Winding Insulation Improvement by Thin Film Metalized Winding Head Support for Fast Switching SiC-Voltage Inverter Drives

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***Abstract*—This paper proposes a winding head support design with a thin film surface metallization for edge rounding to avoid high electric field strengths and thereby winding insulation failures. Base materials of the winding head support are high performance plastics like polyetheretherketone (PEEK) or high temperature resins with good heat resistance capabilities and a low electrical conductivity to minimize eddy current losses. The metallization layer of the support is manufactured in thin film technology for the same purpose. The main focus of the work lies on investigating the improvement of dielectric strength of the insulation system. Electrostatic FEM-calculations are being conducted to estimate the distribution of the electric field strength in the area of the stator edges. Within this work eddy current losses inside the metallization layer are also considered. Although the conductive film of the support is with a thickness fewer than 100 microns [1] very thin, heating, especially in the area of the winding head, may cause structural and lifetime issues. On this account, FEM-simulations regarding eddy current losses and thermal distributions are being progressed.**

Keywords—winding head; insulation; overvoltage; SiC; metallizing; PEEK; traction drives; thin film; fast switching; insulation failure

I. Introduction

Benefits of fast switching voltage inverters for electrical machines which use modern silicon carbide (SiC) semiconductor materials are reducing switching losses of the inverter and therefore higher possible operation frequencies [2]. This leads to reduced core losses of the machine due to smaller current ripples and a better controllability of the drive system. Beside the semiconductor costs, the increased stress on the winding insulation in the stator of the machine [3] is a disadvantage of this technology. Parasitic capacities between the windings and the stator or the machine housing create resonant circuits with the phase inductances. Triggered by high-frequency portions of the fast switching procedure of the SiC-semiconductors, these resonant circuits can reach peak voltages multiple times higher than the operating voltage of the drive system. Thus, winding insulation damages from partial discharge events to total insulation failures may occur in standard winding designs.

A weak spot of the insulation system is located in the area of the winding head. The sharp edge of the stator lamination causes high electric field strengths in its vicinity. The state-of-the-art solutions for this technical issue are expanded insulation gaps or graduated stator laminations [4]. The expansion of the insulation gap reduces the copper fill factor and therefore the power density of the electrical machine. Graduated stator laminations demand higher effort in production with regard to the packaging process and the various press tools. Furthermore, the lamination stack also contains many sharp edges within the stepped arrangement causing local electric field maxima.

Winding head supports are typical machine components which are required for the winding process and therefore already present in the machine design. Fig. 1 shows a segment of a stator with edge-rounded winding head supports on both sides.

Consequently, the idea of this work is to design an edgeless winding head support made from high temperature non-conductive material, which is metalized by thin film technique to create a homogenous electrical field distribution on its surface. Thin film metallization is used to prevent major heat generation due to eddy current losses caused by the stator stray-field compared to a full metal head support design.

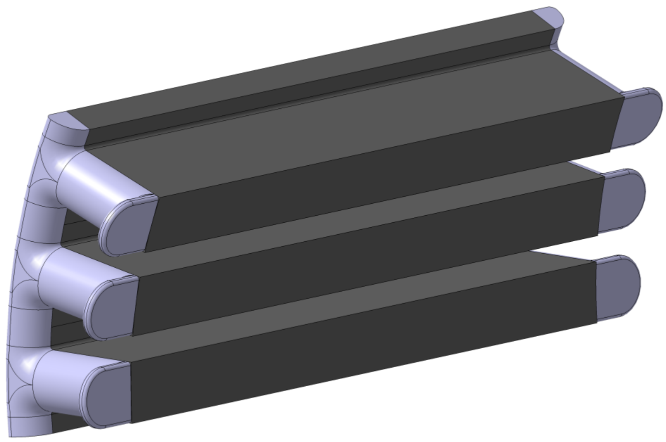

Fig. 1. Image of a stator segment with winding head supports.

II. PROBLEM DESCRIPTION

The thickness of the insulation material between the stator-winding and the stator lamination stack is designed with regards to the maximum occurring field strength inside the dielectric. Thus, high voltage machines require thicker insulation layers than low voltage machines, whereas thicker insulations reduce the copper fill factor of the stator slots.

