FRAUNHOFER INSTITUTE FOR MANUFACTURING TECHNOLOGY AND ADVANCED MATERIALS IFAM

DOCUMENTATION OF INSULATION MEASUREMENTS FOR ELECTRICAL MACHINES

Processing period: February 2018 – September 2018

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Offer number: A218102
Purchase number: 3200259751
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1 Objective

The aim of the project is to verify the work carried out in the previous year on the offer A217279. The estimation of the heat dissipation properties of a new insulation system developed by DuPont (Electronics & Imaging - Interconnect Solutions) in a slot for electrical machines compared to conventional insulation systems will be verified within this project by means of a measurement setup. The focus is on the determination and comparison of the stationary temperatures of the windings within the slots of a lamination stack with two different slot insulations.

2 Temperature measurement methods for comparability of simulation and measurement

In the previous project, the stationary temperatures in the individual winding layers were calculated using the schematic simulation model in Figure 1, which represents the tooth-slot symmetry of the stator of an electric machine representative of the application.

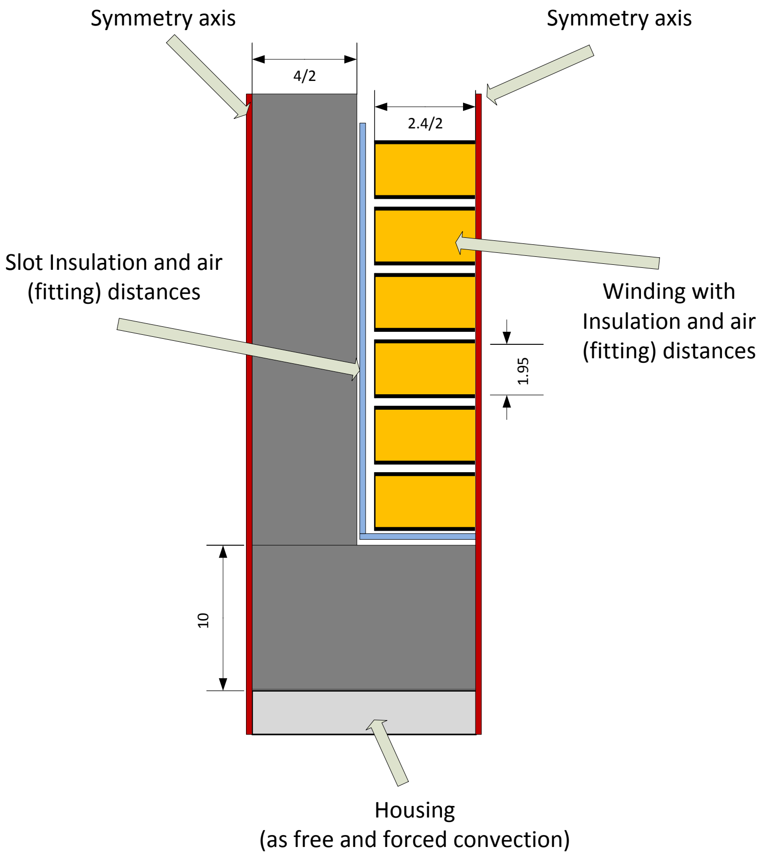


Figure 1: Schematic simulation model of the tooth-slot symmetry of an electrical machine

Due to the relatively small dimensions of the wires and the slot width, a direct temperature measurement of the windings in the different layers with e.g. embedded or bonded thermocouples is not suitable. Because of their considerable size, these would detect a wrong value in the very limited space within the slot due to a considerable change in the heat path. For this reason, the temperature is determined using an indirect measuring method. The temperature of the conductor can be calculated from the change in the electrical resistance due to a temperature difference. The physical relationship between the temperature-dependent electrical conductivity of a material can be described as follows: In general, the ohmic resistance of a conductor with cross-sectional area A, length l and specific resistance ρ at an initial temperature of 20 °C is defined as follows:

$$R_{20} = \rho \cdot \frac{l}{A} = R(T_0)$$

However, the temperature dependence of a physical quantity, including an electrical resistance, is generally not linear. A good approximation of this dependence can be described by a Taylor polynomial of nth degree with the following equation:

$$R(T) = R(T_0)\cdot(1+\alpha(T-T_0)+\beta(T-T_0)^2+\gamma(T-T_0)^3+...+k_n(T-T_0)^n)$$

where:

