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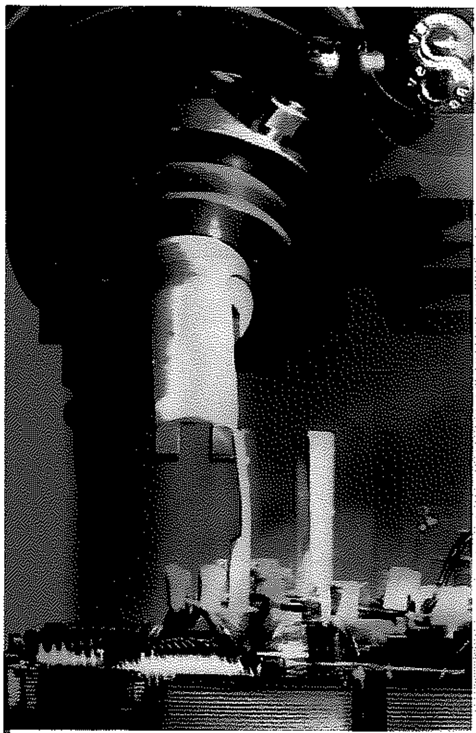

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On the Effect of Material Processing: Microstructural and Magnetic Properties of Electrical Steel Sheets

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Abstract— **This paper presents both the effect of cutting 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. Modifications in the local mechanical properties due to the cutting process are investigated in detail. 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, this analysis is conducted for a wide range of frequencies and magnetic polarizations. Nanoindentation is used to analyze the effect of strain from cutting on the hardness near the surface. A major conclusion is that it is indispensable to take into account influences due to material processing on magnetic materials properties during the design process of electrical machines.**

Keywords— *Electrical steel, material development, soft-magnetic material, tailor-made electrical steel, annealing, material processing, punching*

I. Introduction

In order to address the challenge of increasing demands in terms of mobility in sustainable and climate-friendly manner, the German federal government is pushing the increased application of full electric and hybrid vehicles. A 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 to date, the optimization of the 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.

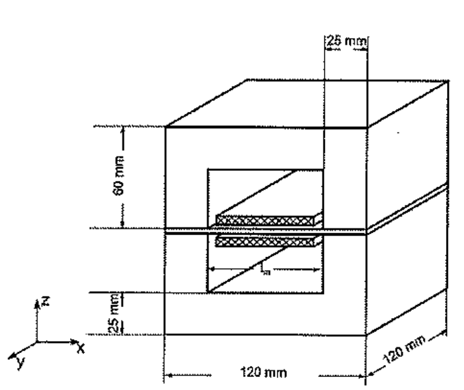

Fig. 1 Single sheet tester for metrological characterization of samples.

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 - 1,500 Hz, i.e. well above the power line frequency.

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. Knowledge on these adverse influences is indispensable in order to improve the material properties for the desired application or redesign the electrical machine to take advantage of specific properties.

The deterioration of magnetic sample properties during manufacturing has been investigated through analyzing microstructural changes and resulting increase of micro hardness after the cutting process [3-5]. Different deterioration mechanisms appear depending on the used cutting method [3, 6]. However, the relation between the mechanical or thermal deterioration and the resulting macroscopic magnetic properties stays undiscovered [6]. But exactly this knowledge is indispensable for improved material modeling, to understand commonly used building factors and the design process of electrical machines [10, 14].

In this paper we present in the first part the influence of annealing during cold rolling on macroscopic magnetic properties [13] 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. Nanoindentation is used to analyze the effect of strain from cutting on the hardness near the surface.

II. METROLOGICAL CHARACTER-IZATION

Several 500 mm by 500 mm 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 is conducted.

Thereby, the 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).

III. INFLUENCE OF ANNEALING

The influence of heating time and temperature on the microstructure and electro-magnetic properties of the cold rolled samples is studied. In order to evaluate the influence of annealing [13], samples annealed at two different temperatures are magnetically characterized at the single sheet tester at 50Hz and 1.0T as well as 1.5T magnetic polarization.

