Design Guidelines for interlocked stator cores made of CoFe sheets

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Abstract. CoFe lamination stacks used for high-performance electric motors can be manufactured economically in high volumes by interlocking. In order to ensure sufficient joint strength with minimized sheet thickness, a comprehensive knowledge of the influences of various process parameters, such as embossing depth, clearance and counter punch force, is essential. To analyze these parameters, which also influence the magnetic properties, experiments are carried out and resulting joint strengths are determined in top tensile tests. The negative influences of the cutting process on magnetic conductivity and thus hysteresis losses due to residual stresses and plastic deformation are well known. In the subsequent stacking step, an influence of embossing and pre-stresses on the material properties is expected. In addition, local electrical contacts between the sheets may occur due to the interlocking process, causing additional eddy currents. Loss measurements are conducted to investigate the effect of the joining process on the magnetic properties of the stack. In doing so, the influence of process parameters such as the embossing depth and clearance on eddy current power losses is analyzed.
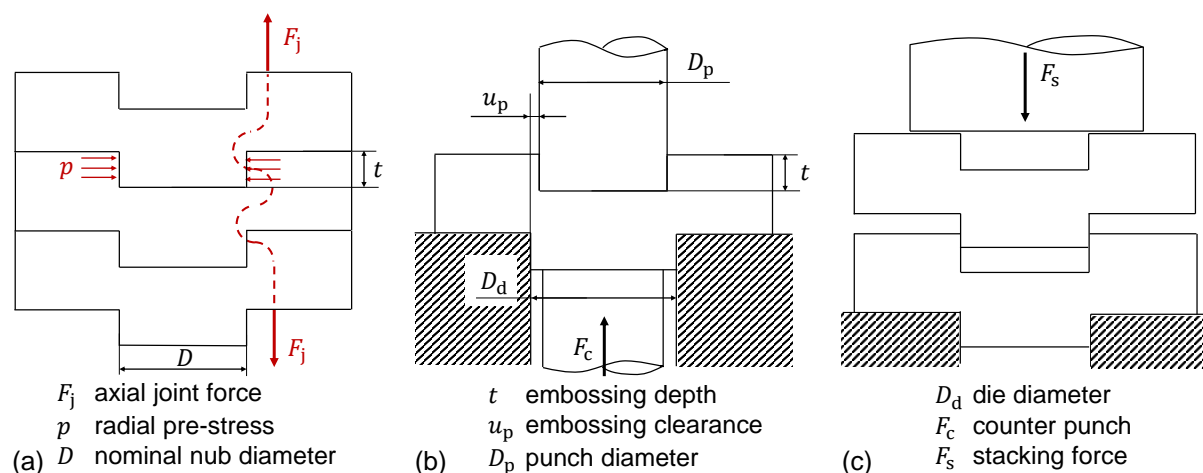
1. Introduction

As a result of progressive electrification, particularly in the mobility sector, the importance of economical manufacturing processes for components of electric drives is increasing while product quality requirements remain high. In vehicles that have to meet high performance requirements, lamination stacks made from CoFe alloys are used in the manufacturing of stator cores for electric motors. Compared with conventional FeSi electrical steel, these are characterized by a higher saturation flux density, allowing higher torques to be achieved within the same assembly space and higher power density at high rotational speeds.

In addition to the hysteresis losses, which depend on the material properties and are dominant at low frequencies, power losses in the stators of electrical machines consist mainly of eddy current losses, which represent a significant share of the power losses at medium and especially at high speeds [1]. These arise from eddy currents, caused by an induced voltage perpendicular to a time-varying magnetic field in the soft-magnetic core. The thickness t of the individual sheets enters quadratically into the specific mass-related eddy current power loss p_{W}. Therefore, iron cores do not consist of a solid body, but are made of individual laminations electrically insulated

from each other. For the same height of the stator or rotor, the added losses of the laminated core are thus lower. For this reason, efforts are being made to further reduce the thickness of the laminations in order to reduce iron losses. In the present work, CoFe laminations with a thickness of 0.2 mm are investigated.

