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Evaluation of the interdependency of mechanical cutting and magnetic anisotropy on the magnetic properties of FeSi electrical steel

Abstract. Due to present-day challenges for the improvement of the operating characteristics of rotating electrical machines, the core material is regarded as increasingly important. Non-oriented (NO) electrical steel sheets are conventionally used for the construction of magnetic cores of rotating electrical machines. The most appropriate choice of material and machine design is based on standardized material data obtained from Epstein frames or single sheet testers. Both, low losses as well as good magnetizability in any spatial direction of the sheet plane are requested. Despite their name, NO electrical steels do show a magnetic anisotropy. A significant increase of loss and decrease of permeability can additionally be induced by mechanical cutting processes to shape the magnetic circuit. Magnetic anisotropy and induced mechanical stress can affect the local iron-loss distribution, magnetizability, acoustic behavior and therefore, have to be considered in numerical simulations of electrical machines. In this paper, the interdependency of the magnetic anisotropy with the effect of cutting is studied in order to improve the necessary understanding of the material behavior.

*Streszczenie. I. W procesie mechanicznego cięcia blchy elektrotechnicznej mogą ulec degradacji podstawowe jej parametry – straty I przenikalność. Indukowane w procesie cięcia naprężenia wpływają na anizotropię I rozkład strumienia. W artykule W artykule analizowany jest wpływ procesu cięcia na właściwości niezorientowanych blach elektrotechnicznych. **Wpływ mechanicznego cięcia i anizotropii na właściwości magnetyczne blach elektrotechnicznych SiFe***

Keywords: electrical steel, magnetic anisotropy, cutting effect.
Słowa kluczowe: blachy elektrotechniczne, anizotropia, cięcie blach, naprężenia mechaniczne.

Introduction

Machine modeling is the standard tool to design electrical machines. Accurate modeling enables the possibility to achieve high power densities and low losses without unnecessary oversizing, at compact geometries. The potential for improvement by constructive measures is largely exploited and subsequently, the focus for future progress is laid on material design and optimization. In order to incorporate actual material behavior in the design stage of the electrical machines, i.e., during the finite-element (FE) machine simulations or post-processing, advanced material models have to be developed, which are able to portrait the most relevant occurring effects. These relevant effects include, amongst others, the anisotropy of non-oriented (NO) electrical steels as well as the strong local material deterioration due to mechanical processing.

To maximize the energetic efficiency of the electrical machine, iron losses have to be minimized. The mechanical processing of electrical steel components is generally disregarded in machine design, because data from material testing, is standardized for single sheet tester (SST) or Epstein frame (EPF) measurements. In this case gentle processing of samples according to international standards, e.g. IEC60404-3 is required for fixed geometries. However, the geometry and processing majorly affect the properties of the NO in its application and are ideally incorporated already during the design stage [1]. Cutting is highly detrimental to the magnetic properties of the steel sheets, e.g., losses and magnetizability [2][3][4].

a) Influence of cutting
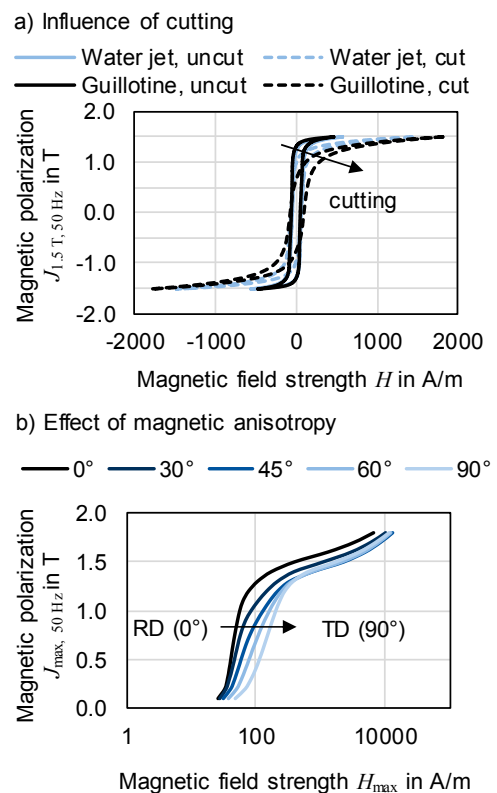

b) Effect of magnetic anisotropy

Fig.1. Influence of cutting and magnetic anisotropy of a conventional 2.9 wt.% FeSi at 50 Hz

