Skinning of Insulated Copper Wires within the Production Chain of Hairpin Windings for Electric Traction Drives

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***Abstract*— Due to the influence of electric mobility drives used in the automotive powertrain are experiencing a boost in innovation. Caused by the accompanying demand for an increase in power density and the necessity to reduce costs in series production, the winding of electric machines and associated production processes are being improved. A promising novel type of winding with numerous advantages is the bar-wound winding, which introduces new demands on technologies for their production. This winding is manufactured from a wide range of preformed elements made of enameled copper wire, that must be connected to each other mechanically and electrically. For this purpose, it is necessary to remove the insulation of the conducting elements in the joining area. Due to the large number of contacts that have to be prepared in this way, it gets essential to use productive and in particular process-safe skinning technologies. In this paper, the motivation for the application of bar-wound windings and the corresponding production chain is expounded. A method for the metrological quality control of insulation residues in the skinned area is qualified and technologies for the realization of the skinning process are compared. In addition, experiments to create process knowledge for the laser-based removal of the insulation and the skinning by means of rotating brushes are presented.**

***Index Terms*— electric traction drives, hairpin winding, laser-based skinning, fluorescence based quality assurance**

I. Introduction

In the field of automotive production, electric drives already are produced in large quantities. These motors primarily show lower powers and for example are used as actuators. They usually feature conventional windings produced from enameled copper wires with round diameters. The megatrend of electric mobility leading to the electrification of the powertrain necessitates the installation of more powerful electric drives in automobiles. Compared to conventional industrial drives of similar power, this results in numerous new demands on the motors. With regard to the design of the drive, the requirement for increasing powers at reduced sizes and weights combined with rising efficiency rates represent the most important challenges. To meet these demands, the power density of electric machines applied in the automotive drivechain evolves rapidly and dimensions up to ten times higher than those of industrial drives are reached [1]. This is mainly realized by electromagnetic optimizations, which can be achieved by innovations in one of the most important parts of an electric drive, its winding. In most cases the winding is manufactured of enameled copper wires being assembled into the grooves lamination. Besides using special winding schemes, increasing the cross-section of the conducting copper in the groove of the stator is of great importance as higher conducting cross-sections of the winding at a given maximum current density are leading to growing powers of the machine. This is described by the copper filling factor, which indicates the ratio of the total cross-sectional area of the conductive copper to the cross-section of the groove, see (1) [2]. [1]

$$k_{co} = \frac{A_{conductor}}{A_{groove}} \qquad (1)$$

One way to increase the copper filling factor k_{co} is to replace the round cross-section of the conductor with rectangular cross-sections. Analytical estimations of Juergens et al. showed, that stators with a winding produced from conventional round wires produced in pull-in technology show a copper filling factor k_{co} of 43% while comparable stators produced from rectangular conductors reach a value of k_{co} = 65% [3]. This is shown in Fig. 1.

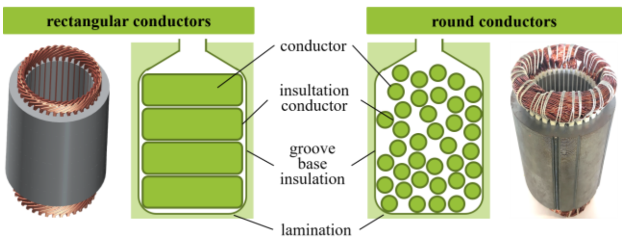


Figure 1. Comparison of grooves with windings made of rectangular and round conductors

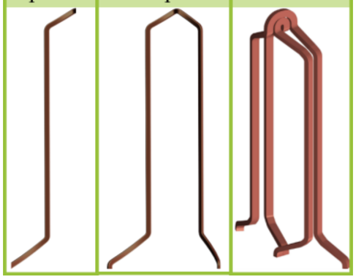
Manuscript received July 26, 2018; revised October 7, 2019.

doi: 10.18178/ijmerr.9.2.163-169

In the field of electric traction drives besides the application of rectangular cross-sections very often new methods for the production of windings are used. Current developments in this area are spotlighting bar-wound windings. Compared to the state of the art, bar-wound windings consist of numerous prefabricated enameled conducting elements being mounted together to realize the winding instead of producing it from a continuous enameled copper wire. One big advantage is, that bar-wound windings result in shorter end-turns of the winding, allowing the active length of the machine to be increased. The three types of bar-wound windings, opened, half-opened and closed bar-wound windings can be distinguished by the geometry of the preformed conductor as shown in Table I. [4,5]

