Investigation of the Forming Behavior of Copper Wires for the Compaction of Windings for Electric Machines

Maximilian Halwas[1,a*], Felix Wirth[1,b], Jürgen Fleischer[1,c]

[1]Karlsruhe Institute of Technology (KIT), wbk Institute of Production Science, Kaiserstraße 12, 76131 Karlsruhe, Germany

[a]Maximilian.Halwas@kit.edu; [b]Felix.Wirth@kit.edu, [c]Juergen.Fleischer@kit.edu

Abstract. To meet the increasing demand for highly efficient electric traction drives, the compact winding process has been developed at the wbk Institute of Production Science. One key element of the process chain is the compaction of the round wire stator windings. In order to enable an estimation of the sensitivities of the influencing factors, a simplified finite element simulation model was set up in the present work. In the calculations, the number of wire layers, the layer structure and the punch stroke were selected as factors with three levels each. The evaluation was performed by means of false-color images and the maximum strains and stresses in the section plane of the slots.

Introduction

Caused by the transformation of conventional internal combustion engines to electrified applications in the automotive industry, the demand for highly efficient electric traction motors is constantly increasing. A promising approach to meet the requirements for efficiency and installation space is the compaction of stator windings consisting of a vast number of individual enameled copper conductors with a round shape. This approach results in an increase of the so-called fill factor of the winding, which contributes to higher efficiencies and power densities of electrical machines. The fill factor indicates the ratio of the conductor area to the available slot area in the stator sheet metal package. [1, 2] The compaction process step is part of the compact winding process, which has been developed at the wbk Institute of Production Science in previous research work [3]. In this context, compaction refers to two process steps: The first is the compression step, which compacts the winding without significant plastic deformation, the second is the forming step with a high degree of plastic deformation. Aim of the compact winding process is the forming of a defined layer structure of round wires to predefined cross-sections, for example rectangular shapes. For this purpose, experimental test series have already been carried out by the authors, especially with regard to the electrical behavior and the associated practical feasibility for electric machines [4]. Since it is very time-consuming to determine the relationships between the forming step and the resulting winding shape in an experimental matter, a simplified model was implemented in the present work using the explicit finite element method (FEM) for basic investigations.

Fundamentals

In the context of this paper, the three producible wire layer structures of round wire windings in slots of electrical machines are investigated, as shown in Figure 1 (compare to [5]). In the cross-sectional views, the insulation layer (enamel) of the wire, the resin and the slot insulation are visible, giving a realistic overview of the layer structure in the stator slots of an electrical machine. In the finite eleement (FE) model, only the round copper wires and a rectangular slot with a rectangular shape was used, further details are described in chapter "Setup of FE model".

The three depicted winding layer structures strongly depend on the applied winding technology. The wild winding is usually manufactured by the insertion or needle winding technique for distributed windings [6].
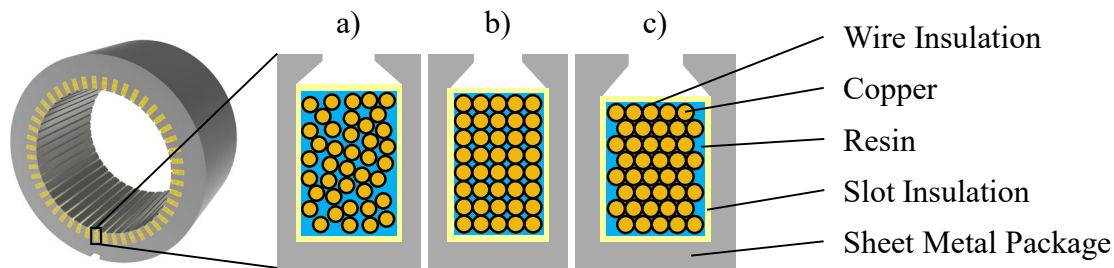
Figure 1: Cross-sections of the investigated layer structures for round wire windings in electrical machines: a) wild winding; b) layer-precise winding; c) orthocyclic winding.

