Effects and advantages of high-strength non grain oriented (NGO) electrical steel for traction drives

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***Abstract*— As a magnetic core material, non grain oriented (NGO) electrical steel is mainly characterized by its magnetic properties, i.e. the specific loss, the magnetic saturation polarization, and the magnetizability, i.e. the permeability. In addition, mechanical properties, e.g. manufacturability, yield strength as well as coatings strongly influence the performance, power density and the cost of the resulting electric machine. This paper presents the effect of various cutting techniques on the material behavior of high-strength NGO electrical steel grades with guaranteed yield strength in rolling direction of 400 – 600 MPa in thickness 0.30 – 0.35 mm. Typical application fields of this material are automotive traction drives with their specific application range at higher frequencies than 50 Hz.**

Keywords*— Electrical steel, material development, high-strength electrical steel, electric vehicles, FEM simulation, soft-magnetic material, tailor-made electrical steel, electric machines with high rotational speed

I. INTRODUCTION

The requirements for NGO electrical steel in traction motors are higher compared to those for standard electric motors. Due to limited construction size in hybrid and electric vehicles, motors usually operate at two to fourfold times higher rotational speed than conventional industrial drives. This results in high requirements on the magnetic core material. These requirements are driven by cost and the requirement of highest possible power density. 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. The steel manufacturer is able to influence the specific total loss by using different alloy contents, choosing different thicknesses or by optimizing the texture. The main factors to reduce the losses in the electrical steel are according to [5] alloy content (mainly silicon or aluminum) and sheet thickness. With increasing silicon content, the specific electric resistivity ρ_e increases. This results in lower eddy current-losses and thus in lower core losses. However, thermal conductivity (TC) and saturation polarization decrease with increasing silicon content. Especially high saturation/polarization is preferable in order to minimize the core material for the magnetic flux. The decrease of the sheet thickness also causes less eddy current-losses. When using NGO electrical steel in thinner thickness, the resulting lower stacking factor of the iron core and adopted costs for the laminations compared to thicker grades have to be taken into account.

In permanent magnet synchronous machines (PMSM) with embedded magnets, additional restrictions for mechanical properties of the rotor core material exist. Smaller bridges at the magnets lead to lower leakage flux allowing for a decrease of the magnet material and therewith magnet materials costs and concomitantly lower overall costs of the electric machine. Beside lower installation space with comparable torque weight savings are possible. In order to fulfill these stronger requirements, SE-AG has continued its permanent optimizations on electrical steel and enables innovative and efficient motor design with it's in this study used application-specific grades.

TABLE I. OVERVIEW OF STANDARD AND HIGH-STRENGTH APPLICATION-SPECIFIC NGO ELECTRICAL STEEL GRADES WITH GUARANTEED MAGNETIC AND MECHANICAL VALUES AND LOWER DETERIORATION OF MAGNETIC PROPERTIES OF THE FINAL LAMINATIONS

	Acc. to EN 10303	Standard grades acc. to EN 10106			
Grade	NO 20	M 235-35 A	M 250-35 A	M 270-35 A	M 330-35 A
Nominal thickness (mm)	0,2	0,35	0,35	0,35	0,35
P1.0 50 Hz (W/kg)	0,9	1,0	1,0	1,0	1,2
P1.5 50 Hz (W/kg)	2,4	2,3	2,4	2,4	2,7
P1.0 400 Hz (W/kg)	11,7	16,6	18,6	18,4	20,9
P1.0 1.000 HZ (W/kg)	43,0	70	82,0	80,0	91
Rp0.2 typical [Mpa]	360	425	370	360	330
Rp0.2 guaranteed [Mpa]	-	> 390	> 350	> 350	> 300
Rm [Mpa]	450	525	480	500	450
HV5	190	220	200	200	165

Typical values for standard grades and indicative values for application-specific grades. Mechanical values are measured at room temperature for rolling direction. Rp0.2 guaranteed for room temperature and for rolling direction.

