Effect of the Interdependence of Cold Rolling Strategies and Subsequent Punching on Magnetic Properties of NO Steel Sheets

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Nowadays, optimization of non-oriented (NO) electrical steels toward lower iron-loss, improved, and isotropic magnetizability is critical to the improvement of rotating electrical machines. The whole production process chain adjusts the microstructure evolution, e.g., grain size and crystallographic texture, determining the magnetic properties. In particular, the interdependence of raw material properties and the resulting mechanical stress distribution during final assembly, e.g., punching, leading to magnetic property deterioration is crucial for the optimization of NO steel properties of rotating machines. This paper studies the effect of different cold rolling strategies, annealing treatments, and sheet metal blanking (punching) regarding microstructure evolution, magnetic properties, and deterioration.

Index Terms— **Cold reduction, grain size, magnetic properties, microstructure, non-oriented (NO) electrical steel, punching, texture.**

I. INTRODUCTION

NON-ORIENTED electrical steels are major components of rotating electrical machines. The high silicon content of such steels ensures a ferrite microstructure over the entire manufacturing process. Consequently, each step of the process chain has an impact on the microstructure evolution, e.g., grain size and magnetic texture, which determines the electromagnetic properties [1], [2]. Thus, it is of interest to optimize the complete manufacturing process toward lower iron losses or other physical properties.

In this paper, the effect of different cold rolling (CR) strategies, annealing treatments as well as sheet metal blanking is studied regarding the microstructure evolution and resulting electromagnetic properties. Hot band samples are cold-rolled and differently annealed in order to produce distinct sample sets of electrical steel sheets of the same thickness and with the same chemical composition. Beside the influence of processing on the microstructure and crystallographic texture, the electromagnetic properties are highly susceptible to residual stresses. Especially residual stresses occurring through the shear cutting process have a negative influence on the magnetic properties of processed electrical steel sheets [3].

In order to study the interdependence of CR and annealing with the corresponding texture and microstructure evolution as well as the deterioration of the magnetic properties as a result of shear cutting, the distinct samples are analyzed throughout the experimental process chain. Comparative measurements of the altered samples are conducted. The magnetic properties are determined as a function of variations of process parameters, e.g., CR reduction or annealing temperature. With the results from the microstructural characterizations, this allows us to draw inferences from the resulting microstructure and texture about the effect on the electromagnetic properties.

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TABLE I
CHEMICAL COMPOSITION (wt.%)

Si	Al	Mn	P	S	C
2.40	0.39	0.30	0.021	0.003	0.002

II. THERMOMECHANICAL PROCESSING

The thermomechanical processing consisting of slab reheating, hot and cold rolling, and recrystallization annealing adjusts the microstructure and texture of electrical steel.

A. Hot Rolling

The microstructure and crystallographic textures are initially influenced by the hot rolling (HR) conditions, such as slab reheating temperature [4], finishing temperature of HR [5], and hot band grain size and thickness [6].

In order to study the influence of different CR reductions, different hot band thicknesses are necessary to achieve a uniform final thickness. The microstructure and the texture of the hot-rolled material are almost identical. Due to the different hot band thicknesses, the CR reduction differs between 50% and 75% and ensures a different CR and final annealing microstructures and textures. The objective of this paper is a Fe-2.4 wt.% Si steel with chemical composition given in Table I. The studied material was reheated to 1150 °C and subsequently hot-rolled to a final thickness of 2 mm (seven roll passes, total reduction 94%) and 1 mm (eight roll passes, total reduction 96%) using a four stand laboratory rolling mill. A finishing temperature of 770 °C and 720 °C was achieved. After HR, the strips were slowly cooled to 200 °C.

