the highest temperature strong grain growth occurs. Samples were annealed for three minutes at temperatures of 800 °C, 900 °C, 1000 °C and 1200 °C. An overview of the final material processing routes is given in Table I.

An investigation of the blanking related magnetic material property deterioration is made possible using an industrial tool setup. With the tool, different blanking parameters, i.e., cutting clearance, cutting edge wear state, etc. could be investigated.[3] The cutting clearance between punch and die

TABLE I. Overview on processing routes for materials produced on the experimental processing line, which included hot rolling, cold rolling, annealing of samples and cutting.

	Processing routes								
Hot strip thickness	1.0 mm						2.4 mm		
Cold strip thickness	0.5 mm (50 % CR)		0.25 mm (75 % CR)				0.5 mm (80 % CR)		
Annealing	1000 °C	1200 °C	800 °C	900 °C	1000 °C	1200 °C	800 °C	1000 °C	1200 °C
Cutting direction and clearance	RD/TD 35 µm	RD/TD 35 µm	RD/TD 15 µm	RD/TD 15 µm	RD/TD 15 µm	RD/TD 15 µm	RD/TD 35 µm	RD/TD 35 µm	RD/TD 35 µm

has been set to 15 μm and 35 μm for both blank thicknesses using sharp cutting edges. The tool was operated on a mechanical single action press, which is also used for industrial processing of rotor and stator cores.

For the material characterization the samples were mechanically polished using 6, 3 and 1 μm diamond suspension. For light microscopy, grain boundary etching with a 5 % Nital solution was employed. Light microscopy images were taken using a Leica DMRM in the ND-RD-Plane. To determine metallographic macro texture, incomplete pole figures were measured by X-ray diffraction by a Bruker D8 Advanced diffractometer, equipped with a High Star area detector. The macro texture was calculated by an automated goniometer tool and the orientation distribution functions (ODF) are presented in this paper. Magnetic measurements are performed on a 60 mm x 60 mm Single-Sheet-Tester with Brockhaus measurement equipment. From previous studies it can be concluded that this sample size is sufficient to provide representative results. *J-H*-hysteresis curves at polarizations between 0.1 T and 1.8 T at different frequencies are analyzed under sinusoidal magnetic flux excitation.

III. RESULTS

A. Microstructure and texture

Evaluation of the microstructure and texture evolution as a result of the different processing routes demonstrates typical varieties of obtainable microstructures and textures of conventional NO. From the grain size distribution and texture, basic magnetic properties can be estimated.

A quantitative way to describe texture for electrical steel is the so called *A*-parameter as introduced by Kestens and Jacobs.[4] This parameter describes the mean angle *A* of all individual crystallographic orientations of a sample between easy magnetization axes, i.e., cube edges in bcc iron and the magnetization angle (1).[4]

$$A_\theta = \int f(g) A_\theta(g) \mathrm{d}g \tag{1}$$

$$\text{with} \quad f(g)\mathrm{d}g = \frac{\mathrm{dV}}{\mathrm{V}} \tag{2}$$

From the three-dimensional orientation distribution function (ODF) of the texture, the intensity dV/V, i.e., the volume fraction of the material represented by an orientation element *dg* around an arbitrary orientation *g* can be determined by (2).[4] The index θ describes the angle relative to the rolling direction, as depicted in Fig. 1. Consequently, a small averaged value of A_θ indicates easy magnetization in the respective spatial direction because many easy axes are aligned close to this direction.