	Application-specific NGO grades			High-strength NGO grades		Extra high-strength NGO grade
Grade	330-30 AP	* 270-27AP	280-30AP Var. 1	280-30AP Var. 2	* xxx-35AP Var.2	** Extra high-strength NGO
Nominal thickness (mm)	0,30	0,27	0,30	0,30	0,35	0,35
P1.0 50 Hz (W/kg)	1,2	1,1	1,1	1,1	1,1	on request
P1.5 50 Hz (W/kg)	2,8	2,6	2,5	2,5	3,0	on request
P1.0 400 Hz (W/kg)	18,0	15,0	16,0	16,0	22,0	< 40
P1.0 1.000 HZ (W/kg)	75,0	59,0	65,0	62,0	80,0	on request
Rp0.2 typical [Mpa]	330	390	410	440	450	520-620
Rp0.2 guaranteed [Mpa]	> 300	> 350	> 370	> 420	> 420	> 500
Rm [Mpa]	450	510	530	550	560	670-800
HV5	168	180	190	200	200	200

Typical values for standard grades and indicative values for application-specific grades. Mechanical values are measured at room temperature for rolling direction. Rp0.2 guaranteed for room temperature and for rolling direction. * New trial, ** Several grades under development

High-strength application-specific NGO electrical steel grades with guaranteed magnetic and mechanical values and lower deterioration of magnetic properties of the final laminations enable cost optimized and improved motor designs. To demonstrate the advantages of high-strength NGO electrical steel, a permanent magnet motor with 40 kW nominal power and 12.000 rpm max speed was designed.

- P_N = 40 kW
- n_N = 5.000 rpm
- n_{max} = 12.000 rpm
- $n_{overspeed}$ = 14.400 rpm
- Number of slots = 12
- Number of poles = 8
- M235-35A
- Thickness = 0.35 mm

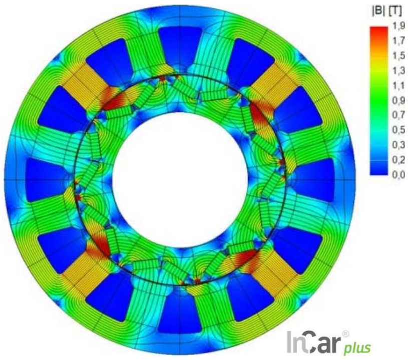

Fig. 1. Field plot of a PMSM simulation.

For the stator in Fig. 1, the high-strength NGO electrical steel grade 280-30 AP Var. 2 with low magnetic losses at high-frequencies was chosen. Three different steel concepts, best standard NGO grade M235-35A, high-strength NGO grade 280-30 AP Var. 2 and one extra-high strength NGO grade, are examined for the rotor. In order to compare the possibilities and impacts of this three different steel grades, motor design, size and stator core remained constant at the three designs.

Best standard NGO grade

- M235-35A
- Thickness = 0.35 mm
- P1.0 (400 Hz) typical 17 W/kg
- Rp02 guarantee * > 390 MPa

* in rolling direction for room temperature

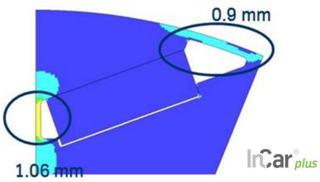

Fig. 2. Mechanical consideration at the stressed rotor parts for the standard grade M235-35A.

High-strength NGO

- xxx-35AP Var. 2
- Thickness = 0.35 mm
- P1.0 (400 Hz) typical 19 W/kg
- Rp02 guarantee * > 420 MPa

* in rolling direction for room temperature

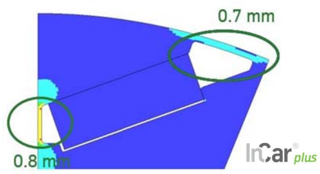

Fig. 3. Mechanical consideration at the stressed rotor parts for the high-strength grade xxx-35AP Var. 2.

Extra high-strength (E H-S) NGO

- Extra-high strength NGO
- Thickness = 0.35 mm
- P1.0 (400 Hz) < 40 W/kg
- Rp02 guarantee * > 500 MPa

* in rolling direction for room temperature

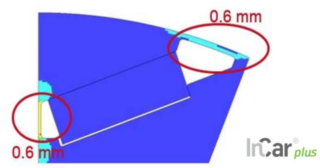

Fig. 4. Mechanical consideration at the stressed rotor parts for the extra high-strength NGO grade E H-S.