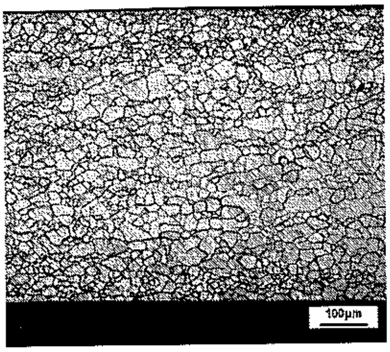

Fig. 2 Microstructure after annealing for 60s at 900°C (avg. grain size: 20-30 µm).

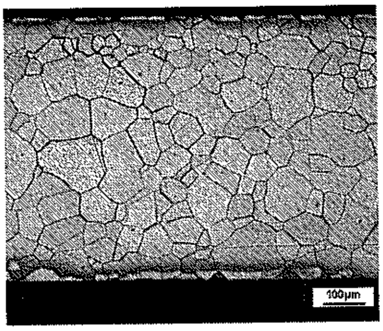

Fig. 3 Microstructure after annealing for 60s at 1000°C (avg. grain size: 100-120 µm).

A. EXPERIMENTAL PROCEDURE

The steel used in this investigations is an industrial hot rolled 2.4 wt.% Silicon steel of 2.0 mm thickness, manufactured by compact strip casting. These hot strips are pre-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 are cut from the annealed hot rolled strip. After pickling of the specimens in a 15 % HCl compound, they are 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 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 are annealed at temperatures of 900 and 1000 °C for 60 s using an electric resistance furnace. To avoid oxidation the samples are wraped in an annealing foil and the furnace is purged with argon. The microstructure is characterized by light optical microscopy (LOM) after etching in 5 % natal solution.

B. EXPERIMENTAL RESULTS

The microstructures resulting from the different heat treatments are illustrated in Fig. 2 and Fig. 3. Both

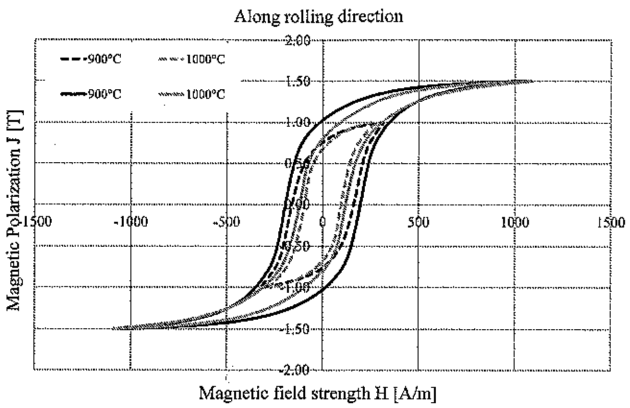

Fig. 4 Influence of annealing temperature on the major hysteresis loop at 50Hz at 1.0 and 1.5T measured in rolling direction.

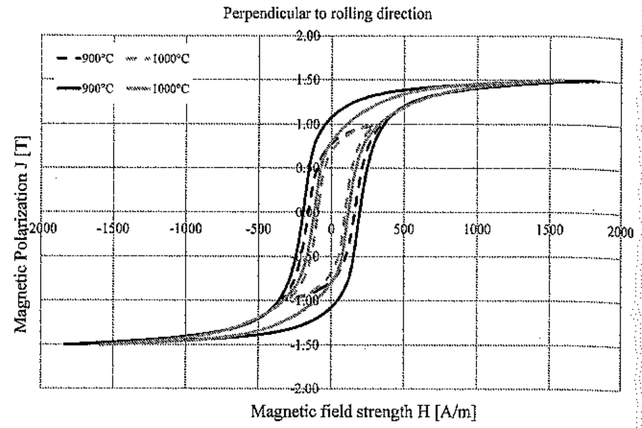

Fig. 5 Influence of annealing temperature on the major hysteresis loop at 50Hz at 1.0 and 1.5T measured perpendicular to rolling direction.

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.