In the compact winding process coils with a layer-precise structure are produced and compacted, so that the initial round wires are formed to rectangular shapes [3]. Orthocyclic layer structures are commonly used in concentrated windings and can be manufactured by linear, needle or flyer winding technologies [6].

At this point, it must be mentioned that compression only occurs in wild windings in the context of winding compaction. This is due to the characteristic that layer-precise and orthocyclic windings are already in a high packing density in which the wires are positioned next to each other. There are no cavities anymore that can be filled without plastic deformation.

State of the Art for Numerical Analysis of Round Wire Windings

The technological and scientific state of the art for the compression of windings of electrical machines can be found in a past publication of the authors [4], in which also experimental studies were carried out. For this work, approaches with numerical analysis of round wire windings are listed in detail.

An electrostatic FE model was used by Asokan [7], to estimate the behavior of electrical stresses in windings with round, rectangular and hexagonal wire cross-sections. The hexagonal packing of magnet wires was assumed for compressed orthocyclic windings. As a main result it was shown that acute angels in the air-gaps between the wire cross-sections result in high electrical stresses. Therefore, the hexagonal conductor shape has lower electrical stresses than undeformed round ones. Further numerical methods for the forming steps were not elaborated.

Kulan published numerical approaches for modeling of the insulation layer in forming processes for the production of stator windings [8–10]. In this works, orthocyclic windings with two and five layers are investigated. Significant uncertainties regarding the plastic material properties of the insulation layer show the unsolved challenge of an accurate modeling of the insulation layer.

The production and experimental investigation of prototypes of twisted and pressed shaped coils was described by Vogt [11]. Winding tools for wire twisting and pressing tools for coil forming were worked out. The functionality of the primary insulation system and a sufficient enamel thicknesses of the pressed wires were demonstrated experimentally. A FE model for a layer precise winding with four wires per layer and four layers in total was presented. Here, the wire bundle was twisted 180 degrees in the course of the slot and no insulation was considered. Important findings of the FE simulations were an occurrence of wire thinning during large wire deformations, irregular surface structures due to the first work contact and an increase in width due to twisting. Interactions of pressing forces with functional parameters of the coils were not investigated.

Further works of state of the art have to be considered, which contain the forming and bending of rectangular wires or round wire windings with large diameters and a small number of wires in the winding. Rectangular wires are mainly used in hairpin windings for electric traction motors and are described in several scientific works and publications [12–16]. Round wires with large diameters are mostly used for hairpin windings in smaller applications than in traction machines, for example in starter generators. Novel approaches also apply wires with large cross-section dimensions in combination with a forming process to generate windings with high fill factors. Here, the cross-

sections can often be varied depending on their position in the stator slot, also round or rectangular wires are used as an incoming semi-finished product. [17–21]

For the numerical analysis, the input material parameters are essential. Detailed investigations for round enameled copper wires were carried out by Komodromos [22] with a focus on the linear winding process, and the obtained density, Young's modulus and Poissons's ratio are used in this work. The assumed values for the material properties of copper are noted in Table 1. The coefficients of friction in Kulan [8] and Vogt [11] are specified with 0.1 for friction between wires and 0.2 was defined for wire to tooling surface, but the background of these assumptions was not further specified. Demiri [23] investigated the sliding behavior of enamel copper wires in electric motors and stated lower values, so for this work, a coefficient of friction of 0.05 was chosen for wire to wire contacts and 0.1 for wire to tooling contacts.

Table 1: Material properties of enameled round copper wires

Material property	Value	Unit
Density	8.94	g/cm^3
Young's modulus	99	GPa
Poisson's ratio	0.34	-
Coeffient of friction (wire to wire)	0.05	-
Coeffient of friction (wire to tooling)	0.1	-