In Figs. 2 - 4, only the steel bridges between the magnets and the outer rotor surface were adjusted based on the guaranteed stress limits of each particular NGO electrical steel grade. For the high-strength electrical steel grade (xxx-35AP), a decrease of the bridges of about 20 % was possible. With extra high-strength electrical steel a reduction of more than 40 % was possible. The mechanical stress in the steel bridges between the magnets of one pole was calculated with an established FEM tool for the three rotor variations in Figs. 2 - 4. In each rotor, the stress limit for the particular electrical steel grade is nearly reached at over speed (maximum speed +20 %). With these three rotor designs electromagnetic FEM calculations have been conducted.

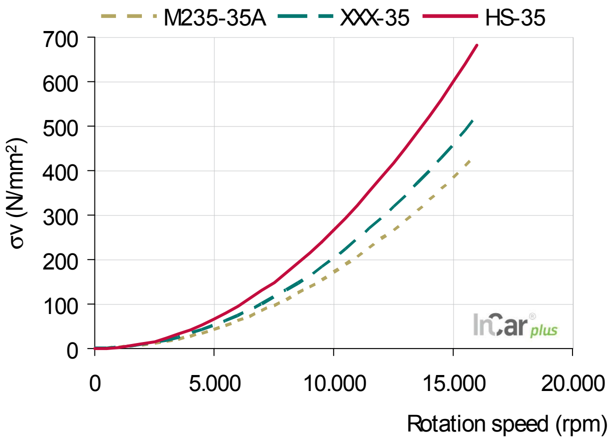

Fig. 5. Mechanical stress at steel bridge between magnets and outer rotor surface.

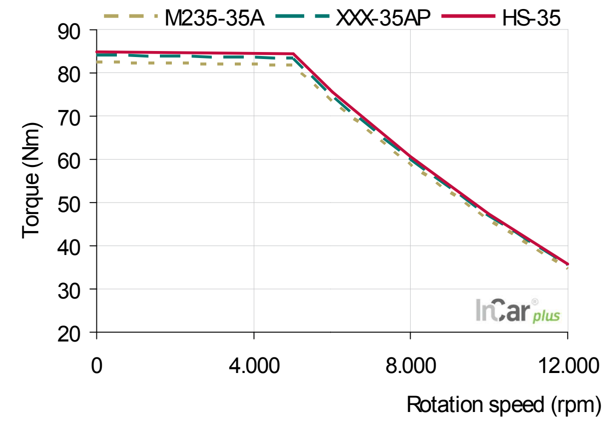

Fig. 6. Torque-speed characteristic at nominal current for the three different motor designs.

The calculated torque - speed characteristic in Fig. 6 displays the advantages of electrical steel with high-strength in the complete speed range. An increase of torque about 2 % with high-strength and 3.5 % with extra high-strength electrical steel at the nominal point (see Fig. 6) was compared to the determined standard grade.

According to the conducted FEM simulation, the use of electrical steel with high-strength in permanent magnet synchronous machines enables (TABLE II.) higher power densities and also higher efficiencies.

TABLE II. BEHAVIOR OF TORQUE AND EFFICIENCY CONCERNING DIFFERENT STEEL GRADES.

Grade	Torque/ Power Density	Efficiency
M235-35A	Reference	Reference
xxx-35AP Var. 2	↗	↗
Extra high-strength	↑	→

The possibility to reduce the mass of the permanent magnets about 2 - 4% resulting in a reduction of the total costs is also another mayor advantage of high-strength NGO electrical steel. The second part of this study gives a first outlook on possible cutting effects which have to be considered for an effective FEM motor design.

II. Experimental Procedure

The study focuses on the SE-AG NGO grades 280-30AP Var. 1, 280-30AP Var. 2 in thickness 0.30 mm as well as the grade xxx-35AP Var. 2 in thickness 0.35 mm. All grades are optimized in order to have lower deterioration of magnetic properties of the laminations. Low losses at high frequencies and guaranteed yield strength in rolling direction for room temperature are other advantages of these grades.

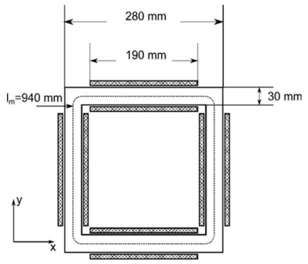

Fig. 7. Epstein frame (EF) [4].

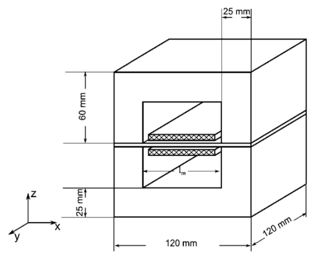

Fig. 8. Single sheet tester (SST) [4].

