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Impact of grain size distribution on the magnetic deterioration due to cutting of electrical steel sheets

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ABSTRACT

Efforts to increase the power density and continuous power of electric machines have intensified the request for tailored non-grain oriented electrical steel grades. Possible measures to optimize electrical steel grades are the use of thinner gauges as well as grades with tailor-made microstructural properties. However, these grades are developed mainly focusing on the magnetic and mechanical properties, neglecting the detrimental and strongly material-dependent processing effect on the magnetic properties of electrical steel, especially the cutting influence. In this paper, the microstructure-dependence of the magnetic material deterioration due to guillotine cutting is studied on ten industrial non-grain oriented electrical steels with thicknesses between 0.1mm and 0.35mm, all of which the chemical composition, grain structure and texture is known. This allows a consideration of the interdependence of material thickness, microstructure, alloy content with the cutting effect. The magnetic deterioration is characterized on a single-sheet-tester with samples in rolling as well as transverse direction. The grain size distribution and homogeneity is evaluated and linked to magnetic-loss and magnetization-curve deterioration by means of statistical methods. As a result sheet-thickness-dependent microstructures are evaluated with respect to their cutting influence.

1. Introduction

Non-grain oriented (NO) electrical steels are typically used in rotating electrical machines. The magnetic proprieties of the electrical steel laminations determine the operational characteristics of the electrical machine, because the torque is proportional to the magnetic flux density in the air gap and the speed is related to the magnetizing frequency. If the electrical steel is easier to magnetize, less magnetic field is required and, thereby, the copper losses decrease. Together with the reduction of iron losses in an alternating or rotating magnetic field, the efficiency and power density of the machine can be increased. Easy magnetization, low losses and a low frequency dependence of the electrical steel are targets for NO material design.

Common production measures to obtain the required magnetic properties include the alloying with Silicon (Si) and Aluminum (Al), to increase the specific electrical resistivity and, thereby, reduce classical Foucault eddy currents [1–3]. Due to the accompanied decrease of saturation polarization and increase of mechanical strength that hampers the cold-rolling reduction, the Si-content is often limited to 3.3 wt% [1]. Eddy-current losses are further proportional to the thickness of the steel sheets [4]. A decrease of the sheet thickness is another measure to reduce losses [5].

The development of advanced NO electrical steels by means of microstructure and texture optimization is a recent and ongoing topic of various research groups [6–9]. Magnetic favorable textures are hard to control with conventional rolling techniques. The microstructure, however, is relatively easy to alter, with adaptation of annealing treatment, i.e., time, temperature and cooling conditions. Alloying, rolling reductions to achieve a certain final thickness, grain structure and texture evolution interrelate throughout the process chain, which can be utilized to produced tailor-made materials [10–12]. What is often neglected with this approach, is the detrimental effect of the proceeding mechanical processing, for example of punching [13,14]. Punching induces plastic deformation and mechanical residual stress in the vicinity of the cut edge. The deterioration can depend on the thickness, alloying and grain structure [15].

Considering the aforementioned relations, the material design should not stop at the stage of the sheet material that is tested with a single-sheet-tester (SST) or an Epstein-frame (EF), but include the processing of these materials. Therefore, the effect of cutting depending on the material characteristics is studied on ten industrial NO grades in this paper. A strong focus is placed on the microstructure, which is

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Table 1
Sample widths and magnetic measurements.

Polarization J_{max}	0.1 T to 1.8 T in 0.1 T-steps
Frequency f	5 Hz, 10 Hz 50 Hz 100 Hz …5000 Hz
Strip widths d_{strip}	120 mm, 60 mm,30 mm, 15 mm, 10 mm, 7.5 mm, 5 mm, 4 mm

evaluated statistically and correlated to the cutting degradation. This information allows the motor designer to add further selection criteria to the material selection process depending on the geometry and size of the electric machine.

