INFLUENCE OF MATERIAL PROCESSING STEPS ANNEALING AND CUTTING ON MAGNETIC MATERIALS' PROPERTIES RELEVANT FOR ELECTRICAL MACHINE DESIGN

S. Steentjes[1*], K. Hameyer[1], S. Vogt[2], M. Bednarz[2], W. Volk[2], J. Dierdorf[3], G. Hirt[3]

[1]Institute of Electrical Machines (IEM), RWTH Aachen University
[2]Institute of Metal Forming and Casting (utg), Technische Universität München
[3]Institute of Metal Forming (IBF), RWTH Aachen University

ABSTRACT: Non grain oriented (NGO) electrical steel used in traction drives is mainly characterized by its magnetic properties, i.e. the specific loss, magnetic saturation polarization, and permeability. Additionally mechanical properties, e.g. manufacturability, yield strength and coatings become more and more important since they strongly influence the power density and cost of the resulting electric machine. This paper presents both the effect of punching on the material behavior of a typical used NGO electrical steel grade M230-30A as well as a study of the effect of annealing temperature after cold rolling on microstructure and magnetic properties beginning with an industrial hot rolled 2.4 wt.% silicon steel of 2.0mm thickness.

The decrease in magnetic permeability and increase of local hysteresis loss in the vicinity of lamination edges originating from the cutting process needs to be accounted for during the design of electrical machines. A quantitative analysis of the impact of material degradation for non-oriented electrical steels applied in traction drives is presented. In order to consider the large speed range of drives in automotive applications and the presence of higher harmonics (PWM supply), this analysis is conducted for a wide range of frequency and magnetic polarization.

KEYWORDS: Electrical steel, material development, soft-magnetic material, tailor-made electrical steel, annealing, material processing, punching

1 INTRODUCTION

In order to come up with the challenge of increasing demands in terms of mobility in sustainable and climate-friendly manner, the federal government is pushing the increased application of full electric and hybrid vehicles. Major requirement for the successful launch is the overcoming of the existing restriction regarding energy efficiency and operating range. Next to the inclusion of high-capacity energy storages the efficiency improvement of the electrical traction drive is of central importance.

Due to the strong limitation of the batteries capacity up to date, the optimization of electrical machine's efficiency for various operating points and operation modes ranks first. The efficiency improvement of rotating electrical machines – whether they are high power motors/generators, traction motors for electrical/hybrid vehicles, and/or smaller power motors in appliances – is and has always been a key driver in the electrical steel market, pushing the material choice towards electrical steel grades with lower intrinsic iron losses.

This is not only triggered by the objective to reduce operational costs by downsizing the energy dissipation during the electromechanical energy conversion, but also to comply with more and more stringent worldwide regulations concerning energy efficiency, for instance as stipulated by the IEC standard 60034-30 efficiency classes for asynchronous motors.

In addition, the emerging market of electrical and hybrid vehicles is boosting intensively the research in highly efficient electrical drive systems, for which in particular electrical machines are demanded with high torque densities (which means high torque production with low weight motors) in wide speed ranges, and with elevated operating frequencies, typically within the range 200-800Hz, i.e. well above the power line frequency.

* Corresponding author: Schinkelstraße 4, D-52056 Aachen, Phone: +492418097667, Fax: +492418092270,
E-Mail: simon.steentjes@iem.rwth-aachen.de

An important aspect during the design of electrical machines is attributed to the soft magnetic material [1], i.e., the mechanical and electromagnetic properties as well as its workability. For instance, the magnetic flux density in the air-gap plays an important role for the torque production in electrical machines and is significantly influenced by the magnetizability of the installed soft magnetic material. Mechanical properties, otherwise, gain more relevance when going to higher rotational speeds, i.e., for synchronous machines with buried magnets the mechanical tensile strength of the rotor laminations is of key importance [2]. In particular, the specific total loss at higher frequencies has to be minimized and the deterioration of magnetic properties has to be as low as possible due to the manufacturing process. In order to utilize the existing possibilities both during the material and electrical machine development, the complex correlations between processing steps and magnetic properties need to be investigated.