One manufacturing process for stacking sheets, which represents an economical alternative for the production of larger quantities, is interlocking. After the cutting step (usually a shear cutting process), the process is subdivided into the process steps embossing (Figure 1(b)) and stacking (c), in which the laminations are pressed together with the stacking force F_s. The mechanism of action in interlocking is based on an interference fit between the outer and inner diameter of the punching nubs [2], see Figure 1(a). The resulting joint strength F_j must be sufficiently high to ensure safe handling during transport and further processing as well as the necessary strength during operation. In addition, high geometric accuracy is required to avoid stacking errors like curved or skewed stacks.

F_j	axial joint force	t	embossing depth	D_d	die diameter
p	radial pre-stress	u_p	embossing clearance	F_c	counter punch
(a) D	nominal nub diameter	(b) D_p	punch diameter	(c) F_s	stacking force

Figure 1. Schematic representation of the process steps in.

To ensure reliable joining of the individual sheets into a stack and at the same time minimize the sheet thickness to reduce eddy current losses, comprehensive knowledge of the process variables in the design process is essential. To enable prediction of joint strength, the interrelationships of numerous process parameters must be analyzed.

Thereby, the aim is to quantify the influence of the parameters embossing depth t, clearance u_p, counter punch force F_c and stacking force F_s on the resulting joint strength by means of experiments. However, different effects act along the process chain, which influence not only the mechanical strength but also the magnetic properties of the lamination stacks leading to increased iron losses [3]. Depending on the cutting process, thermal and/or mechanical residual stresses are introduced into the material during the cutting step [4, 5], and plastic deformations can cause changes in the microstructure [6].

A negative influence of these mechanisms on the electro-magnetic conductivity and thus the iron losses has been known for FeSi electrical sheet for a long time [7, 8, 9] and can be described with various modeling approaches [10], but are still the subject of current research activities [11]. During the stacking step, local electrical contacting between the layers may occur, which causes additional eddy currents. Furthermore, the deformations caused by the embossing of the nubs and the pre-stressing generated during stacking influence the material properties analogously to the cutting process [3, 12].

In previous experimental investigations, the significance of eddy current losses in the area of the punching nubs has been demonstrated [13]. This is due to the electrical contacting (damage

to the insulation induces additional eddy current paths) as well as the change in the magnetic flux density in the area of the formed nub [1]. As a result, field displacement effects lead to a local reduction of the magnetic flux density and thus to a reduction of the available mechanical power. Furthermore, the influence of the nub shape on the joint strength was considered [13]. An investigation of the influence of the embossing clearance of cylindrical nubs on the deformation of the contact zone and the joint strength was carried out by Lin et al. [14] and Park et al. [15].

The presented work investigates which parameters are relevant for the design of interlocked joints for use in electric motors. Experimental investigations are used to determine the influence of these parameters on the target variables joint strength and iron losses in a stator core.

2. Methods and Materials
The subject of the investigations are test stacks made of 10 layers of CeFe test rings of sheet thickness 0.2 mm with the geometry shown in Figure 2(a) which are stacked using interlocking. Each layer, including the bottom one, is provided with one cylindrical punching nubs with a diameter of 1 mm. The interlocking process takes place in the unannealed state. Top tensile tests are used to identify which influencing variables have the greatest impact on mechanical joint strength. To determine the influence of the most significant design parameters on the component properties with regard to the subsequent application, an annealing process is carried out in the further test series after the stacking process before the mechanical and electromagnetic target values of the stacks are determined experimentally.

In the annealed condition, the test material has the properties listed in Table 1. The annealing process after stacking is performed for optimum magnetic properties at 880 °C for 6 h. The sheets are coated with a magnesium ethylate coating which is transformed to MgO during annealing. The influence of annealing on the joint strength of interlocked components has not yet been investigated so far. In the case of CoFe alloys, however, it is known that the mechanical and magnetic material properties can be influenced by an annealing process, with lower coercivity being associated with lower yield strength and vice versa. Also for FeSi alloys the influence of the annealing process on the magnetic properties due to the strain distribution has been proved [3]. Thus, the mechanical and magnetic properties of the material behave in opposite ways. The investigations presented are based on material that has not yet been heat treated prior to processing and is annealed for optimum magnetic properties following the interlocking process.

