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Application-specific development of non-oriented electrical steel for EV traction drives

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***Abstract*— Electrical steel is mainly characterized by its magnetic properties, i.e. the specific total loss and the magnetic polarization. In addition, mechanical and physical properties as well as coating and workability can strongly influence the performance and the cost of the resulting electric machine. The various properties can be controlled e.g. via the chemical composition and the production process of the electrical steel. However, strong interdependences and physical or economical limits require tailored electrical steel grades to be developed and specifically optimized for its application. The key parameters and limits of this optimization process will be reviewed in this paper.**

***Index Terms*— Electrical steel, electric vehicles, FEM simulation, soft-magnetic material development, tailor-made electrical steel**

I. INTRODUCTION

Major activities in the field of electrification of vehicles still characterize the worldwide automotive industry in 2012. Numerous European car manufacturers will start their production of EVs and HEVs in the next years; therefore NGO (non-oriented) electrical steel comes more into focus.

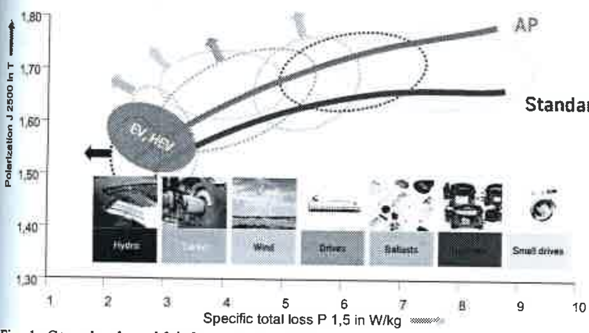

Fig. 1: Standard and higher permeability AP grades and development trends.

The requirements for NGO electrical steel in traction motors of cars are higher when compared to those for standard electric motors, due to higher rotational speed, limited available space and higher complexity of the traction drive's cooling system. Based on previous developments (330-30AP), ThyssenKrupp Electrical Steel GmbH (SE-ES) has continued the consistent optimization of NGO electrical steel for particular applications. As a global player, SE-ES offers the full electrical steel product range for electrical applications (Fig. 1). The supply of NGO electrical steel for customers all over the world is ensured by specialized cold rolling mills in Bochum (Germany) and Nashik (India). Furthermore, ThyssenKrupp Electrical Steel has a slitting services centre in Motta Visconti (Italy).

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II. KEY PARAMETERS OF NGO ELECTRICAL STEEL AND THE MANUFACTURING PROCESS

Although the development of electrical steel has started around the beginning of the 20th century, when it was discovered [1] that the increase of the electrical resistivity by alloying reduces the eddy-currents, the development has not finished yet. Especially in the case of HEVs and EVs, the requirements for the NGO electrical steel are higher than ever before. Based on limited constructed size and the higher operational frequencies, specific total losses, eddy-current losses, polarization, thermal conductivity and mechanical properties are of particular interest at elevated temperatures as well. An accurate [2] prediction of iron losses for various operating points is necessary. The resulting loss P consists [3], according to (1) of quasi-static hysteresis losses, classic eddy-current losses and dynamic excess losses [4]. When using (1), a good prediction [2] can be achieved especially for linear soft magnetic behavior at low frequencies and low inductions.

$$P = k_h B^2 f + \frac{\pi^2 d^2}{6 \rho_e \rho} B^2 f^2 + k_{excess} B^{1.5} f^{1.5} \qquad (1)$$

A way to get more accurate results is the 5-Parameter-IEM-Formula [2], (2) which yields a good approximation for a wide range of frequencies up to 10.000 Hz.

$$P = a_1 B^2 f + a_2 B^2 f^2 \left(1 + a_3 B^{a4}\right) + a_5 B^{1.5} f^{1.5} \qquad (2)$$

The steel manufacturer is able to influence the specific total loss (1) by using different alloy contents, choosing a different thickness or by optimizing the texture. The frequency is strongly affected by the layout of the electrical machine. The hysteresis losses decrease with larger grain size; classic eddy-current losses are constant and dynamic excess losses are increasing linearly with higher grain size [3]. The main factor to reduce the electrical steels losses is alloy content (mainly silicon or aluminum), sheet thickness (d) and the purity of the electrical steel. With increasing silicon content the specific electric resistivity ρ_e increases. This results in lower eddy current-losses and thus in lower core losses (Fig. 2). However, thermal conductivity (TC) and saturation polarization decrease with increasing silicon content. Especially high saturation/polarization is preferable, in order to gain higher torque in an electric drive.