2. Experimental

The magnetic measurements in this study are conducted on a 120mm x 120mm SST with a Brockhaus measurement system MPG200. Samples are cut in rolling direction (RD) and transverse direction (TD) of the steel sheets in order to account for the materials anisotropy. The cut-edge effect is studied by cutting the rectangular samples into different separate strips with a guillotine shear and adjusting strips of equal width d_{strip} parallel, up to the original sample size of 120 mm × 120 mm, i.e., 2 strips of 60 mm × 120 mm, 4 strips of 30 mm × 120 mm, etc. [16,17]. The samples are characterized under an alternating, sinusoidal magnetic flux density with magnetizing frequencies of 5 Hz up to 5000 Hz. The studied widths, frequencies and polarizations are collected in Table 1.

The ten studied materials are all conventional, industrial NO electrical steels with a silicon content above 2.5 wt%. This means no phase transition occurs during the production process. The thicknesses, mean grain diameter and alloying content of Si and Al are presented in Table 2. The grain size is determined with the line intercept method on optical surface micrographs in the middle of the sheet plane. For each material, at least 300 mean grain diameters are evaluated.

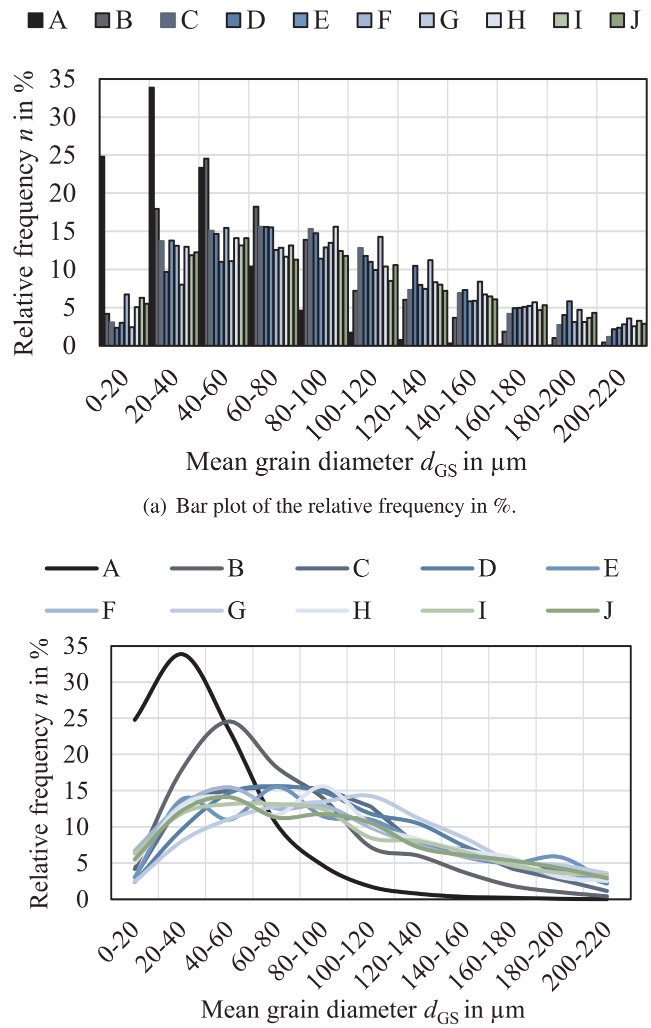
3. Results and discussion

3.1. Statistical grain size evaluation

The mean grain diameter of the ten materials are displayed in Table 2. Magnetic properties are very sensitive to grain size, especially losses [6,8]. The grain size distribution can, however, be more or less homogeneous. A material with very large grains and small grains can have the same mean value as a material with more or less all medium sized grains. Therefore, a histogram is a first statistical technique to consider grain size distribution. In Fig. 1 a histogram for the studied materials is displayed. The bars are ordered by their material name, i.e., mean grain size from A to J. Material A is an example for a material with a sharp peak in grain size at relatively low grain sizes. Materials F

Table 2
Nominal thickness d_{sheet}, chemical composition and mean grain diameter d_{GS} of the studied materials.

	d_{sheet}	wt% Si	wt% Al	d_{GS} in µm
Material A	0.10 mm	3.30	0.5	45
Material B	0.10 mm	2.87	1.23	79
Material C	0.20 mm	3.77	0.89	95
Material D	0.30 mm	2.91	1.51	98
Material E	0.23 mm	3.64	0.87	110
Material F	0.25 mm	3.34	0.83	114
Material G	0.23 mm	3.60	1.17	116
Material H	0.27 mm	3.16	1.23	118
Material I	0.35 mm	3.32	0.76	130
Material J	0.27 mm	3.39	1.50	134



(a) Bar plot of the relative frequency in %.