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TABLE II
PROCESS PARAMETERS

Number of process chain	Hot Rolling	Cold Rolling		Annealing	
	Thickness of hot-rolled sheet [mm]	Thickness reduction [%]	Thickness of cold-rolled sheet [mm]	Temperature [°C]	Time [s]
#1	2	75	0.5	900	60
#2	2	75		1000	
#3	1	50		1000	

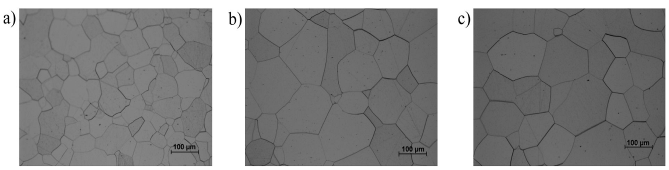

Fig. 1. Microstructure after CR and annealing. (a) 75% CR/annealing at 900 °C. (b) 75% CR/1000 °C. (c) 50% CR/1000 °C.

B. Cold Rolling and Annealing

The two hot-rolled states were used to produce three sheet grades denoted by #1, #2, and #3 with different CR and annealing strategies (Table II). Therefore, specimens with the dimension of 60 mm × 200 mm were cut from the hot-rolled sheets. After descaling the surface by sandblasting, they were cold-rolled on a Sack quarto rolling mill to the final thickness of 0.5 mm using two pass schedules. Pass schedule one conducted for hot sheet with 2 mm thickness (#1 and #2) had 12 passes in total (75% thickness reduction), while pass schedule two for hot sheet with 1 mm thickness (#3) had 6 passes. The diameter of the work rolls during CR was 134 mm, and the maximum rolling force was 450 kN. Afterward, the specimens were annealed using two different methods in an electric resistance furnace: an annealing temperature of 900 °C and a holding time of 60 s for process chain #1, and 1000 °C and 60 s for process chains #2 and #3. During the annealing step, the specimens were wrapped with annealing foils, and the furnace was purged with argon in order to avoid oxidation. After annealing, the samples were cooled in air.

The annealed samples were mechanically grinded, to remove the oxide layer, and polished and etched in 5% Nital to reveal the grain boundaries. From the metallographic pictures, the grain size was evaluated using the line interception method. After the annealing treatment, all samples show a fully recrystallized microstructure (Fig. 1). It can be observed that the grain size after annealing is mainly determined by the annealing temperature. After 75% thickness reduction and annealing at 900 °C (#1), the average grain size is 54 μm ± 2 μm. Samples #2 and #3 were annealed at a higher temperature of 1000 °C. As a result, faster grain growth occurs and the average grain size increases to 107 μm ± 16 μm (75% thickness reduction) and 101 μm ± 9 μm (50% thickness reduction), respectively. Furthermore, the results show that different CR strategies only have a minor influence on the grain size, since the differences of the average grain size of the samples #2 and #3 can be due to statistical uncertainties.

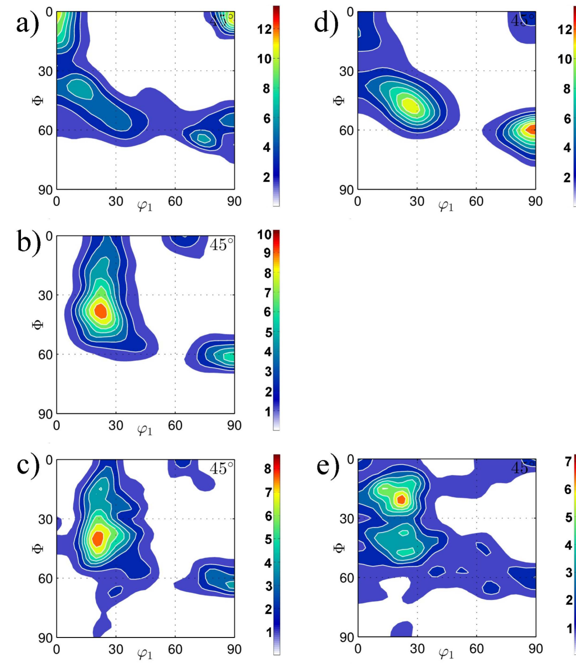

Fig. 2. Texture measurements of the $\varphi_2 = 45°$ ODF sections. (a) 75% CR/prior to annealing. (b) 75% CR/annealing at 900 °C. (c) 75% CR/1000 °C. (d) 50% CR/prior to annealing. (e) 50% CR/annealing at 1000 °C.