In Fig. 2 the *A*-parameter of samples from the 0.25-mm cold strip with a cold CR of 75 % are presented. Fig. 2 a) shows the texture of the cold strip, which exhibits a strong γ-fiber with additional intensities of Cube-ND45. This orientation leads to the evident small value for A_{45}, i.e., easier expected magnetization in 45°. In Fig. 2 b) the cold strip is annealed at four different temperatures. The texture evolution can be summarized as follows. At 800 °C the annealing time is too short to allow full recrystallization, so that the texture closely resembles the preceding cold-strip texture. At 900 °C and 1000 °C, recrystallization occurs and the γ-fiber decreases its intensity, as well as the Cube-ND45 orientation. Additionally, some intensity increases in the middle of the cube-fiber and at the Goss-orientation. The resulting *A*-parameter is smallest in RD and increases for 45° and TD. The textures for both annealing temperatures is very similar. An annealing at even higher temperatures of

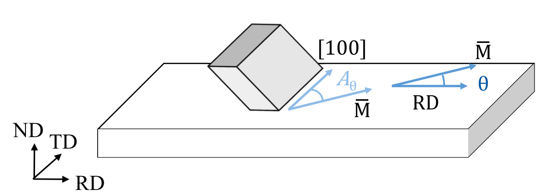

FIG. 1. Schematic illustration of *A*-parameter to describe crystal orientation and magnetization in electrical steel sheets as introduced by Reference 4.

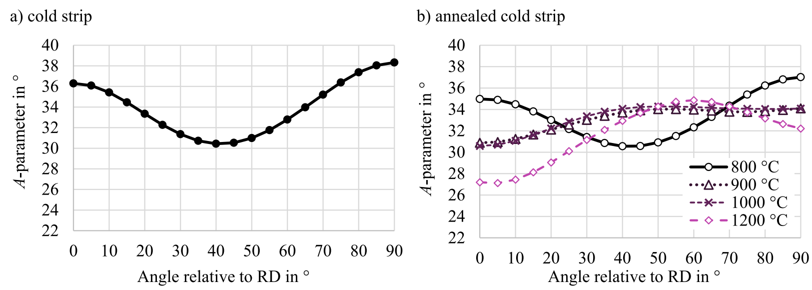

FIG. 2. Angular dependence of the *A*-parameter calculated from the ODF along the sheet plane between 0° and 90° on the surface of the RD-TD plane for a) 0.25 mm cold strip b) 0.25 mm col strip annealed at different temperatures.

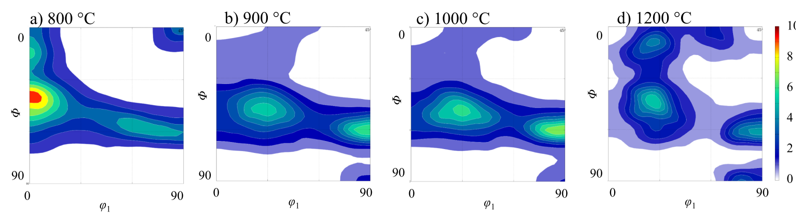

FIG. 3. ODF $\varphi_2 = 45°$ sections (sample surface) of the 0.25mm-thin cold strip annealed at different temperatures a) 800 °C, b) 900 °C, c) 1000 °C, d) 1200 °C.

1200 °C leads to additional increase of Goss-texture and thus, improved magnetization in RD. The corresponding $\varphi_2 = 45°$ sections of the Euler-room from ODF measurements are depicted in Fig. 3.

Fig. 4 depicts *A*-parameter variations for both sets of samples with a final thickness of 0.5 mm. On one route the CR is 50 % coming from the 1.0-mm thick hot strip, the other one is from the 2.4-mm thick hot strip with a CR of 80 %. Annealing was performed at 1000 °C and 1200 °C. The only change in processing is the CR. For these samples, the texture was measured in different layers