Table 1. Material properties of the CoFe alloy (*measured at a sheet thickness of 0.35 mm; [1]annealed for optimum magnetic properties) [16].

composition by weight	saturation magnetization B_s	mass density ρ	coercivity $H_\mathrm{c}^{*,1}$	yield strength $R_\mathrm{p0.2}^{*,1}$	tensile strength $R_\mathrm{m}^{*,1}$	modulus of elasticity $E^{*,1}$
49 % Fe, 49 % Co, 2% V and Nb	2.35 T	8.12 g/cm^3	50 A/m	210 MPa	400 MPa	200 GPa

The test tools shown in Figure 2 are used to produce the interlocked lamination stacks. In order to reduce complexity and avoid unwanted interdependencies between the process steps, embossing and stacking are implemented in separate tools. Figure 2(b) shows the tool for the embossing process. This has a three-part design and consists mainly of an upper tool carrying the punches, a lower tool containing the dies and the counter punch mechanism, and a guidance plane inbetween that carries the blank holder. The embossing tests are carried out on an eccentric press in single-stroke operation, whereby the embossing depth t is specified by

setting the bottom dead center. Figure 2(c) shows the stacking tool, in which the lamellae are pressed into a stack by applying a defined force in the axial direction. The individual test rings are inserted manually and centered radially via a guidance component in the middle. The tangential centering is achieved via the nubs themselves.
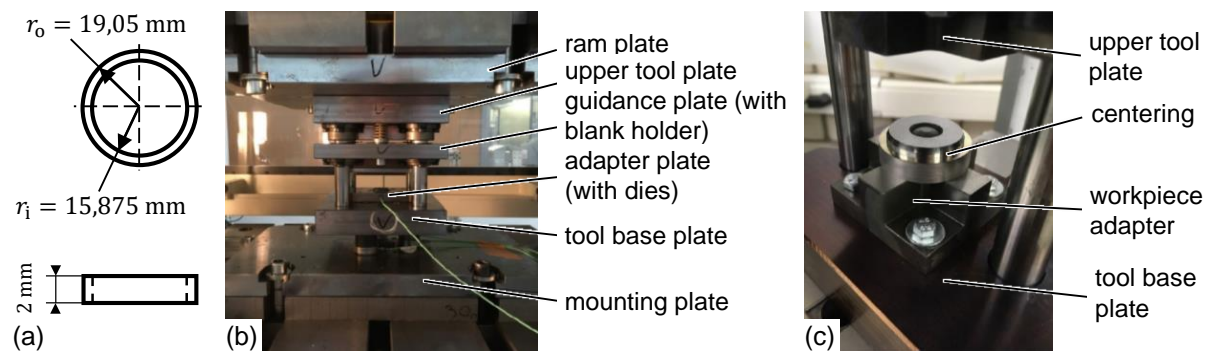

Figure 2. Test stack geometrie (a), embossing tool (b) and stacking tool (c).

The joint strength F_j of the interlocked specimens is evaluated by means of top tensile tests on a tensile testing machine, whereby a force in the axial direction is applied and slowly increased continuously until failure of the joint by separation of the stack occurs. As shown in Figure 3, the force is applied via disposable adapters made of plastic (PLA), which are bonded both to the test rings and to receptacles made of aluminum, which are clamped in the testing machine.

To investigate the magnetic properties, iron loss measurements are performed according to [17] in the frequency range 50 Hz to 1000 Hz at field strengths of 0.5 T to 2 T. For this purpose, the test stacks are placed in a trough and mechanically wrapped with a copper coil, as shown in Figure 4. To evaluate the influence of the joining process on the iron losses in the core, reference measurements are made for all frequencies and field strengths on a loosely stacked package of sheets without punching nubs, which serve as a reference for the additional losses due to interlocking.
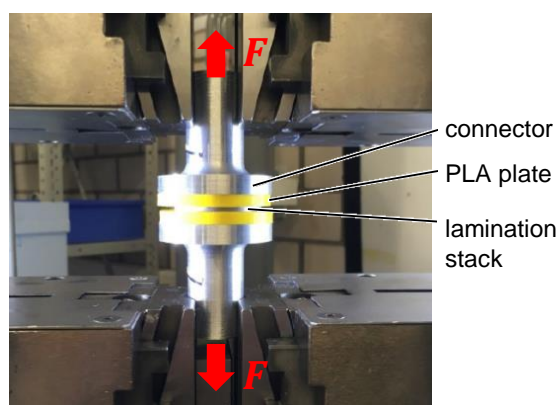