(b) Line graph of the relative frequency in %.

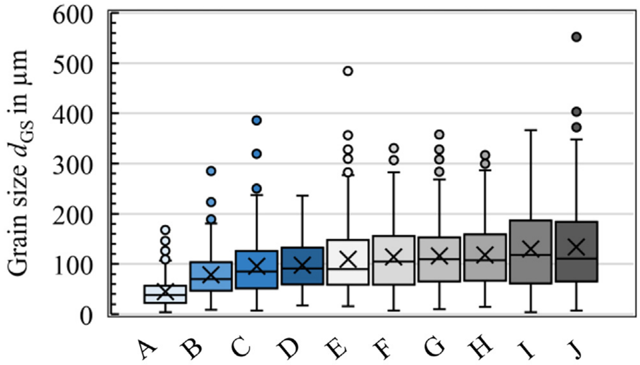
Fig. 1. Statistical grain-size evaluation of the studied materials by histogram comparison.

and G have a wider distribution of grain sizes. None of the materials shows two local distinct peaks in the histogram, which would suggest inhomogeneous grain growth. The materials can therefore be described as generally homogeneous with different ranges of the grain-size distribution.

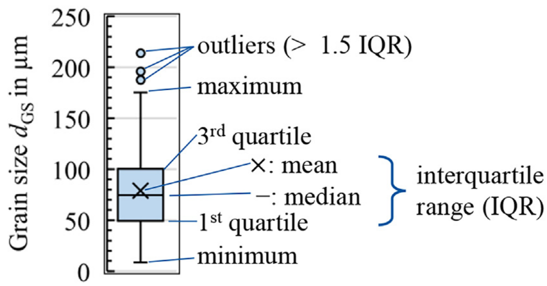
Another possibility for a statistical evaluation is the so-called Boxplot, as depicted in Fig. 2 (a) for the studied materials. Here, the mean value, the median, first and third quartile and distribution of measurements, including the identification of statistical outliers is displayed. Accompanied, is a brief explanation in Fig. 2 (b). The interquartile range varies distinctly for the materials. There is, however, a relation to the median value. In Fig. 3 it can bee seen that the interquartile range and median have an almost linear relation.

3.2. Influence of cutting

The effect of cutting on the magnetic properties of electrical steel has been studied in various research [13,14,18,19]. The plastic deformation in the vicinity of the cut edge and residual mechanical stress leads to a shearing of the hysteresis curves [20–22]. The coercivity and required magnetic field increases, whereas the remanence decreases. This study focuses on differences of the magnetic deterioration of different materials as a result of an identical cutting procedure. With this focus, the quantitative evaluation of actual losses in W/kg and magnetic



(a) Results for the different materials.



(b) Description of the boxplot.

Fig. 2. Statistical grain-size evaluation of the studied materials by boxplot comparison.