R ≅ Temperature-dependent resistor
T ≅ Temperature to be considered
T_0 ≅ Reference temperature, frequently 20 °C
α ≅ Temperaturcoeffizient 1st degree
β ≅ Temperaturcoeffizient 2nd degree
γ ≅ Temperaturcoeffizient 3rd degree
k_n ≅ Temperaturcoeffizient nth degree

Due to the temperature range for wires in electrical machines of insulation class H (200 °C), in the following only the first term from the above Taylor polynomial is used to determine resistance. The resulting error compared to the quadratic approximation is approx. 1.2 % at a temperature sweep of 180 K for copper wires and can be assumed to be negligible. With the help of the temperature coefficient $\boldsymbol{\alpha}$ the following expression for the resistance results:

$$R(T) = R(T_0)\cdot(1+\alpha(T-T_0))$$

For the determination of resistance, this test setup relies on the method of voltage-correct measurement of ohmic resistances. It is particularly suitable for measurements of very low-impedance resistors where contact and line resistances can no longer be neglected. Figure 2 illustrates the wiring, which is comparable to a four-wire measurement.

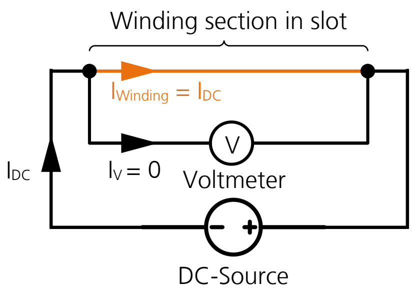


Figure 2: Principle circuit for voltage correct measurement of ohmic resistances

The resistance value $R(T_0)$ is first determined using a micro-ohmmeter. An adjustable DC-source is connected to the terminals of an ohmic resistor so that the test specimen heats up. The stationary temperature condition of the test specimen is awaited. Afterwards the voltage over the low-impedance resistor can be measured directly at the terminals using a high-impedance voltage meter. With the help of ohm´s law

$$R(T) = U/I$$

and

$$T_{avg} = \frac{R(T)}{\alpha \cdot R(T_0)} - \frac{1}{\alpha} + T_0$$

it is possible to calculate the mean temperature of the conductor section in the slot.

3 Test specimen and measuring setup

Description of the test specimen

Based on the nomenclature of the previous offer A217279 Table 1 shows the selection of the materials to be tested for the test specimen. All three materials have been provided by DuPont. The mean cross-section geometry including insulation of the wires used for this test is 2.65 mm x 1.71 mm. Since this differs from the geometric dimensions from the simulation work of the previous work, additional simulations have been carried out within this project which takes the real dimensions into account. The results are presented in the following chapter.

Table 1: Selection of the wire and insulation materials to be investigated

Typ	Type of insulation	Material	Thickness of insulation (µm)	Thermal conductivity (W/mK)
Wire2	Winding wire	Film A (Kapton® FWN), foil thickness 33 µm, 1 foil with 50 % overlap	66	0.19
SlotA	Nomex® Paper	Nomex® 410	0.18	0.12
SlotC	NKN Laminate	Laminate B, (1.5-5-1.5, Kapton® MT$^+$ Film)	0.22	0.35

The schematic simulation model in Figure 1 represents the basis for the construction of a suitable test specimen. It shows a tooth-slot symmetry of the stator of an electrical machine representative of the intended purpose. This two-dimensional model must be converted into a three-dimensional model for a real test setup. In order to obtain a statistical estimation, two sheet packages in the form of linear stators with six identical slots each for the different wire and insulation paper combinations were constructed. Table 2 shows the characteristic values of the two sheet packages.

