WHITE PAPER

How Proper Application of Thermally Conductive Materials Will Improve Motor Power Density

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ABSTRACT

Motor designers have battled heat in motor designs for years. Thermal losses in electric machines rob motion systems of power and degrade efficiency. Excess heat can reduce reliability of motors and shorten their lifetimes. Meanwhile, electrification in all transportation sectors is driving requirements for motors with ever-higher power densities. Good thermal management in electric machines and their power electronic drives can minimize losses, particularly copper (I^2R) losses, and yield improved performance, reliability and efficiency. Research shows a potting or encapsulation process using high thermal conductivity material from LORD Corporation can dramatically decrease the operating temperature of an electric machine at a given load. Proof-of-concept research explored the benefits of potting motor end windings and power electronics with thermally conductive materials. Results showed significant decreases in operating temperature that correlate to higher motor efficiency and double-digit increases in output power.

INTRODUCTION

The ability of high thermal conductivity materials to improve performance in electric machines was demonstrated during research conducted by Shafigh Nategh while a graduate student at KTH School of Electrical Engineering, Stockholm, Sweden. Nategh's research, "Thermal Analysis and Management of High-Performance Electrical Machines," dealt with thermal management aspects of electric machinery used in high-performance applications, with particular focus on electric motors designed for hybrid electric vehicle applications.

LORD CoolTherm™ SC-320 Thermally Conductive Silicone Encapsulant, a relatively soft, high thermal conductivity material (3.2 W/m·K) with sufficiently low viscosity to be used in vacuum potting, was evaluated in Nategh's research. The electrically-insulating silicone encapsulant, designed for electrical/electronic applications, offers excellent thermal conductivity properties while retaining the desirable properties associated with silicones. CoolTherm SC-320 encapsulant is a two-component system that exhibits low shrinkage and stress on components as it cures and maintains a low viscosity for ease of component encapsulation. Environmentally resistant and UL-rated to UL94V0 and 180C RTI, CoolTherm SC-320 encapsulant is composed of an addition-curing polydimethyl siloxane polymer that will not depolymerize when heated in confined spaces.

In the first part of Nategh's thesis, new thermal models of liquid-cooled (water and oil) electric machines (i.e., motors) were proposed based on a combination of lumped parameter (LP) and numerical methods. A permanent-magnet assisted synchronous reluctance machine (PMaSRM) equipped with a housing water jacket, as well as an oil-cooled induction motor where the oil was in direct contact with the stator laminations, were evaluated. In the second part of the thesis, the thermal impact of using different winding impregnation and steel lamination materials was evaluated.

Conventional varnish and epoxy, as well as a silicone-based thermally conductive impregnation material (CoolTherm SC-320 encapsulant), were investigated and the resulting temperature distributions in three small permanent magnet motors were compared.

In comparing the effects of various impregnation materials, the hot spot temperatures of the windings were measured under various coolant flow rates and current levels for each of the potted motors. The hot spot temperatures of the motor impregnated with CoolTherm SC-320 encapsulant were generally 40°C to 45°C cooler than the varnish-only motor, and about 12°C to 15°C cooler than the epoxy-potted motor.

No difficulties in vacuum filling were noted with CoolTherm SC-320 encapsulant despite its viscosity being somewhat higher than those of the epoxy and varnish. In addition, the potting compound was effective at decreasing the hot spot temperatures even when the potting was not 100% dense. For example, the hot-spot temperature of motors potted with CoolTherm SC-320 encapsulant increased by only 3°C as the potting density was decreased from 80% to 50%, whereas the hot spot temperatures of epoxy- and varnish-potted motors increased by 19°C and 25°C, respectively, as their potting densities were lowered from 80% to 50%.

Nategh's research showed that hot spot temperatures can be reduced by 35% to 50% using CoolTherm SC-320 encapsulant as compared to an unpotted motor, compared to improvements of only 20% to 30% using typical epoxy potting materials. The potting compound may provide significant improvements in power density of electric motors.