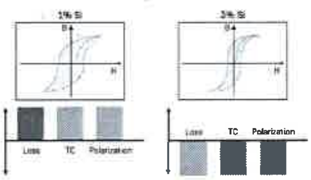

Fig. 2: Effects of Si content on core loss ($P \sim B^2/\rho_e$).

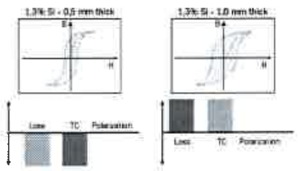

Fig. 3: Effects of sheet thickness on core loss ($P \sim d^2$).

Fig. 3 and Fig. 5 show the high influence of the sheet thickness on the core loss. A thinner sheet results in lower core loss, but also in lower thermal conductivity. The steel thickness has no significant effect on the polarization. An increase in frequency (Fig. 4) results in a higher core loss, but has almost no effect on thermal conductivity and polarization.

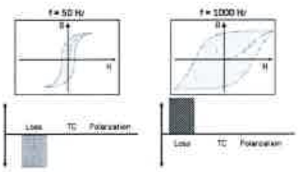

Fig. 4: Effects of frequency increase on core loss ($P1.5 \sim f^2$).

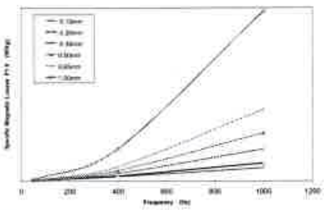
Fig. 5: Influence of sheet thickness on core loss.

The temperatures inside the electrical machine are of high importance, as various parts of the electrical machine have limited working temperatures. Tests [5] have shown that the total loss of the tested grades decreases with rising temperature (see Fig. 6) and that the coercive force is increasing (see Fig. 7).

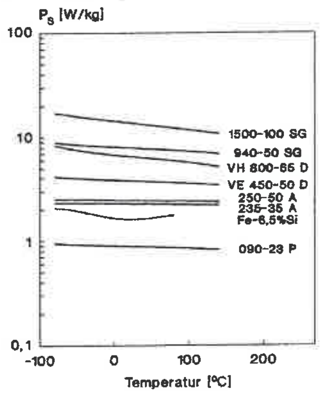

Fig. 6: Temperature dependency of total loss [5].

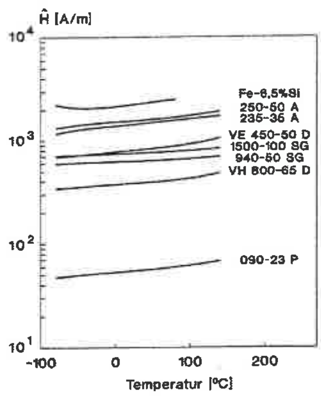

Fig. 7: Temperature dependency of coercive force [5].

The changes of magnetic properties with increasing temperature are linked to two effects [5]: on the one hand, the increase of electric resistivity results in a decrease of eddy-currents inside the material; on the other hand the decrease of saturation polarization requires an increased magnetic field strength. The temperature dependency is more distinct for electrical steel with lower alloy content [5]. The same holds for thicker material because of its higher eddy-current losses.

As finite element simulation play an important role in the motor's design stage, the data of electric resistivity and thermal conductivity can be used in the numerical models. ThyssenKrupp Electrical Steel GmbH is estimating these data from literature values in combination with the chemical composition.

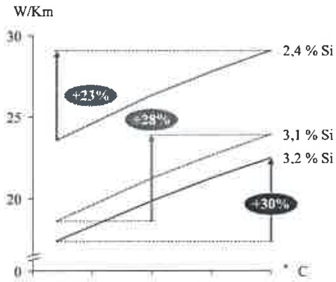

Fig. 8: Temperature dependency of electric resistivity.