Different cutting techniques, as depicted in Fig. 1 a), as well as the cutting parameters influence the properties to a different extent, dependent on the magnitude of the physical impact, primarily the induced mechanical stress [5]. The insufficient knowledge regarding the quantification of material deterioration and the cutting impact motivates consecutive studies on this topic.
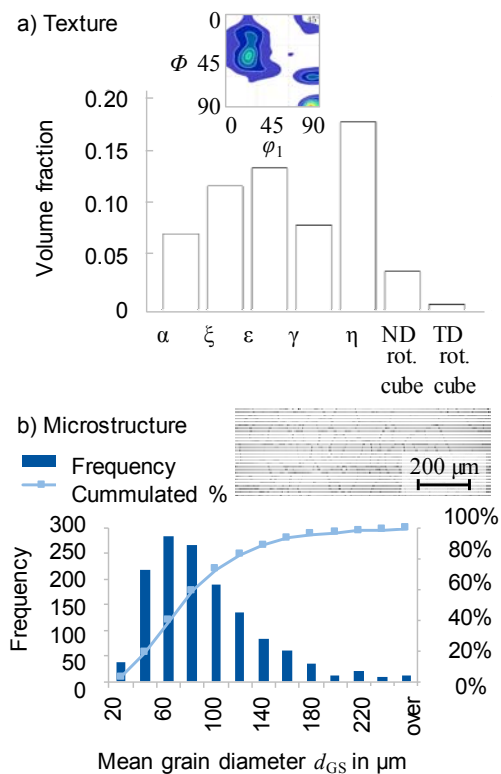

Fig.2. Material characteristics of the non-oriented 2.9 wt.% FeSi under study a) Fiber volume fraction and φ_2=45° orientation distribution function, b) LOM micrograph and histrogram of mean grain diameter.

The magnetic anisotropy is a further subject, which is mostly neglected by standardized material measurements. Properties are either determined in rolling (RD) or transverse direction (TD), or joint in one measurement with EPFs of both orientations. The angular dependence of properties in between those directions is not linear, as depicted in Fig. 1 b) and, therefore, needs to be studied as well [6]. Dependent on the NO grade, the impact of the magnetic texture can also differ [7]. In this paper, the interdependency of the effect of cutting and the magnetic anisotropy is studied, in order to gain knowledge on the phenomenology of both effects. This knowledge is essential to improve the validity range of material models for the FE simulation of electrical machines. In [8] it has been shown that the incorporation of a phenomenological continuous local cut edge model which enables the consideration of the permeability decrease as a function of the distance to the cut edge, can significantly increase the accuracy of FE simulations. The insufficient understanding of the interrelation of the physical effects are however, still a limiting factor in this context. Thus, the deterioration mechanisms due to mechanical processing and the interdependency with the magnetic anisotropy need to be understood, and therefore studied.

