Loss Reduction due to Blanking Parameter Optimization for Different Non-Grain Oriented Electrical Steel Grades

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***Abstract*—An optimized electrical machine design can improve its efficiency and power density. While magnetic and mechanical design of rotor and stator laminations for varying types of electrical machines is well understood, influence of process induced mechanical stresses on magnetic behavior of non-oriented electrical steel grades is widely unknown. Especially when looking at the blanking process, magnetic properties like iron losses and magnetizability are detrimentally altered due to cutting induced residual stresses. There have been investigations of individual electrical steel grades, which show a significant extent of magnetic property deterioration depending on the process parameters used. This paper studies influences of different blanking process parameters on magnetic properties of various non-oriented electrical steel grades. Several materials with different grain size, silicon content and thickness are investigated. Magnetic properties of processed electrical steel specimens are analyzed using a single sheet tester. The results enable a correlation between material grade, sheet thickness, blanking parameters and magnetic properties to be studied.**

Keywords*—non-oriented electrical steel; shear cutting; blanking; magnetic property deterioration; loss reduction

I. Introduction

Rotor and stator cores of electrical machines are built up from stacked non-oriented electrical steel laminations. The overall efficiency and performance of an electrical machine strongly depends on alloying elements, thickness and heat treatment of the material used. Besides these influencing factors, the production process significantly alters magnetic properties of rotor and stator cores which results in decreased machine efficiency and power density [1]. This behavior is caused by the inverse magnetostrictive effect, which describes a reduced domain wall mobility in regions where process-related residual stresses are present [2]. In order to investigate the extent of this effect the electrical steel grade M270-50A has been processed by water jet cutting, blanking and guillotining and magnetically analyzed using a single sheet tester. Fig. 1 displays local material hardness H with respect to virgin material hardness H_0 as well as differences in magnetic behavior at 100 Hz and 1.0 T. The cutting line and magnetic field orientation are aligned in rolling direction. A correlation between process-related material hardening and magnetic property degradation can be noticed. In comparison to water jet cutting, blanking and guillotining lead to increased material hardening due to plastic material deformation. Thereby more residual stresses are induced into the area next to the cutting surface. This results in increased hysteresis shearing, which leads to higher magnetic field strengths being needed to reach the same magnetic polarization. In addition specific losses rise with increasing material deformation.

Taking a closer look on the manufacturing process, it can be noticed that even small changes like alternating blanking parameters result in different residual stress states. Using worn instead of sharp cutting edges for example leads to larger plastic material deformations and thereby more residual stresses [3]. Residual stresses' impact on electromagnetic behavior is also dependent on magnetic field strength and frequency [4]. Additionally, the induced residual stress magnitude as well as proportion of tensile and compressive stresses affect the magnetizability of an electrical steel [5, 6].

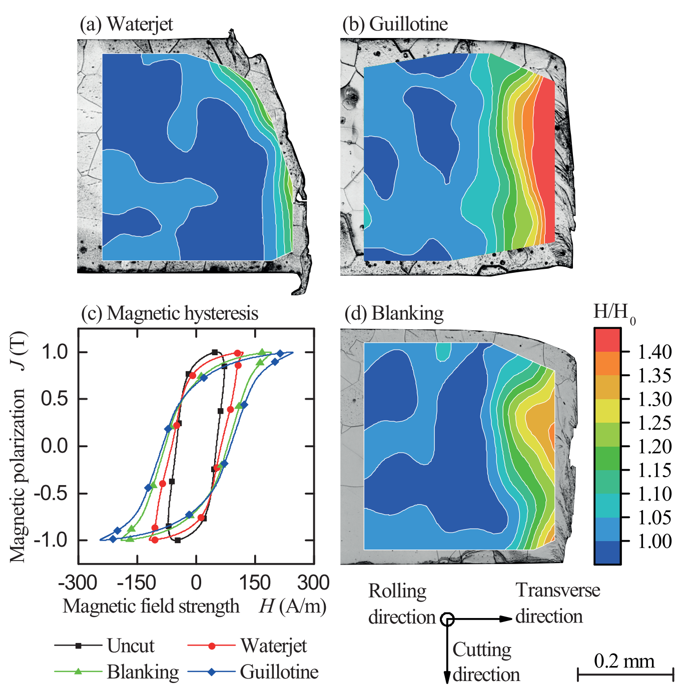

Fig. 1 Influence of the three different cutting techniques waterjet cutting (a), guillotining (b) and blanking (d) on material hardness next to the cutting surface as well as on the magnetization behavior at 100 Hz and 1.0 T in rolling direction (c)

