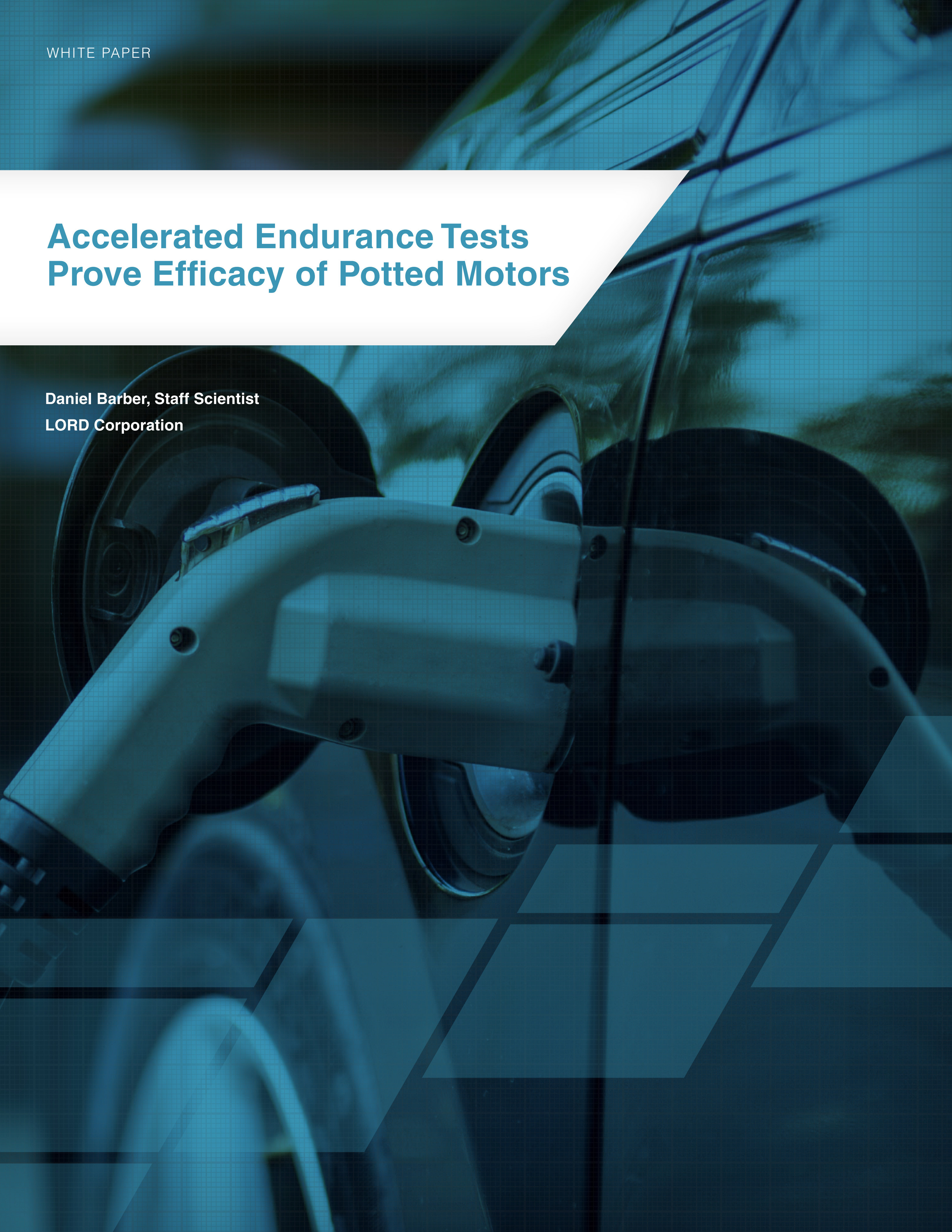


WHITE PAPER

Accelerated Endurance Tests Prove Efficacy of Potted Motors

Daniel Barber, Staff Scientist

LORD Corporation

Accelerated Endurance Tests Prove Efficacy of Potted Motors

ABSTRACT

For years, motor designers have been battling heat in motor designs. Thermal losses in electric machines rob motion systems of power and degrade efficiency, while excess heat can reduce the 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. Earlier research showed that 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. Further research has revealed significant decreases in operating temperature that correlate to higher motor efficiency and double-digit increases in output power when using a high thermal conductivity epoxy. Additionally, these motors are highly resistant to cracking during severe thermal cycling, paving the way for designing long-lasting, thermally efficient motors that can achieve more power/torque at smaller sizes.