Experimental approach
A conventional 2.9 wt.% FeSi with 0.5-mm thickness is characterized by using a 120 mm x 120 mm SST on a Brockhaus measurement systems test bench (MPG 200D). Samples are cut to different strip widths in different angles relative to RD. Reference samples, have dimensions of 120 mm x 120 mm and represent the "uncut" material, as in Fig. 1. With smaller strip width, the proportion of cut surface increases. In Fig. 1 the "cut" samples consist of 24 samples with 5-mm strips. Two different cutting techniques are studied, which are water jet and guillotine. The magnetic measurements are performed between 0.1 T and 1.8 T at 50 Hz. The deterioration of magnetic properties due to the cutting can thereby be evaluated in different spatial directions of the sheet plane and the directional sensitivity can be quantified and discussed. Material properties, i.e., crystallographic macro-texture and grain size are determined by X-ray goniometry and light optical microscopy (LOM) respectively.
Microhardness measurements in the vicinity of the cut edge are performed to quantify the impact of plastic deformation as a result of the cutting procedure. Neutron grating interferometry (nGI) at the ANTARES instrument of the Heinz Maier-Leibnitz Zentrum in Garching is performed to study the penetration depths of the cutting techniques and their influence on the domain wall distribution [9][10][11].

The texture and grain size of the material under study is displayed in Fig. 2. The grain size affects the cutting procedure, because more grain boundaries, according to the principle of grain refinement, lead to an increased mechanical strength and, therefore, affects the cutting force. The grain size is determined from surface micrographs with the line intercept method and it emerged that the grains are spherical. This implies that the magnetic anisotropy for this material, is not affected by anisotropic grain size. The texture, on the other hand, is estimated to have a significant effect on the anisotropy and is therefore studied. Although, the material is NO, the texture has some intensity of Goss-orientation. The typical rolling fiber is less pronounced compared with other NO.

Results and Discussion
a) Study of different cutting techniques
It is well known that different cutting techniques deteriorate the magnetic properties to a different extent [2][4][12]. In Fig. 3, the magnetization curves at 50 Hz for guillotine and water jet cut samples are displayed in RD and TD. For the water jet cut samples, the strip width is reduced to 2 mm. For the guillotine cut samples, the minimum strip width is 5 mm. Below this width, the strips started to twist due to the shear stress induced by guillotine cutting. For the 120 mm x 120 mm initial samples, the cutting procedure has no effect, i.e., water jet and guillotine cut samples of this size have the same magnetization curve. A magnetic anisotropy in RD and TD can be denoted with an easier magnetization along RD than along TD. Concerning the effect of cutting, the samples comprised of the narrowest strips show a strong deterioration of magnetization behavior compared with the largest samples, for both cutting techniques. The curves are distinctly more linear in all cases. A difference between the cutting techniques still, can be noted. For guillotine cut samples of both orientations and for water jet cut samples in RD, the deterioration and linearization of the magnetization curves is continuous with decreasing strip width, whereas for the samples cut by water jet in TD, the curves initially shift to smaller field strength at small polarization, while linearizing. This unexpected behavior highlights that the process of cutting is not completely understood at this point. Overall, guillotine cutting is more detrimental than water jet cutting [13].
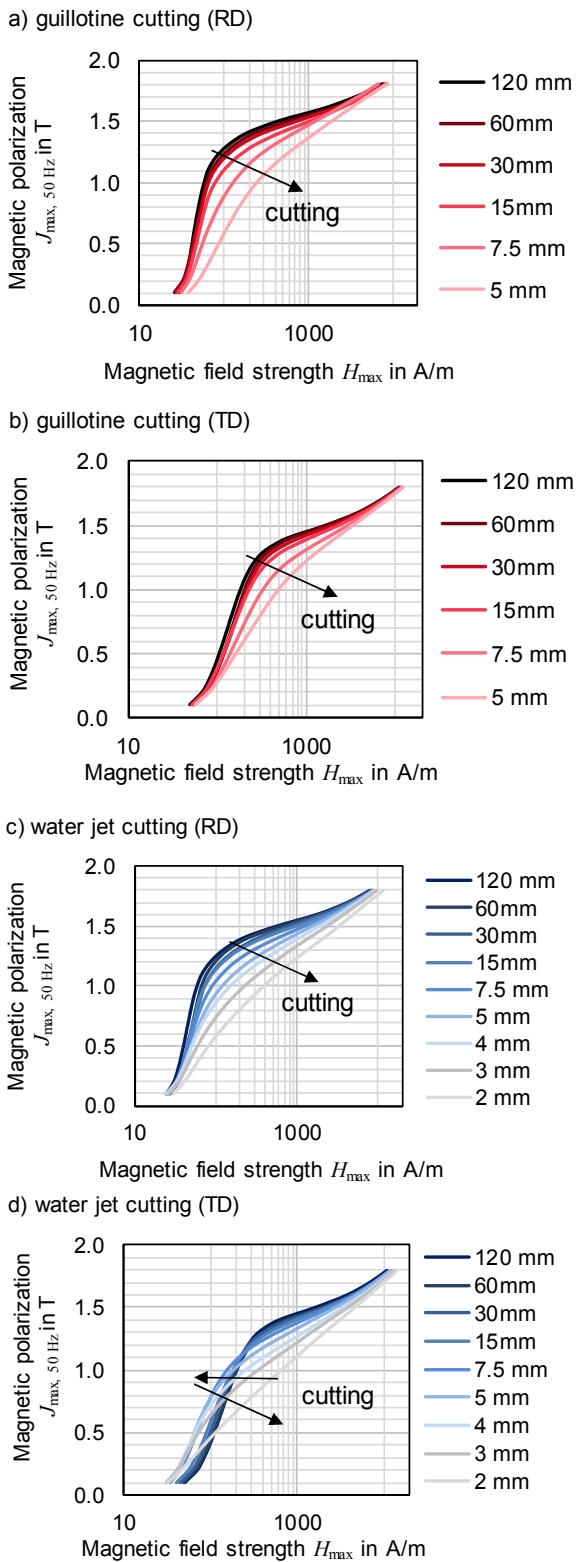
a) guillotine cutting (RD)