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The influence of a blanking-related magnetic property deterioration when processing different electrical steel grades has not been investigated in detail until now. By comparing the impact of blanking parameter variations on the magnetizability of different alloyed, rolled and heat-treated electrical steels, an optimized manufacturing strategy that leads to minimized iron losses can be found. This analysis also allows a better consideration of blanking related losses when designing new electromagnetic components. In addition, the results are transferable to other non-grain oriented electrical steel grades. In order for this goal to be achieved, a combined mechanical and electromagnetic investigation of blanked electrical steels is required.

II. Materials

Within this investigation, eight different electrical steel grades are analyzed. The materials have been chosen in such a way that a wide field of application can benefit from the results. Processing influence is examined for four different thicknesses s_0 0.3, 0.35, 0.5 and 0.65 mm. The materials have a silicon content ranging between 1.5 and 2.8 wt % and have been rolled and heat-treated differently. This results in a broad spectrum of different effective grain sizes, material hardnesses as well as mechanical and magnetic properties. All investigated materials are coated with an inorganic C-5 coating with organic components.

All electrical steels used are metallographically, mechanically, chemically and magnetically characterized. Average grain size d_g is determined analyzing micrographs according to EN ISO 643. A micro hardness tester is used to measure virgin material hardness according to Vickers. Mechanical characteristics like ultimate tensile strength R_m or uniform elongation A_g are determined in tensile tests according to EN ISO 6892-1. In addition, magnetic properties are determined using a 60 x 60 mm single sheet tester according to EN 10106. Table I shows the material properties investigated. Mechanical and magnetic properties displayed are average values of measurements in rolling direction (RD) and transverse direction (TD).

Due to the different alloys, cold rolling and heat treatment strategies the ratio of blank thickness to average grain size reaches from 2.8 for material A to 6.6 for material H. High silicon contents lead to larger average grain size, elevated material hardness, higher ultimate tensile strengths and lower uniform elongation. The specific loss P_S also decreases with rising silicon content at constant sheet thicknesses.

III. Experimental Setup

A high-precision blanking tool in four-pillar design enables the production of specimen for electromagnetic investigations using specific cutting parameters. The tool is operated within a mechanical stamping press at 100 strokes per minute. Punches and dies are made of a tungsten carbide tool material that is also used in industrial processing of electrical steel. A sketch of the basic tool construction and the real blanking tool setup is shown in Fig. 2 (a) and Fig. 2 (b).

During the actual blanking process, the sheet metal is clamped between blank holder and die. The material is then cut by the punch that travels towards the die. Grooves milled into the die help prevailing burr at the generated cutting surfaces from getting deformed when cutting small sample widths and therefore changing the process-related residual stress state. An integrated piezo force and inductive tool travel measurement system allow an online blanking process monitoring with 100.000 samples per second.

Cutting clearance (CCL) and wear state of punch R_P and die R_D have a great effect on induced residual stresses when blanking electrical steel [3]. In order to investigate process-related residual stress impact on magnetic property degradation, punch and die can be changed. This allows CCL from 15 to 70 µm to be realized. The dimensions are selected in such a way that similar CCL-blank-thickness-ratios can be examined for different materials. Table II gives an overview of CCL used. Since the impact of tool wear is also investigated, an additional punch and die with grinded cutting edges at a CCL of 35 µm exist. The cutting edge chamfer geometry, a tangent-continuous ellipse with the two dimensions R_f and R_s, is shown in Fig. 2 (c). The machined edges represent a carbide tool wear after blanking a 0.3 mm electrical steel for four million times ($R_{f,4mil}$ = 70 µm, $R_{s,4mil}$ = 100 µm). The worn cutting edges are referred to as 'worn' and new cutting edges ($R_{f,0}$ = 5 µm, $R_{s,0}$ = 5 µm) without any wear as 'sharp'.