Table 2: Overview of the characteristic values of the two test specimens

	Lamination stack 1	Lamination stack 2
Lamination material	M400-50A with bonding varnish insulation C3 (DIN EN 10106)	M400-50A with bonding varnish insulation C3 (DIN EN 10106)
Wire / Slot insulation (see Table 1)	Wire2 - SlotA	Wire2 - SlotC
Vacuum impregnation	Axalta Voltatex 4250	Axalta Voltatex 4250
Amount of slots	6	6
Slot width/length	3.16 mm / 140 mm	3.24 mm / 140 mm
Tooth width/height	8 mm / 16 mm	8 mm / 16 mm
Yoke height	10 mm	10 mm
Contact surface to cooling plate	140 mm x 140 mm (grounded)	140 mm x 140 mm (grounded)

In addition to the characteristic data from Table 2, the wires of both lamination stacks are meandered into the slots in series and fixed by a slot closure. In order to realistically increase the thermal connection of the coils to the laminated stack, the coil was impregnated with an epoxy resin according to Table 2 in a vacuum impregnation process. Figure 3 shows the complete setup in different views.

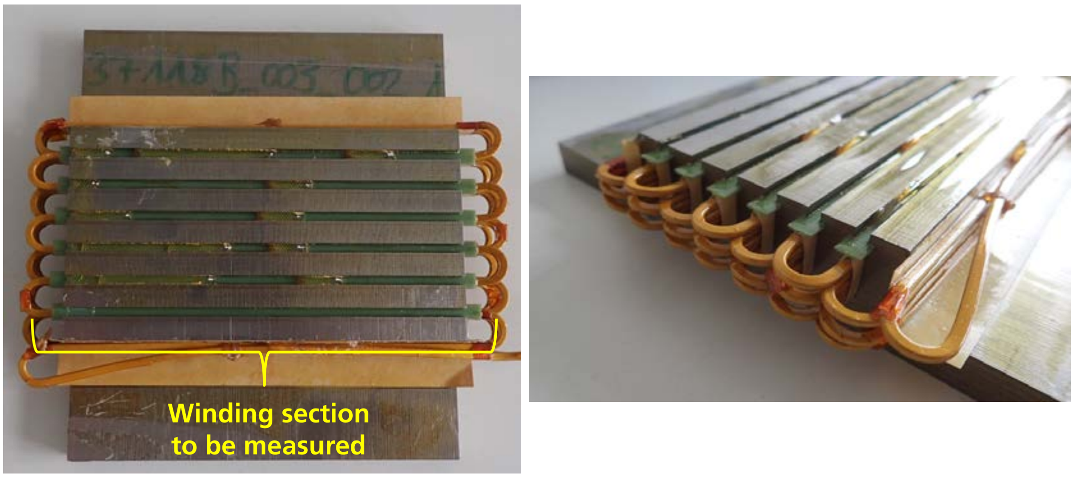


Figure 3: Lamination stack as test specimen

In order to be able to measure the voltages over the winding layers for the measurements (example see Figure 3), the copper has been stripped for a contact surface at the end of the respective end winding section on both sides. Viewed from the slot opening, the 1st, 3rd and 6th winding layer in all slots have been prepared for the voltage measurement. Thus, for each lamination stack there are 18 winding sections for the measurements (Figure 4).