INTRODUCTION

LORD CoolTherm™ SC-320 Thermally Conductive Silicone Encapsulant was developed over a decade ago by LORD Corporation — a leading supplier of thermal management, potting and encapsulation materials to the electronics industry — in response to market needs in a variety of industries for high thermal conductivity silicones with low viscosity. Specially designed to provide greater thermal conductivity for electrical/electronic encapsulating applications, the benefits of this long-established material have, in recent years, been proven by automotive end users.

This electrically insulating silicone encapsulant is a relatively soft, high thermal conductivity material (3.2 W/m·K) with sufficiently low viscosity for use in vacuum potting. It is a two-component system designed to retain the desirable properties associated with silicones. Environmentally resistant and UL-rated to UL94V0 and 180°C RTI, CoolTherm SC-320 encapsulant is composed of an addition-curing polydimethylsiloxane polymer that will not depolymerize when heated in confined spaces. It exhibits low shrinkage and stress on components as it cures and maintains a low viscosity for ease of component encapsulation (as compared with other high thermal conductivity materials).

Possible applications for CoolTherm SC-320 encapsulant include those in which higher power at lighter weight is needed, such as motors and on-board chargers for electric vehicles; aerospace actuators, generators and power electronics; 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. It also can allow for a longer motor lifetime. Cost savings because of the reduced amount of copper wire required for the motor windings may also be possible. Thus, savings in weight, energy and/or cost may all be possible depending on the application.

EARLIER RESEARCH

From 2009 through 2013, Shafigh Nategh — a graduate student at KTH School of Electrical Engineering in Stockholm, Sweden — conducted groundbreaking research on the thermal management aspects of electric machinery in high-performance applications, with particular focus on electric motors designed for hybrid electric vehicle applications. Nategh's findings ascertained that hot spot temperatures can be reduced by 35 to 50°C when using a thermally conductive material rather than no potting materials at all. The study also found that typical epoxy potting materials, which contain an organic filler to lower the CTE (coefficient of thermal expansion) but not specifically designed for thermal conductivity, provide only 20 to 30°C improvements over unpotted motors.

Nategh used CoolTherm SC-320 encapsulant as the thermally conductive material in his research, demonstrating that the encapsulant can provide significant improvements in the power density of electric motors. The decrease in hot spot temperature, depending on current, can provide:

- An increase in achievable power/torque for a given motor size.
- A decrease in motor size for the required power/torque.
- Longer operation of the motor before reaching its temperature limit.

Nategh's 2013 Ph.D. dissertation, titled "Thermal Analysis and Management of High-Performance Electrical Machines," details the nearly five-year study. In the first part of his 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. An oil-cooled induction motor where the oil was in direct contact with the stator laminations and a permanent magnet-assisted synchronous reluctance machine (PMaSRM) equipped with a housing water jacket were evaluated.

The second part of the thesis evaluated the thermal impact of using different winding impregnation and steel lamination materials. Conventional varnish, epoxy and a silicone-based thermally conductive impregnation material (CoolTherm SC-320 encapsulant) were investigated, and the resulting temperature distributions in three small induction motors were compared.

In comparing the effects of various impregnation materials, Nategh evaluated the hot spot temperatures of the windings while 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 to 45°C cooler than the varnish-only motor, and about 12 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 encapsulant 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 when the potting density was decreased from 80% to 50%, whereas the hot spot temperatures of epoxy- and varnish-potted motors increased by 19 and 25°C, respectively, when their potting densities were lowered from 80% to 50%.

To verify these results in a more conventional motor, LORD conducted initial studies on industrial induction motors (3 horsepower [hp], totally-enclosed fan-cooled motors) both as-received and potted with CoolTherm SC-320 encapsulant, in collaboration with Keith Klontz, Ph.D., and his team at Advanced MotorTech in St. Petersburg, FL. Results showed that the motors impregnated with the thermally conductive material, CoolTherm SC-320 encapsulant, were 35°C lower as compared to the unpotted motor, using only convection to cool the outer housing. LORD presented the results in the following venues:

– https://chargedevs.com/motor-power-density-whitepaper-download/

– IEEE International Electric Machines & Drives Conference (IEMDC), May 10-13, 2015, Coeur d'Alene, Idaho

– IEEE Electrical Manufacturing & Coil Winding Expo (EMCW 2015), May 13, 2015, Milwaukee, Wis.