TABLE I. Thickness, silicon content, mechanical and magnetic properties of the investigated materials

Material	Thickness s_0 (µm)	Average grain size d_g (µm)	Si (wt %)	Material hardness (HV02)	Mechanical properties		Specific loss P_S (W/kg)		Magnetic polarization J (T)	
					R_m (MPa)	A_g (%)	1.0 T 50 Hz	1.5 T 50 Hz	2,500 A/m 50 Hz	5,000 A/m 50 Hz
A	300	107	2.8	226	596	8.4	1.08	2.60	1.53	1.62
B	350	87	2.8	227	613	9.1	1.30	2.93	1.55	1.63
C	350	70	2.4	196	527	11.0	1.42	3.31	1.55	1.63
D	350	58	1.5	168	429	14.7	1.63	3.46	1.67	1.75
E	500	111	2.8	224	578[a]	8.4	1.26	2.92	1.55	1.63
F	650	121	2.8	221	589	9.3	1.64	3.65	1.57	1.65
G	650	102	2.4	195	513	11.1	1.78	4.08	1.58	1.66
H	650	98	1.5	171	407	14.4	1.99	4.44	1.66	1.74

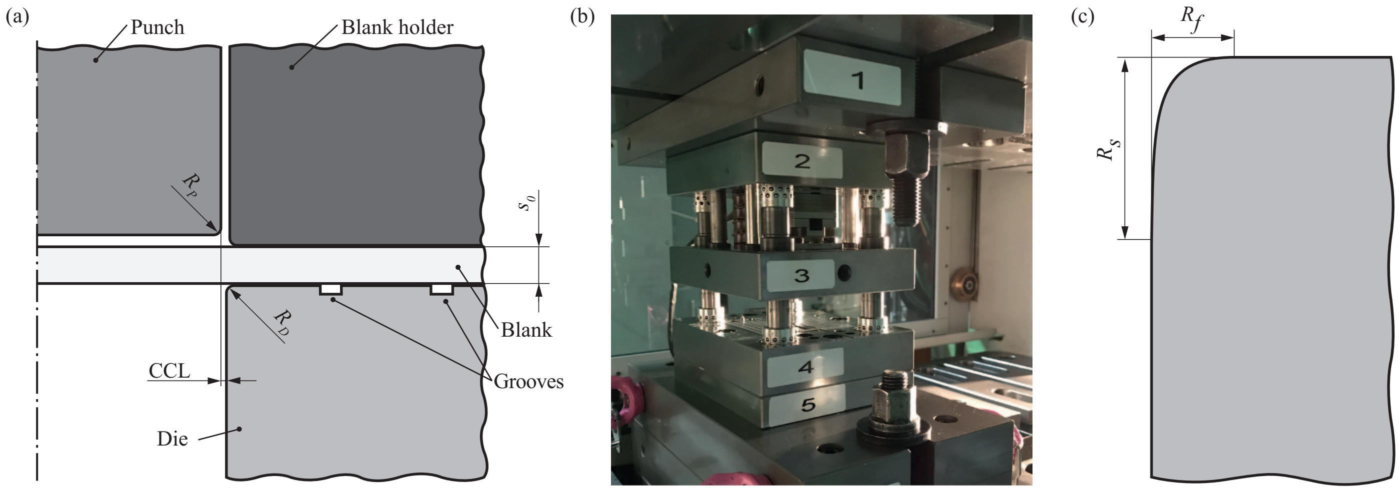

Fig. 2 (a), Blanking tool sketch; (b), Blanking tool inside the mechanical blanking press; (c), Cutting edge chamfer

TABLE II. INVESTIGATED CCL AND CCL-BLANK-THICKNESS-RATIO

s_0 (µm)	CCL (µm)				
	15	**19**	**35**	**50**	**70**
	CCL/s₀* *(%)				
300	5.0	-	11.7	-	-
350	-	5.4	10.0	-	-
500	-	-	7.0	10.0	-
650	-	-	5.4	-	10.8

