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Multi-layer shear cutting of thin non-oriented electrical steel sheets☆

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A B S T R A C T

Industrial cutting of thin non-grain oriented electrical steel sheet is challenging in regard to various aspects. From a processing perspective, the required small cutting clearances and tight tolerances, as well as the handling of thin laminations below 0.23 mm make the manufacturing processes from steel strip to motor core component challenging. Additionally, the increased number of sheets needed to build the axial length of an electrical machine increases material costs. Furthermore, the magnetic deterioration as a result of the cut-edge effect is not fully understood for thin grades. This paper studies the impact of multi-layer cutting, i.e., simultaneous cutting of multiple stacked thin laminations. The magnetic cut-edge effect is characterized with a Single Sheet Tester and results for multi-layer cutting compared to conventional industrial punching. Cut-edges are analyzed using optical microscopy and neutron grating interferometry to link magnetic deterioration to structural changes in the material. Results indicate that multi-layer shear cutting is a promising approach in the handling of thin electrical steel laminations, because the magnetic deterioration is comparable to conventional industrial punching with different cutting parameter variations. However, the output per cut can be increased by a factor of two to three for the studied NO10 and NO20, respectively.

1. Introduction

Non-grain oriented (NO) electrical steel is used to guide the magnetic flux through the magnetic core of electrical machines. The torque of an electric motor is directly proportional to the flux density in the air gap. Therefore, good magnetic properties of the soft magnetic material, i.e., a high permeability and high saturation in combination with the design of the machine are necessary to meet torque requirements. The magnetizing frequency linked by the pole pair number is proportional to the speed of the machine. Low iron losses during continuous re-magnetization are required to achieve high efficiency. For speed-variable drives the full torque-speed range must be considered, which leads to a broad spectrum of requirements for the core materials, including magnetic, mechanic and thermal aspects. However, material and production costs also play a vital role. In order to design and construct advanced high-efficient electrical machines it is necessary to address the complex interdependencies, which requires a deep understanding of how material properties and their interactions affect the overall machine performance. In this paper, a processing method and several resulting challenges in the application of thin NO are studied.

Thin electrical steels can be used to design high efficient electrical machines especially at high speed, since classical eddy current loss is proportional to the sheet thickness squared [1–4]. However, the use of thin steels in the range below 0.23 mm comes with a number of challenges. Material related challenges include the small thickness-to-grain-size ratio (as seen in Fig. 1) which can negatively affect both the expected magnetic properties as well as the mechanical processing of the material. Furthermore, the use of thin laminations in drive systems leads to constructive challenges. As each lamination is electrically isolated from the adjacent laminations, more non-magnetic active material per axial length of the machine is necessary when thinner laminations are used. The electric insulation thickness is not proportional to the sheet thickness. From an economic perspective, thinner steels are also less favorable. The material output after cold rolling and annealing is more or less independent of the thickness, but more laminations are

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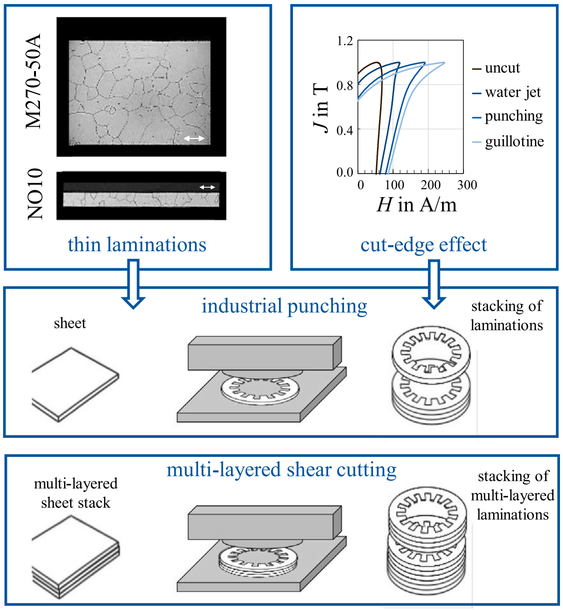

Fig. 1. Schematic visualization of the research objectives: thin laminations, cut-edge effect and multi-layer shear cutting.