The plastic material properties were experimentally characterized according to the directives for tensile testing of metallic materials described in DIN EN ISO 6892-1. The analysis was conducted on a 10 kN tensile machine of ZwickRoell GmbH & Co. KG and based on traverse measurement. With reference to the appendix C.2 of the standard as well as the installation space of the clamping device, the dimensions of the specimen were set to 150 mm of measuring length and 250 mm of total length. The flow curves of the ten specimens and the resulting average are shown in Figure 2. For extrapolation, the Hockett-Sherby law was applied according to previous analyses of the authors.
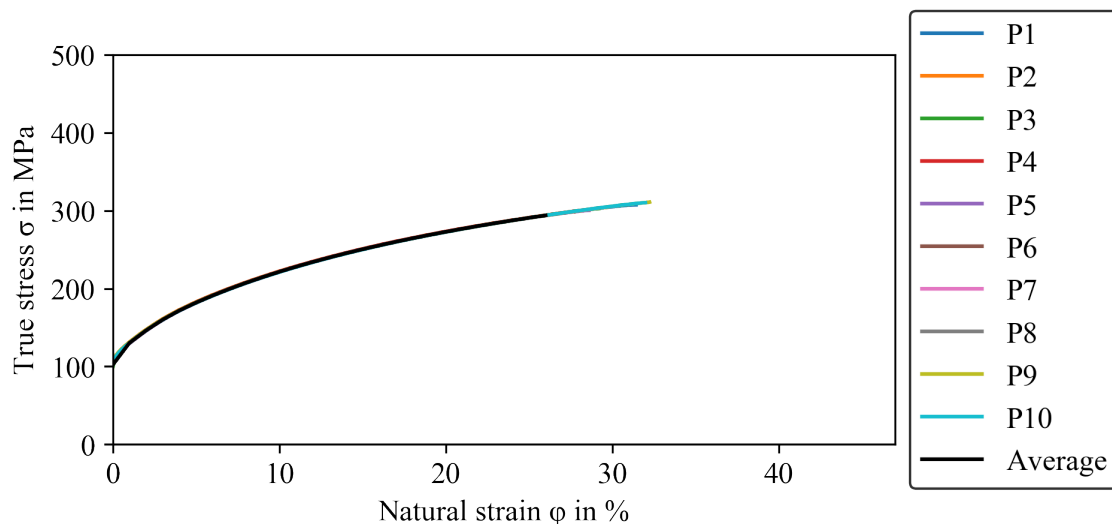

Figure 2: Experimental flow curves acquired by uniaxial tensile tests and resulting average for ten specimens of round wires with an insulation of grade 2 and a diameter 0.71 mm.

Design of Experiments

At the beginning of the design of experiments (DoE), an overview of all input and output parameters was created, as shown in Table 2. Input parameters can be divided into control and disturbance parameters, whereas target parameters are output parameters. In this case, the input parameters are distinguished between experimental and numerical applications. The numerical parameters are further described in the following chapter "Setup of FE model". The target values

printed in italic style are values without a direct influence on the forming behavior, but interesting for the winding performance in further experimental investigations. The underlined control parameters are used as factors in the simulation study described in the following chapters.

Table 2: Overview of possible parameters on the compacting process of round wire windings

	Control parameters	Disturbance parameters	Target parameters
Experimental	Slot dimensions Number of wires Number of wire layers Wire diameter Layer structure 3-D shape (wire crossings) Coefficient of friction Pressing force Punch stroke Tooling dimensions Material properties	Humidity Temperature Wire tolerances Coil tolerances Measurement uncertainty Repeatability Surface properties (tools)	Stresses Strains Displacements Surface pressures Springback Fill factors *Electric resistances* *Partial discharge resistance* *Insulation strength* *DC losses* *AC losses*
Numerical	Element size Element type Mass scaling Time step size Type of solver	Model simplifications Element size Element type Mass scaling Time step size Type of solver	