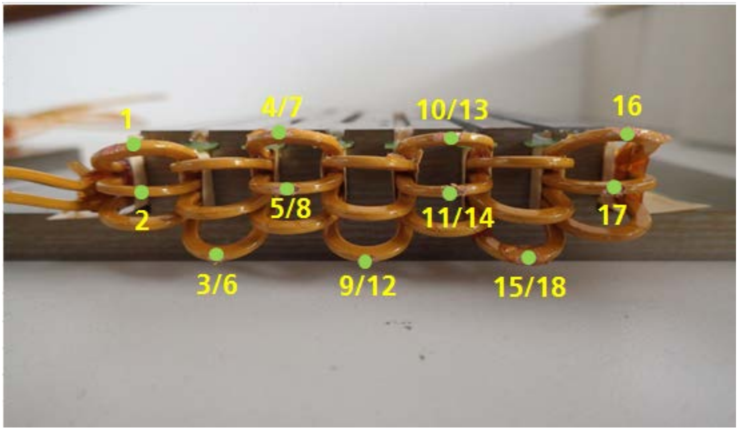


Figure 4: Measuring points on the test specimen

Description of the measurement setup

The measuring setup should reproduce the coil with the slot insulations in a water-cooled lamination stack, which is usually to be found in highly utilised electrical machines. For a comparable thermal connection of the lamination stack, it is mounted horizontally on a water-cooled aluminium heat sink with four screw clamps, the teeth pointing upwards. Figure 5 demonstrates the completely installed test specimen in the test environment.

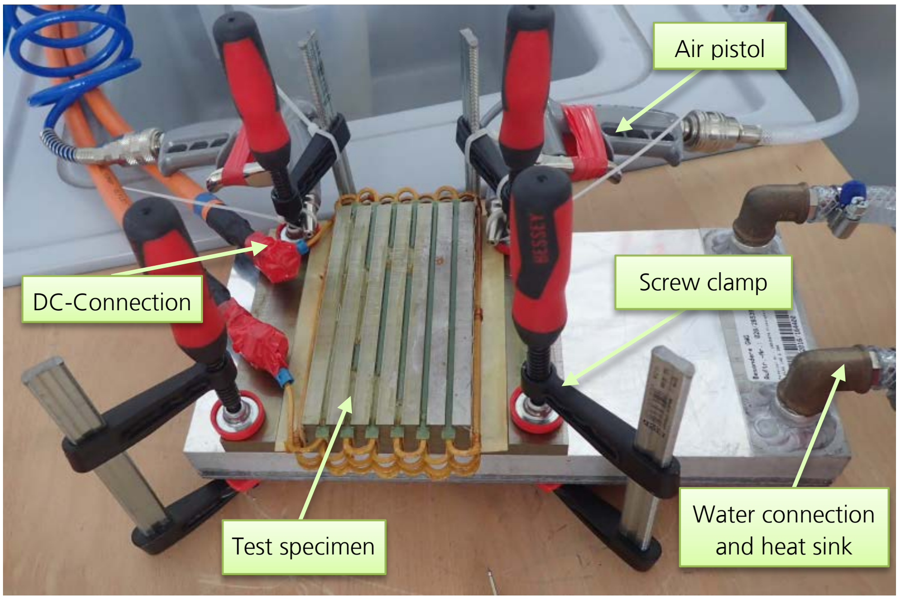


Figure 5: Test specimen in the test environment

The air pistols only blow linearly along the two outer teeth in order to protect the outer wires from overheating. A temperature-controlled water circuit is used to cool the lamination stack. The inlet temperature of the cooling water into the heat sink is maintained at 30 °C at a flow rate of about 1 l/min. Table 3 lists the devices used for the test.

Table 3: List of test bench equipment used

Manufacturer	Modell	Type	Purpose of use
Keysight	34461 A	Digital Multimeter	Voltage measurement, calibrated
InfraTec	VarioCAM HR	IR-Camera	Temperature measurement/monitoring
EA Elektro Automatik	EA-PSI 9080-120	DC power source	DC power source, calibrated
TFA Dostmann	Digital Thermo-Hygrometer	Temperature/humidity meter	Temperature/humidity meter, calibrated
Fluke	54 II Thermometer	Digital Thermometer	Thermometer for countermeasurement
Chauvin Arnoux	CA 6240	Mikro-Ohmmeter	Measurement of ohmic resistant at room temperature

4 Results of the measurements

Thermographic analysis

Thermographic images were taken to show the spatial distribution of temperature and to monitor hotspots. An example for a qualitative distribution is shown in Figure 6. Similar to usual electric machines the hot spots are located at the end windings. In addition, it can be seen from this that the winding layers outside the slots along the tooth do not receive sufficient cooling. So an active cooling by the air pistols described in the measurement setup is necessary to protect the conductor.

