Investigation of ceramic-coated profile conductors regarding insulation strength with the aim of better thermal connection to the laminated core of electrical machines

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***Abstract*—This work addresses an alternative approach to electrical insulation of the winding by using ceramic materials such as aluminum oxide, which in addition to good insulation strength also have relatively high thermal conductivity. This can be applied to copper by thermal spray processes, which also allow the use of profiled conductors. In the present work, the determined values for insulation strength and insulation resistance are presented depending on different layer thicknesses and manufacturing parameters, as well as the influence of post-treatments. For this purpose, a special measurement setup is used which records the corresponding data with a large number of contact points and thus takes into account weak points caused by manufacturing variations.**

***Index Terms*—Ceramic coating, Insulation, Thermal spraying, Winding, Electric machines**

I. INTRODUCTION

Due to the typically poor thermal conductivity of electrically insulating materials such as copper lacquer [1], filling compounds [2], [3] and insulating paper, the thermal connection of a classic winding for electrical machines according to the state of the art [4] to the surrounding laminated core is a weak point in the chain of heat dissipation to the cooling medium. A technologically limited copper fill factor due to the use of round wire as well as an associated low effective contact area to the slot wall further increase the effect. [5]

An interesting alternative is the use of ceramic materials as insulation material for the conductors of electrical machines [6], [7]. In particular, the material aluminum oxide stands out here, which in sintered form has a dielectric strength of up to 15 $\mathrm{kV\,mm^{-1}}$, a specific electrical resistance of 10^{14} bis 10^{15} $\Omega\,\mathrm{m}$ and, at 20 to 30 $\mathrm{W/mK}$, significantly better thermal conductivity than most other electrical insulators. [8] In addition, this material is relatively inexpensive compared to other engineering ceramics. It can be melted via thermal spray processes and applied as a coating to a variety of materials. [9]

As an assumption of a later production by insertion technology, similar to a hairpin winding [10], copper bar conductors with a square profile are to receive a coating with aluminum oxide in this paper. With a process-stable ceramic insulation coating, this structure could transfer the heat dissipated in the slot via the large contact area of the individual profile conductors to each other to the laminated core much better than the conventional insulation structure with copper lacquer and insulation paper. Due to the hard and robust aluminum oxide layer, the need for insulation paper to protect the insulation layer could even be completely eliminated, which would lead to a further improvement in the thermal connection of the winding to the stack of laminations.

II. PRODUCTION OF THE INSULATION LAYER BY THERMAL SPRAYING

The flame spraying process was used to produce the ceramic coating. This is a process within the manufacturing technique of thermal spraying [11]. With the aid of a flame, which burns through a fuel gas-oxygen mixture, very fine particles of an aluminum oxide powder are melted and accelerated by the flame jet in the direction of the workpiece. The thickness of the ceramic coating increases depending on the duration of exposure to the flame jet containing ceramic particles. The fuel gas is acetylene, which burns off together with oxygen at up

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to 3160 °C and thus enables the ceramic particles to melt. To ensure that the heat input due to the flame does not lead to deformation of the copper rod, it is clamped in a lathe for rapid rotation. The flame spray nozzle also moves simultaneously along the rotating rod. This technique also ensures a uniform coating thickness on the rod. Figure 1 illustrates the automated flame spraying process.

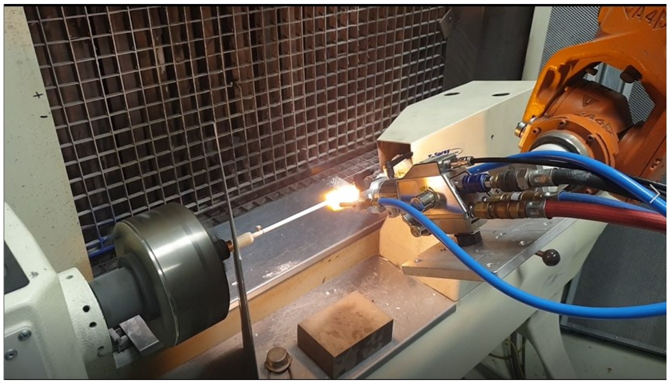

Fig. 1: Thermal spraying of a profiled conductor.

Flame spraying was selected as the process because it is a less expensive process than plasma spraying, and allows more accurate coating thicknesses to be produced compared to arc spraying. [12]

A copper rod with a length of 220 mm and a square profile of 4x4 mm was used as the profile conductor. With smaller profiles, the heat input turned out to be too great compared to the thermal mass, which is why deformations of the conductors occurred. In addition, the edges of the profile conductor had to be grinded over so that a radius of 0.6 mm was created, as otherwise the coating could peel off at the sharp edges.