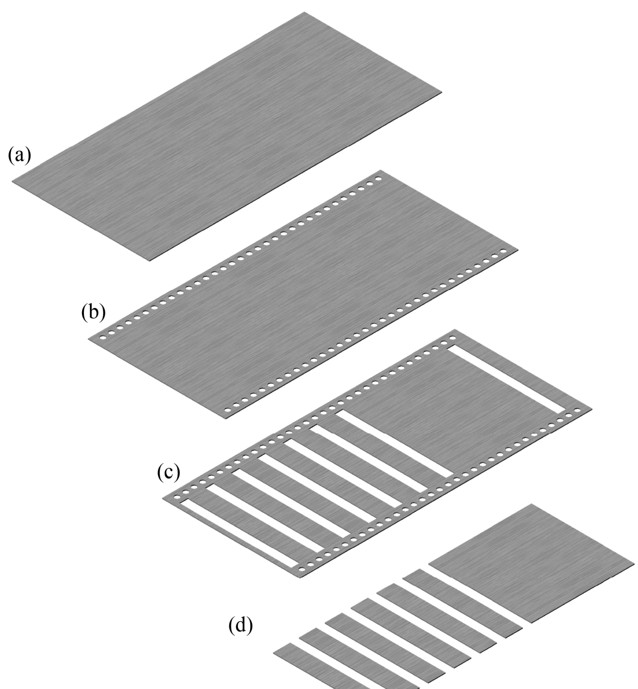

Fig. 3 Manufacturing process of single sheet tester specimens; (a), uncut sheet; (b), punching the positioning grid; (c), blanking of six 10 mm specimen and one 60 mm specimen with various different process parameters; (d), positioning grid removal

The specimen manufacturing process for electromagnetic determination of the blanking influence is shown in Fig. 3. Sheet metal strips with a dimension of 165 x 82.5 mm are cut parallel and transverse to rolling direction from the electrical sheets (Fig. 3 (a)). This permits an examination of the blanking influence as a function of cutting line position relative to rolling direction. Afterwards, a positioning grid, which guarantees a constant specimen width, is punched into the sheet metal strips (Fig. 3 (b)). Subsequently, the strips are blanked with specific blanking process parameters. Depending on the positioning of the rectangular cutout, strip widths of 5 to 60 mm can be produced as shown in Fig. 3 (c). Finally, the positioning grid is removed so that sheet metal strips with a variable width and a length of 60 mm are created. Fig. 3 (d) shows a 60 x 60 mm and six 10 x 60 mm samples.

Measuring the degraded electromagnetic properties of blanked electrical steel is made possible by inserting more residual-stress-affected material volume into the measuring volume of a 60 x 60 mm single sheet tester. The electromagnetic properties are tested at excitation frequencies f of 10, 50, 100 and 400 Hz. Maximum magnetic polarizations J_{max} of 0.5, 1.0, 1.5 and 1.8 T are investigated. Magnetization direction is always aligned within same direction as the cutting line. The single sheet tester is integrated into a computer-assisted test set-up according to international standard IEC 60404 3.

When determining the blanking-related electromagnetic property degradation, first an electrical steel specimen with dimensions of 60 x 60 mm is examined. As a result of increasing cutting line length due to reduction of sheet metal strip width at constant material volume, more and more stress affected material is inserted into the single sheet tester's measuring volume. When twelve 5 x 60 mm strips are tested, the cutting line length as well as residual stress affected material volume increases by a factor of twelve compared to a 60 x 60 mm specimen. Comparing varying cutting line length measurements at different magnetic field intensities and excitation frequencies allows a detailed investigation of blanking process parameter variations.

IV. Results

First the magnetic property degradation due to blanking is examined depending on the cutting line orientation to rolling direction. Therefore, cutting line lengths of 120, 720 and 1440 mm which correspond to the specimen quantity and size of one 60 x 60 mm, six 10 x 60 mm and twelve 5 x 60 mm are investigated. Fig. 4 shows specific losses (a, b) and magnetic hysteresis (c, d) measured at 50 Hz and at different maximum magnetic polarizations for material F depending on the orientation of cutting line to rolling direction. Specimens were blanked using a CCL of 10.8 % and sharp cutting edges.