Based on the preliminary investigations [4] and the resulting prior knowledge, the experimental design is to be limited to three main factors with three levels each for the simplified simulation model. The aim was to create an impact analysis of these main factors with a full factorial design. The number of layers, the layer structure, and the punch stroke are varied in three levels. The slot width was changed just for the orthocyclic winding scheme, as it could not have been realized otherwise. One layer in the winding contains five wires with a diameter of 0.71 mm. The stamp travel in the compaction process was calculated in relation to the initial height of the winding. Here, the maximum punch stroke of 21 % of the initial winding height was determined on the basis of a simplified theoretical consideration and divided into the three stages, each with a 7 % difference: If a circular geometry with a constant area is to be converted into a rectangular shape and the width is to correspond to the original diameter, the height of the resulting rectangle is the diameter scaled by a factor of 0.785. Rounded, this corresponds to 79 % of the original height and a punch stroke of 21 % in relation to its starting point. This consideration corresponds to the forming of layer-precise windings without transverse contraction. In comparison, orthocyclic windings, except for the edge areas, are packed more densely, which is why the maximum punch stroke would already exceed the framework.

In the case of wild windings, an estimation is more difficult, but it can be assumed that more punch stroke is required for a complete deformation. In order to establish comparability, however, assumptions for the percentage value were made. Since the wild winding has a higher build-up of the layer structure, the punch stroke is correspondingly increased.

The target variables that are evaluated in the numerical simulation study are:
- von Mises stresses,
- equivalent plastic strain (PEEQ),
- fill factors (wire cross-section area divided by slot cross-section area),
- and geometric effects that can be seen from the false color images.
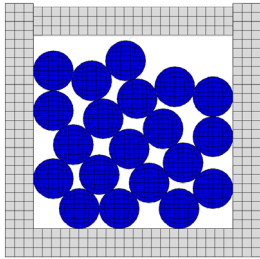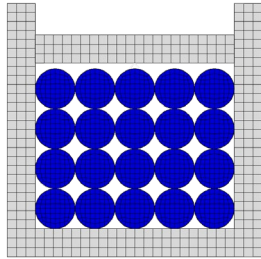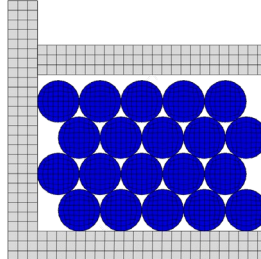
Table 3: Factors and chosen levels for the numerical simulation studies

Factor	Factor levels
Number of wire layers	2 layers of winding (≙ 10 wires)
	4 layers of winding (≙ 20 wires)
	8 layers of winding (≙ 40 wires)
Layer structure	Wild winding
	Layer precise winding
	Orthocyclic winding
Punch stroke	7 % of initial height
	14 % of initial height
	21 % of initial height

Setup of FE Model

Modeling and Assumptions. In order to simulate the complex behavior of the round wires during the compaction process, the experimental setup was simplified and mass scaling was used to reduce the calculation effort. Because the elastic-plastic forming characteristics of the insulation layer are unknown and an initial influence analysis of the parameters with the number of wire layers, layer structure and punch stroke is to be analyzed, the modeling of the insulation layer was neglected. Hence, the wires are estimated as pure copper wires, but the coefficients of friction are estimated for enameled wires, as described in the previous chapters. This simplification leads to the fact that no statements can be made about the insulation layer and the surface layer of the copper wires. Experimental investigations were carried out for this purpose [4].

Table 4: Simulation setup and chosen simulation parameters

	Wild winding	Layer-precise winding	Orthocyclic winding
Type of solver	Explicit	Explicit	Explicit
Element type	C3D8R	C3D8R	C3D8R
Element size wires	0.1 mm	0.1 mm	0.1 mm
Element size tooling	0.16 mm	0.16 mm	0.16 mm
Contact type	Penalty contact	Penalty contact	Penalty contact
Step time	0.1 s	0.1 s	0.1 s
Mass scaling	256	256	256
Punch stroke	0.129 mm – 1.306 mm	0.099 mm – 1.193 mm	0.093 mm – 1.053 mm
Slot width	5 x 0.71 mm = 3.55 mm	5 x 0.71 mm = 3.55 mm	5.5 x 0.71 mm = 3.91 mm
Slot length	25 mm	25 mm	25 mm
Simulation setup (4-layer setup)			

Setup of Simulation. The implementation of the explicit FE model is essentially based on the assumptions and conditions which has been described before. In addition, several methods were considered regarding the mesh design, virtual process time (step time) and contact models, in order to reduce the calculation effort and to increase the stability as well as the accuracy of the simulation. Furthermore, an extensive independence of the numerical results from the geometric discretization is guaranteed by means of convergence studies. The optimized simulation parameters are shown in

Table 4, whereas the material data can be taken from the chapter "State of the art for numerical analysis of round wire windings".