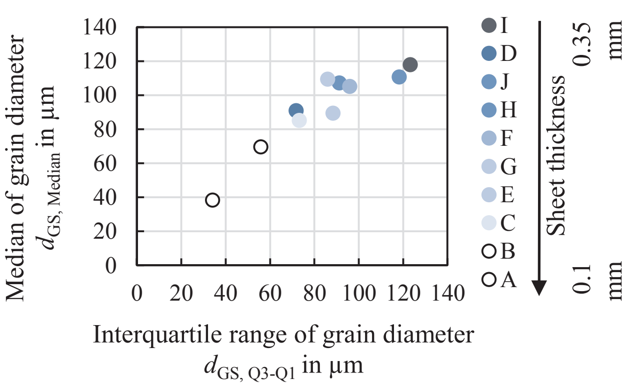


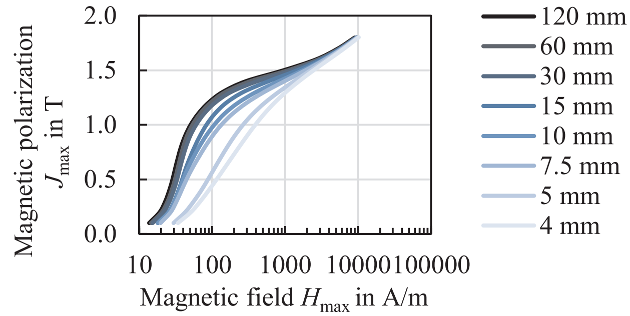
Fig. 3. Statistical grain-size evaluation of the studied materials by means of interquartile range and the median value.

field in A/m is replaced by the evaluation of the relative deterioration for each material. The cutting effect is quantified by the relative increase of the magnetic field for a fixed polarization ΔH_{max} and the relative loss increase due to cutting ΔP_s compared with the 120-mm wide reference sample according to the following equations:

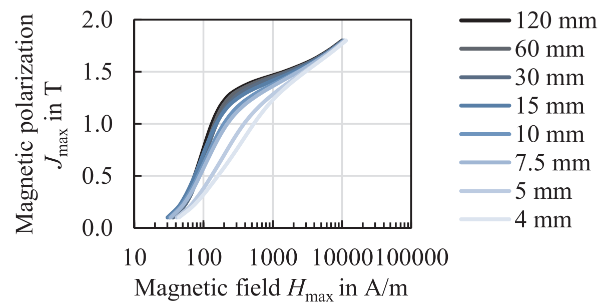
$$H_{ratio,\,cut/uncut} = \frac{H_{max,d_{strip}}}{H_{max,120\,mm}} \tag{1}$$

$$P_{ratio,\,cut/uncut} = \frac{P_{max,d_{strip}}}{P_{s,120\,mm}} \tag{2}$$

In previous work, it was established, that for the utilized SST-setup the effect of cutting on the reference samples size can be neglected for different cutting techniques and cutting parameters, i.e., speed, tool sharpness, cutting clearance [20]. In the following section, the phenomenological effects of cutting for all materials are evaluated regarding the anisotropy of the cutting, the polarization dependence and



(a) Rolling direction.



(b) Transverse direction.

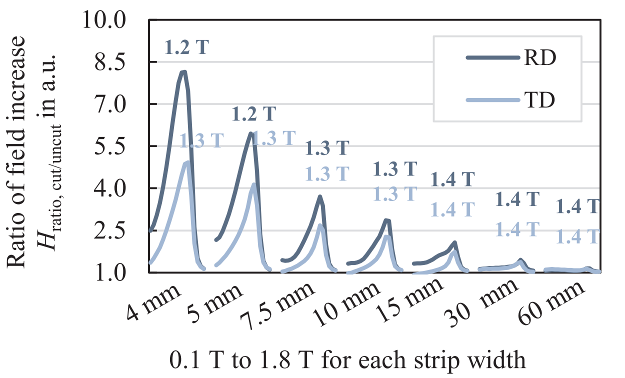
Fig. 4. The effect of cutting on the magnetization curves at 50 Hz for material I, studied for different strip widths d_{strip}.

the frequency dependence.

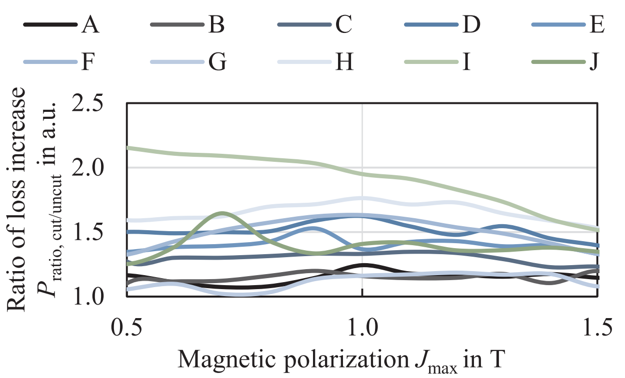
The effect of cutting and magnetic anisotropy of NO materials shows an interrelation. In the uncut state, samples are easier to magnetize along RD than TD, which is in accordance to the general state of the art. The deterioration of magnetization behavior and increase of losses due to cutting is however more pronounced in RD compared with cutting in TD. This is a distinct behavior which can be observed for all studied materials. The magnetization curves for different strip width are displayed exemplarily, for one studied material (Fig. 4).