Figure 3. Test setup for determination of the axial joint force.
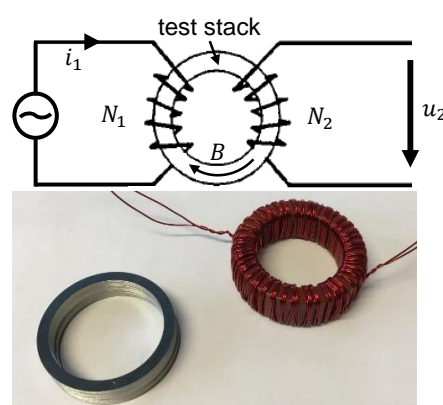
Figure 4. Test setup for measuring iron losses of test rings according to [17].

In a preliminary test, it is first checked whether the number of interlocking spots has a significant influence on the joint strength of the stacks. A comparison of the joint strength of a stack provided with 5 nubs distributed over the circumference with a stack with only one nub per

layer shows that the achieved strength scales in good approximation with the number of nubs. The result of this comparison normalized to the joint strength of the one-nub stack is shown in Figure 5. For this reason, the following investigations can be carried out representatively using rings with only one nub. In this way, the influence of the varied process variables on the individual nubs can be considered.
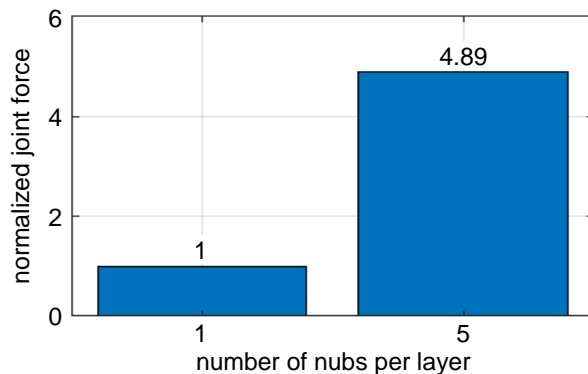
Figure 5. Influence of the punching nub number on the joint force of the lamination stack normalized to the joint strength of a stack with one interlocking spot.

3. Results

3.1. Joint Strength

To identify the main influencing variables on the target quantity joint strength, a full factorial 2^3 DOE is carried out varying the embossing depth, the embossing gap and the blank holder force. Previously, a variation of the stacking force was done to evaluate its influence on the joint strength. The results of this is shown in Figure 6(a). It should be mentioned that all results are normalized to the maximum achieved joint force in this test series. Accordingly, the joint strength increases slightly with increasing stacking force. For the conducted experiments, a stacking force of $1500\,\mathrm{N}$ was considered to be sufficient to investigate the influence of the relevant process parameters of the embossing step. The blank holder force was set to 30% of the maximum punch force during emobssing, according to preliminary experiments. The embossing depth is set to 50% or 90% of the sheet thickness s by adjusting the lower dead center. The embossing clearance is varied between 0.5% and 1.5%s by changing the punching dies. The counter punch force is set to 15% or 25% of the maximum punch force by varying the pre-stress of a spring in the counter punch mechanism located in the tool base plate. As can be seen in Figure 6(b), an increase in the embossing depth leads to a significant increase in the joint strength achieved. An increase in the embossing clearance leads to a moderate decrease (Fig. 6(c)) while increasing the counter punch force only leads to a slight drop in the joint strength (Fig. 6(d)).

Using the normalized step values listed in Table 2, the effect of the varied parameters and their combinations on the resulting joint strength is calculated. These are shown in Figure 7. It can be seen that embossing depth and clearance have the greatest influence on the joint strength, while the counter punch force has no direct influence. However, it can be observed that a higher counter punch force helps to increase the maximum achievable embossing depth, without failure due to nub break-off or local fracture.