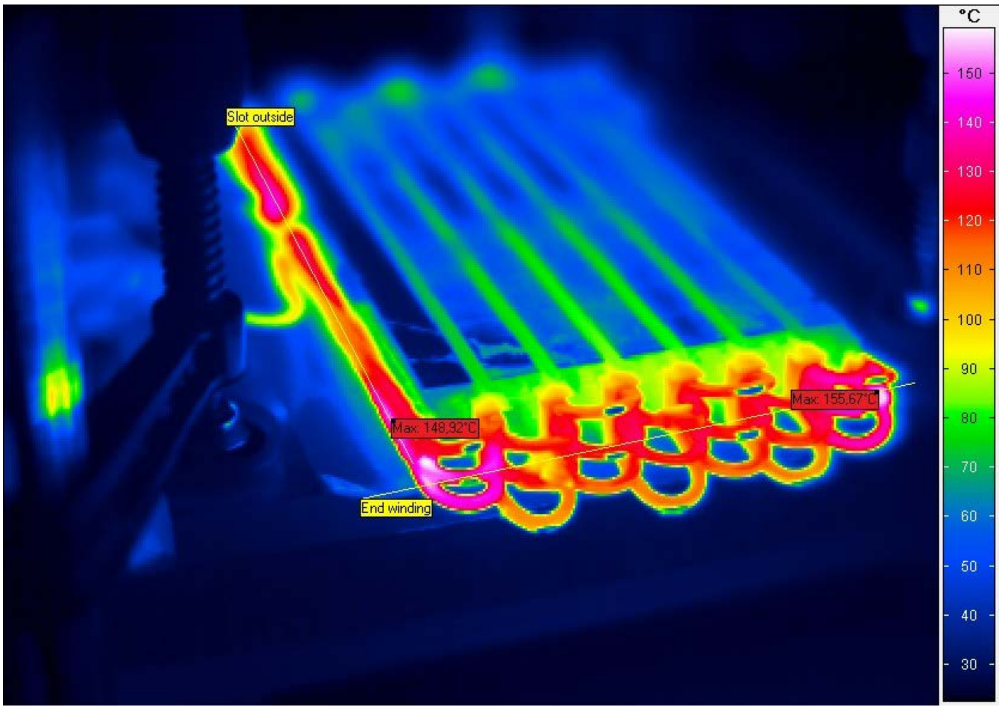


Figure 6: Exemplary thermographic image for qualitative spatially resolved temperature display and monitoring

Due to the difference in the setup as described above adapted simulations have been carried out in order to be compared with the measurements. The following modified boundary conditions were assumed for the calculations:

1. Two heat sinks
    a. Upper side tooth end: α=50-70 W/m²K (temperature-dependent) representative of free convection
    b. Contact surface to cooling plate: α=2500 W/m²K, representative of forced convection (e.g. water jacket cooling of a housing)
2. To consider the impregnation of the coil
    a. Each winding layer has a gap of 5 µm to the adjacent winding layer due to the mounting distance which has the thermal properties of air.
    b. Each winding position has a mounting distance to the adjoining tooth flank of 10 µm, which has the thermal properties of air
3. The DC losses respectively the currents are adjusted so that a temperature level of around 100 °C, 150 °C and 200 °C is obtained.

Simulation and measurement results

Figure 7 shows the simulation results of the winding temperatures of a complete coil at different temperature levels at 23 °C ambient temperature, which are achieved by imprinting three different DC currents. An average temperature difference of approx. 13 K (100 °C), 22 K (150 °C) or 30 K (200 °C) is achieved between the two lamination stacks over all winding positions. This indicates an increase in heat dissipation with the combination "Wire2-NutC". Furthermore, as expected, the temperature drops from the middle windings to the two heat sinks.