The polarization dependence of relative deterioration due to cutting is different for the magnetization behavior and magnetic loss. In Fig. 5 the general trends are shown. The required magnetic field for cut samples compared with the uncut reference increases with polarization and has a maximum around 1.3 T. When the saturation is approached the effect decreases again. The magnetic anisotropy can also be seen in Fig. 5 (a). It should be noted, that for the 4-mm samples, the required magnetic field is up to eight times higher, when compared with the reference sample. For the magnetic loss, the relative deterioration, as well as the polarization dependence is less pronounced. The relative loss increase is in the range of 2.5 times the magnetic loss, depending on the material. In Fig. 5 (b), the range between 0.5 T and 1.5 T is depicted. For some material the relative deterioration shows a decrease with increasing polarization and for other materials, the relative deterioration in this range is constant.

The effect of relative loss increase decreases with increasing frequency. For example, in Fig. 6, the losses of the 4-mm sample compared to the reference increase by 100% at 50 Hz, but at 5000 Hz they only increase by approximately 40%. This can be explained by the loss components [4]. The eddy-current losses increase quadratically with the frequency f. The static losses increase linearly. The proportion of hysteresis loss component of the total losses decreases with increasing frequency. The mechanical residual stress and plastic deformation has a strong effect on the hysteresis loss component. Therefore, the effect decreases with increasing frequency and can be observed for all studied materials.



(a) Ratio of magnetic field increase (1) as a function of polarization and d_{strip} for material I, highlighting anisotropy at 50 Hz.



(b) Ratio of loss increase (2) with d_{cut} of 5 mm for different materials at 5 Hz in RD.

Fig. 5. Examples for the polarization dependence of the effect of cutting on magnetic loss and magnetization behavior.

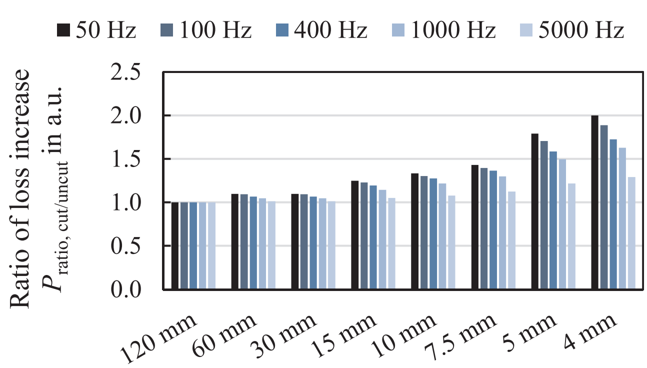


Fig. 6. Example for the frequency dependence of the effect of cutting (2) on magnetic loss for material I at 1.0 T.

3.3. Correlation of material parameters and cutting deterioration

The objective of the presented research is to study fundamental relations between the effect of cutting and the resulting magnetic deterioration of electrical steel. Although, highly interesting for definite application purposes, the use of quantitative results, e.g., iron losses of a certain strip width, limit the relevance for general correlations and conclusions. For example, the losses of the two materials J and I at $d_{\text{strip}} = 4$mm at 1.5 T and 50 Hz are 2.3 W kg^{-1}. However, for the strip width of $d_{\text{strip}} = 120$ mm, material J has significantly lower losses with 1.6 W kg^{-1} compared with 1.8 W kg^{-1} of material I. Although is has beneficial properties for the reference sample size, the relative deterioration is higher for material J. It is more sensitive to the same cutting procedure. With increasing frequency to 400 Hz the losses for the $d_{\text{strip}} = 4$ mm samples at 1.5 T are 37 W kg^{-1} for material J and 34 W kg^{-1} for material I. The advantageous trend for material I at higher frequencies is related to the difference in thickness of the materials (Table 2) and the increasing share of classical eddy-current losses. For a specific frequency, operating point J and strip size, the quantitative results can be used to compare different materials. If, in the case of applications to an electrical machine, ranges of these variables have to be considered the quantitative comparisons are not sufficient. These considerations highlight the limitation of quantitative analysis of the effect of cutting for correlation purposes. Therefore, in the following section, the relative deterioration is studied and correlated to certain material parameters.