Based on these findings, the influence of stamping depth and embossing clearance is further investigated in another fully factorial 3^2 series of experiments. Figure 8(a) shows the joint strength as a function of embossing depth at an embossing clearance of 1%, and Figure 8(b) shows the joint strength as a function of embossing clearance at an embossing depth of 70%. Analogously to the results in Fig. 7, all results in Fig. 8 are normalized to the maximum joint strength achieved in this test series. From these results, a regression model was used to derive the diagram shown in Figure 8(c) to predict the achievable joint strength when the embossing
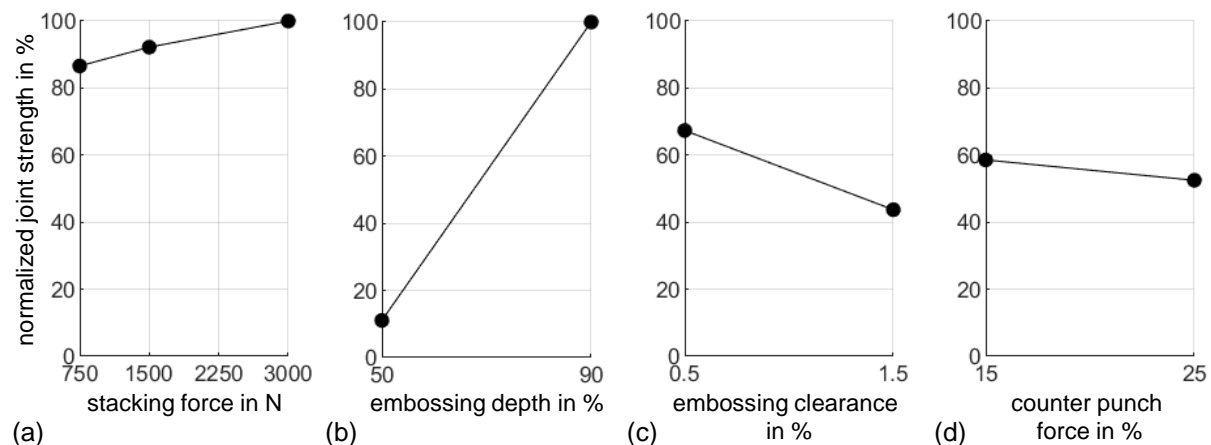
Figure 6. Influence of the embossing depth and clearance on the joint strength of a single interlocking nub.

**Table 2.** Standardized step values of variation parameters for calculating the effects on the joint force.

standardized step values	-1	1
embossing depth t in $\%s$	50	90
embossing clearance u_{p} in $\%s$	0.5	1.5
counter punch force F_{c} in $\%F_{\mathrm{s}}$	15	25
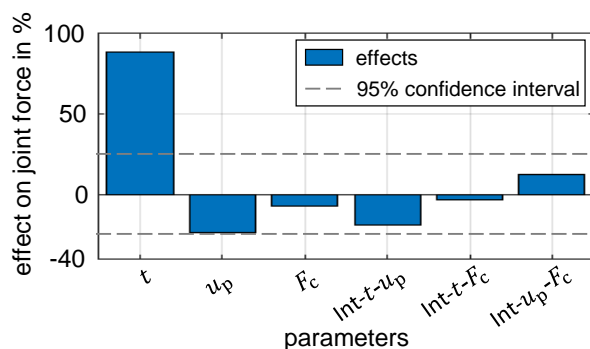
Figure 7. Effects of process parameters on joint force; entries labelled with 'Int-...' denote the effects of the interaction of two parameters.

depth and clearance are varied. Increasing the embossing depth from 50% to 70% results in a significant increase in joint strength. A further increase in the embossing depth only causes a smaller increase. Up to an embossing depth of 80%, reliable stacking was possible in all configurations. With further increase, a critical range was identified. Above an embossing depth of 80%, there is an increased risk for failure of the nubs during the embossing process and thus a safe joining process is not guaranteed.