TABLE III
MECHANICAL PROPERTIES

Number of process chain	Yield stress [MPa]	Tensile strength [MPa]	Uniform elongation [%]
#1	382	486	22
#2	323	438	17
#3	335	451	18

The effect of annealing temperature on the texture of the samples was investigated using an X-ray goniometer. Fig. 2 shows the $\varphi_2 = 45°$ orientation distribution function (ODF) sections of the texture measurement before and after annealing. Before the different annealing treatments, the samples, which are 75% cold-rolled, show a α-fiber with CubeND45 as its strongest orientation. The samples with 50% deformation during CR also show the CubeND45 as its strongest orientation but in comparison to the 75% cold-rolled; the 50% cold-rolled sample has a strong ε-fiber with high γ-fiber parts. During annealing, the α-fiber disappears in every sample and the CubeND45 orientation becomes weaker. As a result, the CubeND22 orientation gets a higher volume fraction. In sample #3, the CubeRD22 gets nearly as strong as the CubeND22. Fig. 2(b) and (c) shows that higher annealing temperatures lead to more randomly distributed textures.

For each steel grade (#1, #2, and #3), three tensile test samples along the rolling direction were conducted according to DIN 50125:2009-07. The mechanical properties are shown in Table III and the stress–strain curves in Fig. 3. Overall, the tests show a good repeatability. For steel grade #1, the lower annealing temperature of 900 °C results in a higher yield stress as well as a higher tensile strength. This is caused by the smaller final grain size (Hall–Petch effect). In addition, the uniform elongation of the samples annealed at 900 °C is

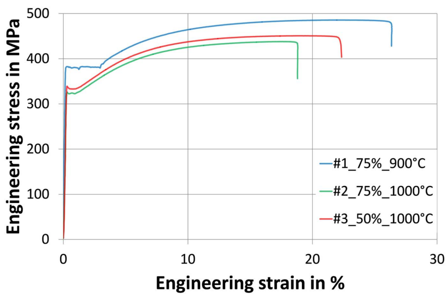

Fig. 3. Engineering stress and strain curves of tensile tests in the SERVOTEST testing machine with the same testing speed of 6 mm/min.

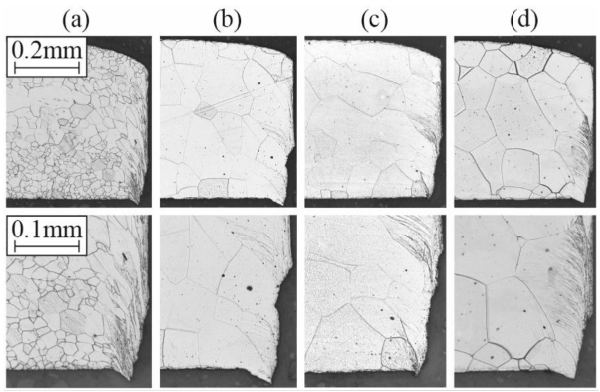

Fig. 4. (a) Sample #1—75% CR, 900 °C. (b) and (c) sample #2—75% CR, 1000 °C. (d) Sample #3—50% CR, 1000 °C.

higher than for the samples annealed at 1000 °C. This effect might be caused by the very coarse grain size after annealing at 1000 °C, which results in a brittle fracture behavior. The mechanical properties of sheet grades annealed at 1000 °C are very similar.

III. Processing—Shear Cutting

Due to the large influence of the cutting process on the electromagnetic properties during the manufacturing of electrical steel components [8], [9], the shear cutting is incorporated in this paper. The investigations were carried out on a mechanical single action press, which is also used for the industrial processing of electrical steel sheets, thereby ensuring a practice-oriented evaluation of the cutting influence on the magnetic properties.

The resulting cutting surface usually is characterized by the parameters (rollover, clean-cut, fracture, and burr height) according to VDI 2906 2. When it comes to evaluating the punching process regarding electrical steel, only the burr height, and sometimes also the rollover height, is measured to avoid magnetic short circuit in between the stacked metal sheets. A correlation of electromagnetic properties and cutting surface characteristics is lacking.