Results of the Simulation Studies

To get a first impression of the results of the simulation studies, a false color images for the von Mises stresses of all layer structures and punch strokes for the 4-layer setup are shown in Figure 3. In the following, the influences of the chosen factors (number of layers, layer structure and punch stroke) are evaluated. Figure 5 shows all measured, maximum results of the FE simulations in the middle plane of the slot at 12.5 mm.
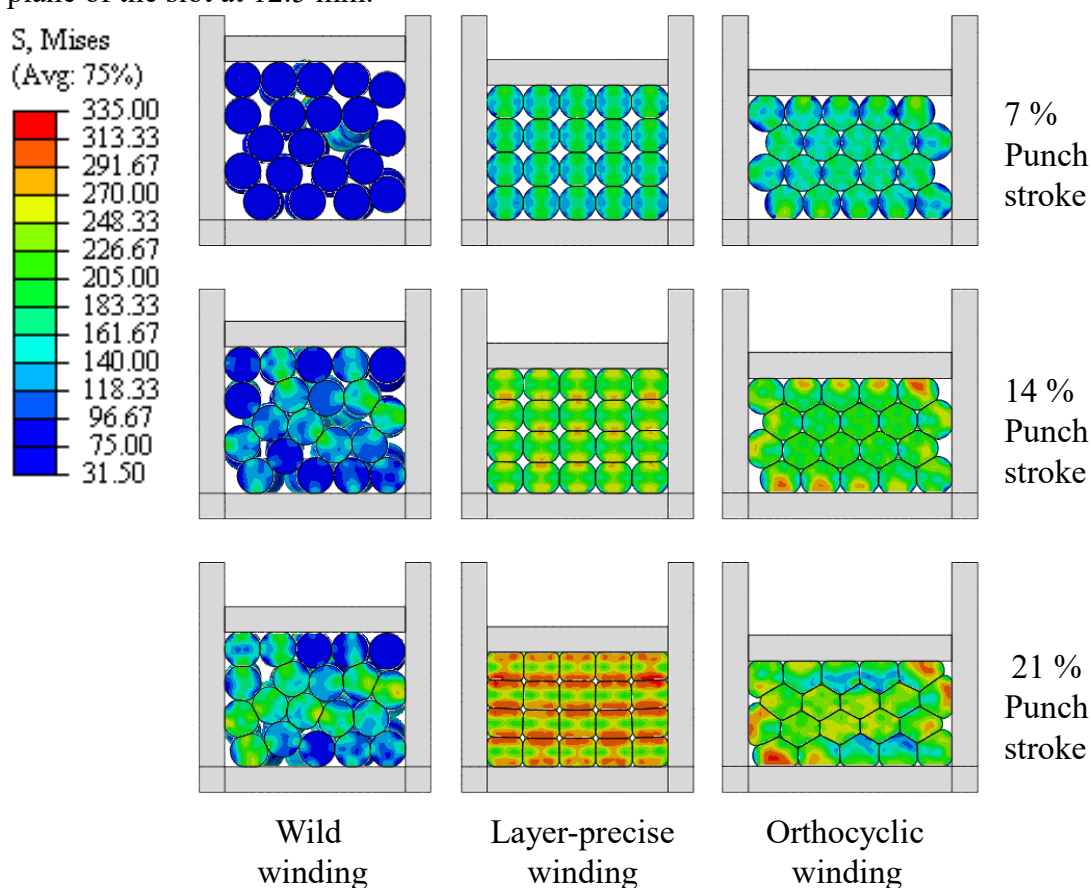

Figure 3: False-color results of von Mises stresses of the FE simulations using the example of the 4-layer setup. The evaluation is based on cross-sections in the middle of the slots at 12.5 mm.