III. TEST SETUP FOR DETERMINING THE DIELECTRIC STRENGTH OF THE INSULATION LAYER

In order to be able to examine the coated rod samples for their electrical insulation properties, different test beds were set up. In a first approach, the test piece was placed under a series of spring-loaded contact pins. The test voltage was then applied to the contact pins with respect to the copper conductor. With this test method, however, it was found that depending on the position of the test piece, the values achieved in terms of dielectric strength and electrical resistance varied greatly. The reason for this was the insufficient number of sampling points on the coating. Due to the porosity of the insulation layer, there were strong fluctuations in the electrical properties distributed over the surface. Figure 2 shows the corresponding measurement setup.

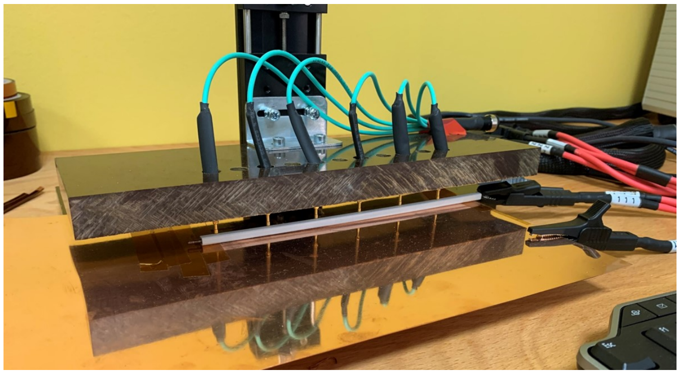

Fig. 2: First test setup with six contact pins.

Due to the above-mentioned disadvantages of the first test setup, a second test setup was developed, which should significantly increase the number of sampling points on the surface of the coating. For this purpose, a housing was built in which the conductor rod to be tested is placed. The space around the test piece is then filled with small balls made of stainless steel. These balls have a diameter of only 1 mm. This results in countless contact points with the coating surface. A cable contacting the micro-balls applies test voltage to them with respect to the coated conductor segment. Figure 3 and 4 show the second test setup, once partially and once completely filled with balls.

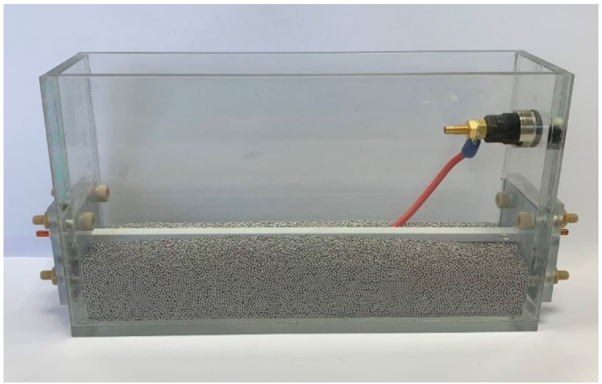

Fig. 3: Second test setup with half filled with contact balls.

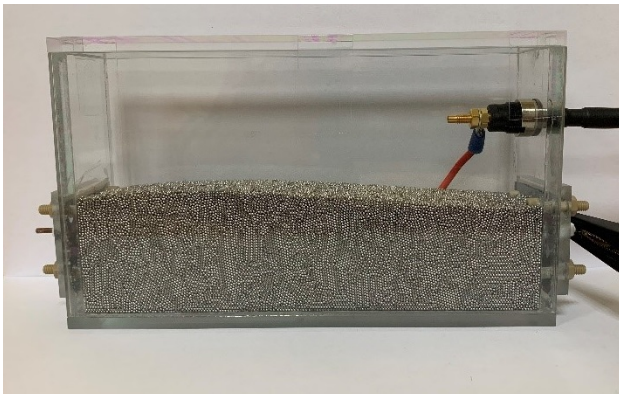

Fig. 4: Second test setup with completely filled with contact balls.

IV. Evaluation of the Measurement Results

The test setups described in section III will now be followed by exemplary measured values. Figure 5 shows the test curves for the dielectric strength and the ohmic resistance of the coating on the first test setup with six contact pins loaded by springs.