This paper studies in the first part the influence of annealing during cold rolling on macroscopic magnetic properties measured at a single-sheet-tester. Subsequently, the influence of material degradation due to punching on iron losses and magnetizability is analyzed. In addition, spark erosion cutting is studied as a more expensive alternative, commonly assumed to have less negative effects on magnetic material properties.

2 METROLOGICAL CHARACTERIZATION

Several 500mm by 500mm samples are taken from different positions in a cold rolled strip. In order to ensure that the different base materials are magnetically equivalent, a metrological characterisation of the samples using unidirectional, sinusoidal magnetic flux density waveforms was conducted.
Thereby, direction of magnetization is chosen to be perpendicular to and along the rolling direction in order to ensure that the tested samples obey homogeneous magnetic properties in both directions. Measurements to characterize the magnetic material, i.e., its magnetizability and losses, are conducted at a single sheet tester (depicted in Fig. 1).

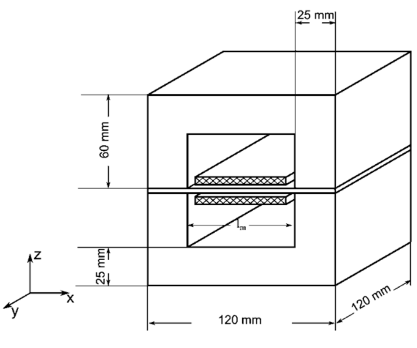

Fig. 1 *Single sheet tester for metrological characterisation of samples.*

3 INFLUENCE OF ANNEALING

In order to investigate the effect of heating time on microstructure and electro-magnetic properties the cold rolled samples were annealed at different temperatures and concomitantly surveyed at the single sheet tester at 50Hz and 1.0T as well as 1.5T magnetic polarization.

3.1 EXPERIMENTAL PROCEDURE

The steel used in this investigations is an industrial hot rolled 2.4 wt.% Silicon steel of 2.0 mm thickness, produced by compact strip casting. These hot strips were first annealed for 180 s at 850 °C – with a heating time of 120 s - aiming at a completely recrystallized microstructure.
Specimens with 130 x 200 mm dimensions were cut form the annealed hot rolled strip. After pickling in 15 % HCL solution the specimen were cold rolled on a Sack quarto rolling mill to 0.6 mm in 9 passes. In this setting the mill uses working rolls with 134 mm in diameter and has a maximum rolling force of 1.4 MN.
To investigate the effect of heating time on microstructure and electrical properties the cold rolled samples were annealed at temperatures of 900 and 1000 °C for 60 s using an electric resistance furnace. To avoid oxidation the samples were packed in annealing foil and the furnace was purged with argon.
The microstructure was characterized by light optical microscopy (LOM) after etching in 5 % natal solution.

3.2 EXPERIMENTAL RESULTS

The microstructures after the different heat treatments are illustrated in Fig. 1 and Fig. 2. Both microscopic pictures show a homogenous recrystallized microstructure nearly free of precipitations but with difference in grain size. After Annealing at 900 °C the average grain size is up to 20 to 30 µm while annealing at 1000 °C results in an average grain size of 100 to 120 µm. This indicates a fast grain growth at these temperatures.

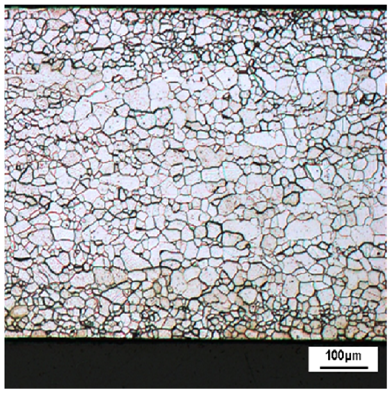

Fig. 2 *Microstructure after annealing for 60s at 900°C (avg. grain size: 20-30 µm).*

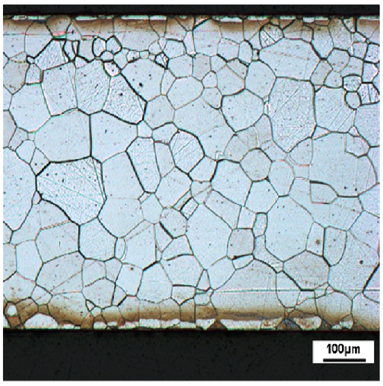

Fig. 3 *Microstructure after annealing for 60s at 1000°C (avg. grain size: 100-120 µm)*