TABLE I. TYPES OF BAR-WOUND WINDINGS

bar-wound windings		
opened	half-opened	closed



The new methods of replacing round wires by rectangular cross sections and the application of bar-wound windings very often are used in combination, because conventional production technologies for stator windings only are suitable for the processing of round wires. To summarize the advantages of this new method of winding design, the short end-turn of the winding combined with increased copper fill rations k_{co} enables the dc resistance of the winding to be minimized. Additionally, the increased area of contact between the conductor and the lamination is leading to an optimized copper to steel path improving the cooling of the winding. In combination with the possibility of increasing the active length by means of the shortened end-turn, the application of bar-wound windings made of flat wire enables the production of high-performance electric traction drives. [5]

II. Technologies for the Production of Bar-Wound Windings

Besides the product-oriented advantages described above, the application of bar-wound windings features big potentials for automated large-volume production. To manufacture windings for automotive traction drives, especially the use of half-opened bar-wound windings, the so called hairpin winding currently gains in popularity. The designation is derived from the U-shaped geometry that is similar to the shape of a hairpin. At present, the main technologies used for the production of windings for stators of traction drives are needle winding and the pull-in technology. However, these technologies in actual practice are not suitable for the manufacturing of stator windings made of rectangular enameled copper wires because they are designed for axially symmetric geometries. Additionally, the needle winding is an expensive and time-consuming process while the pull-in technology shows major drawbacks concerning the copper fill ratio k_{co}. [6]

For the manufacturing of hairpin windings, a new process chain offering different advantages and challenges is necessary. The production of hairpin windings can be divided into five major steps. After the skinning of the conductor the hairpin needs to be shaped from the enameled copper wire before the hairpin is assembled into the lamination. In the fourth step the free ends of the hairpin are twisted to enable the concluding contacting operation. The process chain is illustrated in Fig. 2.

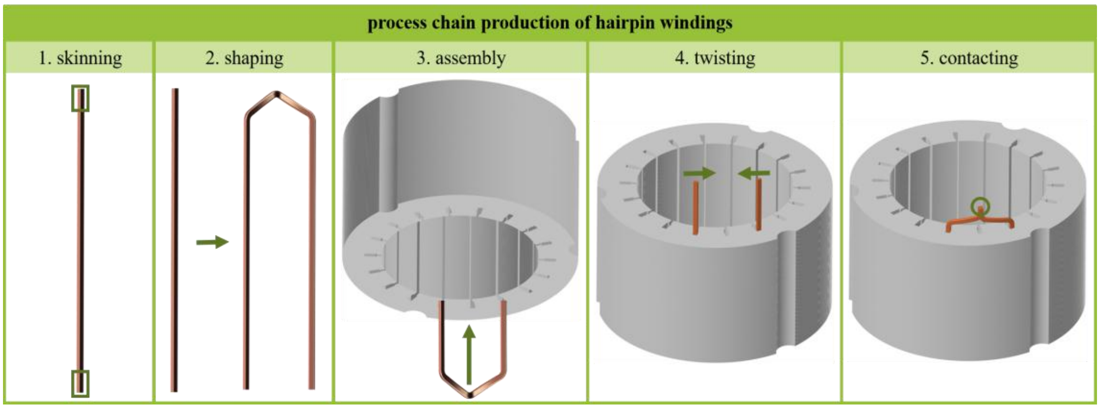


Figure 2. Process chain for the production of hairpin windings

The hairpins can be prepared outside of the lamination. In most cases, they need to be assembled to the lamination in one or more preassembled baskets consisting of several hairpins depending on the design and overlapping hairpins of the winding. Also in the twisting operation, the ends of multiple hairpins are shaped at once before the high number of contacts is realized consecutively. In addition to the necessity to shape the hairpins reproducibly and without damaging the insulation, the twisting operation poses a challenge because of the poor accessibility of the insulated conductors and the risk of damaging them. Due to several reasons the main challenge in the production of hairpin windings are the contacting operation that can be realized in a welding process. High welding depths without pore formation must be achieved reproducibly to reach low electrical resistances and, in particular, short circuits within the winding or between adjacent contact points have to be prevented. Here, the quality of the skinned area, especially concerning residues of the insulation plays a major role as evaporating insulating material in the joining area is one of the main reasons for the formation of welding spatter.