b) guillotine cutting (TD)

c) water jet cutting (RD)

d) water jet cutting (TD)

Fig.3. Effect of cutting on the magnetization curves, with an incressing amount of cut surface for a) gullotine cut (RD), b) guillotine cut (TD), c) water jet cut (RD), d) water jet cut (TD).

From the material science point of view, cutting induces mechanical stress. This leads to plastic deformation in the vicinity of the cut edge and residual stress that remains in the samples. The plastically deformed region after guillotine cutting is larger compared with water jet cutting. The respective penetration depths of approximately 200 µm and 50 µm are obtained from microhardness measurements and averaged over four samples for each cutting technique,

exemplarily depicted in Fig. 4 a) and b). Compared with plastic deformation, the penetration depths of the residual stress is estimated to be larger, as it has been subject of various research. In [5] the relation between magnetic properties, plastic deformation and the residual stress, calculated by mechanical FE simulations, has been studied. One of the central conclusions is, that larger plastic deformation due to higher induced stress results in overall higher residual stress and a greater penetration depths as well as magnetic deterioration. The penetration depths of residual stress for mechanical cutting is expected to be up to three times the sheet thickness, i.e., in the range of 1.5 mm for a 0.5-mm thick electrical steel lamination. By means of nGI measurements this penetration depths can be studied. Neutrons from the neutron beam scatter at domain walls. A darker contrast means a higher domain wall density in terms of the number of domain walls in a volume element. This domain wall density is affected by residual stress and thus proportional to the stress induced by cutting [14]. In Fig. 5 nGI dark-field images of the material under study for both cutting techniques are depicted. Consistent with mechanical simulations, the penetration depths, i.e. residual stress, is much larger than the penetration depth of plastic deformation. Furthermore, the penetration depths changes with the magnetization. Contrary to the results of [14], the penetration depths decreases with increasing magnetization. A physical interpretation of this behavior has not been concluded but is likely related to the magneto-elastic coupling.