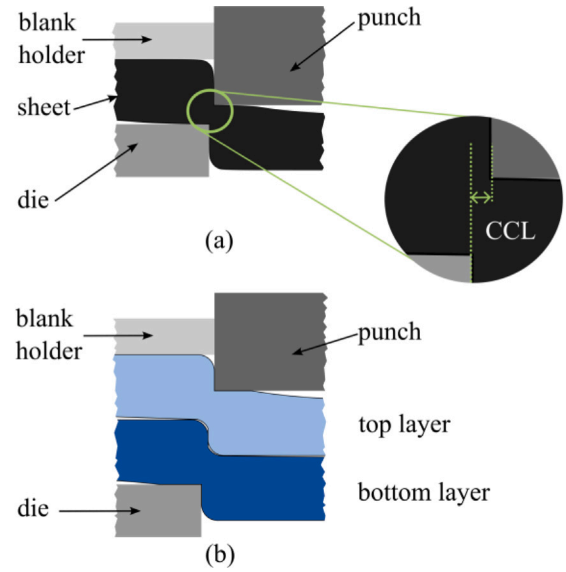

Fig. 2. Experimental setup to manufacture shear-cut samples, (a) single-layer cutting, (b) multi-layer cutting.

needed for thinner sheets. This results in increased costs due to more required laminations and more complex manufacturing.

Another challenge in the application of thin laminations is the actual manufacturing of rotor and stator laminations by cutting. In series production, mechanical shear cutting (i.e., punching or blanking) is usually performed [5–7]. However, for very thin laminations, the small cutting clearances required, which are proportional to the sheet thickness are challenging from a technical perspective. Conventional cutting clearances in the blanking process of non-oriented electrical steel are typically 2%–10% of the sheet thickness [6,8]. Narrower cutting clearances are associated with several process-related disadvantages. In particular, they lead to increased tool wear, which consequently raises tooling costs [8,9]. In addition, the manufacturing costs of active tool components increase with the required level of precision. For example, a relative cutting clearance of 7% applied to NO25 corresponds to an absolute cutting clearance of 17.5 μm, whereas the same relative cutting clearance for a NO10 steel results in an absolute cutting clearance of 7 μm. This results not only in higher manufacturing costs for active tool components, but also requires more precise tool concepts, such as those employed in [10] and in the presented study, which do not allow straightforward integration into existing manufacturing processes. Furthermore, a smaller cutting clearance (CCL) requires higher press forces, thereby reducing overall process efficiency [8]. In addition, the cutting process itself represents a production bottleneck in stator and rotor package manufacturing. Analogous to the increased material output following cold rolling and annealing, thinner laminations require a larger number of sheets to be cut and stacked in order to achieve the desired axial package length.

The magnetic cut-edge effect, i.e., the deterioration of magnetic properties as a result of cutting also needs to be considered [7,11–13]. Plastic deformation as well as residual stress remains in the areas in the vicinity of mechanically cut edges and significantly alter the local magnetic properties [6,14,15]. It has been shown that not only local properties are affected but the overall machine performance can change. Despite this, the cut-edge effect is often neglected or oversimplified during the design process.

The approach studied in this paper is the process of multi-layer shear cutting, i.e., the stacking of thin sheets before simultaneously shear cutting, as schematically depicted in Fig. 1. The research objectives of this study are the feasibility of the cutting method as well as the cut-edge deterioration of thin-grades by mechanical cutting. Besides the potential increase in productivity, successful implementation of this approach could reduce tool wear and relax the requirements on extremely small cutting clearances, thereby lowering tooling costs and facilitating integration into existing stator and rotor package manufacturing processes. The influence on magnetic property deterioration is studied in comparison to conventional single-layer shear cutting on Single Sheet Tester (SST) samples. Furthermore, the effect of cutting variations, i.e., number of stacked sheets and cutting-clearance (CCL) variations is studied. The results help to understand what happens during multi-layer cutting and answer the question if it provides a basis for process optimization of industrial shear cutting of thin NO laminations in the future.