Enameled copper wires for the production of windings mainly are insulated with plastics based on polymer hydrocarbons. Therefore, they are assigned to organic materials. In addition to good insulating properties like high volume resistance, surface resistance, creep resistance and dielectric strength these materials feature a high ductility which results in good formability and thus processability in winding goods. Enamels made of polyurethane, polyetheretherketone, polyimide, polyesterimide and polyamide-imide can be listed as common insulation materials and show the characteristics listed in Table II [7]. The insulation often is built up by combining different insulation materials in layers. Thus, a significant part of the enameled copper wire is produced with polyesterimide as insulation with an overcoat of polyamide-imide. The thickness of the insulation layer is differentiated between three main grades of insulation with an insulation of grade 1 showing the smallest lamination strength while grade 3 exhibits the thickest insulation. The layer thicknesses and permissible number of imperfections in the insulation are specified in standards for each grade.

TABLE II. ESTABLISHED INSULATING MATERIALS

properties	polyurethane	polyetheretherketone	polyimide	polyamide-imide	polyesterimide
abbreviation	PUR	PEEK	PI	PAI	PEI
adhesive strength on metals	+	o	o	o	o
chemical stability	+	+	o	+	o
electrical insulation (dielectric strength)	24 [kV/mm]	19 [kV/mm]	56 [kV/mm]	25 [kV/mm]	23 [kV/mm]
temperature stability (temperature index)	180 [°C]	250 [°C]	240 [°C]	260 [°C]	180 [°C]
mechanical strength (elastic modulus)	400 [MPa]	3,500 [MPa]	2,300 [MPa]	4,500 [MPa]	2,000 [MPa]
plasticity (elongation at rupture)	3%	50%	4%	7%	--
glide characteristics	o	+	+	o	o

A. Determination of the Stripping Quality Using the Fluorescence Measurment Method

In order to implement experimental investigations and to establish a basis for process monitoring, the metrological quantification of the skinning quality is required. Therefore, it is necessary to measure the amount of remaining insulating material after the skinning process while the influence of different degrees of oxidation and surface conditions must be avoided. This is necessary because thermal skinning processes in particular facilitate the oxidation of the stripped area, while mechanical technologies are leading to varying surface geometries. Since the insulation systems used are based on polymer hydrocarbons, they can be assigned to organic materials. These materials have in common that they fluoresce under the influence of ultraviolet radiation. Fluorescence is generally referred to as the emission of long-wave light caused by excitation with short-wave light. The electrons of the irradiated material absorb the radiation and are moved to an unstable, elevated energy level before they revert to the ground level. The absorbed radiation of the electrons is emitted as fluorescence radiation with a higher wavelength and thus less energy resulting in the heating of the fluorescent material.

To validate the suitability of this measuring principle for monitoring the skinning quality of enameled copper wires, experiments are carried out to determine a correlation between the remaining amount of insulation material and the value determined in the fluorescence measurement. For this purpose, sample parts with varying insulation thicknesses are produced based on an enameled copper wire Thermex® FL 220 of the supplier von Roll. The conductor is produced from Cu-ETC (Electrolytics Tough-Pitch Copper) which features a good thermal and electrical conductivity and measures dimensions of 4.20 x 2.50 mm. The insulation is made of polyamide-imide and shows a layer thickness of 0.09 - 0.11 mm. The chemical skinning is used for the production of the samples. This process allows the realization of varying remaining insulation thicknesses by diversifying the dwell time in the chemical. The stripper TechniStrip® P1316 used consists of a tetramethyl-ammonia dissolution and is suitable for the dissolving of heavily cross-linked materials. At a temperature of approx. 75 ° the insulation is dissolved by dry etching and ion implantation.