– H. Li, K. W. Klontz, V. E. Ferrell, D. E. Barber, IEEE Transactions on Industry Applications, 2017, 53(2), 1063-1069.

The work above verified the key benefits that thermally conductive materials like CoolTherm SC-320 encapsulant can provide to electric motor designers: increased horsepower, longer lifetime and higher efficiency. LORD has continued to develop materials, verify thermal and thermal cycling performance, and identify early adopters for the technology.

NEW FINDINGS

The performance studies were extended to epoxy materials — including a LORD prototype epoxy with 3.5 W/m·K conductivity and high thermal stability that has now been commercialized as LORD CoolTherm EP-3500 Thermally Conductive Epoxy Encapsulant — and two competitor epoxies. In addition, to assess the impact of potting on the motor lifetime, LORD completed accelerated aging tests that included thermal cycling between room temperature and temperatures greater than 200°C.

Performance Testing

LORD extended the work with Advanced MotorTech to include additional potted motors of the same type as the previous work (3-hp NEMA Premium Efficiency, thermal Class F industrial electric motors): one unpotted and three potted with various materials. Before potting, each motor stator was fitted with six thermocouples on each end of the windings (two per phase). Reported temperatures were the calculated average of the thermocouple readings. The epoxy materials used for potting the stators were CoolTherm EP-3500 encapsulant (3.5 W/m·K epoxy); a competitor epoxy (Competitor 1) with thermal conductivity of 1.2 W/m·K; and a second competitor (Competitor 2) whose technical data sheet claimed a thermal conductivity of 4 W/m·K but had an actual bulk conductivity of 1.6 W/m·K as measured by LORD.

All motors were tested at rated speed (1750 RPM) and various values of output power (100%, about 160%, and about 174% of rated power) and operated continuously until the temperature stabilized (generally about two hours). Detailed methodology was described in our previous white paper and publication describing initial results with CoolTherm SC-320 encapsulant. End winding temperatures at 174% of rated torque are shown in Figure 1 and correlate with the bulk thermal conductivity of the various materials. Temperatures with CoolTherm EP-3500 encapsulant were 10 to 15°C lower than competitors and about 30°C lower than the unpotted motor, verifying our previous results.

Accelerated Aging Tests

These same four motors were then sent to the Motors and Drives Test Laboratory at Advanced Energy in Raleigh, NC for accelerated aging tests. The goal was to cause the motors to fail in a relatively short amount of time, so the motors were pushed beyond typical thermal limits. The Class F motors, which have a 155°C maximum temperature, were forced to operate well above this temperature, exceeding 200°C during much of the test.

Test conditions were adjusted so that the Competitor 1 motor would reach a predetermined target end winding temperature; the other motors were operated under identical conditions and their resulting temperatures measured. All motors were operated well above the 155°C temperature limit for this motor type. The Competitor 1 motor temperature was increased weekly to a final temperature of 240°C.

The test protocol included more than 400 starts per hour with high torque, low speed and short cycle durations, so the inrush current would heat the motors to their equilibrium temperatures. The on-cycle time for each bank of motors was 2.7 seconds and remained fixed throughout testing. Adjustments to the starts per hour

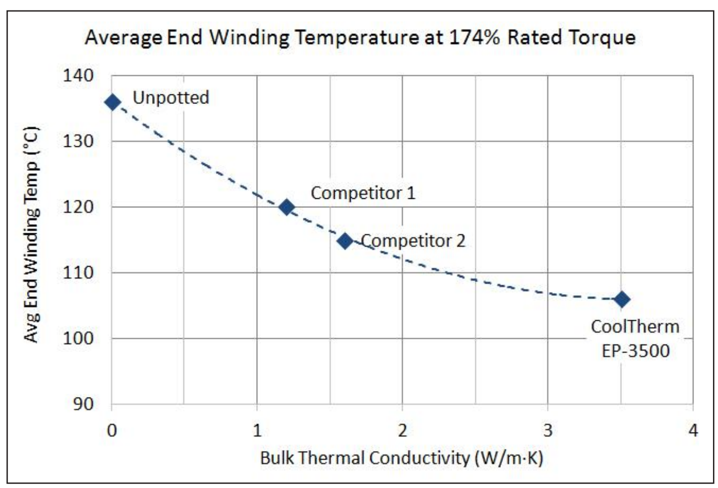


Figure 1: Average End Winding Temperature at 174% Rated Torque

were made only by varying the duration of the off-cycle time, which allowed the motors to reach and sustain stator temperatures well above their insulation class rating. Motor temperature, ambient temperature and total cycles were recorded every 10 seconds throughout testing.