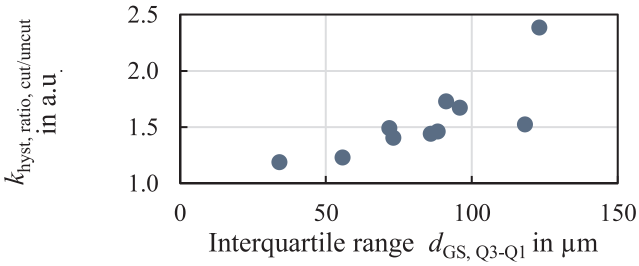
In order to quantify and compare the relative loss increase between the materials, low frequency measurements at 5 Hz are studied. Thereby, the impact of the classical eddy-current loss is decreased. The effect of sheet thickness and alloying, i.e., Si and Al content on the classical eddy-current losses, can thereby be separated from the effect of cutting on the hysteresis losses. The Bertotti hysteresis loss formulation is used and approximated from 5 Hz measurements by subtracting the Foucault eddy-current loss to identify k_{hyst}, according to (3),

$$P_{\text{approx. hyst}} = k_{\text{hyst}} \cdot B^{\alpha} \cdot f. \tag{3}$$

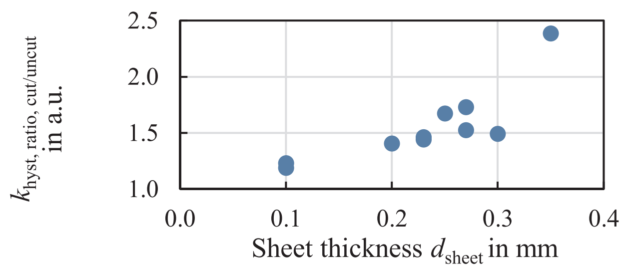
In Fig. 7 the relative cutting deterioration as a function of different material parameters is displayed. Fig. 7 (a) shows that Δk_{hyst} increases with an increasing interquartile range, i.e., the wider the grain-size range, the larger the cutting deterioration. This trend is followed generally by all studied materials. The relative deterioration is in the range between 120% and 250% for the 5mm samples compred to the reference. Due to the almost linear relation between the median and interquartile range, as displayed in Fig. 3 it is however impossible to attribute this behavior solely to either one of these parameters. In order to distinct both influences, a material with inhomogeneous microstrucutre, for example created by selective grain growth, resulting in two peaks in the histogram could to be studied. For the industrial NO grades, none of the studied materials showed such a microstructure. The general trend regarding the microstructure is, that with an increasing grain size, the effect of cutting becomes more detrimental. In general, the grain size of electrical steels can be easily varied by annealing conditions, i.e., annealing time and annealing temperature. In various scientific publications, the optimization of frequency-dependent magnetic properties by means of grain size variation has been presented [6,8]. The presented correlations in this paper highlight that grain size optimization approaches should not only cover the frequency dependence, but also the cutting deterioration, due to the trends presented in Fig. 7 (a) and (d). Stator teeth or rotor geometries are often in the range below 10mm, where the cutting effect is significant.

In Fig. 7 (b) a similar trend is shown with increasing sheet thickness, i.e., the smaller the sheet thickness the lower the deterioration. However, as seen in Fig. 7 (c), the sheet thickness and interquartile range also shows a distinct trend.