Fig. 4 shows the shear cutting surface of the three processed materials. The resulting cutting surfaces still show the characteristic parameters. Nevertheless, due to the big grain size, the distribution of the cutting surface parameters varies along the cutting line. This effect can be observed on the cutting surfaces of a test material #2 [Fig. 4(b) and (c)]. The smaller the grain size of the processed material, the smaller is the variation of the cutting surface parameters

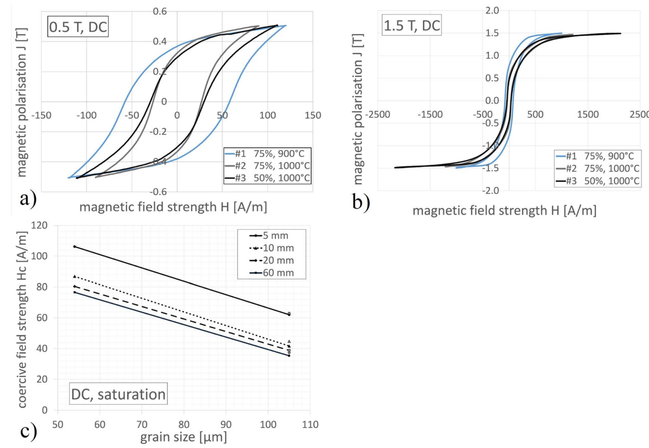

Fig. 5. Hysteresis curves for the samples at two different polarizations. (a) 0.5 T. (b) 1.5 T. (c) Coercive field as a function of grain size.

along the cutting line. Looking at the fracture area, it can be observed that the fracture behavior is intercrystalline as well as transcrystalline (Fig. 4). The crack sometimes runs through the grain and sometimes along the grain boundary. Due to the inhomogeneous cutting surface, a direct correlation between the electromagnetic properties and the shear cutting parameters is not possible.

IV. Electromagnetic Characterization

For the electromagnetic characterization of the material, a single sheet tester was used. The samples were measured up to magnetic saturation from quasi-static excitation up to 1 kHz. To study the influence of cutting stresses on the magnetic properties, the samples of initial size (80 mm × 120 mm) were cut into strips of different widths. These strips were then joined and measured together (if necessary), i.e., 1 strip of 60 mm, 3 strips of 20 mm, 6 strips of 10 mm, and 12 strips of 5 mm each. As a result, the samples show different proportions of cutting surface per initial sample volume, and thus, different states of residual stresses originating from the shear cutting can be realized [8]. The results were compared with regard to the attributes of grain size, texture, and cutting stresses of the distinct samples. Fig. 5(c) shows the linear correlation between grain size and coercive field strength. The sample with a smaller grain size of 54 μm was #1, which was annealed at 900 °C. Samples #2 and #3 show an almost identical grain size of 105 μm. It is apparent that larger grains lead to lower values for H_c. This relation is already described in former research with a proportionality of H_c with $1/d$ [7].

Smaller sample strips result in a higher amount of cutting surface per 60 mm × 120 mm sample, and thus, in greater residual stresses. This leads to parallel shifting of the line to higher coercive forces [Fig. 5(c)]. A proportionality of mechanical stresses and magnetostriction as described in [7] also alters the value of the coercive force explaining the observed behavior. The differences of the values for #2 and #3 can be attributed to small differences in texture (Fig. 2), because the grain size can be assumed to be alike. The hysteresis curves, as shown in Fig. 5, for the polarizations of 0.5 T and 1.5 T illustrate the magnetic properties and their behavior at increasing polarizations. For sample #1 with