Higher specific losses can be noticed with rising cutting line length independent of specimen orientation. The maximum magnetic field strength needed to reach the same polarization levels also increases. Looking at different orientations to rolling direction, elevated specific losses and more hysteresis shearing is observable when magnetizing in transverse direction. Calculating an orientation dependent specific loss increase ratio $P_{S,inc,OR}$ with specific losses $P_{S,1440,OR}$ at 1440 mm and $P_{S,120,OR}$ at 120 mm cutting line length according to (1) helps analyzing magnetic property degradations.

$$P_{S,inc,OR}\ (J_{max}, f) = P_{S,1440,OR}\ (J_{max}, f) \,/\, P_{S,120,OR}\ (J_{max}, f) \quad (1)$$

In case of a cutting line orientation variation, the specific loss increase changes from 1.46 in TD to 1.62 in RD at a magnetic polarization of 1.0 T and an excitation frequency of 50 Hz. At elevated magnetic polarizations of 1.8 T the specific loss increase varies from 1.23 in TD to 1.28 in RD. A higher impact on magnetic property degradation when blanking in RD can be observed regardless of the material examined.

In order to simplify the result analysis, an orientation independent specific loss increase $P_{S,inc}$ can be calculated according to (2).

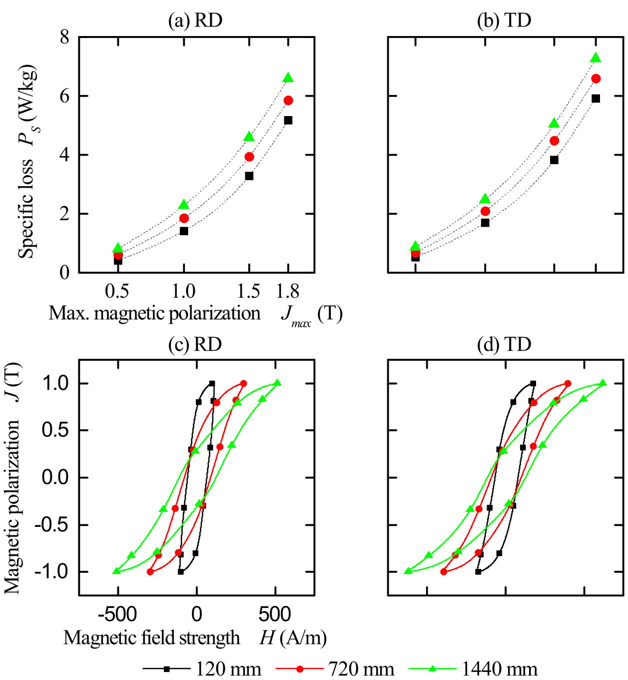

Fig. 4 Strip width and cutting line orientation influence on specific losses at varying polarizations (a) as well as on the hysteresis curve (b) of material F at 50 Hz

$$P_{S,inc}\ (J_{max}, f) = [P_{S,inc,RD}\ (J_{max}, f) + P_{S,inc,TD}\ (J_{max}, f)] \,/\, 2 \quad (2)$$

In Fig. 5 the influence of residual stresses due to blanking with 11.7 % CCL for material A, 10.0 % CCL for material B, C, D, E, 10.8 % CCL for material F, G, H and sharp cutting edges at different excitation frequencies and varying maximum