Number of wire layers. When considering the number of layers, it is noticeable that the dimensional deviations of the geometry within the middle of the slots increase as the number of layers rises for the two ordered layer structures (layer-precise and orthocyclic). This corresponds to observations of the real tests, because slippage of the wires becomes more and more probable as the number of wires increases. In Figure 4, this is especially visible in the layer-precise winding structure with 8 layers. Furthermore, the ordered structures exhibit small variations with respect to the maximum values of the von Mises stress and equivalent plastic strain (PEEQ) in dependency of the number of layers, and are therefore not significant. In contrast, the values for the stresses and strains increase with an increase in the number of wire layers in the wild winding structure (see also Figure 5). This can be explained by the fact that the wires can significantly shift in their disordered position during the initial compression. In this case, a higher number of wire layers also results in greater compression which leads to higher stress and strain values. The number of wire layers has no significant influence on the relative improvement of the fill factor before and after the compaction (compare Figure 6). Due to the geometric changes of the wire positions, however, the fill factors before pressing vary for different wire layer numbers, especially for the wild windings.

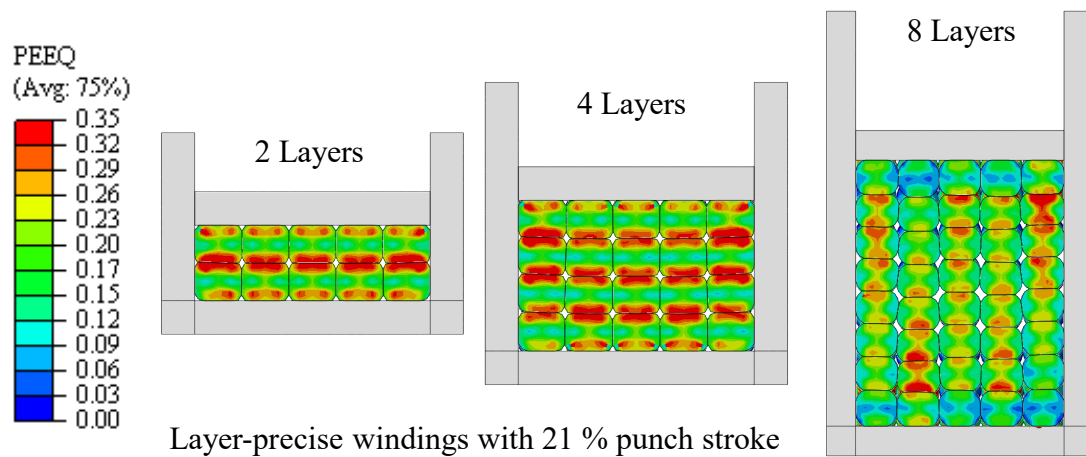Layer-precise windings with 21 % punch stroke

Figure 4: False-color results of the equivalent plastic strain (PEEQ) of the FE simulations for layer-precise windings with 2, 4 and 8 layers at a punch stroke of 21 %. The evaluation is based on cross-sections in the middle of the slots at 12.5 mm