Magnetic properties can be measured with several techniques. Most common and part of relevant standards are the Epstein frame (EF) Fig. 7 [2] and the single sheet tester (SST) Fig. 8 [3] as a measurement device. Fig. 9 to Fig. 12 presents magnetic material properties, such as magnetic flux density, iron losses at different inductions for different frequencies obtained by measurements of the studied material.

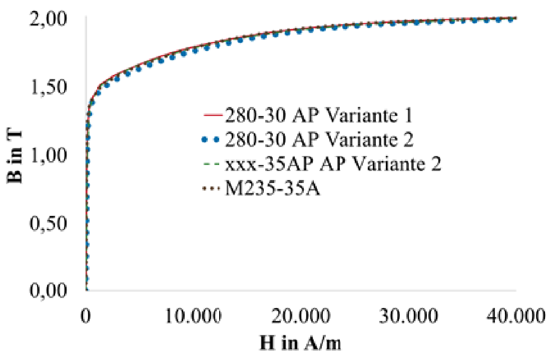

Fig. 9. Virgin B-H curve from EF.

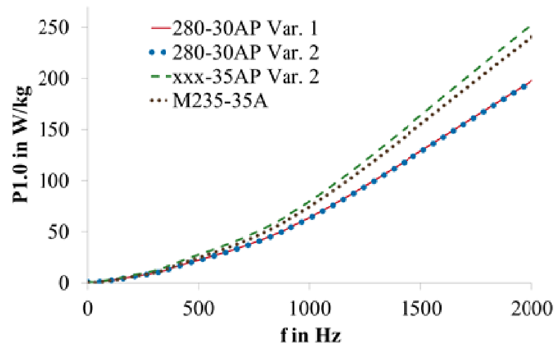

Fig. 10. Iron losses vs. frequency at 1.0 T magnetic flux density from EF.

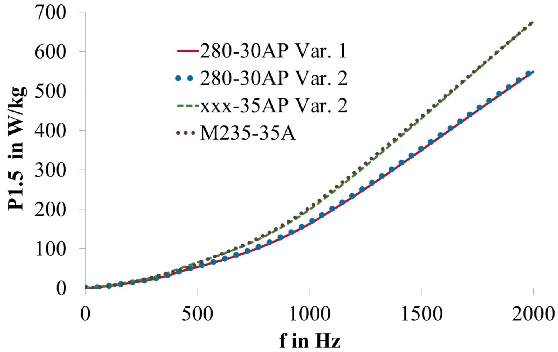

Fig. 11. Iron losses vs. frequency at 1.5 T magnetic flux density from EF.

The advantages of thinner grades at high frequencies compared to the best standard grades e.g. M235-35A are shown in Fig. 10 and Fig. 11.

The values found in this study are verified in [4, 6, 7]. Several 500 mm by 500 mm samples are taken from different positions in a cold strip. For the characteristics of the samples, unidirectional, sinusoidal magnetic flux density waveforms are studied whereby the direction of magnetization is chosen to be perpendicular to (PD) and along (RD) the rolling direction in order to ensure that the tested samples obey homogeneous magnetic properties, (see Fig. 6). Deviations of less than 1% between the values of different samples in RD and PD direction confirm the homogeneity of the studied materials which is an important basis for the next steps of this study.

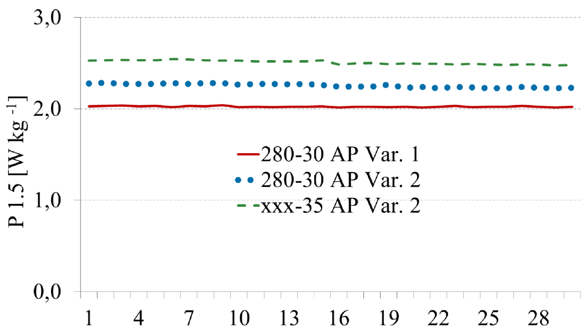

Fig. 12. P1.5 at 50 Hz in (RD) of 500 x 500 mm sheets in SST.