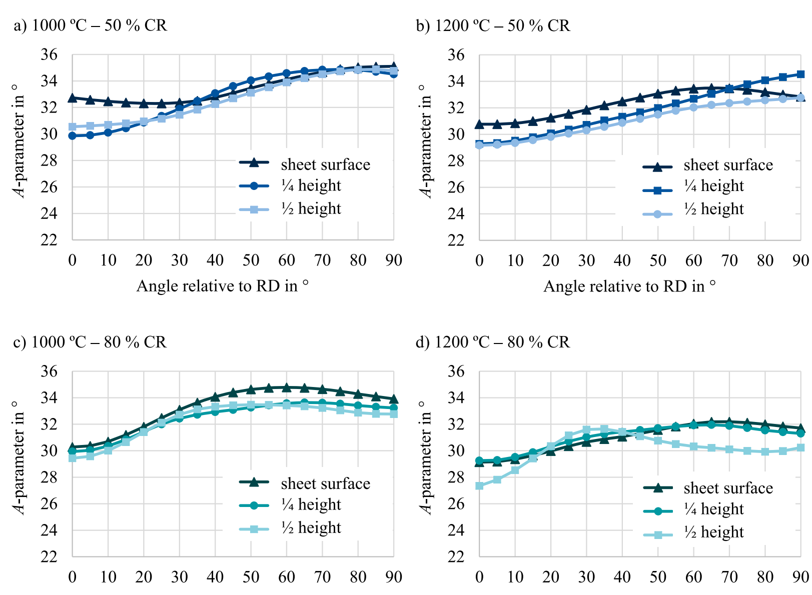

FIG. 4. Angular dependence of the *A*-parameter calculated from the ODF between 0° and 90° in different layers of the RD-TD plane, the definition surface refers to the RD-TD surface of the sample, whereas ¼ and ½ refer to 25% of the sheet thickness and the middle plane of the sample.

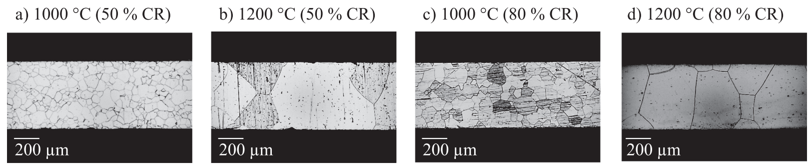

FIG. 5. Microsections of materials with 0.5 mm thickness annealed at different temperatures and with different cold-rolling reduction (CR) a) 1000 °C, 50 % CR, b) 1200 °C, 50 % CR, c) 1000 °C, 80 % CR, d) 1200 °C, 80 % CR.

of the RD-TD plane to enable the evaluation of homogeneity as described in Ref. 5. The notation of 0 %, 25 % and 50 % in the figure refers to the respective layer, where 0 % describes the surface and 50 % the sheet middle plane. Generally, the texture is rather uniformly distributed across the thickness with only minor variation especially for Fig. 4. d) in the middle plane. For all samples, smaller *A*-parameters are observed in RD compared with TD. The course for the 1000 °C annealed samples of both cold reductions is very similar. However, the *A*-parameters for the samples with higher CR are slightly smaller. At higher annealing temperature, the effect observed for the 0.25-mm thin sheet with a strong improvement in RD and TD is not pronounced.

Besides final texture, microstructure is an additional parameter with direct influence on the magnetic properties of the electrical steel. Grain size analysis shows the influence of the annealing treatment and cold reduction on grain growth and grain size distribution. As expected the grain growth is mainly influenced by annealing temperature. For all cold strips the grain size increases with an increase of annealing temperature. A higher deformation also leads to slightly larger grains as shown in Fig. 5 a) and c). Like texture grain size distribution is also relatively homogeneous. The 1000 °C annealed samples have slightly smaller grains close to the surface layers but otherwise homogeneously distributed grain sizes. For the higher annealed samples at 1200 °C the following problem occurs. Because of extreme grain growth grains are in the range of sheet thickness. As a result, there are grains that cover the entire cross section of the sheet. This is a limiting factor for further grain growth, which is uniformly in all spatial directions. This extreme ratio of grain size to sheet thickness is expected to have further strong effects on the cutting experiments, because the material cannot be described by a homogeneous, statistical distribution of crystals, but depend on the orientation and properties of certain dominant grains.