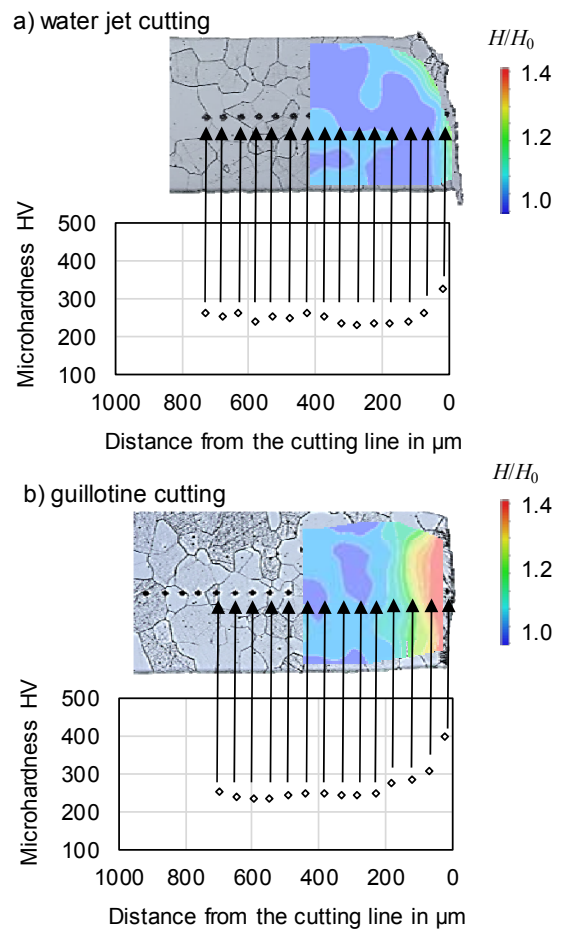
a) water jet cutting

b) guillotine cutting

Fig.4. Schematic overview of microhardness measurements for both cutting methods, a) water jet cutting b) guillotine cutting on cross sections

b) Magnetic evaluation of cutting techniques in RD and TD

The evaluation of the graphs in Fig. 3 concerning the orientation dependence in RD and TD indicates that the relative deterioration due to the cutting is greater in RD than in TD. This means that the magnetically harder direction is less affected by the cutting than the easier magnetization direction. Fig. 6 depicts the magnetic loss at 50 Hz for different polarizations as a function of the cut-edge factor δ_{cut} [14]. This factor describes the number of cutting lines per millimeter sample width, i.e. a strip of 2 mm has 2 cutting lines, one left and one right and a resulting δ_{cut} of 1.0 mm-1, a strip of 5 mm consequently has a δ_{cut} 0.4 mm-1. Due to the preceding discussions of the mechanisms of material deterioration as a result of plastic deformation and residual stress, the assumption that each cut has a proportional effect on the magnetic properties can be deduced. Each cut affects a fixed volume of the material with the length of the cut, delimited by the sheet thickness and penetration depths. The magnetic deterioration is proportional to the induced mechanical stress. For guillotine cutting, in comparison to industrial punching, the first and second cut on each strip is different. One cut relates to the punched part and one the second cut corresponds to the slug. Due to the fact that each strip has one of the aforementioned cuts, the proportionality should pertain for the magnetic evaluation. The proportionality in the graphs of Fig. 6 is evaluated with a linear regression. For guillotine cut samples the coefficient of determination R^2 is close to 1. The slope is smaller in TD than in RD and increases with polarization. For the water jet cut samples the fit is not as good for RD. For TD linear regression is not justified, especially at low polarizations. The losses for water jet in TD first decrease and then increase slightly with an increased amount of cut lines. At this point, this contradicts the assumptions of before.
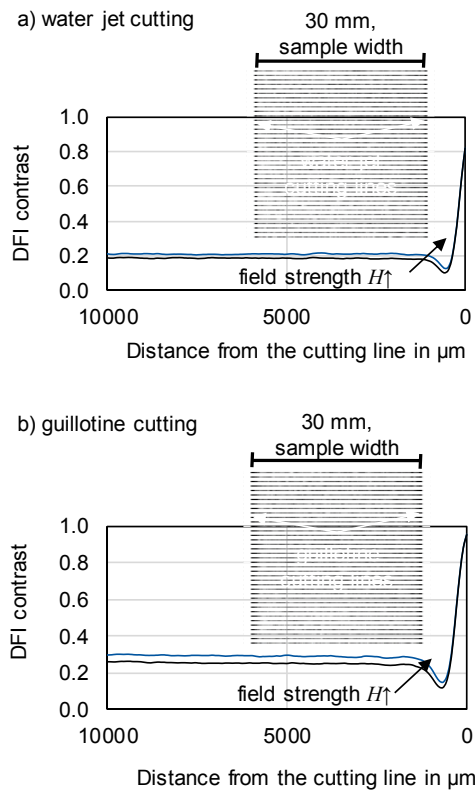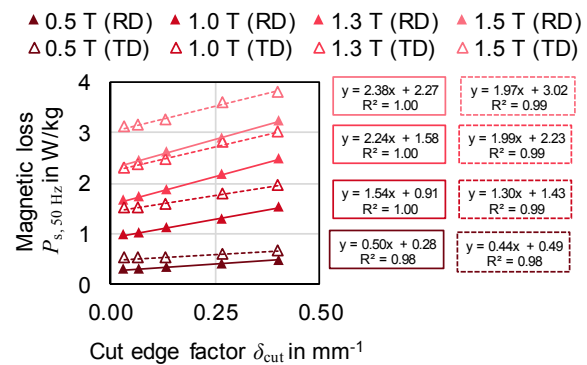
a) water jet cutting