A decrease in the hot-spot temperature of motors, depending on current, may provide an increase in achievable power/torque for a given motor size, decrease in motor size for a required power/torque, and longer motor operation before reaching temperature limits.

ANALYZING THE TEST DATA

Additional analysis of the data found in Nategh's dissertation was performed at LORD Corporation. Hot-spot temperatures from the dissertation were tabulated based on the potting materials thermal conductivity (varnish only, 0.25 W/m·K; Epoxylite, 0.9 W/m·K; and CoolTherm SC-320 encapsulant, 3.2 W/m·K), coolant flow rate, and applied current. Data were analyzed as a three-variable general factorial experimental design using common statistical analysis software. The results showed that end winding temperatures depended strongly on the current and thermal conductivity of the impregnation material, but there was no statistically significant dependence on coolant flow rate.

Statistical analysis further showed that with the CoolTherm SC-320 encapsulant, the average end-winding temperature was 25°C to 45°C lower than the varnish-only motor; and 10°C to 15°C lower than the epoxy-impregnated motor (Figure 1). Compared to varnish alone, the estimated achievable current required to reach the maximum temperature of 150°C is 14% higher with Epoxylite and 26% higher with CoolTherm SC-320 encapsulant.

Since the current is directly related to the torque, improved thermal performance of the potted motors offers several benefits:

- Higher Power Density – More torque/horsepower from a similarly-sized motor; the same torque/horsepower from a smaller motor; and the ability to remove copper or steel from the motor.
- Better Reliability – Low-temperature operation prevents insulation from degrading quickly, increasing the lifetime of motor insulation.
- Lower Copper Losses – Lower operation temperatures translates to lower copper losses; less resistance to current flow = lower I^2R losses.

INDEPENDENT POTTING STUDY

To independently verify the efficacy of using high conductivity thermal materials to improve motor performance, LORD Corporation worked with Advanced MotorTech, an engineering consulting and services company. Advanced MotorTech is involved in the research, development, fabrication, testing, and re-design of industrial and high-performance machines.

Advanced MotorTech tested the potting compound on a different type of motor from the ones used in the LORD Corporation research. They purchased Class F, 3 hp, 182T frame, totally enclosed fan-cooled (TEFC) motors with a rated rpm of 1760; voltage: 208-230/460, three-phase, 60 Hz; full-load current: 8.4-7.8/3.0. For the test procedures, they knew that using a resin in a standard motor could improve a motor's performance by making the motor run cooler or making it run harder without exceeding its temperature rating. Advance MotorTech went into the testing with no preconceived notions of the outcome.

Six thermocouples were installed on each motor end (drive-end and fan-end), two per winding base, for a total of 12 thermocouples measuring winding temperature.

Thermocouples were also added to the motor skin to monitor the outside temperature. Four "as-received" motors were tested using a "quick, full-load test." From that testing, two motors with similar current, power and temperature rise were selected for subsequent tests.

A controlled test for equal comparison was done on the unpotted motors. The motors were coupled to a DC generator. A dynamometer accurately controlled the power output of the generator, and a digital meter provided readout of the torque transducer. To determine an accurate comparison between the motors, the testing was accomplished in the same room, with the same load, generator and meters; and the same ambient temperature (24.8°C). During the testing, the motors were run until they were thermally stable. Temperatures rose in the motors over time. The fan-end ran cooler and the shaft-end ran warmer, and both motors performed according to the manufacturer's instructions.

Of the two motors chosen for the testing, one was left unpotted and one was encapsulated with CoolTherm SC-320 silicone encapsulant. For the potted motor testing, CoolTherm SC-320 resin was mixed with CoolTherm SC-320 hardener. In this work, the CoolTherm SC-320 silicone encapsulant was poured into the motor, although the encapsulant can be applied with handheld cartridges or automatic meter/mix/dispense equipment. A vacuum was used to minimize air bubbles. The encapsulant was allowed to cure for 24 hours at room temperature. It can also be cured faster at 125°C for 60 minutes. After curing, the insert was removed and the air gap cleaned. During the encapsulation process, workers at Advanced MotorTech found that CoolTherm SC-320 encapsulant exhibited none of the "strong" odor or "eye-irritating" fumes commonly noticed in other epoxy compounds.