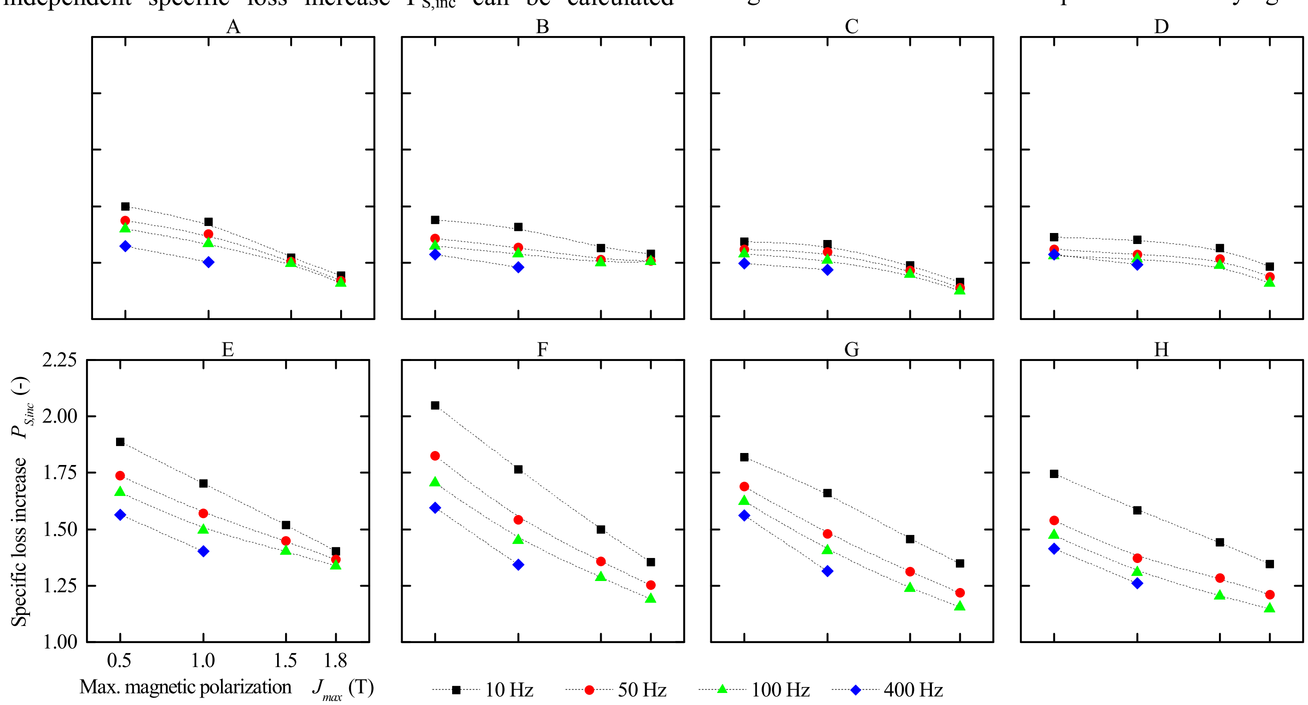

Fig. 5 Specific loss increase when blanking with 11.7 % CCL for material A, 10.0 % CCL for material B, C, D, E, 10.8 % CCL for material F, G, H and sharp cutting edges at different excitation frequencies and varying maximum magnetic polarizations

magnetic polarizations is shown. The specific loss increase due to blanking significantly depends on the magnetic polarization and excitation frequency with which the specimens are tested. Major blanking impacts can be observed at low frequencies and polarization levels. Specific loss increases can reach up above 2.05 for electrical steel grade F at 0.5 T and 10 Hz. Even at polarizations of 1.8 T at 100 Hz specific loss increases still lie in between 1.09 and 1.15.

Looking at different electrical steel grades, specific loss increase rises with a growth in blank thickness. Additionally, materials with higher silicon content and high ultimate tensile strength are more affected by blanking induced residual stresses. For such steels, higher dependencies of specific loss increases due to blanking can be noticed.

The blanking-related magnetic property deteriorations for different maximum magnetic polarizations at an excitation frequency of 50 Hz are depicted in Fig. 6 for each material investigated. The blanking parameter variations shown, range from 5.0 % to 11.7 % CCL and from a sharp to a worn cutting edge.

Regardless of the electrical steel grade observed, the possibility to reduce specific losses using optimized blanking parameters gets smaller when operating electrical steels at rising maximum magnetic polarization levels. This behavior can also be examined at elevated excitation frequencies. Apart from that, the possibility of reducing specific loss by using optimized blanking parameters can improve performance of electrical machines that are operated at low polarization and frequency levels is still given.

Comparing different blanking parameter variations to each other, it can be noticed that higher CCL as well as worn cutting edges result in higher specific losses. Blanking with small cutting CCL and sharp cutting edges leads to minimized specific loss increases. Overall cutting edge wear has a larger impact on specific loss increase than the effect of a CCL variation.

Taking different electrical steel grades into account, it can be recognized that materials with high ultimate tensile strength (A, B, E, and F) can be influenced to a larger extent than materials with lower ultimate tensile strength (C, D, G, and H). Especially cutting edge wear state has a bigger impact on magnetic property deterioration when looking at electrical steel grades with higher ultimate tensile strength.

An analysis of the blanking force over punch travel helps understanding the effect of magnetic property degradation due to blanking parameter variations. In addition to the maximum blanking force that is needed to cut a given geometry out of a steel lamination, the blanking force over tool travel curve indicates the quantity of plastic material deformation. The surface below the blanking force over tool travel curve represents the amount of work needed to deform an electrical steel plastically till fracture occurs. From an electromagnetic point of view, mostly blanking work before start of localized necking and crack initiation contributes to residual stresses that reduce magnetic properties of electrical steels.