2. Measurements and methods

Two thin industrial NO are studied in this research. With a respective nominal thickness of 0.1 mm for the NO10 and 0.2 mm for the NO20, both materials are relatively thin in terms of non-grain oriented electrical steel applications. The studied NO20 has a mean grain size of 97 μm and silicon content of 3.38 wt%, whereas the NO10 has a silicon content of 2.97 wt% and a mean grain size of 80 μm. Grain size is determined by the line intercept method on 300 grains. The chemical composition is analyzed by spark spectrometry.

Samples are cut on an industrial *Bruderer BSTA 50-110* eccentric press, operated in single stroke mode at 100 strokes per minute. The sample geometry stems from the cut-edge evaluation on a 60 x 60 mm SST. The uncut reference utilizes the full 60 mm x 60 mm sample, whereas cut-edge samples consist of six strips of 10 mm *x* 60 mm taped together as described in [16]. In this study, only samples with cutting parallel to the rolling direction are studied. Experimental variations of the number of stacked laminations, cutting clearance CCL and magnetic measurements are summarized in Tables 1 and 2 (see Fig. 2).

The magnetic measurements in this study are conducted with a MPG200 system (*Brockhaus Measurements*). Samples are measured under alternating, sinusoidal excitation with magnetic polarization controlled from 0.1 T to 1.8 T in 0.1 T steps at a magnetizing frequency of 50 Hz. In order to analyze and quantify the cut-edge effect, the $J(H)$-hysteresis curves, magnetization curves $J_{max}(H_{max})$, magnetic

Table 1
Overview of experimental cutting process variations for NO20, whereby the relative CCL refers to CCL to stacking height.

Mode	Material	Sheet/stack thickness	abs. CCL	rel. CCL
One-layer	NO20	200 µm	25 µm	12.5%
One-layer	NO20	200 µm	35 µm	17.5%
Two-layer	NO20	400 µm	35 µm	8.8%
Two-layer	NO20	400 µm	50 µm	12.5%

Table 2
Overview of experimental cutting process variations for NO10, whereby the relative CCL refers to CCL to stacking height.

Mode	Material	Sheet/stack thickness	abs. CCL	rel. CCL
One-layer	NO10	100 µm	7 µm	7.0%
One-layer	NO10	100 µm	15 µm	15.0%
Two-layer	NO10	200 µm	15 µm	7.5%
Three-layer	NO10	300 µm	25 µm	8.3%

Table 3
Overview on magnetic measurements.

Material	Industrial NO10 and NO20
Polarization J_{max}	0.1 T to 1.8 T in 0.1 T -steps
Frequency f	50 Hz
Cutting parameters	Number of layers CCL

permeability μ_r and specific loss P_s are evaluated. An overview of measurement parameters is given in Table 3.

For the material characterization of the cut-edges, two methods have been applied. For one, cut-edges are studied with an optical microscope. Furthermore, samples for the NO10 are characterized by neutron grating interferometry (nGI). In this method, a neutron beam passes several gratings to produce an interference pattern on a detector. When a magnetic material is placed in between the gratings, neutrons are scattered at domain walls which leads to a change in the interference pattern, which can be investigated by quantitative analysis of the dark-field image (DFI) [17,18]. A darker contrast means that more domains are present in local areas of the sample. As the neutron beam passes through the entire sample it is a visualization of the entire sheet thickness, i.e., normal direction of the sample strip. The methods can be used to study cut-edge effects in electrical steels as done in [10,19]. The nGI measurements shown in this paper were taken at the new monochromatic imaging beamline MoTo at the Institut Laue Langevin [20]. MoTo is primarily designed as a monochromatic tomography instrument, while also featuring polarized neutron imaging and neutron grating interferometry. As an nGI setup, a variation of the setup shown in [21] was used. MoTo delivers a monochromatic neutron beam with a wavelength of 2.4 Å. At this wavelength, the setup was adjusted to a correlation length of 1.1 µm, corresponding closely to the expected magnetic domain size and providing good contrast. As a result of this adjustment a spatial resolution of approximately 0.5 mm was achieved. A separate publication detailling the capabilities of this setup is currently in preparation.