III. Detailed studies are conducted using a single sheet tester (120 mm by 120 mm).

Further on, the samples were cut in smaller strips, applying either guillotine or laser cutting. The cutting pattern is presented in Fig. 13. Based on these different sample sets, the effect of cutting for the described processes can be studied.

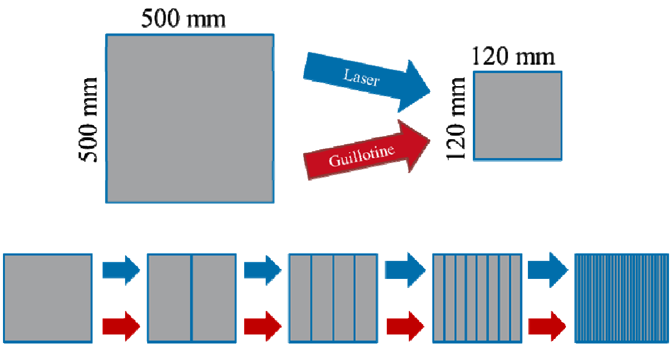

Fig. 13. Process of the sample preparation and processing.

The total width remains 120 mm. But due to the influence of the cutting burr, problems may occur such as placing same amount of sample sets in the joke whilst comparing guillotine and laser. The discussion is limited to the high-strength grade 280-30 AP Var. 2 in RD in order to provide a clear structure. Measurements are performed under controlled sinusoidal magnetic flux density waveforms for different amplitudes and for the following excitation frequencies: 50, 100, 200, 300, 400, 700 Hz and 1 kHz. The behavior of the iron losses in dependency of magnetic polarization J [T] and frequency f [Hz] are recorded in Fig. 14.

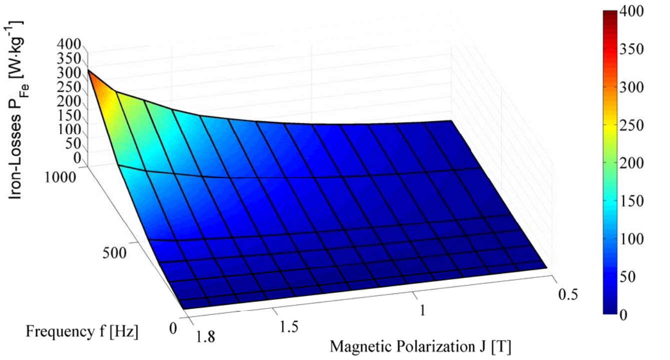

Fig. 14. Iron losses of 280-30 AP Var. 2, laser cutted in RD, for 1 strip 120 mm x 120 mm.

The increase of iron losses with higher frequency due to higher eddy current losses is apparent. The losses are even much higher when thicker NGO grades are used. The additional iron losses of 30 strips 4 mm x 120 mm compared to one single strip 120 mm x 120 mm are shown in Fig. 16. Caused by cutting effects, an increase of iron losses up to 60 W/kg was observed for the grade 280-30 AP Var. 2. In order to quantify the cut edge effect for both cutting methods, magnetic measurements are carried out. Thereby the single valued (virgin) magnetization curve J (H) as well as the iron losses at elevated frequencies (from 50 Hz up to 1 kHz) are measured. In order to evaluate the influence of the material properties, various sets of samples of three different grades with improved mechanical properties (always 120 mm width in total, but with different number of cut edges) were magnetically characterized using a Single Sheet Tester (SST) of 120 mm by 120 mm.

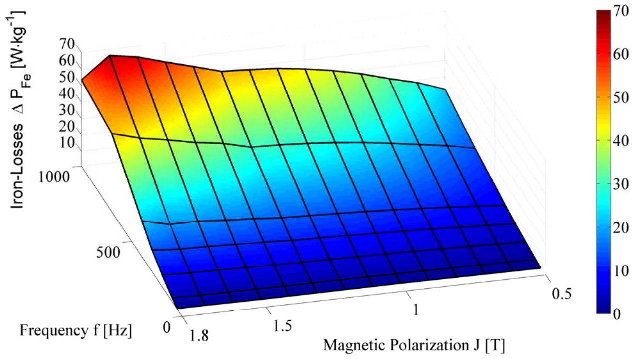

Fig. 15. Additional iron losses of 280-30 AP Var. 2, laser cutted in RD, of for 30 strips 4 mm x 120 mm compared to one strip 120 mm x 120 mm.