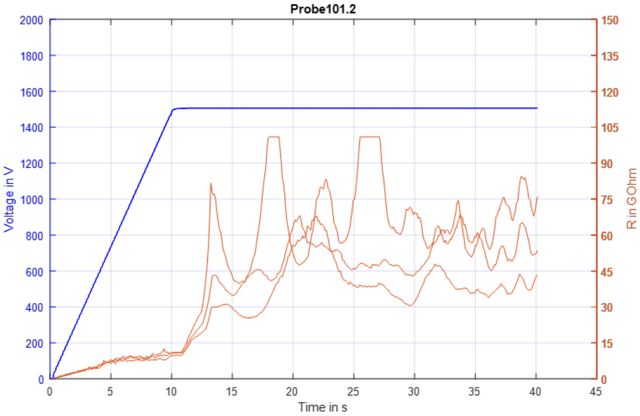

Fig. 5: Measured curves on the first test setup.

For better clarity, the curves of three of the six measuring points are shown. The measuring cycle is such that the voltage is raised from 0 V to 1500 V within 10 s with a ramp. This voltage has to be held for 30 s afterwards. During this process, the ohmic resistances of the insulation layer at the probe points are determined. The test is aborted if a current greater than 1 mA flows across the contact points. The ohmic resistance curves in Figure 5 clearly show the fluctuations. There is also a clear difference in the mean value of the ohmic resistance, depending on the position. Figure 6 shows the curves of the measurement of the same sample in the second test setup.

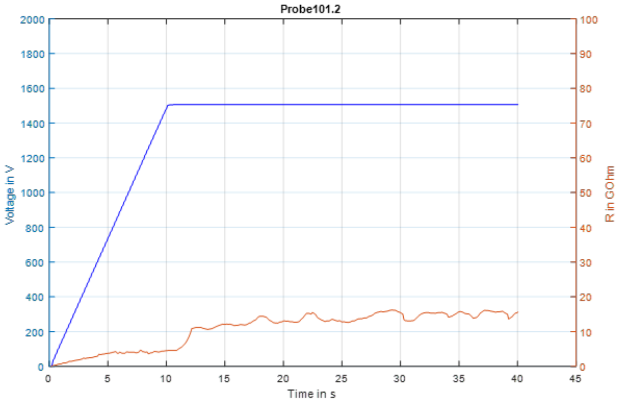

Fig. 6: Measured curves on the second test setup.

Here, only one curve for the ohmic resistance of the insulation coating is measured in accordance with the setup. The curve shows significantly less fluctuation, which indicates an increase in measurement quality, and is also below the curve of the first test setup. This was to be expected and suggests that the weakest point in the insulation of the rod conductor could be determined by the test setup.

The measurement from figure 6 shows which electrical insulation properties could be achieved with an average nominal coating thickness of 0.2 mm aluminum oxide with subsequent post-treatment by sealing. Sealing is necessary because otherwise higher leakage currents and earlier breakdown occur due to the air in the pores of the ceramic coating. The sealant fills the pores and provides a significant improvement in insulation strength due to its good dielectric properties. Figure 7 shows the voltage test curves for a sample with 0.2 mm insulation layer thickness without sealing.

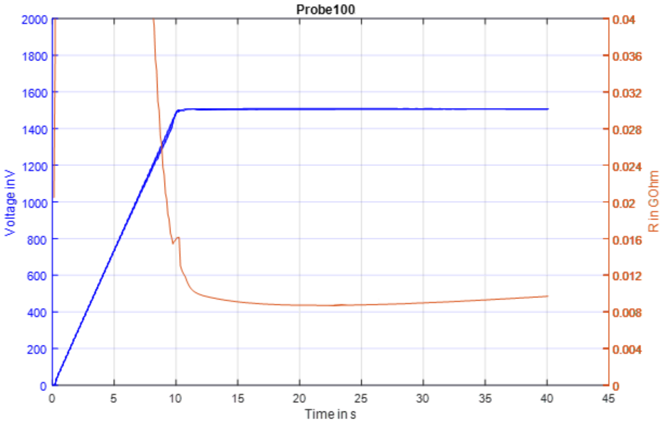

Fig. 7: Measured curves without sealing.

Although the aluminum oxide coating withstands the test voltage, it can be seen from the ohmic resistance that this is over three orders of magnitude smaller than the values achieved with sealing and is only in the megohm range.

In order to draw a comparison with the conventional solution with coating by copper lacquer, rod conductors were also lacquered instead of coated. Figure 8 shows the corresponding measurement.