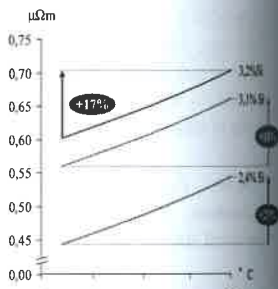

Fig. 9: Temperature dependency of thermal conductivity.

Fig. 8 and Fig. 9 show that the increase in-between room temperature and 200 °C of the electric resistivity is ~ 30 % and the increase of thermal conductivity is ~ 25 % for high silicon electrical steel.

Further important key parameters for the development of electric traction drives are linked to the needed mechanical requirements. Knowing this, SE-ES has made several analyses (for instance [6], [7]) in the past years.

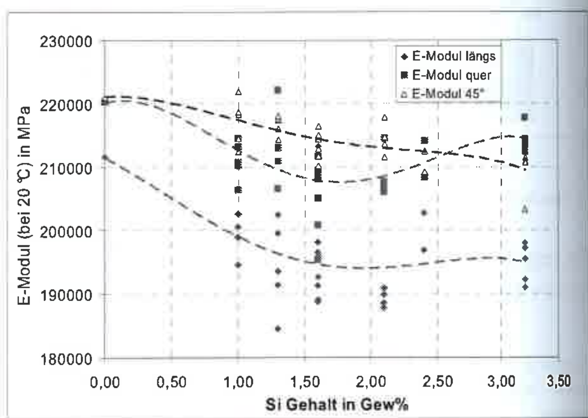

Fig. 10: Behavior of Young's modulus for different electrical steel grades [6].

Fig. 10 shows the behavior of the Young's modulus for different electrical steel grades (different alloys) in rolling direction (RD) (E-Modul längs), perpendicular (PD) (E-Modul quer) as well as in 45° (E-Modul 45°). 0 % Silicon represents unalloyed electrical steel and has with 210.000 MPa the highest values for RD. It has been identified that the Young's modulus in RD and 45° direction are decreasing with rising silicon content. This is also valid in PD direction until 1.5 % of Si; afterwards a decrease was visible.

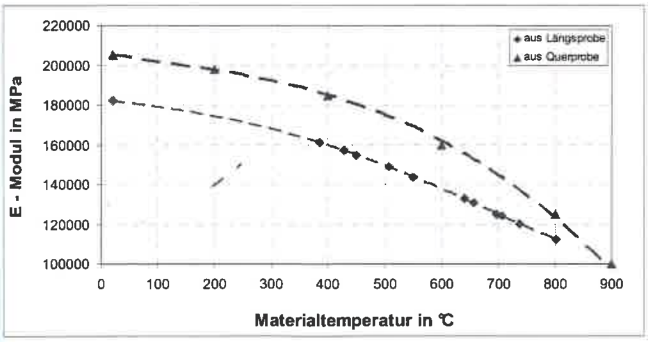

Fig 11: Behavior of Young's modulus for different electrical steel grades [6].

Fig. 11 shows the Young's modulus behavior in RD and PD for different temperatures up to 900 °C. As typical rotor temperatures are below 180 °C (to avoid demagnetization etc.), the effect of a decreasing Young's modulus is not as strong, but has nevertheless to be taken into account. Fig. 12 shows the behavior of the yield strength (YS) for different electrical steel grades and different temperatures.

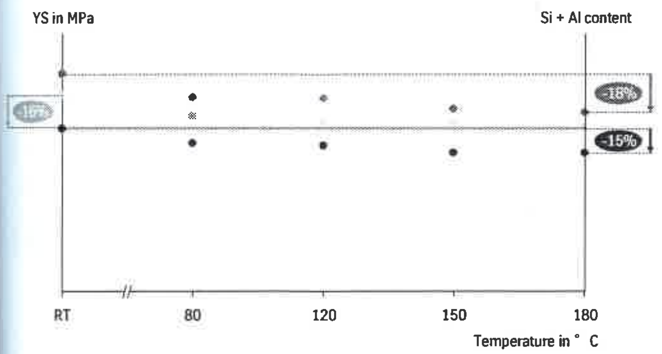

Fig. 12: Behavior of yield strength for different electrical steel grades and different temperatures [7].