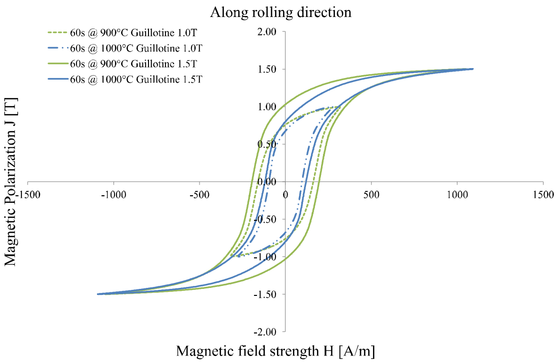

Fig. 4 *Influence of annealing temperature on the major hysteresis loop at 50Hz and 1.5T measured in rolling direction.*

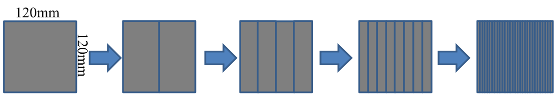

Fig. 5 *Process of the sample preparation and processing.*

The results of the single sheet tester are in good agreement with the observed microstructure. Comparing the major hysteresis loops at a frequency of 50Hz and magnetic flux density of 1.5T of the two different annealing temperatures it is apparent, that the material with the larger average grain size possesses a smaller loop width, i.e., lower coercive field, and subsequently improved magnetization behaviour (Fig. 4). This is additionally stressed by the decrease of iron loss going to higher grain sizes.

Samples 60 seconds annealed at 900°*C* have 7.05 W/kg iron losses at 50Hz and 1.5T along the rolling direction and 7.69 W/kg perpendicular to the rolling direction, respectively. In contrast to this the sample set annealed for 60 seconds at 1000°*C* has significantly lower losses, these are 4.44 W/kg and 4.53 W/kg.

It is important to note that this behaviour could change going to higher frequencies due to the fact that different loss mechanisms become increasingly important. For instance, the excess eddy current loss related to the microstructure is more relevant for larger grain sizes, since it is linked to the movement of the domain walls.

4 INFLUENCE OF CUTTING

Mechanical punching, cutting allows industrial processing of sheet material at low cost and therefore remains the most popular way to produce laminations for electrical machines and transformers. The deteriorating effect of the cutting process on the magnetic properties of the material close to the cut edge is well known. When the sheet experiences plastic deformation, mechanical energy supplied to the material is absorbed by the lattice through a shift of the neighboring layers. Microstructural defects appear, which operate as pinning sites for domain walls. This results in a local modification of the microstructure (dislocations, internal stresses, grain morphology) influencing both the magnetic and mechanical properties of the steel [3], [4].

Improved estimation of iron losses occurring in stator and rotor core of machines is essential for the design of highly efficient electrical drives [5]. Therefore, the relationship between the deterioration of the magnetic properties, alloy type, material thickness, rolling direction, and other parameters like operating range of magnetic flux density and frequency needs to be investigated and included in the design process of electrical machines.

This section presents a quantitative analysis of the influence of lamination processing for non-oriented electrical steels for traction drives used in automotive applications. The analysis is performed over a wide range of frequency f to study the influence of increasing eddy currents on the cut edge effect and to reproduce the operating range of electrical machines in the envisaged applications as well as the presence of higher harmonics due to various parasitic effects [5]. On that account, material characteristics are measured for samples with different ratios of cut edge length vs. overall lamination volume, i.e. varying the amount of cut edge length related to the material volume.

4.1 EXPERIMENTAL PROCEDURE

A number of single sheet tester samples of 120mm by 120mm are cut in smaller stripes by guillotine cutting (simulating the actual punching), resulting in different sample sets with additional guillotine cut edges (Fig. 5). The total width remains 120mm. Studied sample sets consist of thirty 4mm, twenty 6mm, sixteen 7.5mm, eight 15mm, four 30mm, two 60mm and one 120mm wide samples cut along the rolling direction. The sample sets consisting of smaller stripes are fixed by a non-magnetic adhesive tape to yield sample sets with total width of 120mm. Based on these twenty different sample sets, the effect of cutting for the described processes is analyzed using a 120mm by 120mm single-sheet-tester equipped with 50 primary and secondary windings (Fig. 1).