The impact of laser cutting for 120 mm width is comparable to the impact of guillotine cutting. Fig. 16 - Fig. 20 give an overview of the change of the iron loss curve in RD with respect to the amount of cut edges and the two different processing types (laser: straight lines, guillotine: dotted lines).

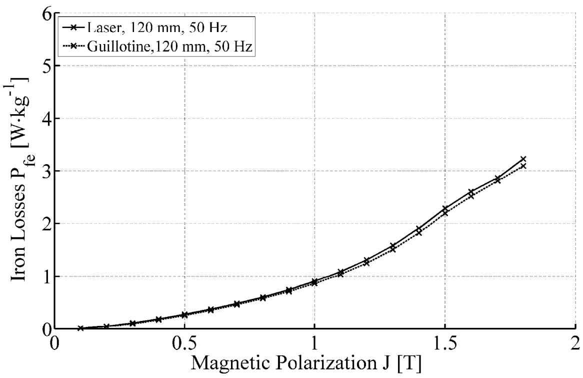

Fig. 16. Change of iron losses vs. cutting technique at 50 Hz on grade 280-30 AP Var. 2 in RD.

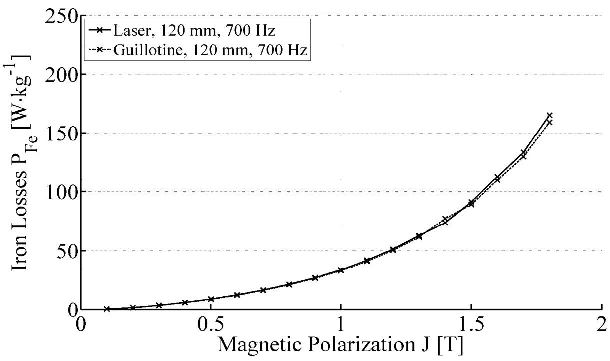

Fig. 17. Change of iron losses vs. cutting technique at 700 Hz on grade 280-30 AP Var. 2 in RD.

In order to discuss the differences resulting from different widths and cutting methods, a factor is defined. This factor represents the difference when comparing one strip in width 120 mm to smaller widths x amount of samples which are needed to achieve 120 mm as total width. Factor 2 in Fig. 19 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.

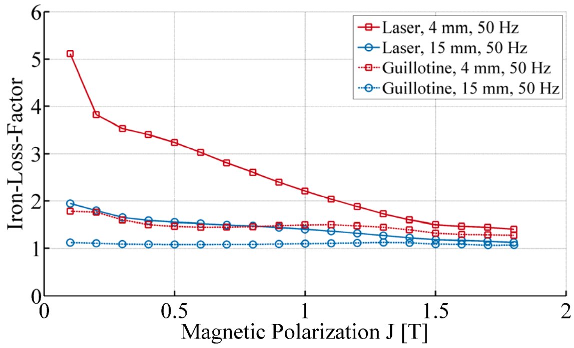

Fig. 18. Increase of iron losses as a factor for two different processing types on grade 280-30 AP Var. 2 due to different amounts of cut edges at 50 Hz.

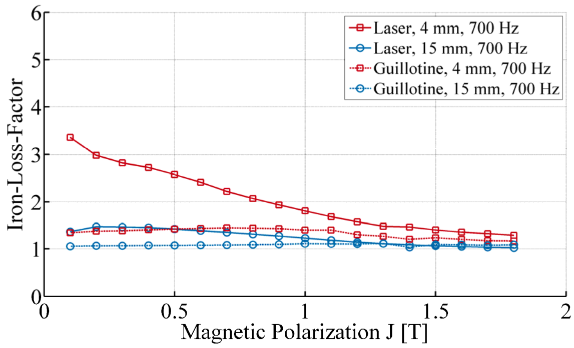

Fig. 19. Increase of iron losses as a factor for two different processing types on grade 280-30 AP Var. 2 due to different amounts of cut edges at 700 Hz.

The impact of laser cutting on the magnetization behavior of the 120 mm samples is comparable to the impact of guillotine cutting. The same tendency as for the iron losses is present for the magnetic field strength. Fig. 20 - Fig. 23 give an overview of the change of the magnetization curve (J_{max} (H_{max})) in RD with respect to the amount of cut edges and the two different processing types (laser: straight lines, guillotine: dotted lines).