Another aspect, besides the amount of active material in the slot is the ability of heat transfer from the winding to the cooled stator laminations. In most cases the thermal conductivity of electrical insulating materials is relatively low. Typical values of insulators like Nomex® paper or Kapton film lies in the range of 0.1-0.5W/m•K [5] [6]. Compared to the thermal conductivity of copper (400W/m•K) or electric sheets (20-50W/m•K), the insulation material constitutes the bottleneck of the thermal flow chain. Therefore, the thickness of the insulation plays an important role for the cooling ability and for the power density of the machine, respectively.

For these reasons, the insulation thickness should be minimized as much as possible. Occurring local peaks of the field strength in the winding insulation area can weaken the whole insulation system. The more homogenous the electric field distribution forms, the more effective can the insulation layer be utilized. Sharp edges, like the boundary of the outer stator laminations, form concentrated electric field lines leading to local high electric field strengths. Fig. 2 shows an example of the electric field strength distribution in the area of the stator edge.

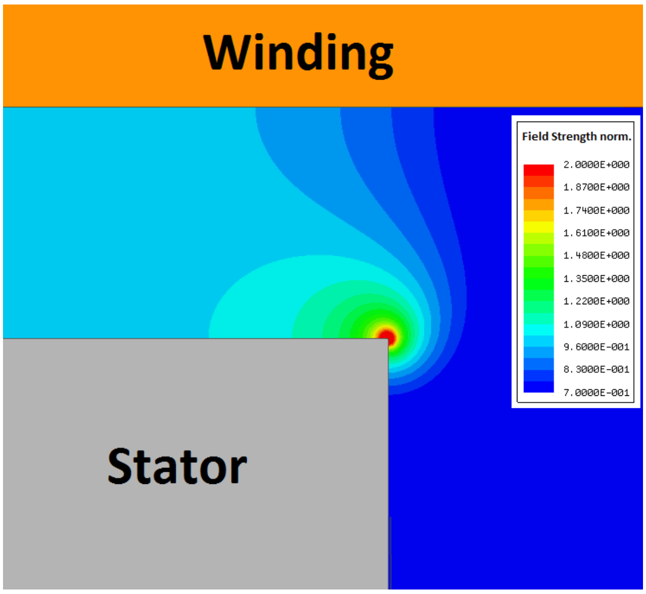

Fig. 2. Simulation of the field strength distribution at a stator corner.

It can be seen, that the maximum field strength at the corner of the stator is much higher than the middle field strength in the space between the winding and the stator. Partial discharges in this spot are presumable and can damage the insulation over time to the point of its total failure. To reduce this field strength excess, a more rounded boundary of the electrical stator potential is necessary. Mechanical post processing of the stator edge would be too expansive in the production process and is thereby not common. Graduated stator laminations are partly used in special applications, but are still expansive because of the complicated implementation at the stacking process.

The typical implemented winding head support has a smooth surface shape to protect the single wires from mechanical damages in the winding process. These shapes can also be used to smooth the electrical field by adding a conductive layer to the surface of the support. This approach will be investigated in the following sections of this paper.

III. ELECTROSTATIC ANALYSIS

The electrical field strength and its dependency on the distance between winding and stator is known for thin or pointed structures [7] and approximately described by (1). In these cases, the peak electrical field strength $E_{\max}$ is proportional to the ratio of the distance d between winding and stator and the radius r of the edge.

$$E_{\max} \sim \frac{d}{r} \tag{1}$$

The suitability of this approximation for a rounded corner of the stator in relation to a flat winding was examined in a two dimensional FEM-simulation, as visualized in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The goal of this simulation was to examine the influences of the sharpness of the stator-edge relating to the distance between winding and stator.

The FEM-simulation was performed for different distances and distance radius ratios. Fig. 3 shows the maximum occurring field strengths normalized to the homogenous field strength in the gap between winding and stator in the area of the stator corner.

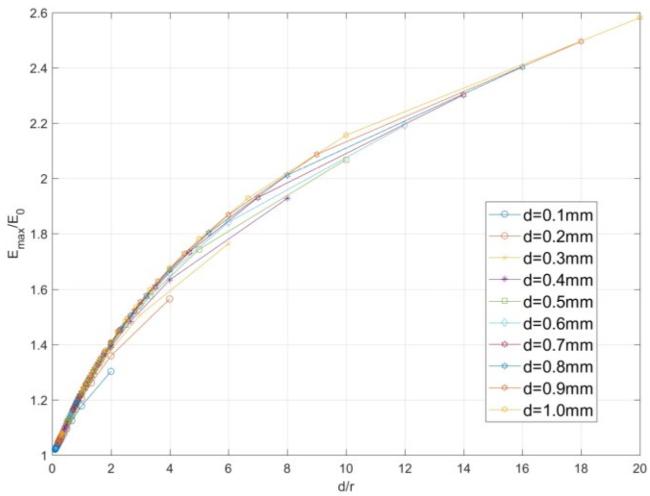

Fig. 3. Normalized maximum electrical field strengths on the surface of the stator (in the area of the stator corner) depending on winding to stator distance and distance to corner radius ratio.