Counter punch force and embossing clearance have been shown to influence the maximum achievable embossing depth. Both factors make it possible to further increase the embossing depth before the residual cross section of the nub fails. The embossing clearance also has a direct influence on the joint strength. As the embossing clearance decreases, an increase in joint strength can be observed. Furthermore, the stacks were subjected to a final annealing to achieve the optimum magnetic properties. This also has an influence on the joint strength
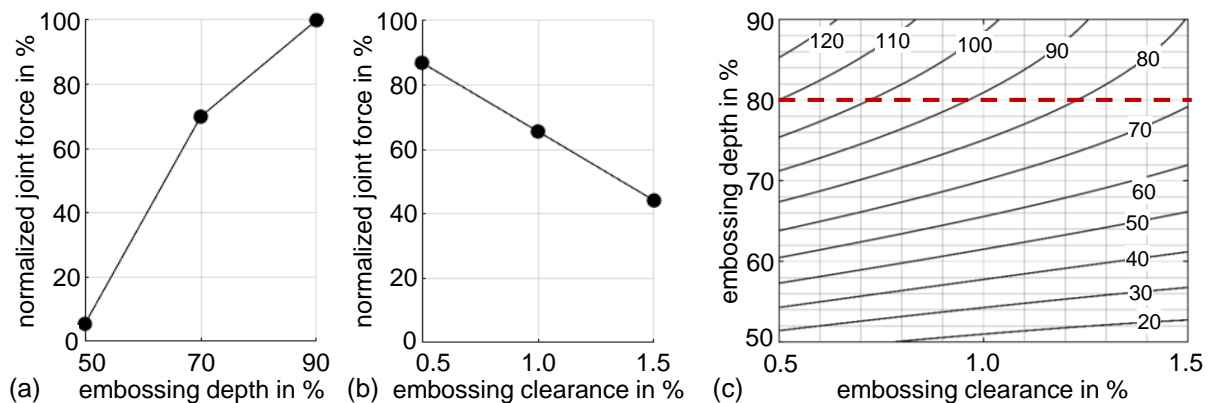
Figure 8. Influence of the embossing depth and clearance on the joint strength of a single interlocking nub: (a) variation of the embossing depth at an embossing clearance of 1.0%; (b) variation of the embossing clearance at an embossing depth of 70%; (c) regression map for variation of embossing depth and clearance

as in all parameter configurations the joint force of the annealed stacks was at least two times higher than the joint force of the unannealed stacks. The explanation for this can be assumed to be locally occurring thermal welding at the contact surfaces of the nubs during the annealing process.
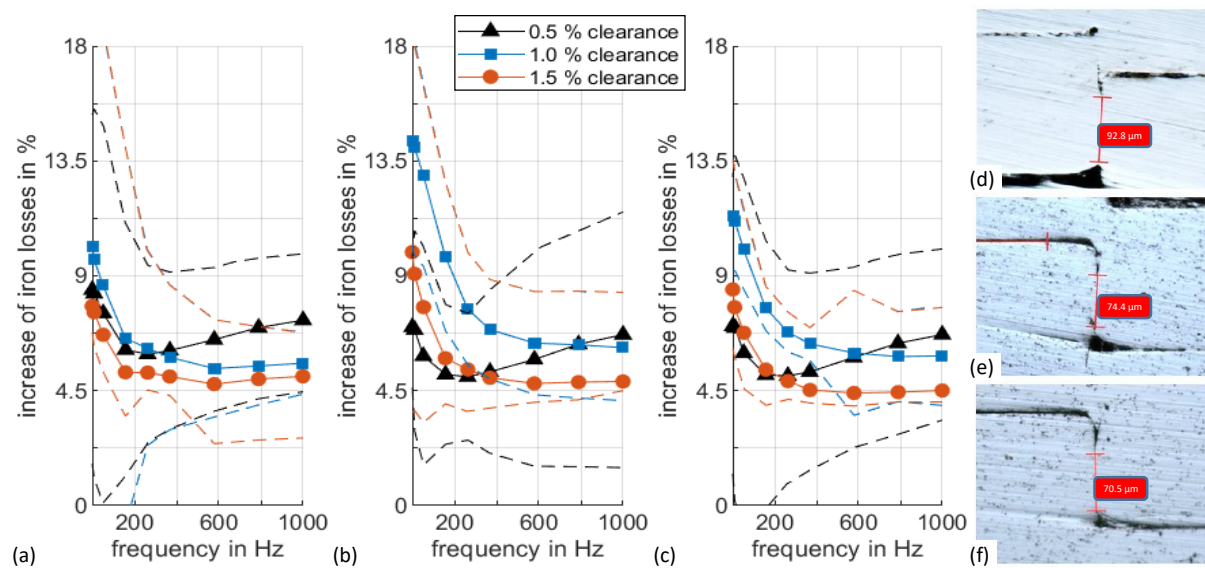
3.2. Iron Losses
Figure 9 shows the results of the iron loss measurements for different embossing depths (a-c) under variation of the embossing clearance. The graphs show the relative change of the total iron losses in the stack compared to the reference measurement on loosely stacked samples. No significant influence of the stamping depth on the core losses can be detected.