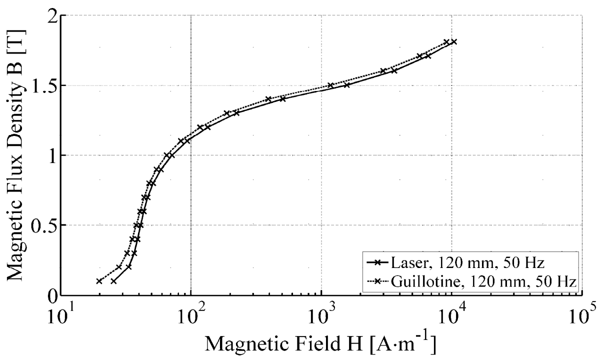

Fig. 20. Change of the magnetization curve in RD for two different processing types (laser: dotted lines, guillotine: straight lines) for 280-30 AP Var. 2 at 50 Hz.

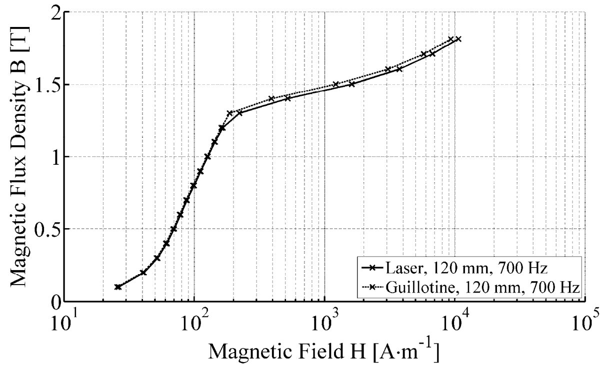

Fig. 21. Change of the magnetization curve in RD for two different processing types for 280-30 AP Var. 2 at 700 Hz.

For measurements with higher amount of cut edges, the mechanical cutting with guillotine shows much lower deteriorations compared to laser cutting. A strong decrease of magnetizability in the same induction range as an effect of laser cutting is also shown in [8]. But the enormous increase of demand on field strength - up to the factor 13 - was unexpected.

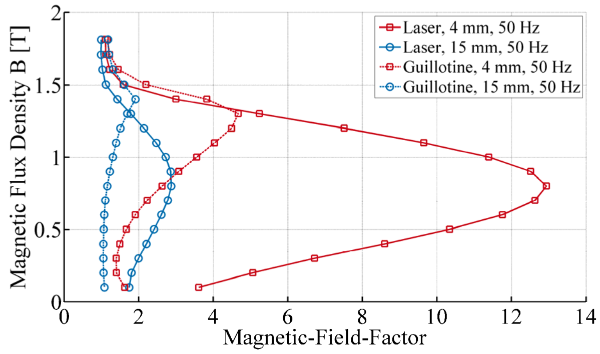

Fig. 22. Change of the magnetization curve as factor in RD with respect to the amount of cut edges and the two different processing types for 280-30 AP Var. 2 at 50 Hz.

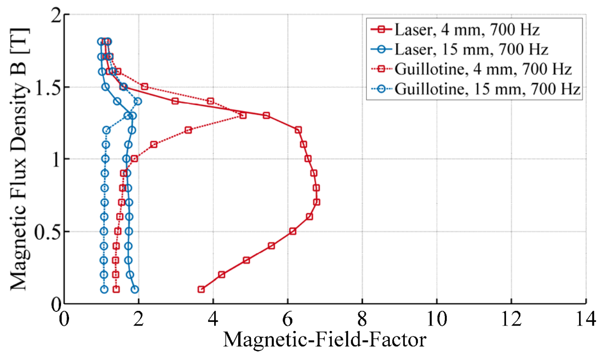

Fig. 23. Change of the magnetization curve as factor in RD with respect to the amount of cut edges and the two different processing types for 280-30 AP Var. 2 at 700 Hz

First trials show that the oversized deteriorations can be decreased by adjusting the laser parameters for the cutting. Trials have to be repeated to compare laser cutting with mechanical cutting more accurately. In order to evaluate the undesirable influence of stresses resulting from unsuitable laser cutting parameters, stress relieved annealing was applied, too. Fig. 24 and Fig. 25 show the possible benefit of stress relieved annealing exemplarily at 50 Hz. For a strip width of 4 mm the applied magnetic field can be reduced down to 10 % of the amount which was needed for the unannealed samples. This yields to a maximum magnetic-field factor of 1 after annealing instead of 12 without annealing. The effect on samples in a width of 15 mm is comparable. The maximum factor without annealing was approximately 3 and with annealing close to 1.Stress relieved annealing achieves no advantages at high magnetic flux densities (higher than 1.6 T) as the electrical steel is close to saturation or saturated.