Tests according to [7] have shown that the yield point decreases with increasing temperature, independent of testing direction. The result was a decrease in yield strength up to 20 % for temperatures in-between room temperature (RT) and +180 °C. Based on this, SE-ES is also focusing on grades with guaranteed and increased mechanical strength.

III. Key Processes for the Optimization on NGO Electrical Steel

By knowing the key parameters discussed earlier in this text, this section assesses some relevant process steps [8] for the magnetic properties (Fig. 13 and Table I).

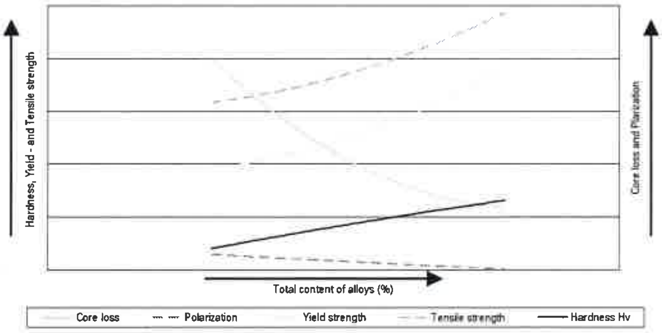

Fig. 13: Magnetic and mechanic properties, depending on the total content of alloys and the process history.

Due to the physical mechanism/effects, such as the influence of the alloy content (Fig. 13) on magnetic and mechanical properties, the production of electrical steel is always driven by the balance of magnetic or mechanical properties.

Table I: Influence of Processing Steps on Magnetic Properties [8].

Processing steps	Determining factor	Influenced magnetical parameters
Cold rolling	Sheet thickness ↑	Hysteresis losses ↓ Eddy-current losses ↑
Steel making	Alloy content (Si + Al) ↑	Eddy-current losses ↓ Polarization ↓
Steel making Hot rolling Annealing	Steel purity ↑ Precipitation ↓	Hysteresis losses ↓
Pickling Cold rolling Annealing	Surface quality ↑	Hysteresis losses ↓
Steel making Cold rolling Annealing	Grain size ↑	Hysteresis losses ↑ Eddy-current losses ↓
Steel making Hot rolling Cold rolling Annealing	Texture ↑	Polarization ↑
Annealing and after-processes	Mechanical stress ↑	Hysteresis losses ↑

Therefore, the steel manufacturer has to focus either on magnetic or mechanical properties (Fig. 13) and will receive typical data for the not very significant properties.

IV. Evaluation of Influences on NGO Electrical Steel

By knowing the key parameters discussed earlier in this text, this section assesses the influences of various processing steps [9], [1] for the magnetic properties. Particularly in the important range of flux density in electrical drives (0.5 T < J < 1.5 T) the influence of processing steps on magnetic properties [9] is according to Table II more relevant than in other ranges of flux density.

TABLE II: INFLUENCE OF PROCESSING STEPS ON MAGNETIC PROPERTIES [9].

Processing steps	Working range J < 0,5 T	Working range 0,5 T < J < 1,5 T	Working range J > 1,5 T
Cutting	Low	High	Very low
Grouting of segments	None	Low to medium	None
Welding	Low	Medium	None
Gluing	None	Low	None
Puching/ packating riveting	very low	Low to medium	Very low
Shrinking of magnatic cores into casting	very low	Low to medium	Very low

The use of coated instead of uncoated (UC) electrical steel has several advantages [1]. As a result of using Stabolit varnishes, stamping and tool life is enhanced, sticking together of laminations is avoided and a minimum surface resistivity is guaranteed. Further, the burr height (Fig. 14), as well as the effect of burrs, is minimized (Fig. 15).

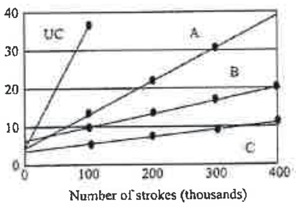

Fig. 14: Punching of uncoated and coated steel [1].