In Figure 9, the 95% confidence intervals of the plotted curves are shown in dashed lines. The large measurement uncertainty is due on the one hand to the small number of samples (3 repetitions) and on the other hand to the fact that test rings with only one interlocking spot were used, which cause only small amounts of additional iron losses, so that the percentage deviations are highly afflicted with uncertainty.

However, it can be observed that the losses of the interlocked samples are always higher than those of the loose lamination stacks for all configurations in the entire frequency range. This leads to the conclusion that interlocking causes an increase in hystereses as well as eddy current losses. At high frequencies, there is a tendency for the iron losses to be higher the smaller the embossing clearance becomes. This indicates that the eddy current losses in particular are influenced by the embossing clearance. One explanation for this is the contact area at the nub flank, which is shown in Figure 9(d-f) as an example for an embossing depth of 80%. In the case shown, the contact area is significantly larger for an embossing clearance of 0.5 % than for a clearance of 1.0 % or 1.5 %.

4. Discussion and Conclusion
The presented investigations show that a reliable interlocking process is possible for 0.2 mm thin sheets of cobalt-iron, where the embossing depth and the embossing clearance can be identified as significant influencing factors on joint strength. Entscheidend für die Verbindungsfestigkeit sind die radialen Spannungen zwischen den Fügepartnern und die Höhe der Kontaktfläche. A larger embossing clearance causes a higher deformation of the joining zone during the stacking step due to the interference fit and a higher draft angle. This leads to a reduction in the

Figure 9. Experimentally determined interlocking-induced iron losses under variation of the embossing clearance at embossing depths of 70% (a), 80% (b), and 90% (c) and contact area height at the nub flank for a embossing depth of 80% at a clearance of 0.5% (d), 1.0% (e), and 1.5% (f).

effective contact area heigth and a lower joint force after removal of the punch. This observation is consistent with the investigations of Lin et al. [14]. A clear influence of embossing depth and clearance on the core losses cannot be proved.

The counter punch force shows no direct influence on the joint strength but is necessary to increase the maximum achievable embossing depth before failure occurs. An increase in the pressing force in stacking leads to a slight increase in the joint strength.

The annealed stacks show at least a doubling of the joint strength compared to the unannealed stacks. The comparison of a stack that has five interlocking spots with the stacks that have only one seems to show good scalability in terms of joint strength.

The interlocking of test stacks consisting of 10 layers of 0.2 mm thick individual sheets of the selected annular geometry made of a CoFe alloy with 49% cobalt using single cylindrical nubs of 1 mm diameter leads to a measurable increase in the core losses in all combinations of embossing depth and clearance considered under variation of the excitation frequency in the range from 0 to 1000 Hz. This increase was demonstrated experimentally. The measured increase in power loss is due to an increase in both hysteresis (offset between the curves) and eddy current losses (higher slope of the curve). However, the difference between the iron losses in the entire stack of sheets with only one interlocking spot compared with the reference measurement on a loose stack of sheets without interlocking spots is small. Taking into account the present measurement uncertainty in the investigated range of the process variables embossing depth and embossing clearance, no clear relationship to the iron loss performance can be described.

This suggests that when designing an interlocked joint in which the area of the nubs is small compared with the total stack, as in the case studied, the embossing depth and embossing clearance can be selected for the maximum achievable joint force of the individual nubs. Accordingly, the number of nubs required to achieve the necessary joint strength of the stack can be minimized. However, this initially applies only to a constant nub diameter. A statement on the influence of the nub diameter and thus an evaluation of whether many smaller nubs should be preferred over a few large ones with the same overall joint strength is not yet possible.

Therefore, additional stack properties such as vibrational behaviour will have to be taken into account in further investigations. In addition, the influence of different nub shapes on the iron losses needs to be further investigated.

Acknowledgments

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