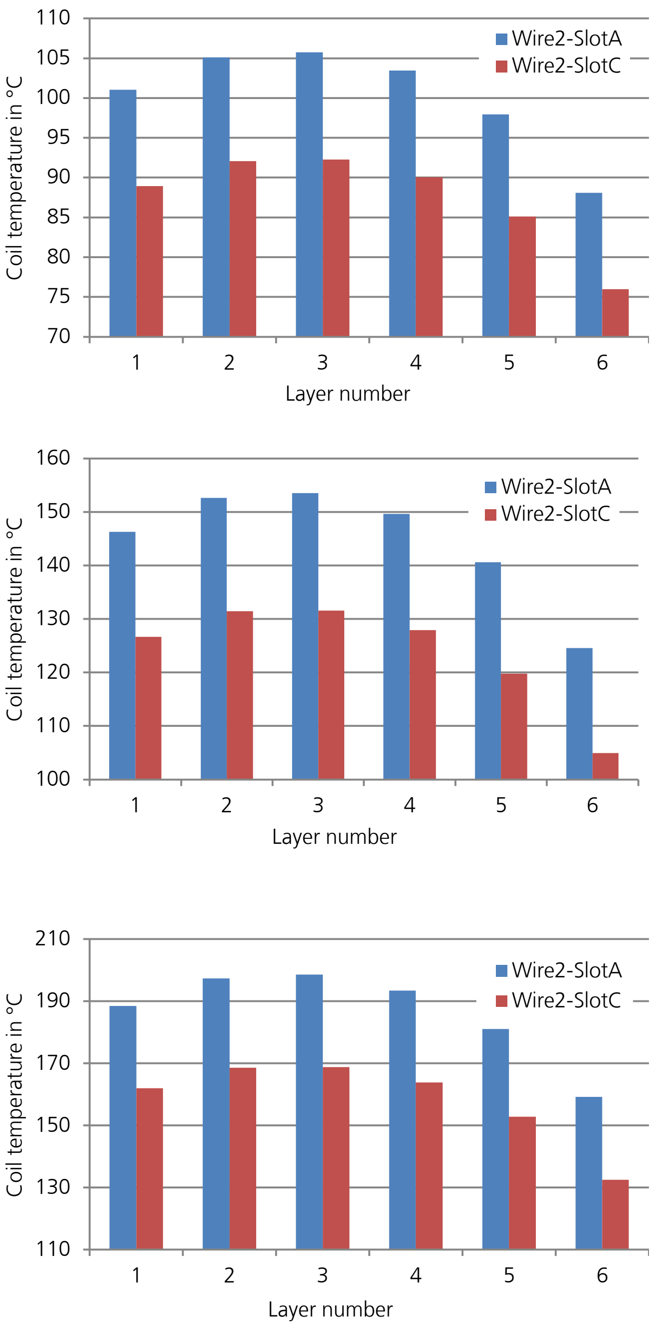
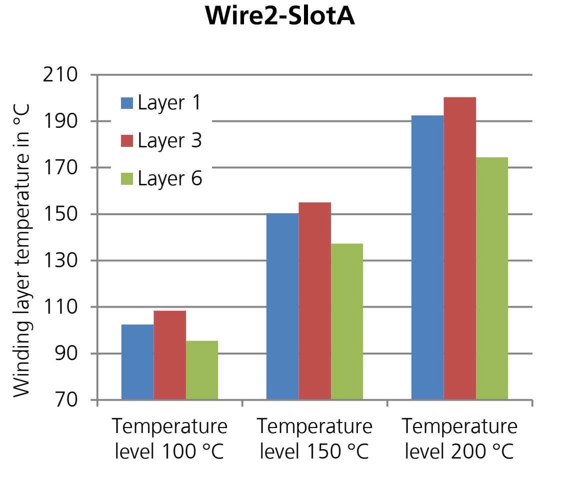


Figure 7: Simulation results of the winding temperatures of a complete coil at different temperature levels

As already illustrated in Figure 4, there are 18 measuring points per test specimen. Only the winding layers of the inner four slots were used for the statistical evaluation, as these have homogeneous boundary conditions. The four measured values of one winding layer were averaged. Figure 8 compares the averaged winding temperatures of the inner four slots of the two lamination stacks at the different temperature levels. The room temperature during the measurements was 24.5 °C for measurement of lamination stack 1 (Wire2-NutA) and 22.5 °C for lamination stack 2 (Wire2-NutC). In agreement with the simulation results in Figure 7, a temperature gradient from the middle of the slot (winding layer 3) to the outside (winding layer 1 and 6) to the two heat sinks is also shown here in both lamination stacks.