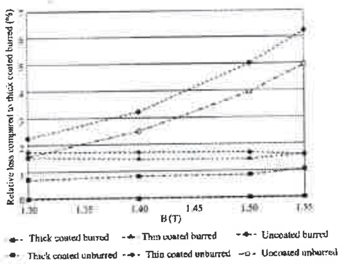

Fig. 15: Effect of burrs [1].

The integrity of the varnish on the punched laminations is also important, as additional eddy-currents and an increase of losses of 5 % to 30 % can appear [10].

V. THYSSENKRUPP ELECTRICAL STEEL'S ANSWERS

Particularly in high frequency applications, a sheet thickness equal to/thinner than 0.30 mm is used. Based on this, ThyssenKrupp Electrical Steel GmbH has developed additional PowerCore® AP grades in thickness 0.30 mm and below, see Table III.

TABLE III: OVERVIEW ON STANDARD GRADES AND APPLICATION-SPECIFIC GRADES FOR LOW SPECIFIC TOTAL LOSS AT HIGH FREQUENCIES.

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

Application-specific grades (typical data)

Grade	330-30 AP	270-25 AP	280-30AP Var. 1	280-30AP Var. 2
Nominal thickness (mm)	0,30	0,25	0,30	0,30
P1.0 50 Hz (W/kg)	1,2	1,1	1,1	1,1
P1.5 50 Hz (W/kg)	2,8	2,6	2,5	2,5
P1.0 400 Hz (W/kg)	18,0	16,0	16,0	16,0
P1.0 1.000 Hz (W/kg)	75,0	63,0	65,0	62,0
Rp0.2 [MPa]	330	320	410	440
Rm [MPa]	450	430	530	550
HV5	165	150	190	200

The aim was to reduce the specific total losses at high frequencies (1.000 Hz) based on different requirements. One application-specific product/answer is our grade 330-30AP with its typical core loss of 75 W/kg at 1.000 Hz @ 1.0 T. A further application needs lower core losses over the entire range of operation of the electric machine as well as a grade with lowest impact of possible influence according to chapter IV. For such requirements, the grade 280-30AP Var. 1 with its typical core loss of P1.5 = 2.5 W/kg and 65 W/kg at 1.000 Hz @ 1.0 T has been developed. For applications with need for higher yield and tensile strength, the grade 280-30AP Var. 2 was developed, see Table III.

In order to fulfill the high requirements on the material, ThyssenKrupp Electrical Steel GmbH is not only concentrating on the properties of its electrical steel grades itself, but on the behavior of the electrical steels inside the electric machine. It is not possible to obtain detailed motor properties only from the measured magnetic properties of the electrical steel itself. For this reason, ThyssenKrupp Electrical Steel GmbH has started the characterization of electrical steel by using FEM simulation tools and building prototypes to validate the calculated results. Each motor design requires an optimal electrical steel grade concerning thickness, magnetic and mechanical properties and costs.

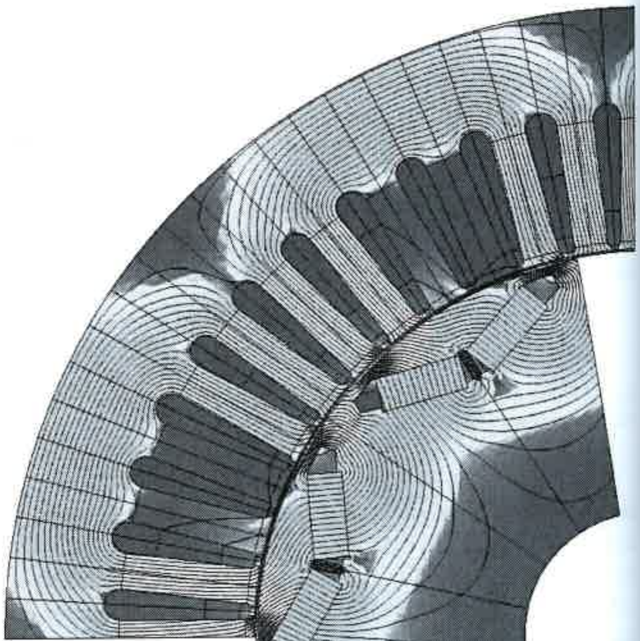

Fig. 17: Flux density plot of PMSM simulation [11].