Wire layer structure. The most significant influence of the layer structure on the compacting of windings is the cross-sectional geometry of the wires after the compacting process. The geometries are difficult to predict in the case of wild windings and a wide variety of geometries can arise after forming – especially because every wild winding has a different structure. Furthermore, the stresses and strains in the cross-section of a slot can highly vary in this context. High values are caused in particular by wire crossings (compare to [24]).
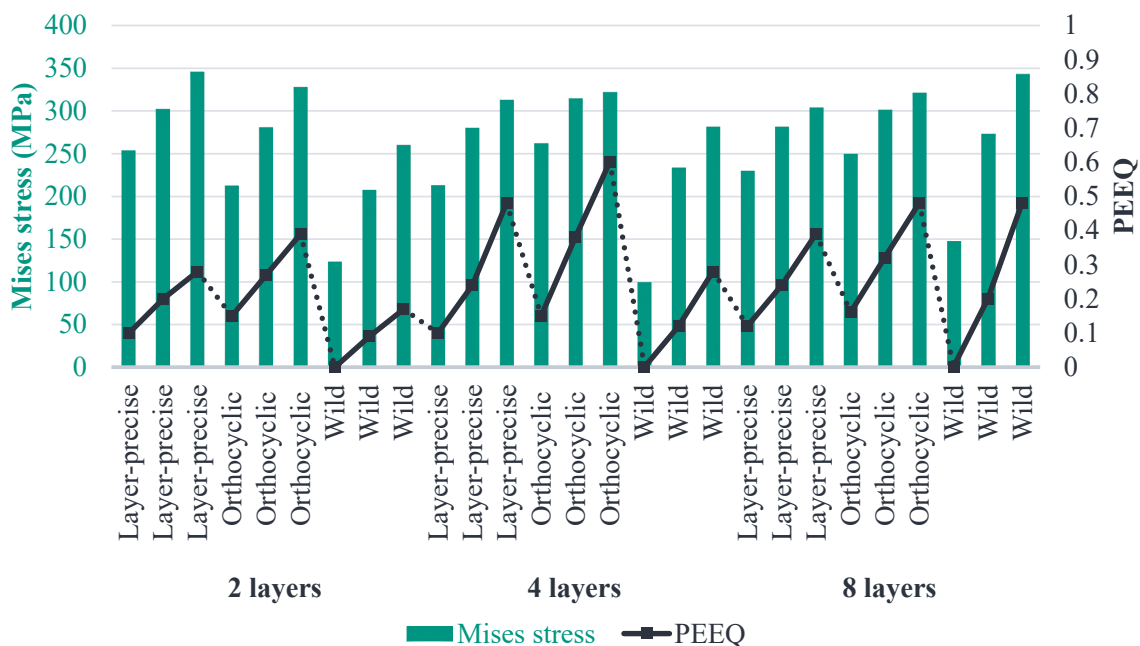

Figure 5: Results of all simulations for maximum von Mises stress and equivalent plastic strain (PEEQ) at cross-sections of the slot models at 12.5 mm.

In the case of a layer-precise winding, rectangular cross-sections of the wires with a similar stress and strain distribution per wire are manufactured over the entire slot cross-section. Typically, hexagonal cross-sectional shapes result from the compaction of orthocyclic windings. However, this does not apply to the wires in contact to the slot surfaces, where the wires tend to be formed into pentagons with severe deformations. Accordingly, the highest stress and strain values occur at the slot edges. The wire layer structure already has a significant influence on the fill factor before compaction. The highest improvements of the fill factor after compaction occur for the wild winding with high punch strokes. The layer-precise winding and the orthocyclic winding show very similar