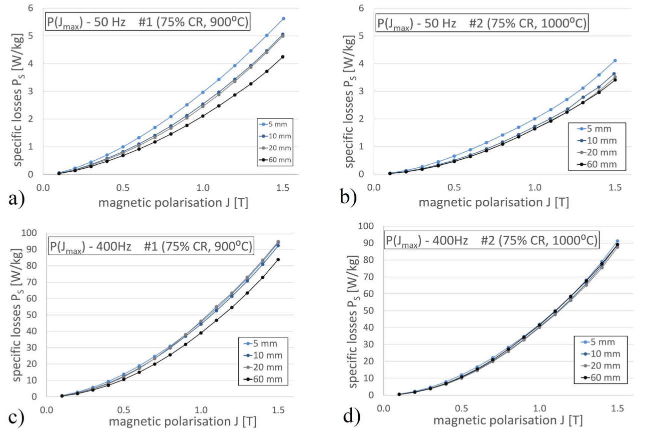

Fig. 6. (a) 75% CR, annealed at 900 °C, 50 Hz. (b) 75% CR, annealed at 1000 °C, 50 Hz. (c) 75% CR, annealed at 900 °C, 400 Hz. (d) 75% CR, annealed at 1000 °C, 400 Hz.

a smaller grain size, the values for coercive field strength and remanence are the highest when compared with the other two samples throughout these polarization levels. The area of the hysteresis loop is significantly larger than the areas for the other two samples, resulting in higher losses. However, the magnetization improves with increased polarization. This means that although for 0.5 T, the #1 sample requires higher field strengths to achieve the demanded polarization in comparison to #2 and #3, for 1.5 T, it requires the smallest field strength of the three samples. Overall, samples #2 and #3 show very similar characteristic magnetic values and hysteresis shapes. Sample #3 with the lower CR grade shows a slightly inferior magnetization, whereas #2, the 75% cold-rolled and 1000 °C annealed sample, requires lower field strengths to achieve the required polarizations. This could be attributed to a sharper texture observed for the 75% cold-rolled and 1000 °C annealed sample in comparison to the 50% cold-rolled sample with exactly the same annealing treatment, as shown in Fig. 2(c). A sharper texture and bigger grain sizes are beneficial for the magnetic properties of the investigated material under unidirectional excitations.

Further investigations of the influence of stresses resulting from the cutting edges show that with an increasing amount of residual stresses, the losses increase significantly (Fig. 6). Samples #2 and #3 show a similar behavior. Therefore, only losses for #2 are displayed. It can be observed that for the sample #1 (75%, 900 °C) and 50 Hz the deterioration is the largest indicating that smaller grain sizes result in larger losses (compared with #2 and #3). Although smaller grains are preferable regarding the cutting process itself (Section III), they are detrimental to specific losses. Fig. 6(c) and (d) further shows the influence of different frequencies on the specific losses. With increasing frequencies, the effects of the shear cutting become smaller, especially for the 75% and 50% cold-rolled samples that were annealed at 1000 °C. Only the sample that was annealed at 900 °C still shows a distinct deterioration of losses with increased amount of cutting edge.

V. Conclusion

The effect of CR and subsequent punching on the magnetic properties of Fe-2.4 wt.% Si steel was studied to correlate microstructural and textural changes from the steel sheet production and the influence of residual stresses from the shear cutting process. It was shown that annealing temperature is critical to grain growth despite different HR and CR reductions. A higher temperature leads to larger grain sizes ensuring lower specific losses and a smaller deterioration of losses when subjected to an increasing amount of residual stresses. The different HR and CR reductions influence the texture evolution during annealing. Higher deformations during CR, of 75%, resulted in a sharper texture compared with the 50% cold-rolled samples when subjected to the same annealing treatment. This sharper texture leads to a slightly superior magnetization behavior compared with the other samples with an equivalent grain size.

The overall results indicate a strong interdependence of grain size and residual stresses. Coarser grains show less deterioration with increasing residual stresses, i.e., smaller strip widths. This strong interdependence outweighs the minor effects of different textures between the three sample series.

The impact of the shear cutting process on the residual stresses and texture has to be accounted for. It is important to understand the effect of interdependence of the manufacturing steps rolling, annealing, and blanking on the magnetic properties of electric steel sheets. Small grain sizes preferable for sheet metal blanking are more prone to deteriorations of magnetic properties than larger grains.

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