3. Results and discussion

The aim of this study is to assess, if multi-layer shear cutting of thin NO laminations (see Fig. 2) is capable to cut electrical steel laminations more efficiently without compromising the magnetic quality of the cut laminations. This is studied while the underlying mechanisms in the material which cause the deterioration are identified. In Fig. 3, the magnetization curves for the NO20 cut under different process conditions are shown. The uncut reference sample, shown in black, exhibits the

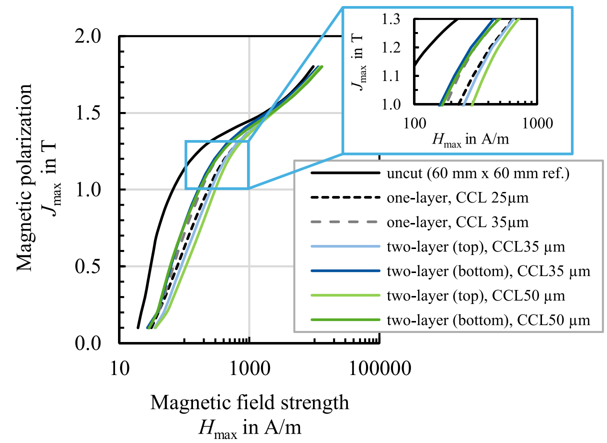

Fig. 3. Magnetization curves for NO20 at 50 Hz for uncut reference and different cutting variations of single- and two-layer shear cutting.

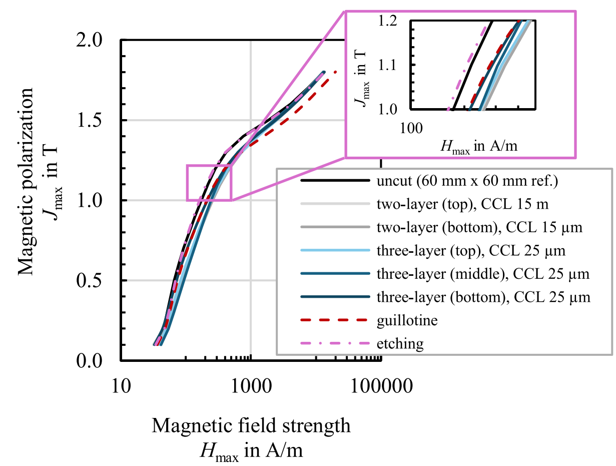

Fig. 4. Magnetization curves for NO10 at 50 Hz for uncut reference, two variations of multi-layer shear cutting and two comparative cutting methods.

highest magnetic permeability, requiring the smallest magnetic field to achieve a given magnetic polarization. The dotted black and gray lines show magnetization curves for conventional punching, i.e., single-layer shear cutting with two different cutting clearances of 25 µm (black dotted line) and 35 µm (gray dotted line) respectively. Both show a strong deterioration of the magnetization behavior compared with the uncut reference, especially in the medium polarization range. For the NO20, a larger CCL of 35 µm leads to better results, i.e., the magnetization shows a smaller deterioration compared to the smaller CCL of 25 µm. In [6], the authors conclude that sharp edges on the punch and the die lead to less magnetic deterioration in the shear-cutting influence zone. For this study, the same punch was used for all specimens, and the dies were changed in order to adjust the cutting clearance. Comparing the edges of the dies, the 25 µm and the 35 µm dies have similar edge radii, which are around 15 µm. The authors in [6] describe that a smaller CCL might give rise to higher residual stress gradients (leading to a stronger magnetic deterioration) in the shear-cutting influence zone, while the authors describe that this would lead to a lower penetration depth of the residual stresses. Since [6] conducted their research on NO50 and NO35, the steeper residual stress gradient effect might dominate for the thinner NO20 specimen presented in the current study. Non-destructive and locally resolved stress measurements are required, however, to validate these assumptions.