The motors operated six to eight hours per day during business hours (8 a.m.- 5 p.m.) and then cooled to room temperature overnight. The cycle was then repeated for 25 days, providing additional information on thermal cycling stability. Every five days, the target temperature was increased. The initial target temperature was 155°C (Class F), then Class H (180°C), and then the temperature was increased weekly by 20°C increments until the motors failed. The test was administered without any attempt to actively cool the motors externally, relying instead on natural convection. Testing began Jan. 15, 2016, and tests were run daily (excluding weekends) until all motors had failed.

Substantial improvements in motor performance were observed due to a decrease in average winding temperature when using high thermal conductivity potting material. A correlation was observed between the average end winding temperature and the use of a thermally conductive material, particularly at higher horsepower. The unpotted motor consistently ran 25°C hotter than the competitor motors. The motor potted with CoolTherm EP-3500 encapsulant operated up to 20°C cooler than the competitor motors and 40 to 45°C cooler than the unpotted motor. Average end winding temperatures by day are shown in Figure 2, and the differences in motor temperatures versus the unpotted motor are shown in Figure 3.

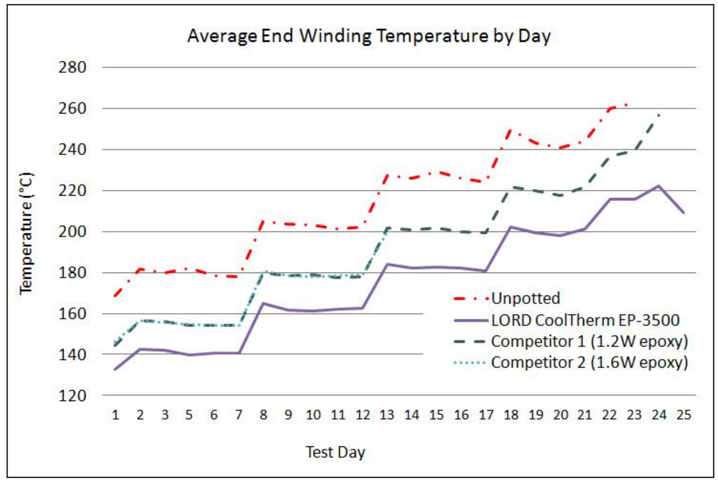


Figure 2: Average End Winding Temperature by Day

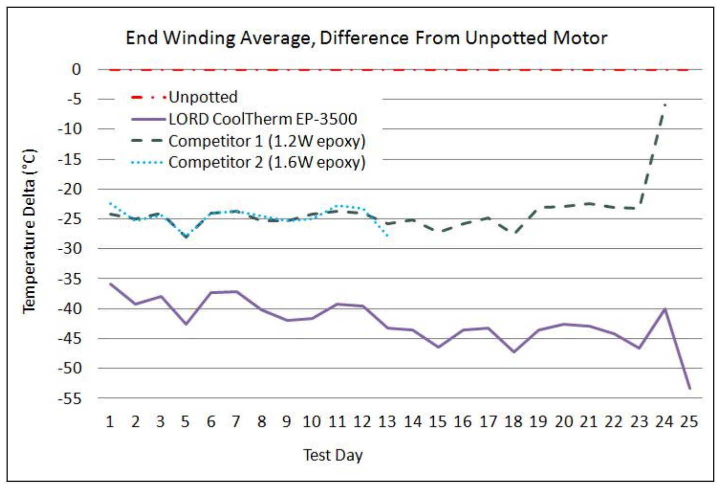


Figure 3: End Winding Average - Difference from Unpotted Motor

The motor with Competitor 2 epoxy failed first on Test Day 13, and Competitor 1 failed on Test Day 24. Both competitor epoxies had multiple large stress cracks through the bulk of the epoxy. The motor with CoolTherm EP-3500 encapsulant survived longest in the aging study and had no stress cracks, which we attribute to its high glass transition temperature (Tg) of 206°C. Figure 4 compares the post-test appearance of the Competitor 1 and CoolTherm EP-3500 encapsulant stators showing the difference in crack behavior.