A rise of the normalized maximum electrical field strength is observable with increasing ratio value of distance and radius, but not linear as expected. For small *d/r*, in particular below ratio of 2, the relationship of both quantities can be approximated by a linear function. The correlation mitigates at higher ratio values, so that a linear rule, like under (1), is not applicable for this geometric conditions.

In Fig. 4 normalized field strength values for a winding to stator distance of 0.8mm along a measurement line at the surface of the stator are displayed. Each progression represents a field distribution for different corner radii between 0.05mm and 1.00mm.

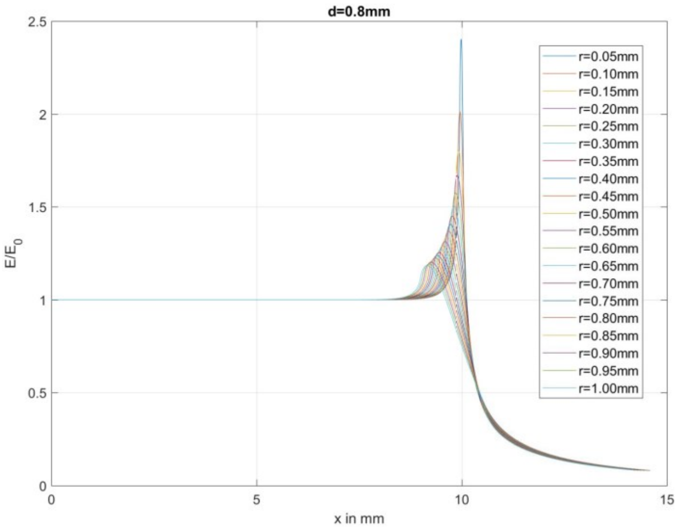

Fig. 4. Normalized electrical field strengths across the surface of the stator at a distance between winding and stator of 0.8mm with varied corner radius.

The maximum electrical field strength in the area of the stator corner increases exponentially and reciprocally to the radius of the corner. For the smallest radius of 0.05mm, the maximum field strength reaches a value of 2.4 times the homogenous field strength in the insulation between winding and stator. For a radius of 1mm (representing 2-4 times the thickness of a stator lamination) the field strength excess is 20% over the homogenous value.

Electrical field strength gradients for a winding to stator distance of 0.3mm are displayed in Fig. 5. It can be seen, that the maximum electrical field strength for the smallest radius of 0.05mm is 1.75 times above the homogenous field strength. The reduced distance to radius ratio leads to a smaller field strength excess. A field strength excess reduction to 8% over the homogenous value can be observed for the maximum radius of 1mm. These observations lead to the following conclusion: The field strength overshoot effect at the stator corners is more important for higher voltage applications with thicker insulation layers. But also at small isolation distances, field strength peaks are distinctive. Furthermore, small variations at the winding process (inaccuracy below 0.5mm) regarding the distance between winding and stator can lead to major fluctuations in the maximum electrical field strength.

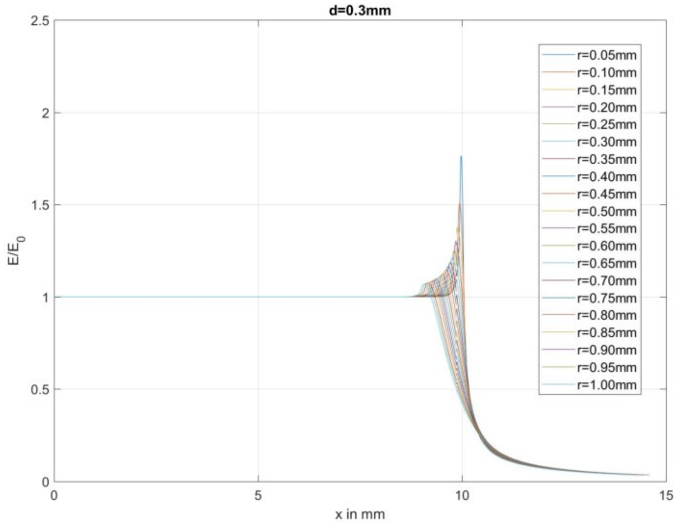

Fig. 5. Normalized electrical field strengths across the surface of the stator at a distance between winding and stator of 0.3mm with varied corner radius.