b) guillotine cutting

Fig.5 DFI contrast images from NGI measurements and top view images of samples processed with a) water jet cutting, 3.5 Å wavelength and b) guillotine cutting 3.2 Å wave-length, at two field strengths

c) Magnetic anisotropy within the sheet plane

For electrical steel, the isotropy not only in RD and TD but also in between these directions is of concern. The crystallographic texture has an effect on the magnetization especially at medium to high polarizations, and field strength respectively [16]. As previously discussed the effect of cutting is not the same in both directions. In Fig. 7 the relative loss increase in four spatial directions is depicted. In Fig. 8 the absolute loss increase at three inductions is presented. Both figures support the hypothesis of the releasing and the correlations to the magnitude of residual stress induced by the cutting techniques. For guillotine cutting the behavior is proportional. The relative effect decreases between RD and TD. Water jet cutting due to the smaller magnitude of induced stress has a more complicated behavior due to the release of production stress and interrelation with locally induced stresses.
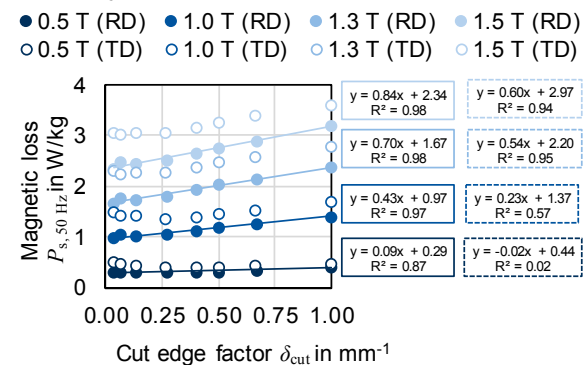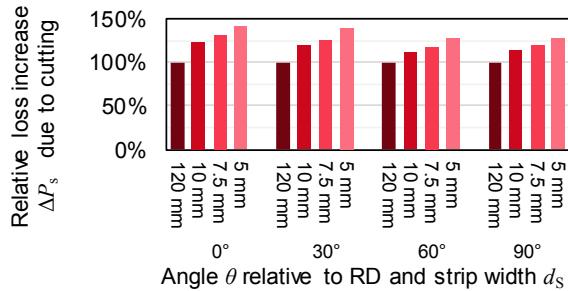
a) guillotine cut

b) water jet cut

Fig.6. Magnetic loss as a function of the cut edge factor at different polarizations and 50 Hz, for a) gullotine cutting and b) water jet cutting