The same load conditions were used for the potted vs. unpotted motors – a full-load test (100% torque). Testing results showed that the average overall temperature was 7°C cooler with the potted motor (54°C compared to 61°C for the unpotted control motor). The temperature difference between the fan and drive sides was only 3°C compared to 5°C to 6°C for the unpotted motor. Therefore, the potted motor, encapsulated with CoolTherm SC-320 encapsulant, ran cooler than the unpotted motor. (Figures 1 and 2)

Both motors were also tested at overload conditions (164% and 174% rated torque) to determine the thermal effects under extreme conditions. The potted motor averaged 30°C cooler than the unpotted motor at the highest torque. This is a significant difference, and could lead to a projected eight-time longer dielectric life. The temperature difference between the drive and fan sides was less in the potted motor (ΔT = 9°C compared to 16°C for potted compared to unpotted motors, respectively).

The potted compared to the unpotted motors also exhibited a dramatic difference in skin temperatures. Testing showed that, while the average skin temperatures were about the same, the potted motor had only an 8°C difference between the hottest and coldest spots, whereas the unpotted motor had a 20°C difference. Thus, there was a more even distribution of skin temperature

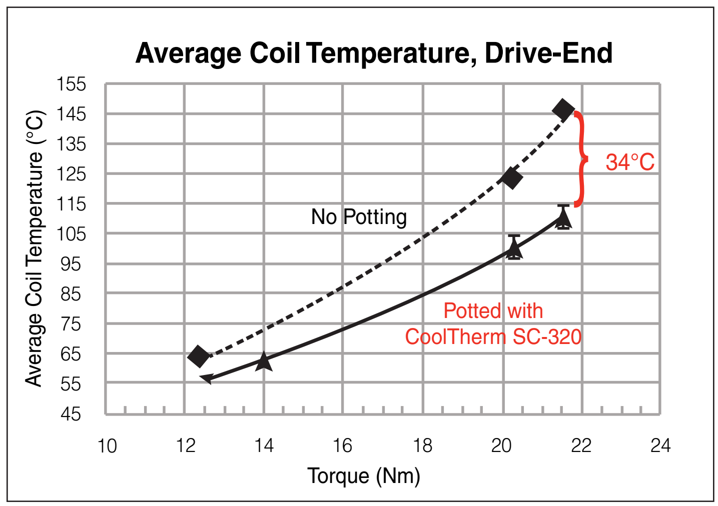


Figure 1: Average Coil Temperature – Drive-End

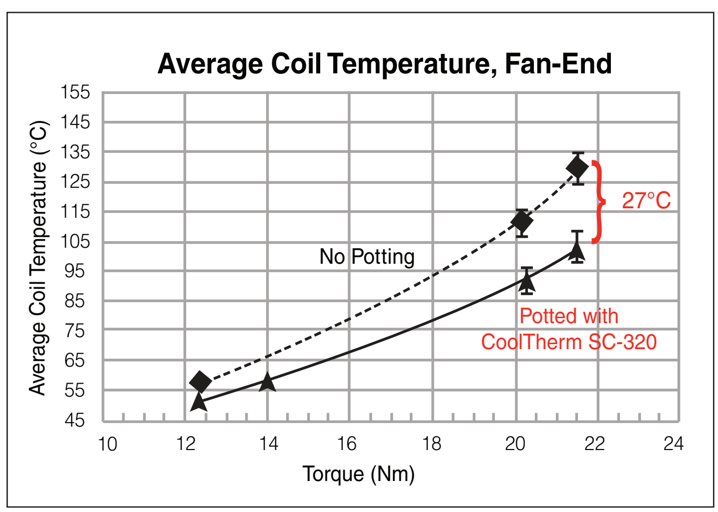


Figure 2: Average Coil Temperature – Fan-End

in the potted motor. This can be attributed to the air-gap-filling properties of the silicone resin. CoolTherm SC-320 encapsulant evenly and smoothly fills in all air gaps around the end windings. This results in even differential temperatures around the motor's frame, and helps to mitigate any stress and performance issues that might be created as the motor operates.