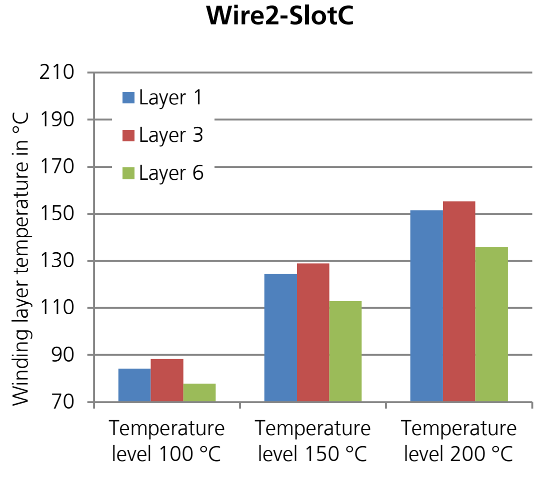


Figure 8: Measured coil temperatures of the two lamination stacks at different temperature levels

In addition, the lower maximum temperatures of the winding layers with lamination stack 2 (Wire2-NutC) are clearly visible. Figure 9 illustrates the temperature difference of the winding layers of the two lamination stacks. Obviously, the temperature difference increases with a higher temperature level.

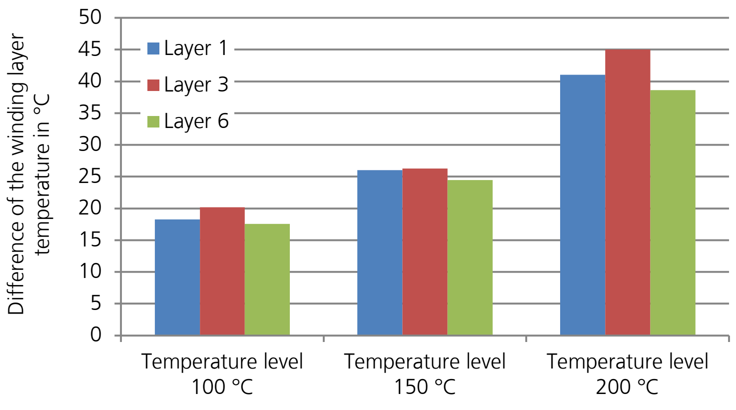


Figure 9: Temperature difference of both lamination stacks

Figure 10 compares the simulation and measurement results for the winding temperatures of the two lamination stacks. For all temperature levels the simulation can confirm the difference between the two setups.