The simulations are based on simplified two-dimensional electrostatic geometries. It can be assumed, that space charges in the insulation material lead to field distortion effects and therefore by trend lower maximum electrical field strengths [8]. This effects is simulative hard to quantify.

A light optical microscope was used to analyze the edges of stator lamination more in detail. Fig. 6 shows a view on the laser cutting edge of a 0.35mm stator lamination.

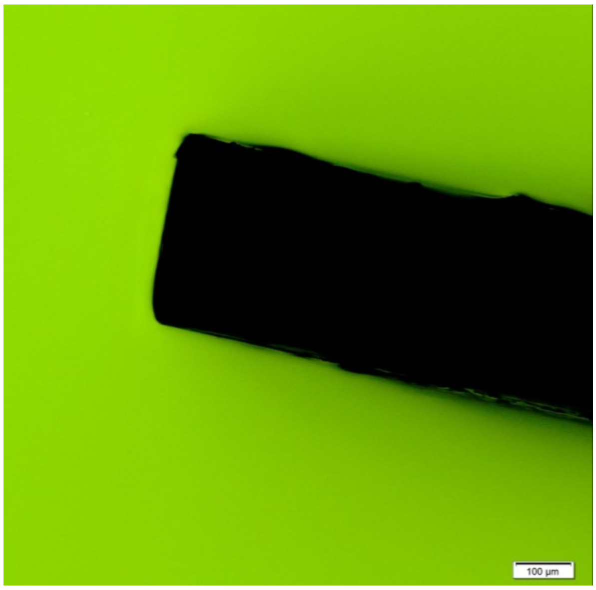

Fig. 6. Light optical microscope image of the laser cutting edge of a 0.35mm stator lamination.

The relatively sharp edges of the stator lamination are clearly visible. Though a consistent curvature cannot be assumed, the radius of the corner segment can be determined in the range of 10-30 microns. Also the recorded surface view on the edge of the stator lamination in Fig. 7 shows its sharp progression. Both pictures illustrate the validity of the simulation conditions.

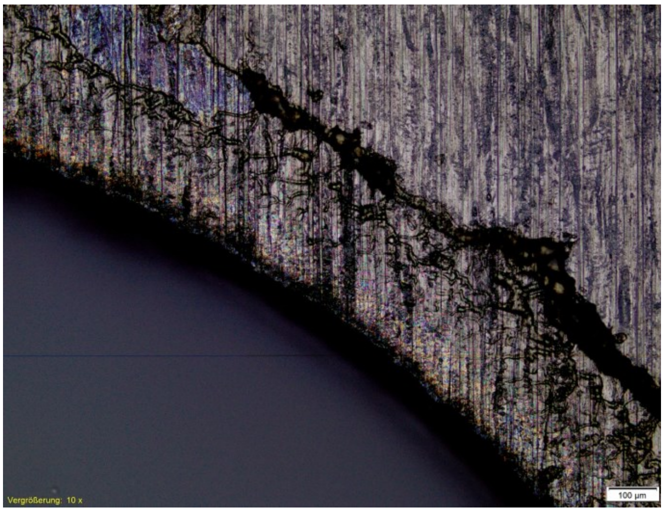

Fig. 7. Light optical microscope image of the surface of a 0.35mm stator lamination in the area of the laser cutting edge.

IV. EDDY CURRENT LOSSES

To investigate potential thermal problems caused by eddy current losses in the conductive layer of the winding head support, a three dimensional FEM-simulation was performed. It was aimed to a quantification of eddy current losses generated by the stray field of the winding and stator. The crucial point of this analysis is the thin dimension of the conductive surface layer compared to the size of the simulation region. To obtain reliable simulation results, the mesh generation in this thin volume has to be observed and adjusted carefully. Geometric simplifications and dimension restrictions of the simulation model are necessary to limit the computing time to reasonable values. Fig. 8 displays the developed simulation model.