However, a new consideration can be proposed. If the initial decrease of loss for water jet cut samples in TD is interpreted as a release of residual production stress, the proportionality of deterioration can still apply. Especially, since a greater amount of cuts does show a linear trend. The difference of RD and TD are also concurrent with this assumption. If the initial mechanical residual stress stems from the production process, the coiling, rolling and strip forces likely induce tensile stress along RD and a small amount of compressive stress in TD. Even though, the material is annealed, a small magnitude of stress can remain in the material. This amount is barely noticeable for global material properties, like mechanical strength, but it can affect the magnetic properties. Especially, since compressive stress is highly detrimental and has a greater effect than tensile stress [15]. Consequently, this mean that

this effect has to be accounted for in all samples, though it is likely that due to the higher impact of guillotine cutting, the stress exceeds the beneficial effect already for a smaller cut edge factor. The main challenge for a closer study of this interaction is that the initial stress acts globally and the cutting stress acts locally. In order to validate and study this theory samples which are stress relief annealed could be testes. However, the evidence of stress relief annealing for electrical steel is another challenge due to the magnitude of the residual stress and the lack of accountable quantification methods of residual stress in electrical steel.

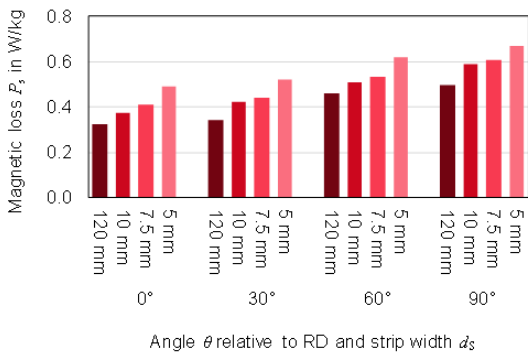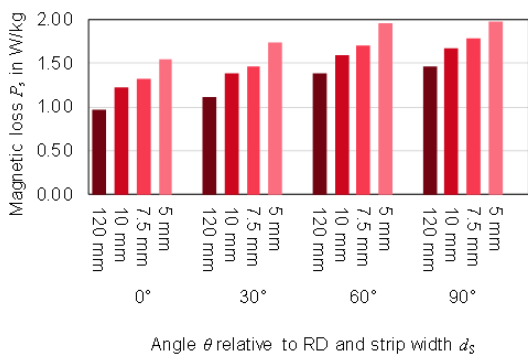a) 1.5 T, 50 Hz, guillotine

b) 1.5 T, 50 Hz, water jet
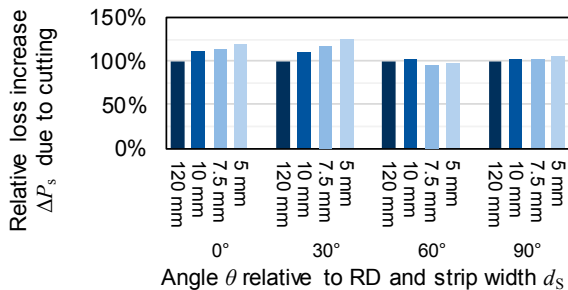
Fig.7. Relative loss increase at 1.5 T and 50 Hz, compared to the uncut sample in different orientations relative to the rolling direction for a) guillotine and b) water jet cut samples
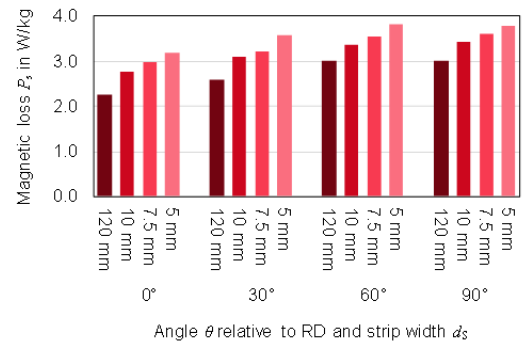
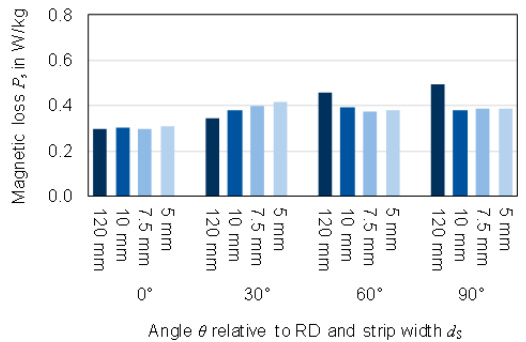a) guillotine cut, 0.5 T, 50 Hz