For the samples with 0.25 mm final thickness and a resulting CR of 75 % the results are similar, as depicted in Fig. 6. However, because of the small sheet thickness the grain size to sheet thickness ratio for the 1200 °C annealed samples is even higher. In section B and C of the results part, the grain sizes will be correlated with the magnetic properties and the magnetic deterioration due to mechanical cutting. Table II summarizes the measured grain sizes, analyzed with the line intercept method on various images. These values are used for the further correlations.

B. Magnetic properties

Magnetic characterization of the materials produced by different processing routes demonstrate distinct trends. Basic relations between magnetic properties and production parameters can be deduced. However, these correlations are not sufficient, because the resulting magnetic properties depend on the changes within the material, which therefore need to be accounted for. This necessity can be motivated from Fig. 7. In general, higher annealing temperatures lead to improved

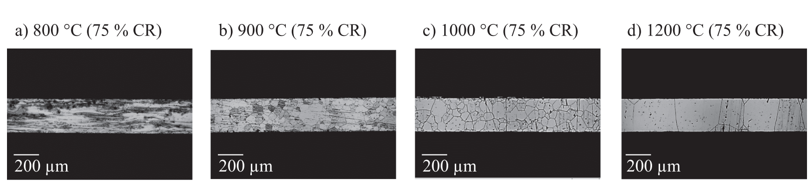

FIG. 6. Microsections of materials with 0.25 mm thickness annealed at different temperatures a) 800 °C, 75 % CR, b) 900 °C, 75 % CR, c) 1000 °C, 75 % CR, d) 1200 °C, 75 % CR.

TABLE II. Overview on processing routes for materials produced on the experimental processing line, which included hot rolling, cold rolling and annealing of samples.

Annealing	1000 °C 50 % CR	1200 °C 50 % CR	900 °C 75 % CR	1000 °C 75 % CR	1200 °C 75 % CR	800 °C 80 % CR	1000 °C 80 % CR	1200 °C 80 % CR
Medium grain size in µm	45	309	27	50	189	15	56	224

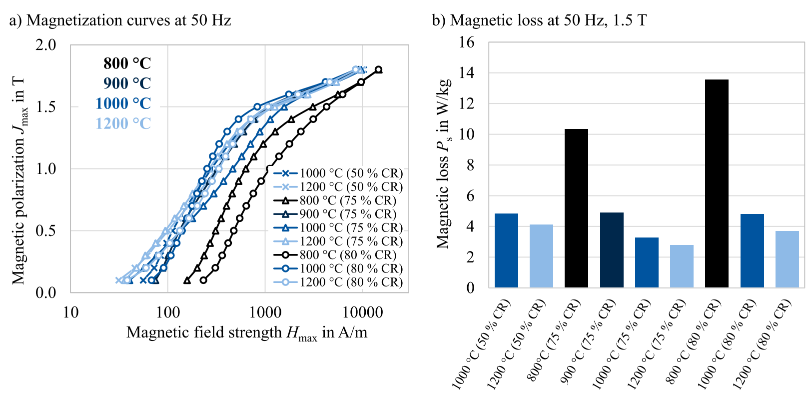

FIG. 7. Magnetic properties of materials produced on different processing routes at 50 Hz, with different cold rolling reductions (CR) and different annealing temperatures, a) magnetization curves, b) magnetic loss at 1.5 T.

magnetization, Fig. 7 a). The 800 °C annealed samples require a magnetic field up to 1000 A/m to induce a magnetic polarization of 1.0 T at 50 Hz, whereas samples annealed at higher temperature require much less magnetic field strength for the same flux density. For the magnetic loss a similar behavior is observed, Fig. 7 b). Though, the trends are similar differences occur for samples annealed at the same temperature but with different production parameters during hot and cold rolling. On the one hand these relations confirm that properties are inherited over the process chain for NO electrical steel, as presented in Ref. 1. On the other hand it highlights that a closer investigation to identify the effect of the processing steps on the material and the correlation between the material and the magnetic properties has to be performed. For example, the smaller loss for the 75 % CR processing routes can partly result from the smaller sheet thickness and less eddy-current loss. The difference of magnetization of the 1000 °C annealed samples with 50 % CR and 80 % CR stems from the CR and hot strip directly, because final thickness and annealing treatment are the same for all samples. In order to evaluate the resulting magnetic properties from different processing routes, certain characteristic magnetic values are correlated with the microstructural features of *section A Microstructure and Texture*.