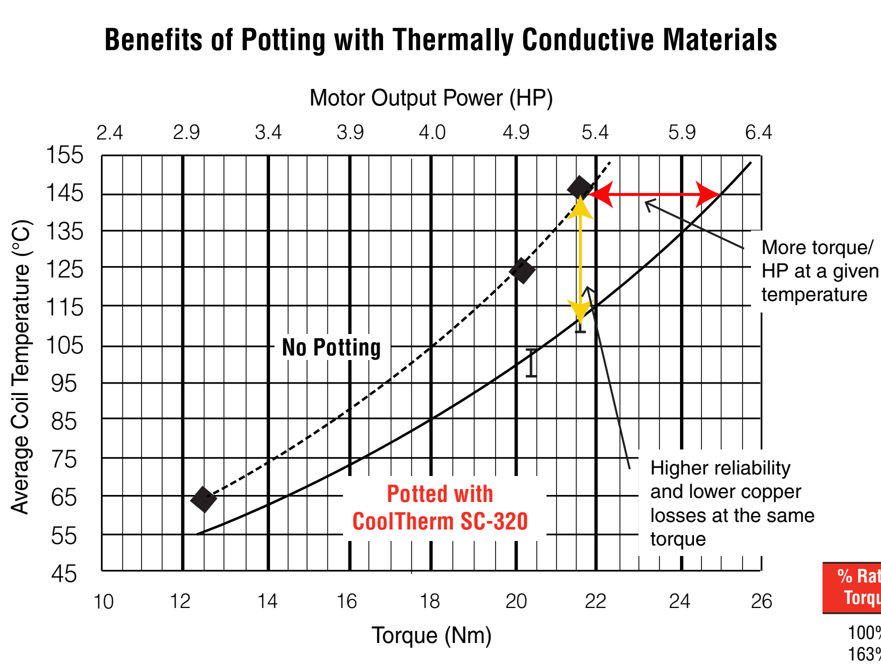
CONCLUSION

The results of testing both at LORD Corporation and at KTH clearly show the benefits of potting with thermally conductive materials. Motors potted with CoolTherm SC-320 encapsulant offer more torque and horsepower at a given temperature and should provide higher reliability and lower copper losses at the same torque (Figure 3). The tests demonstrated a 30°C difference at the highest applied torque and load, and an improvement in copper losses of about 10%. Alternatively, at the same highest temperature, there was a 16% improvement in torque with the potted motor.

Developed to provide exceptional thermal conductivity for electrical/electronic encapsulating, CoolTherm SC-320 encapsulant also retains the desirable properties associated with silicones. The low-viscosity encapsulant provides better flow-ability while reducing the risk of air entrapment. It is designed with lower durometer to reduce mechanical stress on electronic components and lower the probability of failure. Its low coefficient of thermal expansion results in lower stresses due to temperature change.

Possible applications for CoolTherm SC-320 encapsulant include those in which higher power at lighter weight is needed, such as motors for electric vehicles; aerospace actuators and motors; and portable power generation equipment. Better thermal management in electric motors can reduce the current, and therefore, the energy required to provide the necessary power; and can also extend a motor's lifetime. Cost savings may also be possible due to the reduced amount of copper wire required for the motor windings. Thus, savings in weight, energy, and/or cost may all be possible depending on the application.

LORD Corporation is continuing to collaborate with development partners to verify the benefits of using high thermal conductivity materials in motor potting applications. These benefits include: higher power densities - reduced copper and steel weight via thermal potting material; improved reliability – substantially lower operating temperatures and elimination of hot spots; and improved efficiency.



% Rated Torque	% Improvement in copper loss
100%	2.7%
163%	6.6%
174%	10.2%

Figure 3: Benefits of Potting with Thermally Conductive Materials (CoolTherm SC-320 encapsulant)

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