With the use of FEM simulations, SE-ES is able to directly compare different NGO grades in standard motor designs, in order to assist its partners with the choice of the best electrical steel grade. As an example (Fig. 17), a standard PMSM with embedded magnets has been simulated to analyze the behavior of iron losses as a function of the alloy content and lamination thickness (Fig. 18) at a field frequency of 400 Hz.

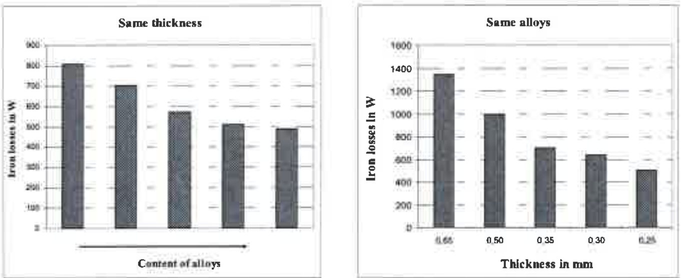

Fig. 18: Iron losses at various thicknesses and alloy contents [11].

In PMSM with high rotational speed and embedded magnets, the mechanical characteristics of the electrical steel are more important than in standard industrial drives. To analyze the mechanical possibilities of a steel grade and to offer an optimal compromise with magnetic properties for a specific application, SE-ES is also able to do mechanical simulation of a motor design.

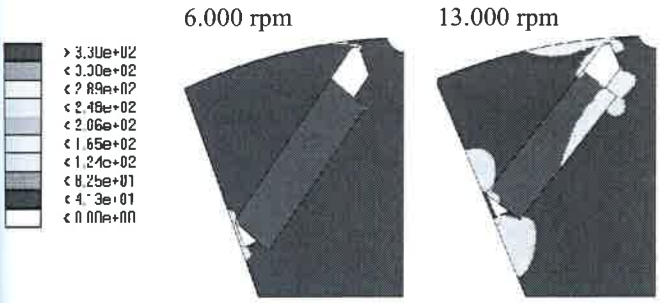

Fig. 19: Mechanical consideration at the stressed rotor parts [12].

In the simulation shown in Fig. 19, a calculation of a symmetric rotor model [11] has been done at various rotational speeds.

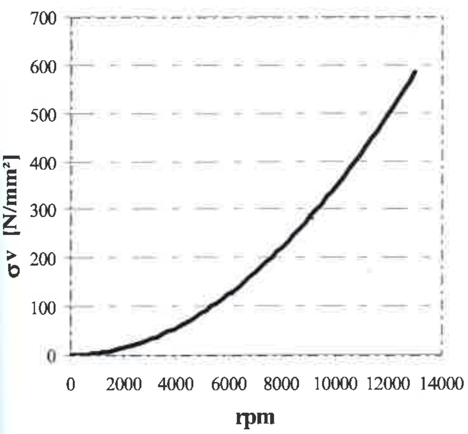

Fig. 20: Mechanical stress between magnets [11].

The critical bridges between the magnets and at the outer boundary were set to 0.8 mm. The mechanical stress in the rotor depending on the rotational speed is shown in Fig. 20.

VI. Conclusions

Key parameters, limits and interaction of mechanical and magnetic properties achieved by an optimization of NGO electrical steel have been reviewed. The changes due to elevated temperature have been under particular interest. Therefore, ThyssenKrupp Electrical Steel GmbH develops application-specific NGO electrical steel grades to fulfill the demands of each specific motor design and to improve its efficiency. They are continuously improving properties and production of electrical steel in order to support customers in building high-efficient electric machines around the world. With the technological background of the complete ThyssenKrupp group in topics of simulation, prototype manufacturing and measuring, SE-ES has a big spectrum to assist its partners in the optimization of new machines or to improve existing machines relating to efficiency and costs. The main target of ThyssenKrupp Electrical Steel GmbH is to generate productivity advantages for their technology driven customers.

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