The macroscopic magnetic characteristics determined using the single sheet tester are in good agreement with the observed microstructure. Comparing the major hysteresis loops at a frequency of 50 Hz and magnetic polarizations of 1.0T and 1.5 T 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 behavior (Figs. 4 and 5). This is additionally stressed by the decrease of iron loss (corresponding to the enclosed area of the hysteresis loop) going to higher grain sizes.

Samples annealed for 60 s 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. In contrast to this the sample set annealed for 60 s at 1000°C has significantly lower losses; these are 4.44 W/kg and 4.53 W/kg, respectively.

It is important to emphasize that these characteristics may change with the 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.

IV. INFLUENCE OF CUTTING

Mechanical punching and 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 neighbouring 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 [4], [5].

Improved estimation of iron losses occurring in stator and rotor core of machines is essential for the design of highly efficient electrical drives [7-9]. 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 frequencies 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 [7-9].

On that account, material characteristics are measured for samples with different ratios of cut surface vs. overall lamination volume, i.e. varying the amount of cut edge length related to the material volume.

A. EXPERIMENTAL PROCEDURE

A number of single sheet tester samples of 120 mm by 120 mm are cut in smaller stripes by guillotine cutting (simulating the actual punching), resulting in different sample sets with additional guillotine cut edges (Fig. 6). The total width remains 120 mm.

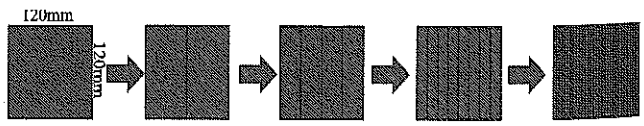

Fig. 6 Process of the sample preparation and processing.

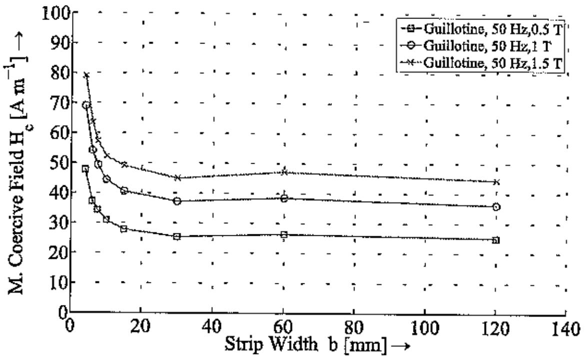

Fig. 7 Magnetic coercive force H_c vs. strip width b at 50 Hz for grade M230-30A.

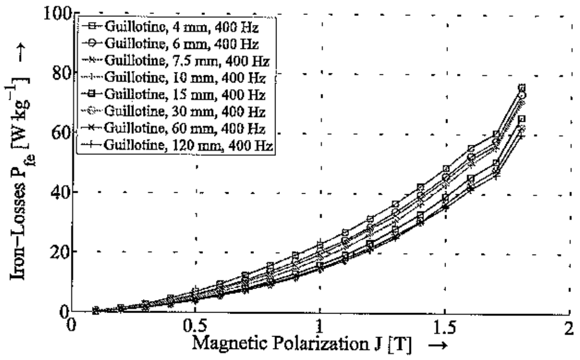

Fig. 9 Change of iron losses vs. sample width at 400 Hz for grade M230-30A.

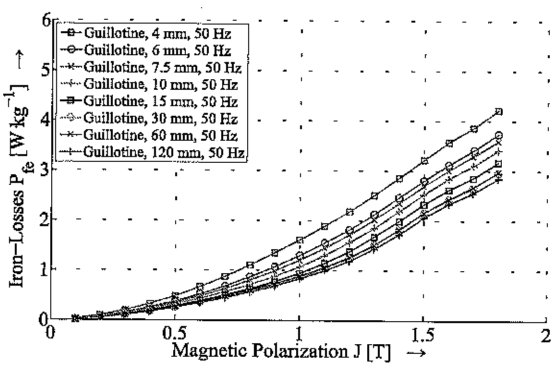

Fig. 8 Change of iron losses vs. sample width at 50 Hz for grade M230-30A.