Measurements are performed utilizing the fielmetric method under sinusoidal magnetic flux densities up to high amplitudes at excitation frequencies of 50, 400 and 700 Hz.

The material under study is a non-grainoriented FeSi 3.2wt.% lamination with a thickness of 0.3mm, called M230-30A.

4.2 EXPERIMENTAL RESULTS

Due to the cutting, a spatial distribution of magnetic polarization *J(x)* as function of the distance x from the cutting edge is present [3], [9]. Thereby, it is important to emphasize that measured magnetic polarizations represent a mean value across the samples' cross section. A non-uniform flux distribution over the width of the sample originates from the degraded properties at the cut edge. That is why measured values need to be handled with caution: measured magnetic polarization has to be envisaged as the value averaged in space; for instance in the bulk, *J(x)* will be somewhat higher than the measured value, whereas at the edge, *J(x)* decreases [3], [9].

The influence of additional pinning points, i.e., dislocations becomes clear analyzing the coercive field H_c as a function of the sample width (Fig. 6).
Characteristics of coercive forces directly correlate with the pinning point strength in the material [10], [11]. It is seen that a decreasing sample size, i.e., an increasing proportion of the degraded zone, leads to much higher coercive forces.
The density of additional dislocations and the residual stresses induced by mechanical cutting is linked to the plastic strain attained by the material during the cutting process, which is itself linked to the applied stress. In case of mechanical cutting, this applied stress must have reached the rupture stress, which is a material constant. The resulting plastic deformation becomes clearly visible near the cut line. The depth of the degraded zone depends on the diffusion process of the rupture stress across the material according to the laws of structural dynamics.

Fig. 7- Fig. 11 give an overview of the change of the iron loss measured along the rolling direction with respect to the amount of cut edges. In order to discuss the differences resulting from different widths and cutting methods, a factor is defined: the *iron-loss-factor* C_{Fe} This factor represents the ratio between the measured losses in the strip of width 120 mm and one of smaller widths.

$$C_{Fe} = \frac{P_b(J,f)}{P_{120mm}(J,f)}, \qquad (1)$$

where *b* represents the width of the sample under study. For instance, factor 2 in Fig. 9 e.g. means that the iron losses at a polarization of 0.1 T are for 30 strips each guillotine cut in 4 mm width twice as much as for one strip in width 120 mm.

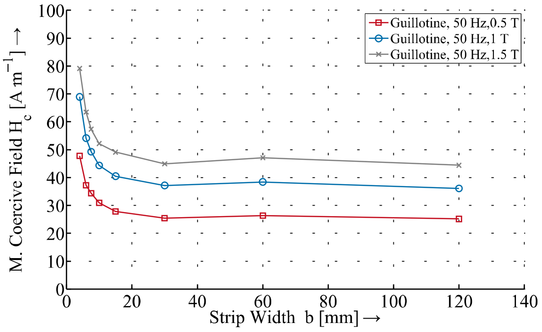

Fig. 6 *Magnetic coercive force H_c vs. strip width b at 50 Hz for grade M230-30A.*