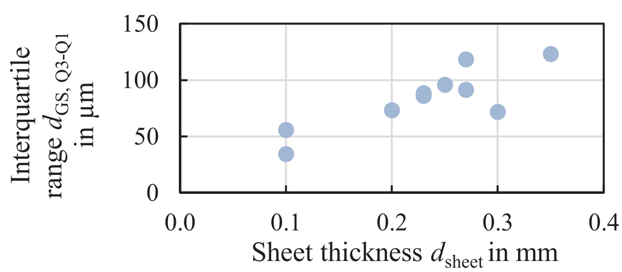
Fig. 7 (d) displays the relation of the deterioration with the alloying. In general, Si and Al are used in electrical steel to increase the specific electrical resistivity to thereby reduce classical eddy-current losses. The alloying, consequently, has a significant effect on the quantitative magnetic loss. The impact of Si and Al on magnetic loss increases at higher frequencies, due to the increasing share of classical eddy-current losses ($\propto f^2$). In this study, the focus is placed on the relative deterioration due to cutting not a quantitative comparison. Therefore, the effect of cutting is studied on the hysteresis loss, that is especially sensitive to mechanical stress, e.g., residual stress due to mechanical cutting [23,22]. Although, it was expected that an increasing Si and Al content leads to a higher deterioration, as results in [15] indicate, this was not observed for the studied materials. Either the effect is overshadowed by the impact of microstructure and thickness, or it has no dominant effect in the range of the alloying between 4 and 5%. The alloying nevertheless, still has indirect effects on the cutting



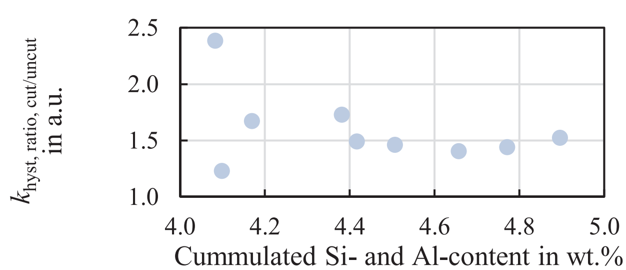
(a) Ratio of hysteresis component increase and interquartile range.



(b) Ratio of hysteresis component increase and sheet thickness.



(c) Interquartile range and sheet thickness



(d) Ratio of hysteresis component increase and alloying.

Fig. 7. Correlation of the relative deterioration due to cutting and different material parameters.

deterioration. Both Si and Al increase the mechanical strength of electrical steel due to solid solution hardening [24]. The mechanical strength affects the residual stress distribution, which alongside plastic deformation, is one of the physical origins of magnetic deterioration due to cutting [18]. In general, the mechanical strength increases with increasing silicon content or decreasing grain size. The cutting force needed for a mechanical shear cut increases with increasing grain size, because it is easier to cut along grain boundaries compared with intergranular cuts. Furthermore, the silicon content affects the recrystallization kinetics, which is responsible for grain growth and texture evolution.

The results as well as literature shows that the deterioration increases with grain size. From the relations displayed it can be assumed that for conventional NO, small sheet thicknesses with a low median and small interquartile range are the least affected by cutting deterioration.

4. Conclusions

In this study the relative deterioration due to cutting is studied on ten industrial NO materials. The work presented here, focuses on the interrelation with the alloying, thickness and microstructure. A strong focus is placed on the evaluation of the microstructure with statistical approaches. The results can be summarized in the following points:

- Sheet thickness, microstructure and relative cutting deterioration show an interrelation for all studied industrial NO.
- Relative deterioration of loss correlates with the interquartile range and median. Due to the linear relation of the latter, the attribution to either one of these values is unambiguous.
- The alloying showed no dominant trend for the cutting deterioration in this study for it to be distinguished from the effects of sheet thickness or microstructure. It should be noted that this can be due to the dominance of the effect of grain size.
- The results of the studied industrial NO indicate that the deterioration due to cutting is lowest for thin electrical steels, with a small grain size, quantified by the median and small interquartile range, independent of the alloying concept.

Because the recommendation for cut-edge-effect-optimized electrical steel sheet does not necessarily follow trends for loss and magnetization optimized sheet materials and handling, the effect of cutting should be incorporated in the material design process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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