Studied sample sets consist of thirty 4 mm, twenty 6 mm, sixteen 7.5 mm, eight 15 mm, four 30 mm, two 60 mm and one 120 mm 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 120 mm. Based on these eight different sample sets, the effect of cutting for the described processes is analysed using a 120 mm by 120 mm single-sheet-tester equipped with 50 primary and secondary windings (Fig. 1).

Measurements are performed utilizing the field-metric 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-grain oriented FeSi 3.2wt.% lamination with a thickness of 0.3 mm, called M230-30A.

B. EXPERIMENTAL RESULTS

Due to the cutting, a spatial distribution of magnetic polarization *J(x)* as a function of the distance x from the cutting edge is present [4], [10]. 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 [4], [10].

The influence of additional pinning sites, i.e., microstructural defects from cutting becomes clear analysing the coercive field H_c as a function of the sample width (Fig. 7).

Characteristics of coercive forces directly correlate with the pinning point strength in the material [11], [12]. It is seen that a decreasing sample size, i.e., an increasing proportion of the degraded zone, leads to much higher coercive forces.

The stresses from the cutting process are significant and induce severe plastic deformation, and consequently also residual stresses, near the cut surface [14]; the plastic deformation near the cut line is optically visible. It is the ratio between the sample width and the region affected by the cutting that can significantly influence the magnetic properties.

Figs. 8-11 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_{Pfe} This factor represents the ratio between the measured losses in the strip of width 120 mm and one of smaller widths.

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

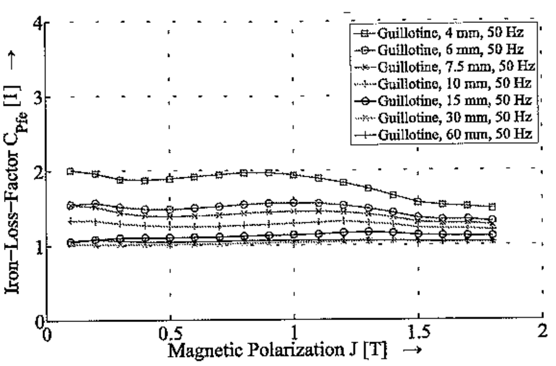

Fig. 10 Iron loss increase due to different amounts of cut edges at 50 Hz for M230-30A.

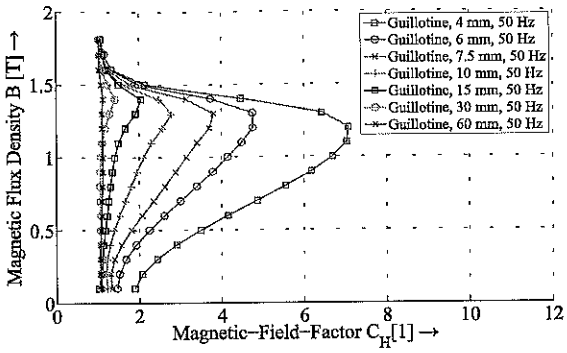

Fig. 12 Increase of required magnetic field strength to reach a certain magnetic flux density level at 50Hz in samples of different width.

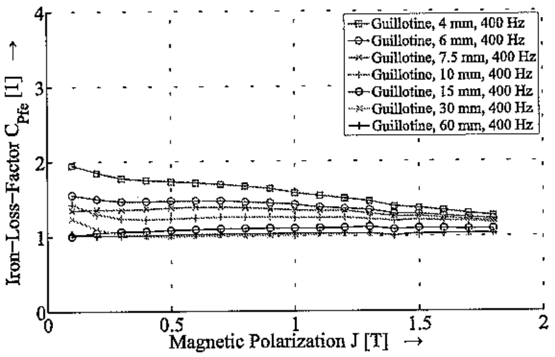

Fig. 11 Iron loss increase due to different amounts of cut edges at 400 Hz for M230-30A.