The blanking force over tool travel curves for electrical steel grades F and H are shown in Fig. 7. The influence of CCL as well as cutting edge wear state variations on resulting blanking forces are displayed. For both electrical steel grades decreasing maximum blanking forces can be observed when reducing CCL from 10.8 % to 5.4 % using sharp cutting edges. Changing cutting edge wear state from sharp to worn at a CCL of 5.4 % results in increasing maximum blanking forces.

Before taking a closer look at the electromagnetic relevant

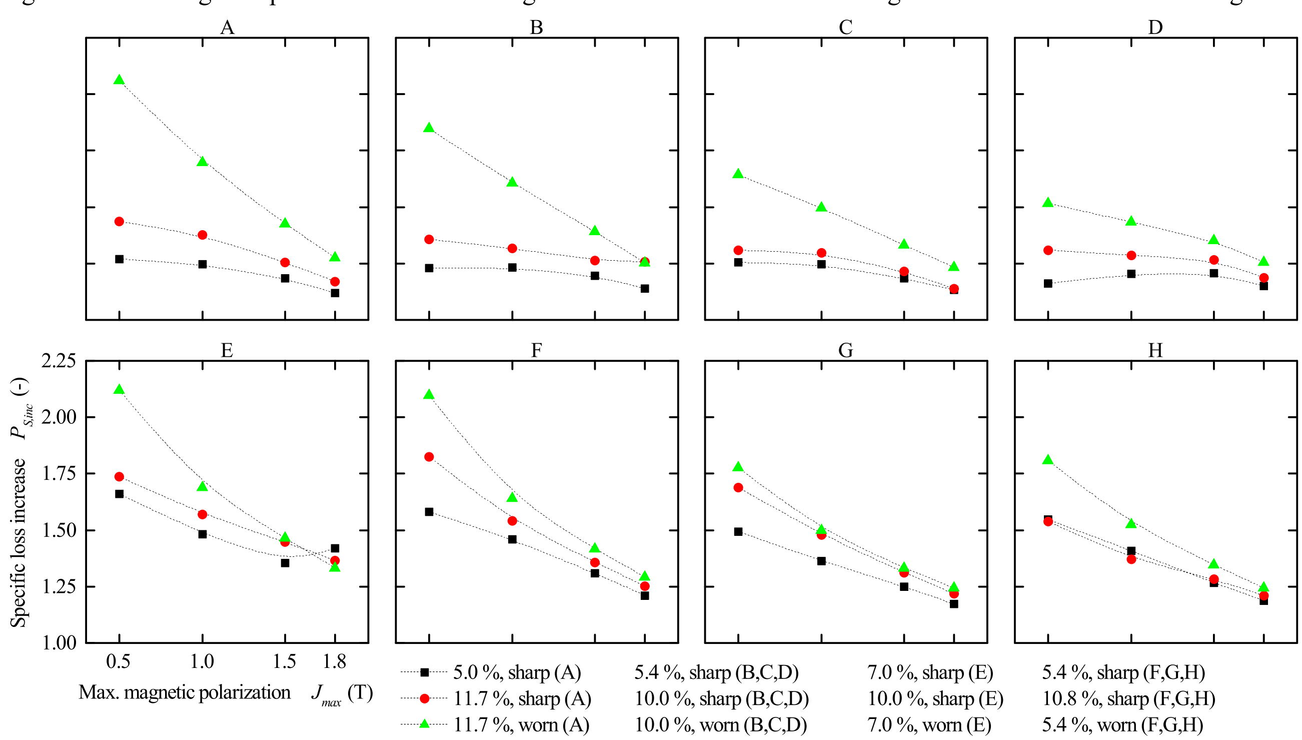

Fig. 6 Blanking parameter influence on specific loss increase for material A to H at an excitation frequency of 50 Hz and at varying magnetic polarizations