The magnetization curves for two-layer cutting are shown in blue and green, representing two different cutting clearances. From the

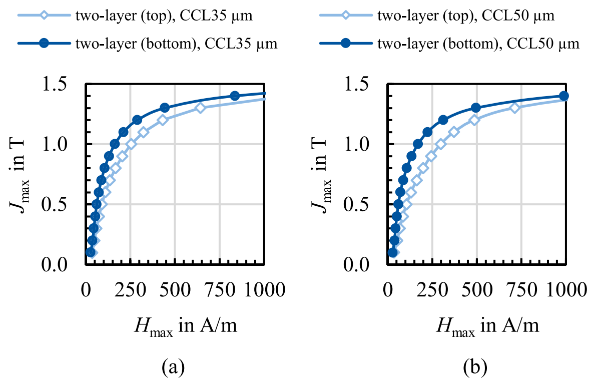

Fig. 5. Magnetization curves at 50 Hz for different layers of two-layer shear cut NO20 cut (a) with a CCL of 35 µm and (b) with a CCL of 50 µm.

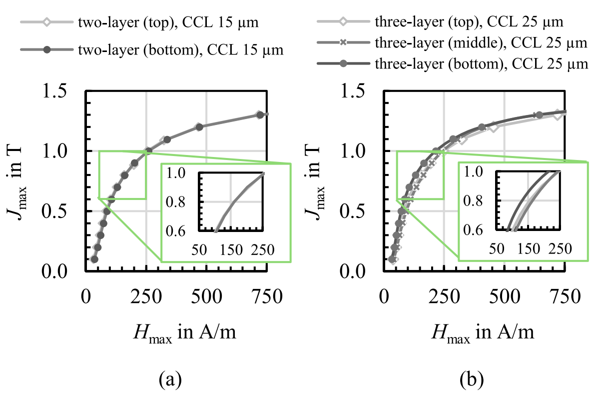

Fig. 6. Magnetization curves at 50 Hz for different layers of (a) two-layer and (b) three-layer shear cut NO10.

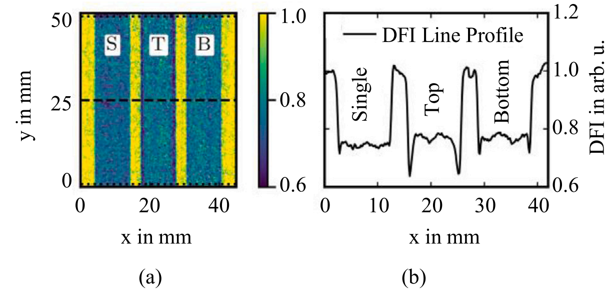

Fig. 7. (a) DFI map of the NO20 samples, single layer cut, two-layer cut top and two-layer cut bottom. The dashed line indicates the profile line shown in (b). The dotted lines denote the vertical averaging of the profile line. In both (a) and (b) the influence of shear cutting on the edges is clearly visible. While the single and bottom sample show little edge effects, the top-layer sample has significant edge effects.

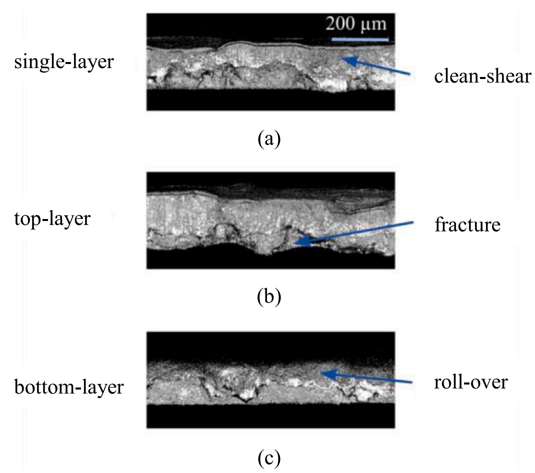

Fig. 8. Laser-scanning microscopy images of shear-cut edges of NO20 for a single-layer shear-cut (a), and a double-layer shear-cut with top-layer (b) and bottom-layer (c). The relative cutting clearance was kept at 12.5% for both configurations at 25 µm in (a) and 50 µm in (b).

results it can be seen that these variations are generally in the range expected for regular single-layer cutting (punching). Multi-layer cut samples exhibit in some cases either improved or deteriorated behavior compared to single-layer cut laminations.