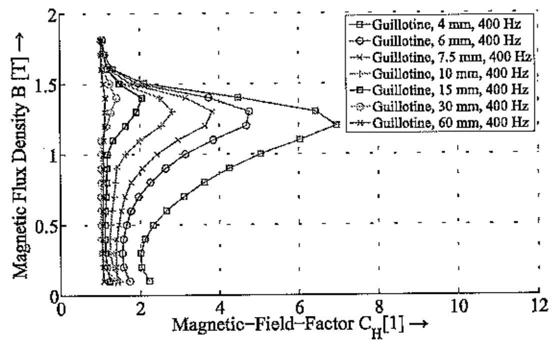

Fig. 13 Increase of required magnetic field strength to reach a certain magnetic flux density level at 400Hz in samples of different width.

where *b* represents the width of the sample under study. For instance, the factor 2 observed in Fig. 11 means that the iron losses at a polarization of 0.1 T for 30 strips, each guillotine cut in 4 mm width, are twice as much as for one strip with a width of 120 mm.

Figs. 12-13 depict the increase of required magnetic field strength in samples 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 become less significant. This is due to increasing influence of disruptive eddy currents, i.e., the magnetic field produced by the induced eddy currents either of macroscopic or microscopic nature.

V. MECHANICAL VS. SPARK EROSION - ANNEALING TEMPERATURE

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

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 heating of the sample. Its effect on the material properties near the edge therefore depend 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. 14 shows the major hysteresis loop at 50 Hz and 1.5 T (straight lines) as well as 1.0 T (dashed lines) for the two cutting techniques. When examining these measured hysteresis loops, it is apparent that the loops get less S-shaped and more square. Additionally the widening of the loops due to guillotine cutting effects is apparent. The value of the coercive magnetic field strength H_c decreases for spark eroded samples.

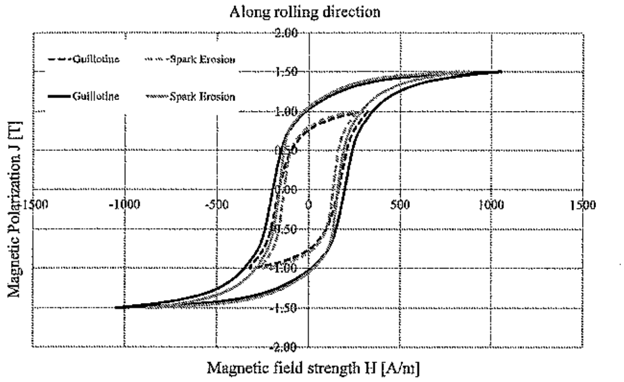

Fig. 14 Influence of cutting technique on the shape of the major hysteresis loop: spark erosion and guillotine cutting.

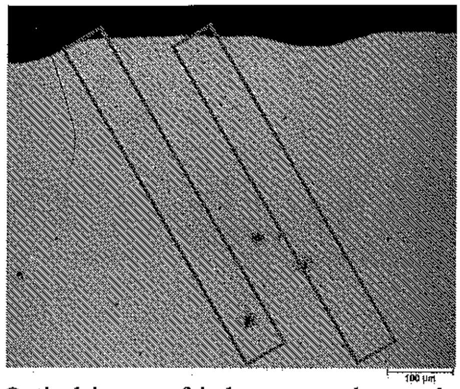

Fig. 15 Optical image of indents towards sample edge of the 4 mm wide sample (scale: 100 μm).

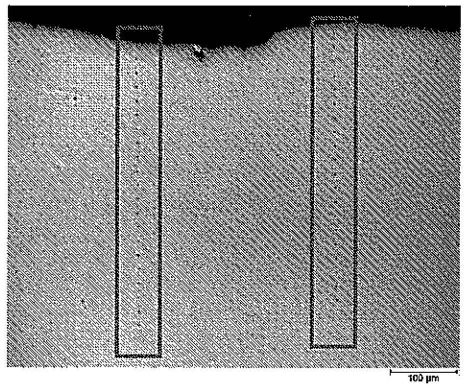

Fig. 16 Optical image of indents towards sample edge of the 10 mm wide sample (scale: 100 μm).