improvements of the fill factor, with a slight advantage for the layer-precise winding. However, it should be mentioned that the cross-sectional wire area decreases about 1.5 % more for the orthocyclic winding at a 21 % punch stroke than for the layer-precise winding (compared to the non-compacted cross-sectional wire area).
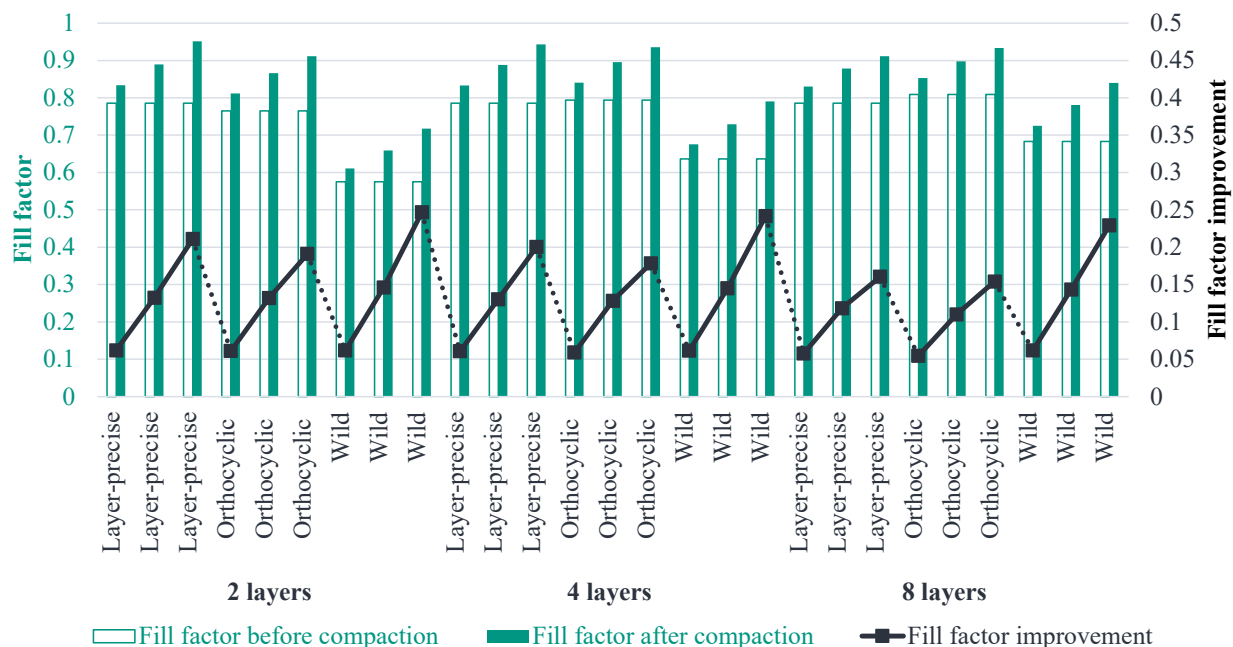

Figure 6: Fill factors before and after compaction as well as relative improvements of the fill factor due to the compaction according to the simulation results.

Punch stroke. When varying the punch stroke in relation to the stresses and strains, it is obvious that these mechanical characteristics also increase with increasing punch travel. For a meaningful analysis of the cause-effect-relationship, it is necessary to investigate a larger number of punch strokes. Nevertheless, the phenomenon described above can be clearly recognized for coils with wild round wire winding. Compression without plastic deformation occurs at the low punch strokes of 7 % of the wild winding; significant plastic deformations can only be noticed at larger strokes in this case. Accordingly, the difference in the maximum PEEQ values between 7 and 21 % punch travel is highest for the wild winding. For the ordered layer structures, the relationship appears to be rather linear. It can be deduced that, as expected, a longer punch stroke leads to higher fill factors. The layer-precise winding with 2 layers and 21 % punch stroke achieves the best fill factor (0.95). However, at the same time 4 % of the original cross-sectional area is pressed out of the slot. It can be assumed that the displacement of material will further increase with higher punch strokes, which is not acceptable.

Summary and Outlook

In this work, a simulation study of the factors influencing the compacting process of round wire stator windings was carried out. The factors analyzed in the study were selected from the most comprehensive consideration of possible parameters, based on experimental preliminary tests. The number of wire layers, the layer structure as well as the punch stroke are considered. The results were evaluated using false color images of cross-sections in the middle of the stators slots as well as graphs. The layer structure has significant influences on the shape of the wires after compactions as well as the resulting stresses, strains and fill factors. The length of the punch stroke primarily influences the heights of stress, strain and fill factor.

In further works, a more accurate simulation model needs to be implemented, especially considering the insulation layer of the copper wire. For further investigations, both detailed knowledge about the elastic-plastic forming behavior of the insulation layer as well as correlations of the insulation thickness and the insulation strength are necessary. Due to the lack of raw material

required for the manufacturing of specimen for conventional material testing processes, new characterization methods must be developed and validated to achieve this goal. Another interesting object of investigation could be the use of more complex tools with multiple moving punches, by complementing the vertical with a horizontal movement direction. This would presumably enable a more precise compaction of stator windings with a higher number of wire layers.

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