In Fig. 4 the results are displayed for the NO10. In general the cut-edge effect is less pronounced compared with the NO20. Results as also shown in [10,22,23] indicate that in general, the cut-edge effect is decreasing with smaller sheet thicknesses of NO and the smaller cut-edge effect is therefore somewhat expected. The results displayed in Fig. 4 show the uncut reference alongside results for two-layer cutting with a CCL of 15 µm and for three-layer cutting with a CCL of 25 µm in all different layers. Additionally, in yellow, samples cut with two alternative cutting methods are shown, guillotine cutting and chemical etching. Guillotine cutting is also a mechanical cutting technique which, in contrast to industrial punching, uses a blade instead of a punch and die. The chemical etching has the least impact on the material as it is the most gentle cutting technique of the presented ones.

In the magnetization curves as well as in the $J(H)$-hysteresis curves a significant shearing occurs for all samples cut with mechanical processes for both thicknesses. This leads to a strong decrease in permeability μ_r. However, there is no distinct general difference between single- or multi-layer cut samples. The studied comparisons of $J(H)$-curves, μ_r and $J_{max}(H_{max})$ highlight the conclusion that multi-layer cut samples show magnetic deterioration in the range of other cutting process variations and are not generally more detrimental to the magnetic performance.

In order to take a closer look at the phenomenology of laminations produced by multi-layered shear cutting, the magnetization curves of samples cut during the same process in different layers are shown in Figs. 5 and 6. In each separate diagram, the results for the different layers are displayed in direct sole comparison to identical cutting conditions. In Fig. 5 the bottom and top layer for a CCL of 35 µm in (a) and a CCL of 50 µm for (b) are displayed. In both cases, the bottom layer shows distinctly better magnetization behavior. The difference between top and bottom layer is slightly more pronounced for the larger CCL. In contrast to that, NO10, as displayed in Fig. 6 for two- and three-layered cutting shows less distinct differences between the layers. For the two layered cutting there is almost no quantitative difference between the magnetization behavior of top and bottom layer. For the three-layered cut samples, although less pronounced compared to NO20, the bottom layer again shows significantly better magnetization behavior. In all studied samples the bottom layer has the same or distinctly better magnetization behavior compared to all other layers during multi-layer shear cutting.

In Fig. 7(a) DFI maps of three NO20 shear cut samples with a width 10 mm and length 60 mm are shown. Sample **S**ingle was shear cut with a CCL of 25 µm, while **T**op and **B**ottom are samples cut in a two-layer process with a CCL of 50 µm. In (b), the corresponding line profile across all three samples is shown. The dashed line represents the direction of the line profile, while the two dotted lines represent the extent of the averaging area. A nearly identical DFI signal of 0.77 is observed in the central region of all samples, whereas the DFI signal at the edges is found to depend on the selected cutting method. In general, as observed for the considered NO20 material, a lower DFI signal is