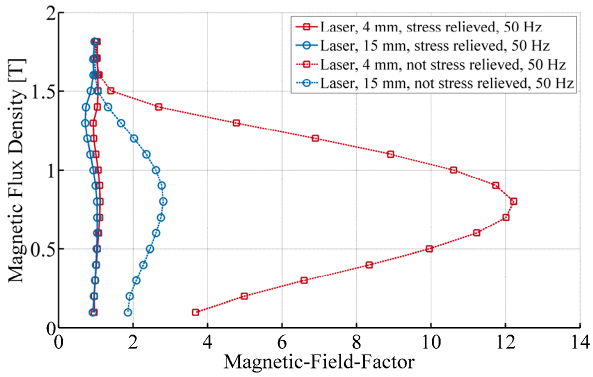

Fig. 24. Change of the magnetization of stress relieved and not stress relieved samples in RD with respect to the amount of cut edges and the two different processing types for 280-30 AP Var. 2 at 50 Hz.

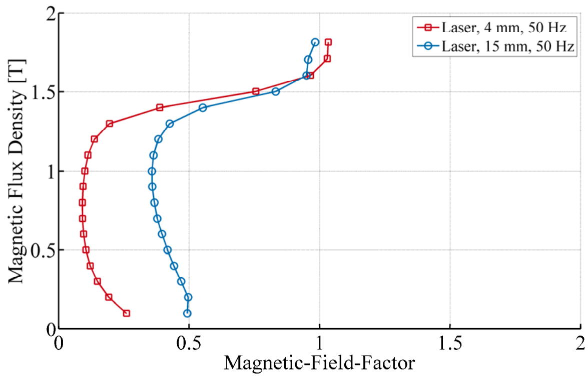

Fig. 25. Change of the magnetization of stress relieved and not stress relieved samples in RD with respect to the amount of cut edges and the two different processing types for 280-30 AP Var. 2 at 50 Hz.

It is important to point out that measurements were only carried out on samples cut along the rolling direction, so that the results have to be interpreted in relation to each other and not as absolute values. At the current stage of this study, it is advisable to take special precautions, e.g. stress relieved annealing, for laser cutting into account.

IV. Conclusion and Outlook

Based on a mechanical and electromagnetic FEM calculation of a PMSM motor design, the advantages resulting from the use of high-strength electrical steel have been shown for three different rotor designs. High-strength electrical steel enables higher power densities and also higher efficiencies of the motors. Based on this, it is possible to reduce the mass of the permanent magnets about 2 - 4% which reduces the total costs of a PMSM motor significantly. This kind of higher efficient motors can only be realized due to the use of high-strength electrical steel.

As the deterioration on electrical steel resulting from lamination process and assembling are not included in today's FEM programs, the FEM programs have to be adopted. A first study to evaluate such effects has started in the second part of this paper with a magnetic characterization of ThyssenKrupp Steel Europe's application-specific high-strength NGO electrical steel grades. The deterioration of the magnetic materials properties due to two different cutting techniques, laser cutting and guillotine cutting, were evaluated. The impact of laser cutting for 120 mm width (standard sample with no additional cut edges) is comparable to the impact of guillotine cutting. The smaller the width of the samples, i.e. the more additional cut edges, the higher is the degradation of magnetic properties. The strongest effects are observed in the lower magnetic field and magnetic polarization area.

The results of these measurements should be interpreted in relation to the other ones of this study and not as absolute values. The deterioration effect of magnetic properties resulting from cutting can be neglected for the steel bridges of the magnet pockets as the electrical steel in this area is saturated. For the other parts of the laminations, it is advisable to take special precautions into account for laser cutting at the current state of this study. First stress relieved annealing trials with laser samples have shown that the applied magnetic field can strongly be reduced by annealing. This leads to the conclusion that stress was present inside the investigated laser samples and that the study has to be continued for other grades with diversified laser parameters as well as with further stress relieved annealing trials.

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