The sample parts produced in this way are analyzed with the fluorescence measuring device Sita CleanoSpector. The measuring device stimulates the samples with ultraviolet radiation (wavelength 365 nm) and a power of 150 mW focused on a spot with a diameter of 1 mm. Thus, the system integrates organic materials in a circle with a diameter of 1 mm for the measurement. The fluorescence is ascertained with a detector that senses radiation in the range of 460 nm. From the radiation detected, the system calculates the dimensionless parameter Relative Fluorescence Unit [RFU] with the measuring range between 0 RFU and 2,000 RFU and a resolution of 0.1 RFU. For surfaces without any organic materials the indicated value is 0 RFU and for heavily contaminated surfaces 2,000 RFU. After measuring the RFU value for the relevant insulation layer thickness, the lamination strength is quantified in a micrograph using a Leica DVM6 digital microscope. The relationship between the RFU value and the layer thickness i is determined calculating the regression equation and the correlation coefficient r. The experimental set-up for the fluorescence measurement, an exemplary micrograph showing the measured layer thickness and the result of the statistical analysis is shown in Fig. 3.

The correlation analysis between the measured RFU value and the associated layer thickness i of the residual insulation with a correlation coefficient of r = 0.92 shows that there is a linear mathematical dependency between the two variables. For this reason, the measuring principle is considered to be suitable for the evaluation of skinning qualities.

B. Process Technologies for the Skinning of Enameled Copper Wires

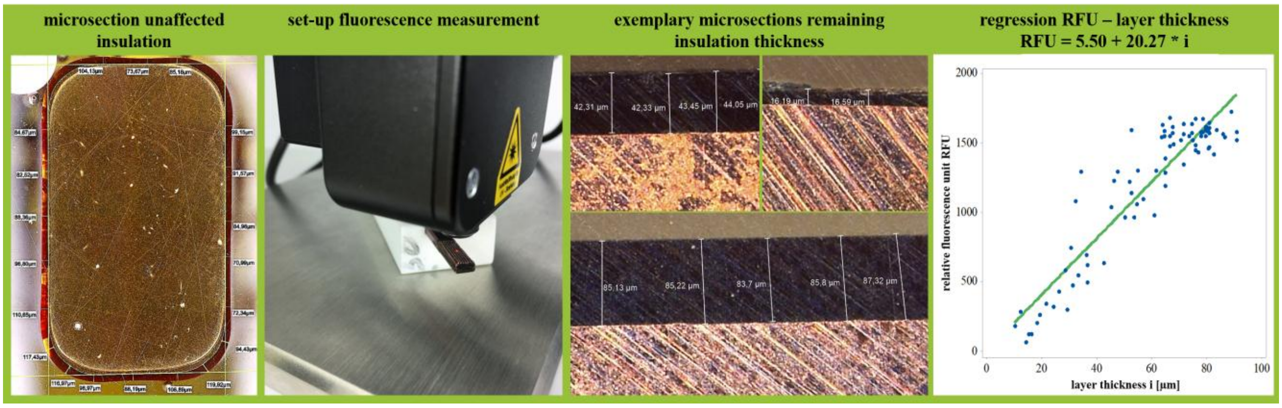


Figure 3. Experimental set-up for the qualification of the fluorescence measurement

The skinning process is of great importance in the process chain for the production of hairpin windings. As described in the previous paragraphs, one of the main challenges in the production of hairpin windings is the contacting process. Due to the large number of contacts that have to be produced in a small space, it therefore is necessary to use a reliable process with low formation of welding spatter. Investigations have shown, that for these reasons, laser welding is the most suitable contacting process, but the stripping quality has a decisive influence on the result of the joining process [6]. On this account, it is necessary for the production of hairpin windings to identify skinning technologies suitable for large series production, that process-reliably are able to achieve low insulation residues in the skinned area. In addition, no impermissible copper removal or deformation of the conductor should occur during the skinning process in order to preclude reductions in the conducting cross section. It must also be avoided that the insulation of the conductor outside of the stripped area gets damaged or detached and that insulation residues are able to fall into the winding.

For large series production, the insulation for example can be removed by means of rotating brushes removing the insulating material mechanically. The enameled copper wire is inserted between two rotating steel brushes arranged opposite from each other where the insulation layer is removed and extracted by suction. Apart from the simple process control and low costs, the process shows the disadvantage that the wearing of the brushes leads to fluctuating skinning qualities causing a poor reproducibility. Moreover, the conductor can be damaged by the mechanical forces occurring during the process. The principle is illustrated in Fig. 4.