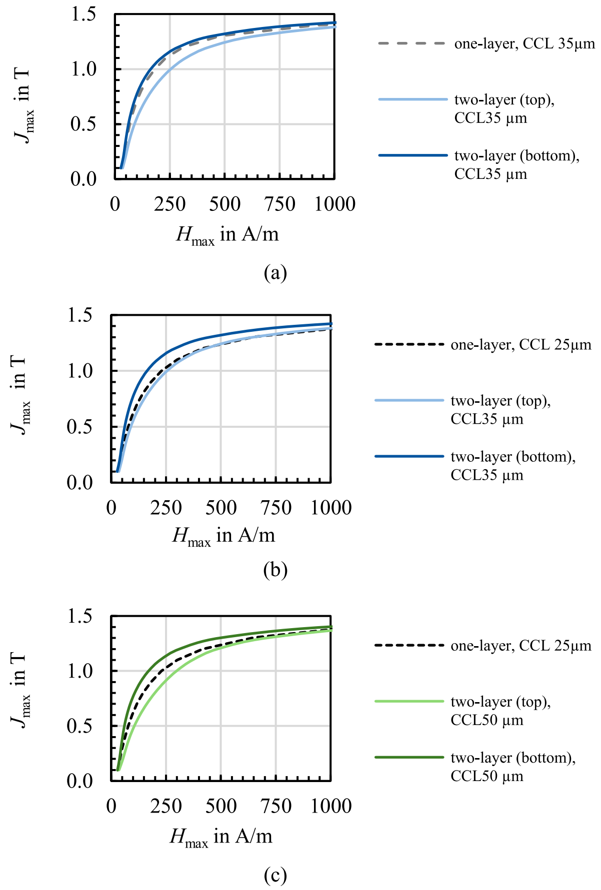

Fig. 9. Magnetization curves of NO20 at 50 Hz for uncut reference, single- and two-layer cut laminations (a) comparison of cut laminations with the same CCL of 35 µm (b) comparison of cut laminations with different CCL (c) comparison of cut laminations with same relative CCL.

associated with a higher magnetic domain density. Since residual stress is one of the factors influencing domain density, the DFI signal may therefore be regarded as an indicator of material deterioration caused by the cutting process. As shown in (b), the lowest DFI signal at the edges is exhibited by the top layer, while the highest DFI signal is observed for the single-layer sample. This observation is consistent with the magnetic measurements, in which the strongest deterioration is also identified in the top layer. Notably, an asymmetry in the DFI signal at the edges is observed for the single-layer cut. Optical inspection of the sample edges revealed different shear cuts on the left and right edge, which may be a result of a slight misalignment of the cutting tool. The CCL is a significant factor in the deterioration at the cut-edges [6].

Two physical methods are used to study the cut-edge properties in more detail in order to interpret the observed magnetic behavior. The nGI results, as described in the previous section, are displayed in Fig. 7. In Fig. 8, laser-scanning-microscopy images of shear-cut edges on NO20 are shown for a one-layer cutting setup (a), and a two-layer cut (b). For the shown samples, the relative CCL was kept constant, i.e., the CCL relative to the sheet thickness, at 12.5%. For the single layer, a cutting clearance of 25 µm and for the double layer of 50 µm was used. The single-layer cut shows distinguishable areas of clean-shear and fracture, as well as the roll-over at the top. The top-layer of the multi-layer cut shows increased clean-shear and decreased fracture area, compared to the single layer. Whereas the bottom layer of the multi-layer cut shows almost no clean-shear and is dominated by fracture and roll-over.

To allow an assessment of whether the magnetic performance is more or less affected by multi-layer cutting compared to single layer

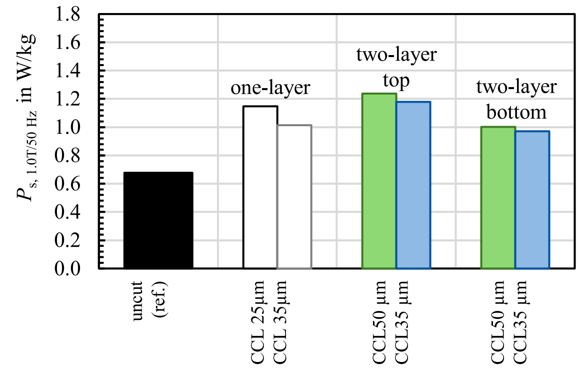

Fig. 10. Specific iron loss of NO20 at 1.0 T and 50 Hz for uncut reference, single- and two-layer cut laminations.

cutting a differentiated perspective is required. For this analysis, the magnetization curves of multi-layer cut samples are shown in relation to different references of single-layer cutting (Fig. 9). It becomes evident that process optimization must always be evaluated from multiple perspectives. In this case, whether the cutting parameters have been initially optimized for single-layer cutting of a specific material. In Fig. 9(a) the double-layer cut NO20 is displayed in comparison to single-layer cutting with the same CCL of 35 µm for both multi- and single-layer cutting. Although the bottom layer is slightly better, the deterioration of the top-layer undoubtedly leads to an overall deterioration of the magnetic properties of the cut laminations, i.e., that multi-layer cutting is more detrimental compared with single-layer cutting.

If the CCL is however changed, as displayed in Fig. 9(b), the results and conclusions can change. Compared to single-layer cutting with a smaller CCL of 25 µm, multi-layer cutting with a CCL of 35 µm is in this case beneficial to the magnetic properties. The bottom layer shows distinctly easier magnetization and the top-layer is similar to the single-layer cut lamination with the magnetization curves even crossing at some point.