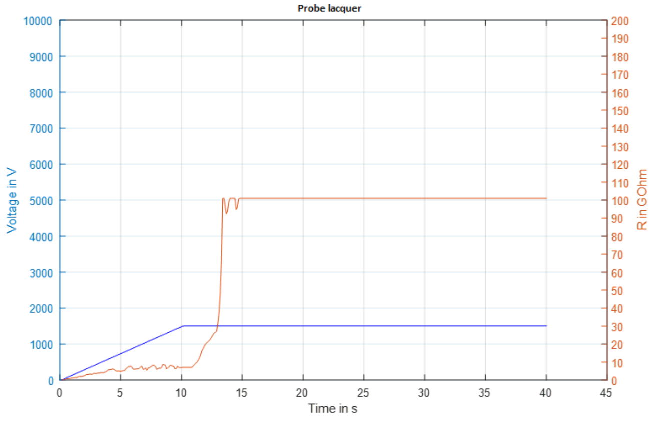

Fig. 8: Measured curves with copper lacquer.

It can be seen that the copper coating has a significantly higher electrical resistance than the ceramic coating. This is so high that it cannot be determined with the available measuring equipment. The measuring device reaches its limit at 100 GΩ, so that it can only be stated that the electrical resistance of the copper coating reaches at least this value. Whether this value actually has to be reached for an electrical machine with an operating voltage of up to 1000 V is another question, which is not asked in this paper.

Electrically, the copper lacquer coating is therefore clearly superior to the ceramic coating. The second property that the insulation system must fulfill in addition to electrical insulation in an electrical machine is heat conduction. The heat, which is generated in the winding due to resistive losses, must be transferred to the cooling system via the laminated core. In the process, the heat must pass through the insulation layer. Although this layer is very thin at 200 µm, a significant temperature drop occurs due to the low thermal conductivity in the range of 0.2 W/mK [1]. The extent to which a ceramic coating produced by flame spraying can achieve improvements was to be determined. In this regard, an experiment was conducted in which the copper conductor segments of the same geometry and different coatings were heated in an oven at 120 °C for more than one hour. Subsequently, the conductor segments have been exposed to the ambient temperature of 22.5 °C and the electrical resistance of the copper conductor has been recorded with an precise resistance meter. Since the electrical resistance of the copper changes at 0.4 %/K, the conductor temperature could thus be concluded. Figure 9 presents the recorded resistance curves of the two cooling processes as well as the corresponding exponential regressions to them.

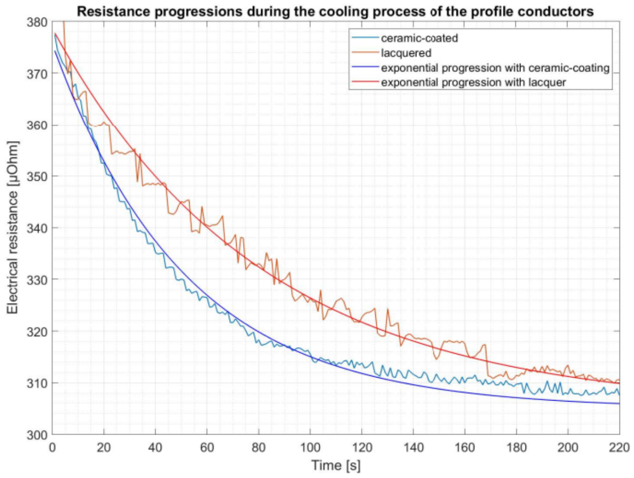

Fig. 9: Resistance progressions during the cooling process of the profile conductors.

Since the identical geometry of the copper conductors as well as the same ambient conditions can be assumed, the thermal conductivity between the two coatings can be directly compared assuming the same heat capacity, initial temperature and existing convection conditions. Here, the ceramic coating exhibits 58% higher thermal conductivity with convective air cooling compared to the lacquer coating.

V. CONCLUSION

In this paper it was investigated how a ceramic insulation coating of aluminum oxide, which was applied by a flame spraying process, has to be manufactured for slot conductors of electrical machines up to 1000 V operating voltage and which electrical and thermal properties it has. It was found that a ceramic coating thickness of 0.2 mm was required using an appropriate manufacturing method to reduce thermal stresses. This coating had to be posttreated with a sealant for better insulation properties to compensate for the porosity of the ceramic coating. In order to be able to reliably assess the manufacturing quality and the properties of the insulation layers by measurement, a special test setup with electrically conductive mircoballs was developed.

The achieved electrical insulation properties of the ceramic coating are sufficient for use in electrical machines, but with an electrical resistance in the range of 10 GΩ, they fall significantly short of the properties of the copper coating. Thermally, however, the situation is different. It has been shown that the ceramic coating enables significantly better heat transfer from the copper conductor. This property, coupled with the greater mechanical hardness of aluminum oxide, makes this coating process an interesting alternative for highly utilized electrical machines.

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