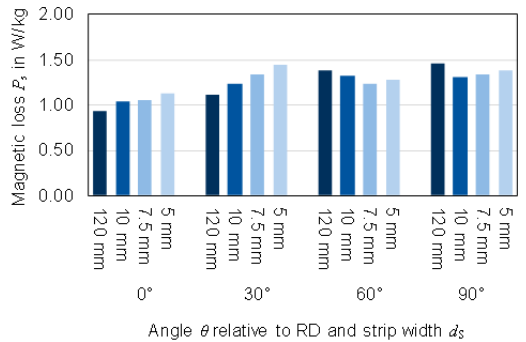
b) guillotine cut, 1.0 T, 50 Hz

c) guillotine cut, 1.5 T, 50 Hz

d) water jet cut, 0.5 T, 50 Hz

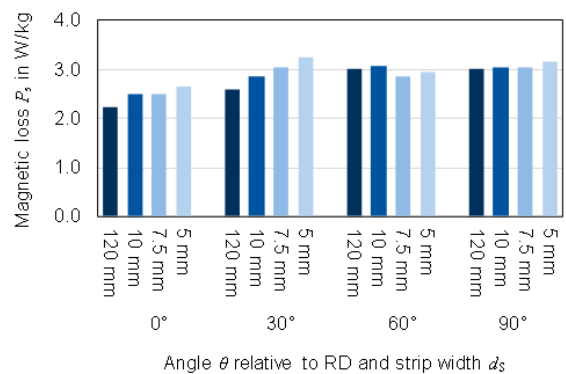e) water jet cut, 1.0 T, 50 Hz

f) water jet cut, 1.5 T, 50 Hz

Fig.8. Magnetic loss at 0.5 T, 1.0 T and 1.5 T at 50 Hz, for different sample orientation and strip widths of 120 mm, 10 mm, 7.5 mm and 5 mm for guillotine and water jet cut samples

Conclusions

In this paper the interdependency between the effects of cutting and the magnetic anisotropy of NO electrical steel has been studied and discussed. For mechanical cutting, i.e., guillotine cutting in the presented case, a strong proportionality of total loss and the number of cuts has been observed, which is in accordance with the physical

understanding behind the cutting technique. Each cut affects the same volume of the material to the same extent due to plastic deformation and residual stress. The residual stress affects the domain wall density and, thus, the magnetically deteriorated region changes with the magnetic induction level. The minimum affected zone is the plastically deformed region.

From the results of the water jet cut samples, another contribution has been deduced. A possible initial mechanical residual stress from the production process is likely cut free. The stress acts globally as a tensile stress in RD and a compressive stress in TD. Due to the local induction by cutting the global stress is cut free. This implies that the release of stress due to cutting has to be further studied. Especially, when cutting techniques with a gentler impact, i.e., smaller induced stress are applied. A further study on the effect of frequency such as the authors of [17] as well as a study with an effective approach for stress-relief-annealing of electrical steel laminations would have to be conducted to further improve the understanding of the interdependencies between the cutting and the magnetic anisotropy to validate the assumptions and conclusions obtained by the presented results.

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