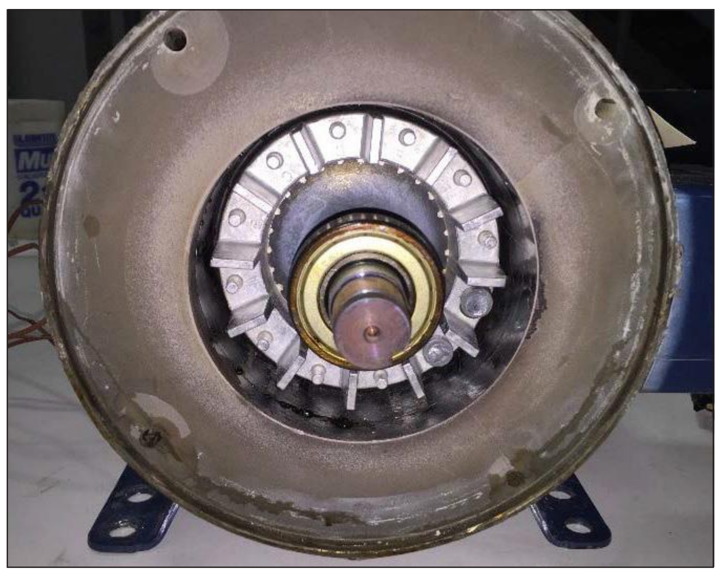
LORD is also finalizing the data related to motor failures. Preliminary results validate that in all potted motors, a black material was found to have collected in the air gap and eventually caused rotors to seize. The unpotted motor contained evidence of a black decomposed material, but the material did not cause the rotor to seize; this motor failed on Day 24 due to an electrical short. The motor with Competitor 2 epoxy failed due to a lead wire short and a seized rotor, while Competitor 1 and the CoolTherm EP-3500 encapsulant motors failed due to seized rotors with no electrical short. The presence of the black material in all motors makes it likely that this is due to decomposed varnish or another material common to all motors.

END-USER EXPERIENCES

In addition to extensive laboratory testing, LORD has already completed in-the-field tests with end users. Depending upon the configuration, improvements of between 20 and 30% in maximum power output at the same peak temperature have been achieved. In addition, temperature reductions of up to 40°C have been observed in customer motors using CoolTherm EP-3500 encapsulant, greatly improving both motor efficiency and lifetime.

LORD has also commercialized another epoxy, LORD CoolTherm EP-2000 Thermally Conductive Epoxy Encapsulant, to address the customer need for a thermally conductive, low-viscosity material that can penetrate into tight windings and/or between fine wires. This material has the same high temperature stability as CoolTherm EP-3500 encapsulant but a lower thermal conductivity of about 2 W/m·K. In customer testing, CoolTherm EP-2000 encapsulant has provided more than 20°C lower temperature, as well has high-temperature and high-pressure stability.

Motor Stator Potted with Competitor 1



Motor Stator Potted with CoolTherm EP-3500 Encapsulant

Figure 4: Post-test Appearance - Crack Behavior Comparison between Competitor 1 and CoolTherm EP-3500 Encapsulant

SUMMARY AND CONCLUSION

The latest tests confirm what Shafigh Nategh, now a Ph.D., reported in 2013: Motors potted with thermally conductive materials can achieve better performance than unpotted or epoxy-potted motors. Our studies show that:

- Hot spot temperatures of motors impregnated with high thermal conductivity materials are generally 40 to 45°C cooler than a varnish-only motor and about 20°C cooler than a motor potted with a standard epoxy .
- During accelerated age testing, motors potted with CoolTherm EP-3500 encapsulant lasted the longest and exhibited no stress cracks in the potting material.

The decrease in hot spot temperature, depending on current, can enable motor designers to:

- Increase achievable power/torque for a given motor size.
- Decrease the motor size for the required power/ torque.
- Greatly increased the lifetimes of motors by decreasing the operating temperatures.

Integrating the LORD solution during the design phase is ideal, as the motor can be designed to maximize ease of potting and take full advantage of the high thermal conductivity of the potting material.

For more information, visit www.LORD.com/CoolTherm or http://ieeexplore.ieee.org/document/7790847/

LORD provides valuable expertise in adhesives and coatings, vibration and motion control, and magnetically responsive technologies. Our people work in collaboration with our customers to help them increase the value of their products. Innovative and responsive in an ever-changing marketplace, we are focused on providing solutions for our customers worldwide ... Ask Us How.

LORD Corporation
World Headquarters
111 Lord Drive
Cary, NC 27511-7923
USA

Customer Support Center (in United States & Canada)
+1 877 ASK LORD (275 5673)

www.lord.com

For a listing of our worldwide locations, visit LORD.com.

Ask Us How™