Fig. 8 depicts direct correlations between magnetic properties and material parameters. The coercivity exhibits a linear trend with the inverse grain size (Fig. 8 a)) and with the yield strength

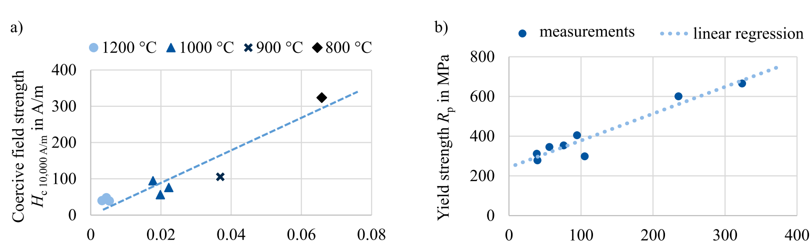

FIG. 8. Correlations between magnetic properties and material parameters, a) grain size and coercive field strength at 10,000 A/m and quasistatic excitation, b) yield strength and coercive field strength at 10,000 A/m and quasistatic excitation.

TABLE III. Magnetic loss and A-parameter in rolling direction (RD) and transverse direction (TD) for 0.5 mm samples with different annealing temperatures and CR.

Processing	1000 °C, 50 % CR		1200 °C, 50 % CR		1000 °C, 80 % CR		1200 °C, 80 % CR	
	RD	TD	RD	TD	RD	TD	RD	TD
P_s at 1.5 T, 50 Hz	4.82	4.84	4.11	4.29	4.79	5.19	3.69	4.19
A-parameter	30.77	34.72	29.55	33.63	29.84	33.08	28.77	31.06

(Fig. 8 b)). Such a linear dependence is also documented in literature, for example for coercivity and inverse grain size.[6] Magnetic loss and coercivity also have a linear dependence according to Ref. 7. Both properties, yield strength as well as coercivity are affected by grain boundaries. A smaller mean grain size means more grain boundaries within the material. This direct correlation also shows the unwanted codependence of mechanical and magnetic properties. A higher coercivity leads to a wider J-H-hysteresis loop and thus, to an increase of hysteresis loss. But with low H_c, i.e., very soft magnetic behavior, the material is also mechanically soft. For electrical machines, this leads to the fact that certain geometries can hardly be realized, for example, high speed rotors with small bridges. However, the optimum grain size for magnetic properties is dependent on the magnetic field and frequency as well, which has to be considered in material selection for specific applications.[8]

Considering the magnetic anisotropy of the produced and processed materials, it is noticeable that the materials are more isotropic when compared with industrial NO grades. At 50 Hz and 1.5 T they usually exhibit greater anisotropy. Still the anisotropy is reflected in the observed texture. In Table III, the A-parameter as well as the loss is smaller in RD compared with TD for all 0.5-mm materials. For some of the 0.25-mm grades the anisotropy, was reversed. This hints at another contributing factor to the anisotropy besides the texture, which is the mechanical stress state. This could also be the reason for the higher loss and smaller anisotropy on the experimental route compared with industrial grades. The rolling conditions on the industrial route are different because the force in rolling direction due to strip tension is not the same as on industrial routes. Thus, the residual stress state is likely to be different.