Furthermore, the insulation can be peeled off mechanically with the aid of blades. For this process blades cut into the copper material in a rectangular geometry and realize a feed motion along the conductor removing the insulation without residues. Though the cutting depth needs to be chosen that the rectangular cutting geometry is able to remove the insulation in the area of the edge radius. For this reason, it can’t be avoided, that conducting material is removed and the cross-sectional area of the conductor gets constricted. This is an unacceptable disadvantage for traction drives, which are usually designed for maximum current densities. Fig. 4 explains the principle.

Because the insulation melts and burns at elevated temperatures, it can also be removed thermally. The process of inductive heating and burning the insulation shows potentials for the skinning of enameled copper wires. For this purpose, the conductor is placed in the middle of an inductive coil which is connected to a high-frequency alternating voltage. The resulting interchanging magnetic field induces eddy currents in the conductor which are displaced to the conductor’s surface due to the skin effect. The following high current density at the surface leads to a strong heating of the conductor burning the insulation. The contactless operating principle and the short process times achievable are advantages of this technology. However, it is a problem that residues remain on the conductor after the process and that the conductor's surface oxidizes immediately due to the high temperatures. In addition, the high heat input can damage the insulation outside of the skinned area. The principle of inductive skinning is illustrated in Fig. 4.

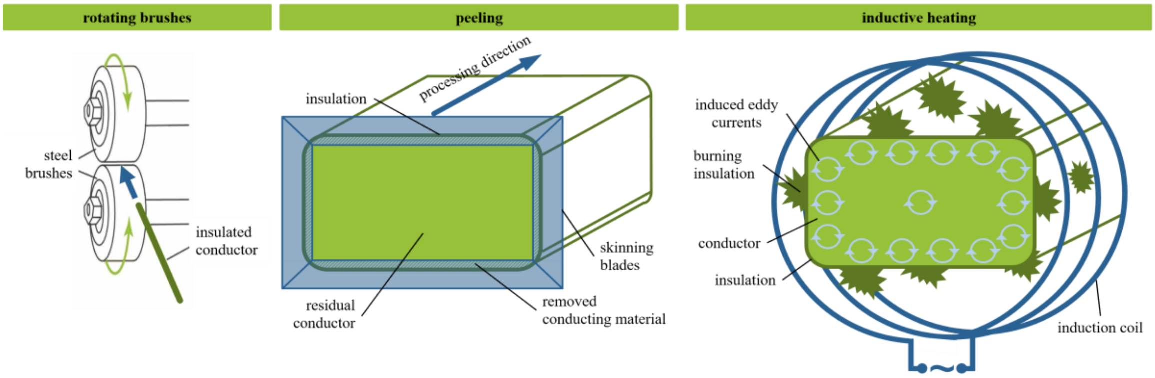


Figure 4. Established mechanical and thermal skinning technologies

Apart from the technologies described above, laser-based skinning processes are moving into the focus of industry and science. Depending on the wavelength of the laser radiation, two different skinning mechanisms can be described for laser-based skinning processes. Long wavelength infrared radiation (LWIR, e.g. carbon dioxide lasers, $\lambda \sim 10{,}600$ nm, pulsed operation) is reflected by the conductor made of copper while it is absorbed in the insulation. This leads to burning the insulation. In this way, high removal rates can be achieved, but insulation residues remain on the surface of the conductor after the skinning process. In opposite, near infrared radiation (SWIR, e.g. neodymium yag lasers, $\lambda \sim 1{,}064$ nm, operated in pulsed mode) is partially absorbed by the surface of the copper conductor after transmitting the insulation. Due to the pulsed feeding of the laser power, the copper material heats up abruptly and expands without melting. This causes mechanical shock waves in the conductor blasting the insulating material with less residues. Both laser-based skinning principles are illustrated in Fig. 5.