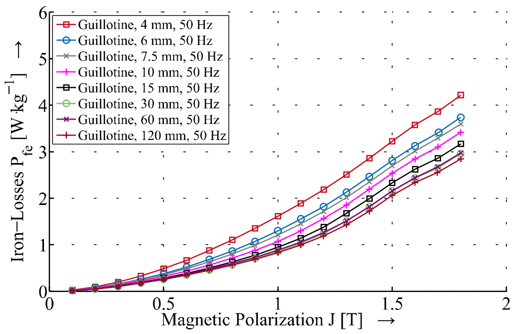

Fig. 7 *Change of iron losses vs. sample width at 50 Hz for grade M230-30A.*

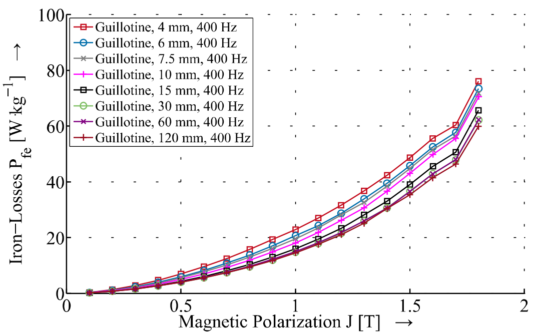

Fig. 8 *Change of iron losses vs. sample width at 400 Hz for grade M230-30A.*

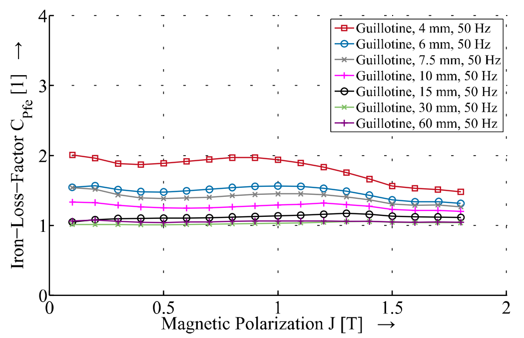

Fig. 9 *Iron loss increase due to different amounts of cut edges at 50 Hz for M230-30A.*

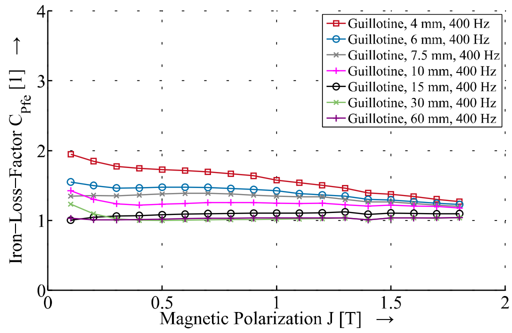

***Fig. 10** Iron-loss increase due to different amounts of cut edges at 400 Hz for M230-30A.*

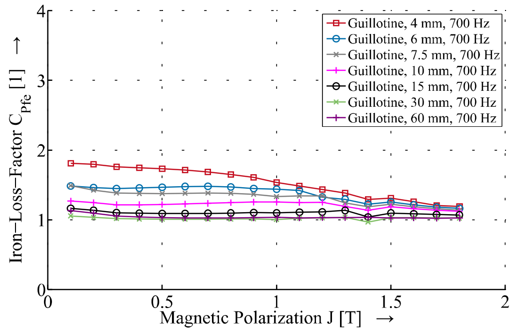

***Fig. 11** Iron-loss increase due to different amounts of cut edges at 700 Hz for M230-30A.*

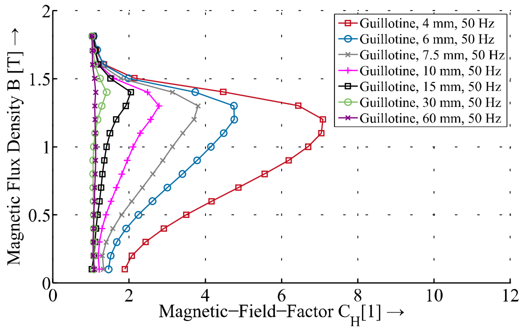

***Fig. 12** Increase of required magnetic field strength to reach a certain magnetic flux density level at 50Hz in samples of different width.*

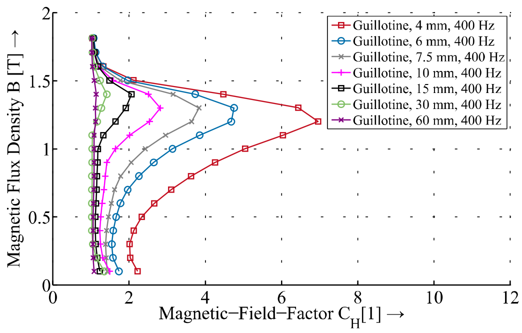

***Fig. 13** Increase of required magnetic field strength to reach a certain magnetic flux density level at 400Hz in samples of different width.*