C. Interdependencies of the material with mechanical processing

For the evaluation of the effect of mechanical cutting on the magnetic properties, samples with an increased proportion of cutting surface per fixed sample volume were manufactured. The original sample geometry of 60 mm x 60 mm was divided into equal sized strips of 5-mm width. The cutting lines are oriented parallel to the magnetic field, so that the effect of air gaps is not interfering the measurements. This technique is established for the quantification of cutting degradation by numerous research.[9,10]

Generally blanking deteriorates the magnetic properties. For the majority of produced samples this relation is observed. With an increased cutting line the J-H-hysteresis loops shear. The required magnetic field to reach a destined polarization increases, as well as coercivity. On the other hand remanence decreases. This effect not only depends on the cutting parameters, but also correlates with the material properties. Fig. 9 a) shows, that although the uncut samples show different magnetization, coercivity and remanence and permeability, the properties after cutting show a similar behavior as the uncut samples. A strong deterioration occurs for both samples, but the relative deterioration for the 1200 °C samples is slightly smaller. The magnetization and coercivity is almost identical. Only the remanence is still distinctly smaller for the 1200 °C annealed samples.

An anomaly occurs for certain samples. As depicted in Fig. 9 b) some samples exhibit an improvement of magnetic properties due to cutting. Two possible effects might be responsible. The first one would be the initial mechanical stress state of the produced material. If the induced mechanical stress due to cutting releases residual stress from the processing, the global resulting mechanical stress state can be smaller compared to the initial state. As a result the magnetic properties improve with cutting. Another possible reason can be effects due to the ratio of grains distributed along the sheet thickness. For the high temperature annealed samples with small thickness, the grain size is in the range

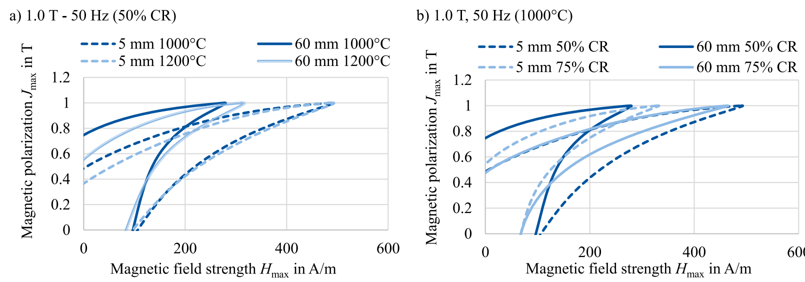

FIG. 9. Effect of cutting on the *J-H*-hysteresis loop at 1.0 T and 50 Hz for material of different processing routes, a) 0.5 mm sheet with 50 % CR, b) 0.5 mm and 0.25 mm sheet annealed at 1000 °C.

of the sheet thickness. In order to examine this effect, a more detailed study with different cutting parameters can be performed. Different cutting parameters change the magnitude and penetration depths of the induced mechanical stress and, therefore, can give further hints at the interrelation of mechanical stress and material parameters.[3]

In Fig. 10 typical loss and magnetization curves for the produced materials are displayed. The magnetization deteriorates and the loss increases slightly. For industrial NO the deterioration is often more pronounced, as presented in Refs. 3 and 10, which again is likely to depend on the initial stress state and condition during hot rolling, cold rolling and annealing. This conception is affirmed by the fact that the microstructure and texture analysis shows great parallels to industrially produced NO. Furthermore, the cutting process is done on a single-action-press close to industrial standards. The difference between rolling and annealing of NO on the experimental route and industrial route are forces due to strip tension and coiling. It is difficult to measure the residual stress of steel sheets because the stress is relatively small. This is subject of a more in-depth study on the effect of residual stress on the magnetic properties of industrially manufactured steel sheets, which is essential to be further investigated in order to fully determine the effect of cutting on the electromagnetic properties.