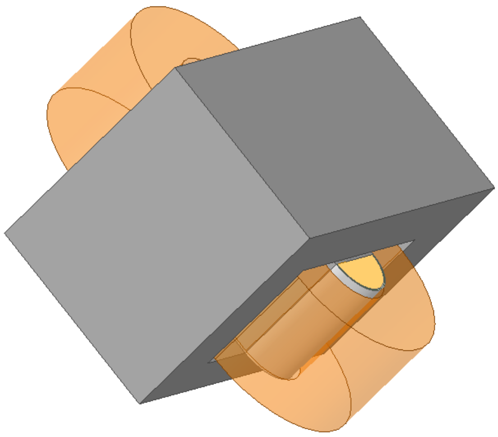

Fig. 8. Simulation model for the 3D eddy current FEM simulation of the conductive winding head support surface layer.

The dimensions of the magnetic circuit core are 59x90x50mm. The inner bar structure of the core, which has a dimension of 32x18x50mm and is surrounded by the winding, contains an air gap of 1.5mm. The amplitude of the alternating current in the winding is impressed in such a way, that the peak magnetic flux density of the inner bar structure has a value of 1.5T. The U-shaped conductive aluminum layer at the front end of the magnetic core has a distance to the winding of 1mm. Aluminum is a typical coating material applied to a variety of synthetic materials [9] and is also very economic. Fig. 9 displays an exemplary distribution of eddy currents in the surface layer. This visualization can be used to review the calculation process for reasonable results and to estimate the trustworthiness of the simulation.

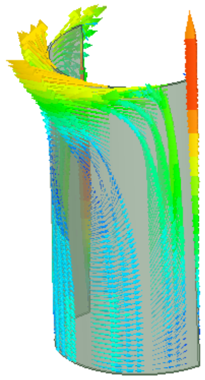

Fig. 9. Exemplary visualization of eddy currents in the conductive surface layer of the winding head support.

The modified parameters of the simulation are the thickness of the conduction layer and the frequency of the impressed winding current and therefore also the frequency of the magnetic flux. Fig. 10 shows the power losses in the aluminum surface layer of the winding head support as a function of the frequency for three different thicknesses. The thinnest layer (50 microns thickness) represents also the lower boundary for trustworthy results of the simulation. Below this thickness, insufficient mesh elements between the boundaries of the conduction layer cause numerical errors.

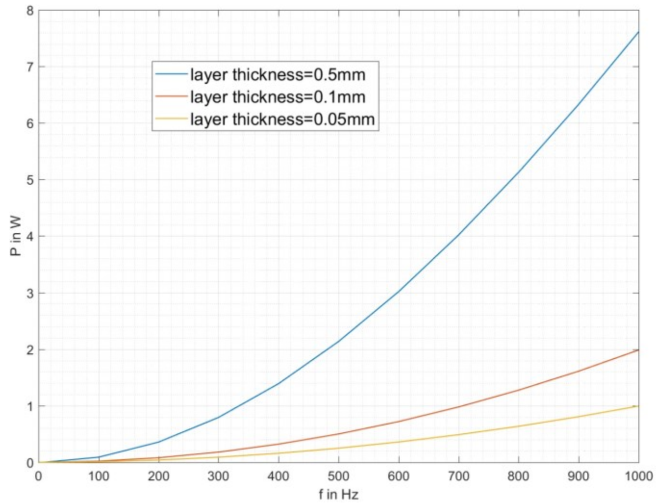

Fig. 10. Eddy current losses in the conductive aluminium surface layer of the winding head support for different thicknesses as a function of magnetic flux frequency.

As expected, the total eddy current losses increase with the frequency and the thickness of the conduction layer. Losses within the typical coating thicknesses below 100 microns, especially between 10 and 50 microns, are in acceptable limits. The volume of the conduction layer with a thickness of 50 microns amounts 44.7mm³. This equates a power density of 11.2W/cm³ at an exemplary stator frequency of 700Hz. Fig. 11 displays the power density of the eddy current losses in the conduction layer for different frequencies of the magnetic flux.