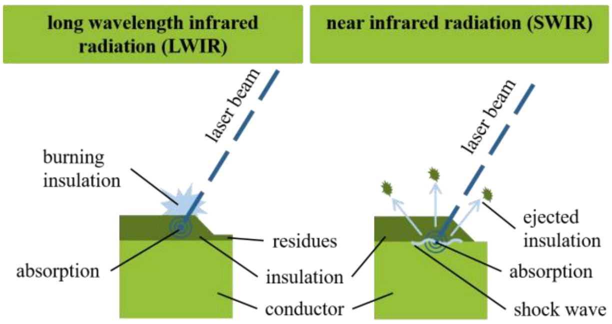


Figure 5. Laser-based skinning technologies

Aside from the non-contact mode of operation, the advantage of these two skinning principles is the fact, that the heat input is small due to the pulsed operation mode of the lasers. For this reason, insulation damages can be reduced.

In order to compare the described skinning technologies for rectangular enameled copper wires, experimental parts were produced in the corresponding technologies. Table III compares the results, advantages and disadvantages observed during the examinations.

TABLE III. COMPARISON OF SKINNING TECHNOLOGIES

	brushes	peeling	induction	laser
result				
advantages	• simple applicability	• simple applicability • defined cutting line • free of residues	• contact-free method	• contact-free method • defined cutting line • free of residues
disadvantages	• remaining residues • wearing of tools • undefined cutting line	• wearing of tools • removal of conducting material	• remaining residues • oxidation of surface • thermal damage of insulation	• elaborate applicability

The result of the investigation shows that the technologies of laser-based skinning and skinning by means of rotating brushes show the greatest potentials for the stripping of rectangular enameled copper wires in the field of hairpin winding production for electric traction drives. Due to the removal of conducting material and the thermal damage of to the insulation, the processes of mechanical peeling and inductive heating do not meet the requirements for skinning technologies.

C. Examination of the Mechanical Skinning Process

As the skinning by means of rotating brushes and laser shows potentials, these two processes are evaluated in further experiments. For this purpose, samples are produced in different parameter combinations before residues are quantified with the previously introduced measurement of the relative fluorescence unit.

For the skinning by means of rotating brushes, the rotational speed n, gap between the brushes d and exposition time t is varied in a full factorial design to skin an area of about 20 mm. Each combination of parameters is realized six times. For the analysis, each of the four stripped surfaces per sample is subjected to five fluorescence measurements and the mean value is calculated from these values. The setup of the experiments and results are shown in Fig. 6.

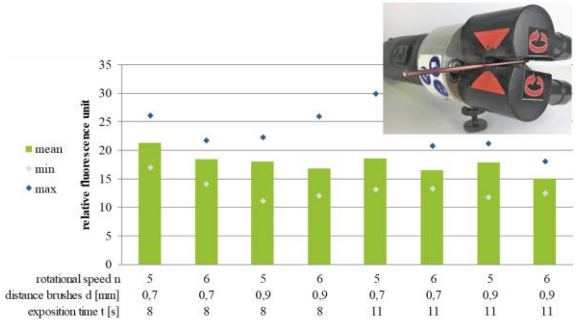


Figure 6. Results design of experiments skinning by means of rotating brushes

The interpretation of the design of experiments shows, that none of the three main effects and four interdependencies is significant. The 95% confidence interval is calculated to be ⩽ -2.4 and ⩾ 2.4. The calculated effect of the exposition time t is -1.2, of the rotational speed n -1,8 and of the distance of the brushes d -2,2. This, as well as the high range of the measured values within the factor combinations, proves that the process has a poor reproducibility and can hardly be influenced.

D. Examination of the Laser-Based Skinning Process

Experiments with a TRUMPF TruDisk 8001 disk laser (wavelength 1030 nm) in combination with a programmable focusing optics TRUMPF PFO 33-2 are operated to determine the interdependencies for the process of laser skinning. A focus diameter of 255 µm results from this setup. The laser is operated in pulsed mode with the maximum pulse frequency f of 1 kHz and minimum pulse width t of 0.3 ms provided by the system. These two parameters are not varied, because the number of pulses per unit of length is taken into account by the feed rate v and the total amount of energy put into the sample should be minimized by short pulse widths t. The area that should be skinned is scanned in lines by the programmable focusing optics. The power P, feed rate v and fill space s are varied utilizing a full factorial design with five replications for each setting of the DOE. Fig. 7 shows the achievable mean fluorescence values and variation of the realized test settings. Before the measurement, the black residues remaining on some parts of the sample are removed with the aid of compressed air as it has been shown that the fluorescence measurement is affected by shadowing effects.