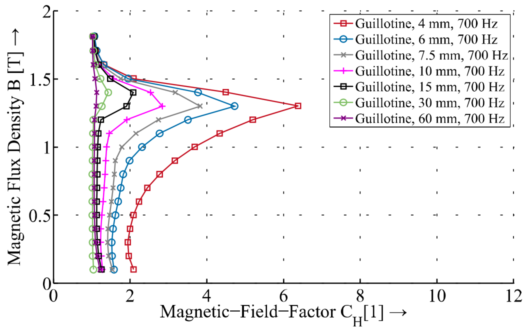

***Fig. 14** Increase of required magnetic field strength to reach a certain magnetic flux density level at 50Hz in samples of different width.*

Figs. 12 – 14 depict the increase of required magnetic field strength in sample of smaller width to reach the same magnetic polarization level. Therefore a magnetic field factor C_H is defined.

$$C_H = \frac{H_b(J,f)}{H_{120mm}(J,f)}. \qquad (2)$$

It is apparent that for increasing frequencies the material degradation effects gets less significant. This is due to increasing influence of disturbing eddy currents, i.e., the magnetic field produced by the induced eddy currents either of macroscopic or microscopic nature.

4.3 MECHANICAL VS. SPARK EROSION - ANNEALING TEMPERATURE

Two samples annealed at 900 °C were machined one by mechanical guillotine cutting and the other by spark eroding to investigate the effect of different cutting methods.

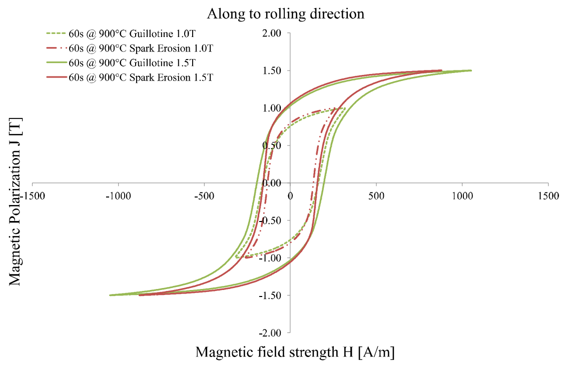

***Fig. 15** Influence of cutting technique on the shape of the major hysteresis loop: spark erosion (red) and guillotine cutting (blue).*

In contrast to the guillotine cutting procedure, spark erosion cutting does not lead to significant changes in the grain morphology, but induces thermal stresses due to heat-up of the sample. It depends hence basically on the geometry of the lamination, in particular on the lamination thickness *d*, as well as on structural elements such as the grain size. Fig. 15 shows the major hysteresis loop at 50Hz and 1.5T for the two cutting techniques. When examining these measured hysteresis loops, it is apparent that the loops get less S-shaped and more squared. Additionally the widening of the loops due to guillotine cutting effects is obvious. The value of the coercive magnetic field strength H_c decreases for spark eroded samples.

This is stressed by the difference in measured iron losses. Guillotine cut sample sets obey 7.05W/kg along and 7.69W/kg perpendicular to the rolling direction at 50Hz and 1.5T. In contrast to this the spark erosion cut samples generate losses of 5.97W/kg along and 6.5W/kg perpendicular to the rolling direction.

5 CONCLUSION

The motivation for this work is the detailed study of the influence of material processing steps on magnetic properties of 3.2 wt.% iron-silicon steel. Both the effect of punching on the material behavior of a typical used NGO electrical steel grade M230-30A as well as a study of the influence of heating time during cold rolling on microstructure and magnetic properties beginning with an industrial hot rolled 2.4 wt.% silicon steel of 2.0mm thickness.

Additionally two different cutting techniques, guillotine (simulating the actual punching process) and spark erosion cutting, are studied.

A major conclusion is that is indispensable to take into account influences due to material processing on magnetic materials properties during the design process of electrical machines. For instance, the deterioration of magnetizability and iron-loss behaviour due to guillotine punching could lead to two-fold iron losses and six-fold demand on magnetic field strength to reach the same magnetic polarization level. As for example in electrical machines this would lead to a worsening of the machines' efficiency.

Considering the different studied annealing temperatures it is important to notice that the annealing temperature as well as the effect of heating time on microstructure and electro-magnetic properties for the cold rolled samples plays an important role and should be investigated in detail.

In order to exploit the magnetic materials capabilities it is necessary to take into account the material processing steps for the design of electrical machines. Therewith it will be possible to improve overall efficiency of electrical machines to come up with more stringent regulations.

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