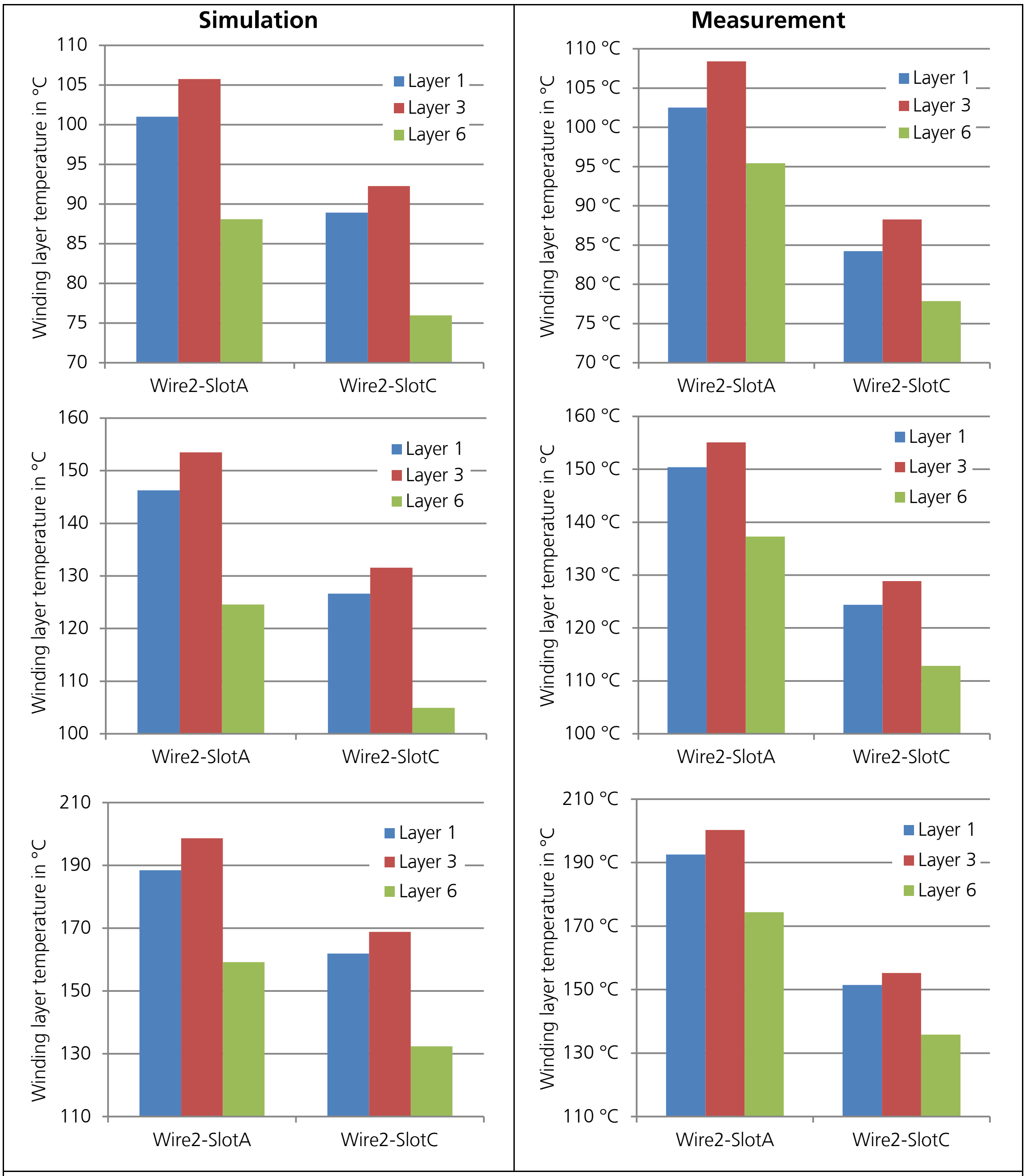


Figure 10: Comparison of the simulation and measurement results of the winding temperatures of the two lamination stacks

5 Conclusion

The simulation results for the lamination stacks with different wire-slot insulations from the previous offer A217279 have been verified within this project. For this purpose, two lamination stacks (test specimens) with identical windings, but with different slot insulations according to Table 1 have been produced. For better heat dissipation, the two lamination stacks were additionally vacuum impregnated. The Fraunhofer IFAM has set up a test environment with appropriate equipment for the implementation of the measurements.

An indirect measuring method was used to determine the temperatures of the individual winding layers in order not to influence the results of the measurements by integrating temperature sensors. For the indirect measuring method, different DC currents have been applied to the windings in order to reach the three coil temperature levels of 100 °C, 150 °C and 200 °C. The voltage has been tapped off at the end windings of different winding layers in the slot. With the aid of the temperature-dependent properties of the conductor it is possible to calculate the temperature in the winding layer section.

Due to changes in the boundary conditions compared to the offer A217279 (change in the geometry of the wire, addition of impregnation processes), the simulations for the comparison of measurement and simulation were adapted to the new boundary conditions and new results generated for these two sheet packages.

The measurements have shown that with the same DC current, the winding layers reach a significantly lower maximum temperature when Kapton® MT$^+$ Film is used for the slot insulation. At a temperature level of 100 °C, the stationary end temperature of the coil is reduced by 20 K with the new insulation paper, by 26 K at 150 °C and by 45 K at 200 °C. This is due to the significantly better heat dissipation properties of the new insulation paper (SlotC) in the slot, which has a three times better thermal conductivity.