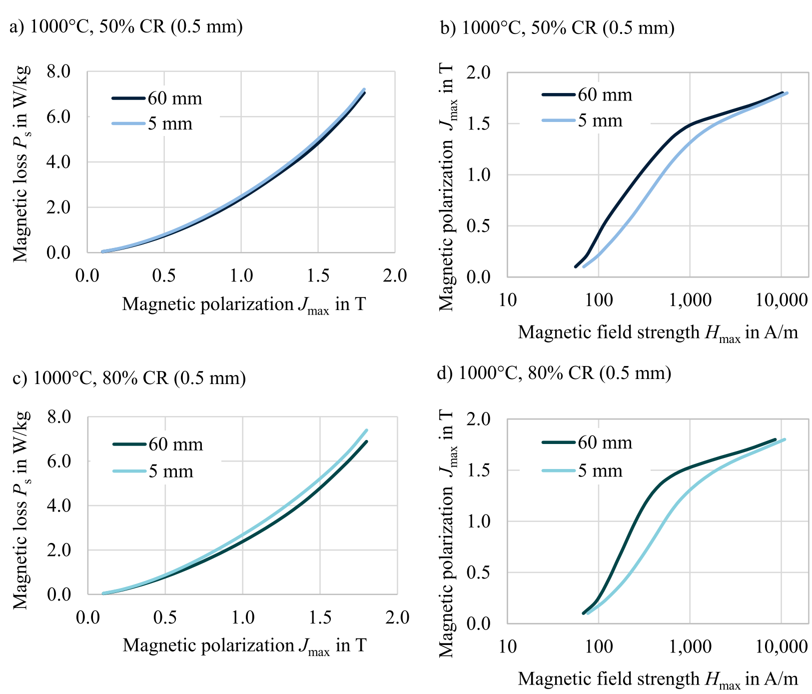

FIG. 10. Effect of cutting on the magnetization curves and magnetic loss at 50 Hz for material of different processing routes, a), b) 0.5 mm sheet with 50 % CR, 1000 °C, c), d) 0.5 mm sheet with 80 % CR, 1000 °C.

IV. CONCLUSIONS

General relations between the influence of the production and processing of electrical steel on the material properties and interdependence with the magnetic behavior can be deduced from the presented study. Nine different processing routes with different hot strip thickness, cold reduction and annealing procedures are studied. Furthermore, the interdependence with the punching process is analyzed.

The hot-strip thickness and cold-rolling reduction has a noticeable influence on the magnetization and loss, even if the proceeding production steps are analogous. A high cold-rolling reduction and annealing at 1000 °C lead to the best magnetization in the medium and high polarization range. The smallest loss at 50 Hz for 1.5 T was achieved for the 0.25-mm 75 % CR and 1200 °C annealing, due to the smaller contribution of eddy currents. For the 0.5-mm thick sheets, the lowest loss at this point are also for the highest annealed samples with 1200 °C and with a high cold reduction (80 %). The results show that no matter which texture or height reduction is used, it always leads to the typical cold-band texture (α- and γ-fiber). Therefore, diverse hot-band textures (e.g. rotated cube texture) and unconventional rolling strategies (e.g. asymmetric rolling) need to be examined, in order to improve the texture during cold rolling. General correlations between grain size, texture and magnetic properties are presented. Tensile strength and coercivity both depend on the grain size and show linear trends. The magnetic anisotropy is observed to correlate with the crystallographic texture, however, it is likely that mechanical stress is also a contributing factor.

Blanking generally has a deteriorating effect on the magnetic properties, which results in a shearing of the J-H-hysteresis loops with a concurrent increase of loss. However, for the 0.25-mm sheets the effect is more complex. For some processing routes the loss decreases with cutting and the tendencies are ambiguous. This is likely related to the ratio of grain size to sheet thickness and the resulting mechanical stress in the sheets. These interrelations need to be studied further.

The observed effects are also polarization- and frequency-dependent. Correlations for coercivity, hysteresis loss and grain size are evident at quasistatic measurements and approaching saturation. At high frequencies, dynamic loss is dominant for overall loss. Further work will focuses on the frequency dependence of the effects and will include further cutting parameters, which will change the magnitude of induced mechanical stress due to cutting.

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