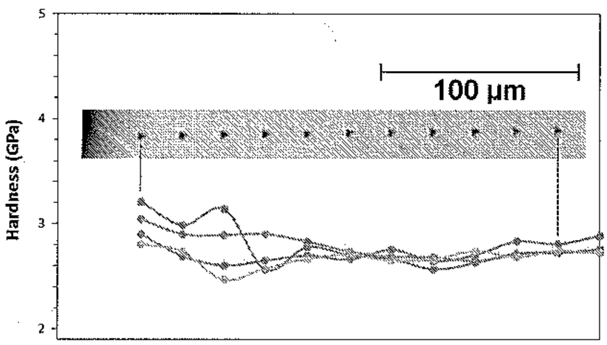

Fig. 17 Representative hardness profile towards the sample cut edge of 10mm wide sample.

This is in agreement with the difference in measured iron losses. Guillotine cut sample sets obey 7.05 W/kg along and 7.69 W/kg perpendicular to the rolling direction at 50 Hz and 1.5 T respectively. In contrast to this the spark erosion cut samples generate losses of 5.97 W/kg along and 6.50 W/kg perpendicular to the rolling direction at 50 Hz and 1.5T.

VI. Microstructural Characterisation – Nanoindentation

The shearing deformation pattern is accompanied by a complex bending deformation pattern during guillotine shear cutting of the electrical steel sheet. This leads to deformations of the sheet shape depending on the size of the sheet. The maximum force during shear cutting depends on the rake angle [15]. The area confined by the force vs. knife-displacement curves [15, 16] defines the energy absorbed by the material through plastic deformation. This plastic deformation strongly deteriorates the magnetic properties and leads to change of hardness of the material.

Therefore, measuring locally the hardness of the material enables to determine the area deformed plastically. The experimental procedure is explained in the next sub-section.

A. Experimental

In order to determine the local modification of the mechanical properties, Nanoindentation is done on two representative electrical sheets of the M230-30A material (4 mm and 10 mm wide sample).

The experiments are carried out with maximum loads of 20 mN (Micro Materials NanoTest) and 10 mN (Hysitron TI 950 Triboindenter) using a diamond Berkovich tip. The tip area function was determined by indenting standard fused silica. All data was analysed using the Oliver-Pharr method [17].

Therewith the mechanical properties can be identified locally as function of the distance to the sample cut edge. In order to avoid the disturbing influence of surface scratches or roughness, the samples are carefully polished and treated by chemically active substances.

B. Results and Discussion

Hardness profiles are obtained towards the sample cut edge using nanoindentation; Figures 15 and 16 show examples of the indents made for the 4 mm and 10 mm wide samples.

The obtained hardness profile of the 10 mm wide sample set is shown in Figure 17, where although there is some scatter in the data, an increase in the hardness is observed towards the sample cut edge. The latter is indicative of the strain induced during the cutting process, which is responsible for the change in the magnetic properties discussed in Section IV of the paper. It is estimated that the layer affected by cutting is 50-100 μm thick, and the increase in the hardness is up to 8-10% compared to the bulk based on the conducted hardness measurements.

These results indicate that cold deformation remains present after mechanical cutting. In the future, a more detailed correlation of grain size, local crystal orientation and distance from the edge by correlated hardness testing and electron back-scatter diffraction might further elucidate the extent of defect generation and the resulting hardening during the cutting process.

VII. CONCLUSION

In this study, we investigated the effect of processing parameters during annealing and sheet cutting on two iron silicon steels with respect to their microstructure and the resulting magnetic properties.

In particular it was found that the choice of cutting process greatly influences the iron losses. For instance, the required magnetic field strength could be reduced by means of spark erosion cutting in place of the commonly applied punching process.

Furthermore, careful control of annealing time and temperature are required in order to control the resulting microstructure, where an increase in annealing temperature of 100 °C was found to result in up to 5 times larger grains.

We show here that it is necessary to take into account the individual processing steps, their influence on the material's microstructure and the resulting electromagnetic properties achieved under operating conditions. A detailed investigation in an interdisciplinary research group enables to work out the coherences and analyze the interdependence of the various influences of the material processing on the material properties.

Thereby, the full potential of the material and processing chain can be exploited in order to achieve greater efficiency of the electrical machines and comply with more stringent regulations.

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