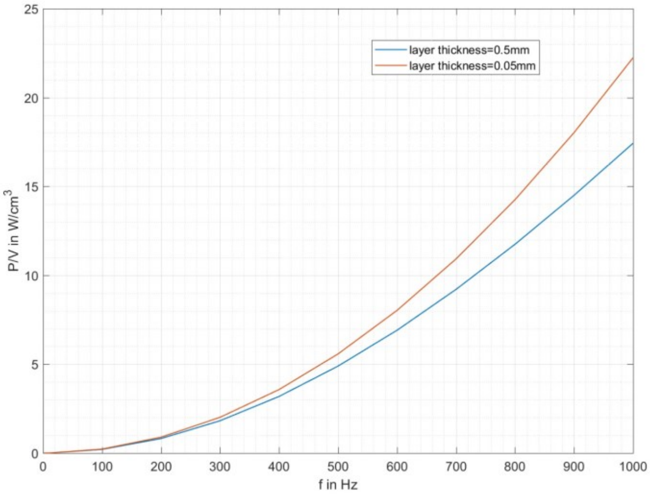

Fig. 11. Eddy current loss power density as a function of magnetic flux frequency.

It can be seen, that the loss power density decreases while the conduction layer thickness increases. The reason for this behavior is the frequency dependent limited eddy current depth. The current density near the surface of the conduction layer is greater than the current density inside the conducting material. Therefore the average eddy current loss density of the conducting volume is lower at thicker layers.

V. Implementation Example

Fig. 12 and 13 show an example of the proposed winding head support with rounded edges for homogenous electrical field strengths. The 3D printed material is a high temperature resin, which can easily be metallized with an aluminum surface layer.

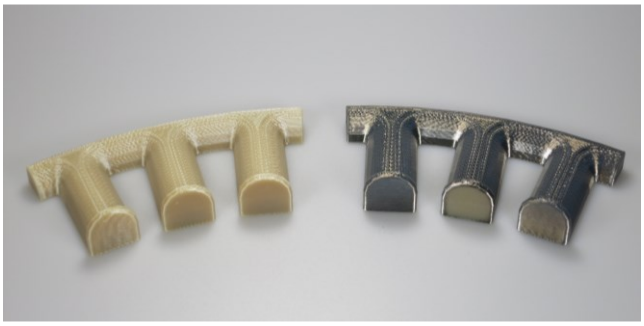

Fig. 12. 3D printed winding head support with (right) and without (left) surface metallization.

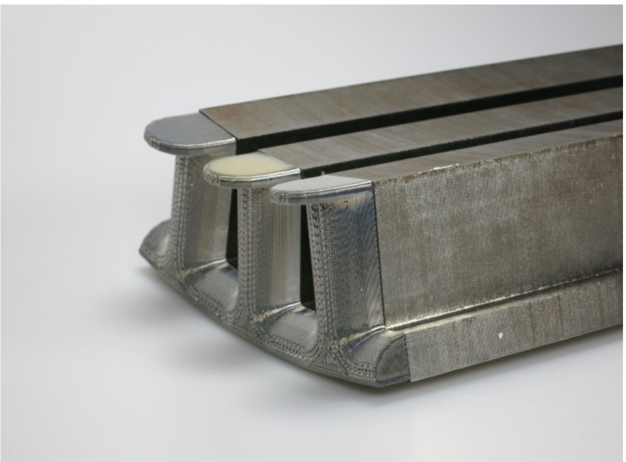

Fig. 13. Metallized winding head support at stator lamination segment.

For the purpose of mass production, other manufacturing methods besides 3D printing should be used to obtain a better surface quality and a more cost efficient production process. However for the demand of prototyping 3D printed parts fulfil their intended function appropriately.

VI. Conclusion

To reduce peak amounts of the electrical field strength in the insulation system of the stator winding, a winding head support with a thin film surface metallization was proposed in this paper. Investigations regarding electrostatic effects of edge rounding were performed for the special problem of the stator corners. It has been shown by simulation, that relatively small radii of the stator edges can provide almost homogenous field distributions. The radius of the winding head support is larger than the analyzed maximum corner radius of 1mm. Hence, the aluminum coating of the winding head support should create a very homogenous field distribution with little field strength excesses.

The second part of the investigations regarded the eddy current losses inside the metallized surface layer. By simulating the effects of the magnetic stray fields in the area of the head supports with a simplified equivalent 3D model, it could be shown that the power losses caused by eddy currents are limited at thin layer thicknesses and therefore are accaptable. Thicker conduction layers above 100 microns thickness can lead to major heat sources in the winding head which may cause thermal strain for the winding insulation to the point of destruction.

Acknowledgment *(Heading 5)*

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