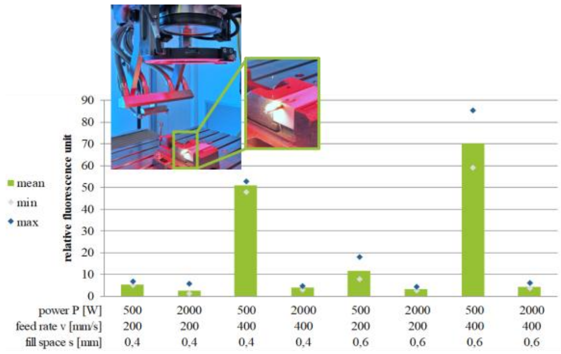


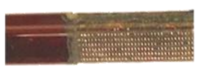
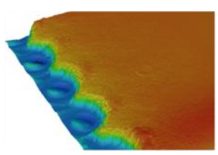
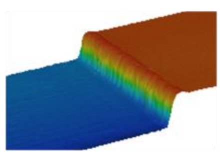
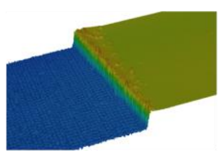
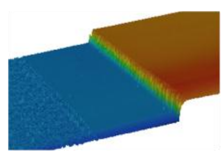
Figure 7. Results design of experiments skinning with disk laser in pulsed operation

The analysis of the experimental data shows, that the power P has the most important standardized effect in the examined parameter range with a value of -20.7. The 95% confidence interval ranges at values of ⩽ -2.0 and ⩾ 2.0. Further significant effects on the insulation residues detected show the feed rate v (17.7), the interaction between power P and feed rate v (-16.8) as well as the fill space s (4.5) and its interaction with the power P (-4.0). As a result, the skinning performance can be optimized with high powers P, reduced feed rates v and reduced fill spaces s.

To compare the four different laser-based skinning methods, for each technology 20 samples are produced with approved parameters before insulation residues are quantified in a fluorescence measurement. The arithmetic mean and standard deviation σ of the fluorescence values as well as the optical analysis of the samples are given in Table IV.

The comparison shows, that high removal rates can be achieved with a CO_2 laser, leaving enamel on the surface. These remains can be removed with a fiber laser in a two-step procedure resulting in low remainders and mean variations of the process. For the optical analysis, photos and three-dimensional scans of the surface contour were taken with a Keyence VK-9710 laserscanning microscope. These investigations show, that the disk laser generates a distinct structuring of the copper surface and a pronounced transitional area, while the CO_2 and fiber laser enable sharp-edged interfaces. The reflective surface of the samples stripped with the CO_2 laser confirms, that no interaction between the conductor and laser radiation occurs in this technology.

TABLE IV. COMPARISON OF LASER-BASED SKINNING TECHNOLOGIES

	disk laser	**CO_2 laser**	**fibre laser**	**CO_2 & fibre laser**
skinning result				
residues [RFU]	average = 25.0 σ = 13.4	average = 44.9 σ = 11.6	average = 139.9 σ = 62.4	average = 6.1 σ = 9.0
analysis of surface				

III. SUMMARY

As a result of the electrification of the automotive drivechain and accompanying new winding designs, contacting technologies gain in importance in the field of electric drives production. This results in the raise of the question, how the enameled copper wire can be skinned for mass production. This paper explains the motivation for the application of bar-wound windings and derives the importance of skinning technologies in this context. The quantification of the skinning result in a fluorescence measurement is established and different skinning technologies are compared and characterized in experiments. The most reproducible skinning results with low residues can be achieved with a two-step procedure consisting of a CO2 laser followed by a fiber laser process. This paper contributes to the establishment of laser-based skinning technologies for mass production, nevertheless the formation of smoke residues while using a disk laser needs be addressed in further investigations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The corresponding author Tobias Glaessel is responsible for all contents of this publication. He thanks Johannes Seefried, Alexander Kuehl and Joerg Franke for reviewing the publication.

ACKNOWLEDGMENT

This research project is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the Program ELEKTRO POWER II, FKZ 01MX150111F. The project is managed by DLR Project Management Agency.

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