Fig. 9(c) compares results with the same relative CCL of 12.5%, i.e., 25 µm for NO20 single-layer and 50 µm for NO20 double-layer. In this comparison, the single-layer magnetization curve lies exactly in between the magnetization curves of the top- and bottom-layer of multi-layer cutting. So, the interpretation depends strongly on a comprehensive consideration of the cutting parameter and material interrelations.

In Fig. 10, the specific iron loss is exemplarily displayed for 1.0 T and 50 Hz. The observed trends are consistent with the magnetization behavior discussed in the previous sections. The displayed samples correspond to the same material conditions as presented in Fig. 9(a), (b) and (c) and are displayed in the same colors. Looking at the loss, for all cases, the bottom layer exhibits best magnetic properties with the lowest loss, while the single-layer cut shows intermediate performance between the top- and bottom-layer results for the displayed NO20.

4. Conclusions

The presented study shows that multi-layer shear cutting of thin NO is promising to increase the quantitative output of the punching process. It gives a basis for optimizing cutting processes regarding both magnetic properties as well as economic improvement. A more resource-efficient manufacturing can be enabled without compromising the magnetic quality of the laminations as the magnetic deterioration due to multi-layer cutting is in the range of single-layer cutting with various techniques and cutting parameters. Some general conclusions can be drawn:

- Both, magnetization behavior and losses are affected by multi-layer cutting and are quantitatively comparable to single-layer shear cutting (industrial punching) with an increase of iron losses and a deterioration of magnetization behavior.
- The effect of multi-layer shear cutting is less pronounced for thinner materials, which is also observed for single-layer shear cutting in case of the studied NO10 and NO20.
- Comparable material properties after cutting can be achieved through multi-layer shear cutting while allowing for significantly larger cutting clearances. This offers advantages, including possible reduced tooling costs due to less demanding tool precision and increased productivity through improved process robustness.
- For all parameter variations, the bottom layer shows identical or better magnetization behavior and lower losses compared to other layers when being multi-layer cut. The DFI analysis obtained by nGI supports that local material changes are responsible, as expected.
- From optical microscopy it becomes evident that multi-layer shear cutting shifts the ratio of shear and fracture components from one layer to individual layers leading to the strong difference in magnetic behavior of the cut laminations
- An assessment if multi-layer cutting leads to less or more deterioration than single-layer cutting becomes a question of cutting parameter optimization for both processes and cannot be answered globally.

The results allow for a process optimization in terms of economic aspects and resource saving while still delivering good magnetic properties of the produced laminations.

In future work, further analysis of the interrelations between material parameters and multi-layer cutting of thin NO grades is necessary to identify general trends, compared to studies on individual grades. Parameters such as sheet thickness, grain size, alloying content, and the grain-size-to-sheet-thickness ratio need to be examined more closely as they interrelate [24,25]. A deeper understanding of the cutting processes could enable the development of strategies for optimizing cutting parameters. Additionally, the impact on the cutting tool and a maximum stack height needs to be studied. Overall, multi-layer cutting appears to be a promising approach for improving the efficiency of cutting thin NO sheets.

CRediT authorship contribution statement

Nora Leuning: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Phillip Stoecks-Morgan:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Tobias Neuwirth:** Writing – review & editing, Visualization, Software, Project administration, Investigation, Data curation. **Danilo G. Aurich:** Writing – review & editing, Data curation. **Jiazhou Shen:** Writing – review & editing, Resources, Investigation. **Ines Gilch:** Writing – review & editing, Investigation, Data curation. **Achref Douiri:** Writing – review & editing, Data curation. **Wolfram Volk:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Michael Schulz:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Simon Steentjes:** Writing – review & editing, Resources, Methodology.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used RWTHgpt exclusively for grammar correction and spell-checking. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nora Leuning reports financial support was provided by German Research Foundation. Tobias Neuwirth, Phillip Stoecks-Morgan, Achref Douiri, Danilo Aurich reports financial support was provided by German Research Foundation. If there are other authors, they 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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Data availability

The data that has been used is confidential.

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