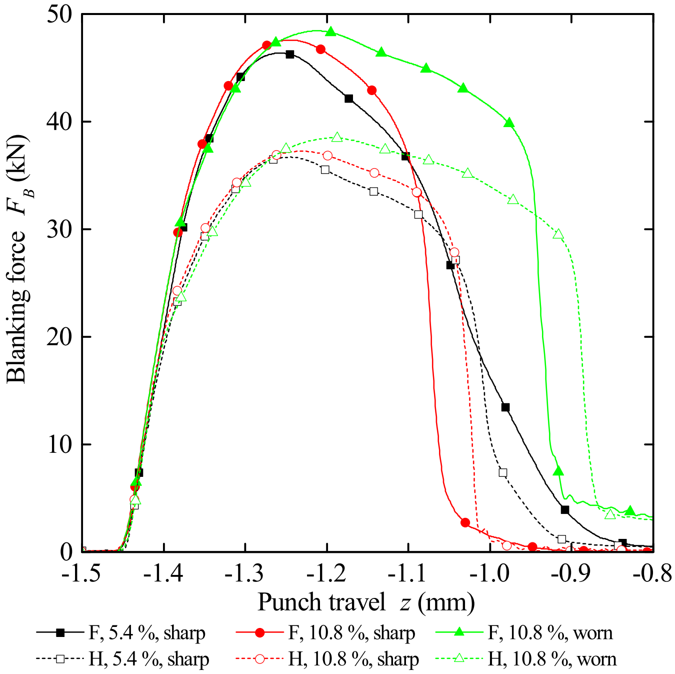

Fig. 7 Blanking force over punch travel for material F and H processed with 5.4 %, 10.8 % CCL using sharp and 10.8 % CCL using worn cutting edges

blanking work, first the point of crack initiation has to be identified. In the cutting force over tool travel curves, a small change in curvature after reaching maximum blanking force and before complete material failure can be observed. Taking this point into account, blanking work increases when cutting with worn instead of sharp cutting edges. Reducing CCL for material F also leads to decreased blanking work needed to reach crack initiation. For material H CCL variation does not have big influence on blanking work till crack initiation. These tendencies for blanking work spent until localization begins correlate to specific loss increase when processing electrical steels with varying blanking parameters at low excitation frequencies and polarization levels.

V. Conclusion and Outlook

For the first time, these investigations allowed an analyzation of how blanking processes impact electromagnetic material properties. Cutting clearance and cutting edge wear state variations were examined. A wide range of different electrical steel grades ensured that interactions between metallographic, mechanical and electromagnetic properties and punching process were identified. The results presented within this paper are intended to facilitate future electric drive layout and design and thus contribute to increasing energy efficiency as well as reducing carbon dioxide emissions.

Regarding magnetic property degradation due to blanking-related residual stresses, the following effects have been observed:

- Increasing cutting line length and thereby rising stress affected volume inside the analyzed measurement volume leads to higher specific loss and larger hysteresis shearing. Varying mechanical and magnetic properties in rolling and transverse direction cause this behavior to differ depending on cutting line orientation.
- Specific loss increase due to residual stresses reaches its maximum for low excitation frequencies and polarizations regardless of the investigated blanking parameter set.
- A reduction of specific losses with optimized blanking parameters is possible. The extent of specific losses that can be reduced depends on the excitation frequency and on the magnetic polarization. For example, specific loss increase has been reduced by up to 80 % at frequencies of 50 Hz and polarizations of 0.5 T for electrical steel grade A.
- Blanking-related magnetic property degradation strongly depends on the mechanical properties of an electrical steel grade. High ultimate tensile strength leads to an increased blanking parameter sensitivity. For example cutting edge wear state has far more influence on high strength electrical steel grades.
- Less cutting clearance and less cutting edge wear can reduce specific loss. An optimized cutting clearance has to be defined in the magnetic machine design process before ordering a new stamping tool. Cutting edge wear can be reduce by using a wear resistant punch and die material like tungsten carbide. Additionally, cutting edges have to be sharpened more often to reduce excessive plastic material deformations.

To improve electric machine simulations, not only the specific loss increase but also the penetration depth of residual stress affected material volume next to the cutting line needs to be known. First blanking process finite element analysis in [3] show that the affected volume reaches 1 mm deep into the material outgoing from the cutting line. To validate these simulations, a neutron grating interferometry analysis of blanked specimens will be presented in the near future. This analysis will help understanding up to which extent domain wall mobility is inhibited by local residual stresses at varying magnetic polarization levels.

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