Thermally Conductive Potting Compounds Enable Higher Power Density Electronics

White Paper

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Thermally Conductive Potting Compounds Enable Higher Power Density Electronics

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Abstract

A key challenge in developing higher power density electronics for electric vehicles and other applications is to manage the heat generated by smaller, high-power devices, such as on-board battery chargers, power inverters and converters, and electric machines. Thermally conductive potting compounds are proving to be an ideal method for rapidly and effectively conducting heat away from power components to the heat sink. In this study, we examine the heat rise of inductors potted in a liquid-cooled aluminum fixture using Parker Lord silicone potting materials with thermal conductivities ranging from 0.1 to 4.0 W/m·K. Comparing an inductor potted with an insulating material (0.1 W/m·K) to the most conductive material (4.0 W/m·K), the heat rise is decreased by about 50°C, and the time required to reach a stable temperature is decreased from nearly two hours to about 15 minutes. These significant improvements in heat management enable the development of dramatically smaller power electronics, saving weight, space, and cost.

Introduction

Currently, there is a strong trend toward the electrification of vehicles in the transportation industry, including automobiles, buses, trains, off-road vehicles, watercraft, and aircraft. Long ranges and/or high horsepower require high power density from their electrical components such as batteries, motors and generators, and the power electronics needed for operation. The trend is towards smaller, lighter, and less expensive components that will save space and reduce costs while boosting power efficiency.

One key challenge in developing these types of components is to manage the heat generated by smaller, high-power devices like on-board battery chargers, power inverters and converters, and electric machines. Thermally conductive potting compounds are proving to be an ideal method for rapidly and effectively conducting heat away from power components to the heat sink. The potting compound fills the component enclosure entirely, leaving no air gaps. As a result, heat is dissipated within the enclosure and rapidly conducted to the heat sink, which has enabled substantial size and weight reductions of the finished component.

Parker Lord has been supplying thermally conductive, electrically insulating potting materials to the power electronics industry for over a decade, and recently, we have been testing the effectiveness of using potting compounds with high thermal conductivity to dissipate heat in high-power applications. For example, we have demonstrated substantial temperature reductions and improved power output using CoolTherm® SC-320 Thermally Conductive Silicone Encapsulant to pot the end windings of electric motors. (For more information on this topic please access our white paper, "How Proper Application of Thermally Conductive Materials Will Improve Motor Power Density"). In this white paper, we present the results of another study on the ability of Parker Lord thermally conductive silicone materials to rapidly and effectively remove heat from high-power inductors.

Potting Materials Used in the Study

Five different Parker Lord silicone potting materials were used in this study. All of the materials are electrically insulating with high dielectric strength and excellent high-temperature stability. Thermoset® SC-400 Silicone Encapsulant is a clear, soft gel with low thermal conductivity (0.1 W/m·K) used for potting sensitive electronics where high dielectric strength and very low mechanical stress are desired.

CoolTherm SC-305, SC-309, SC-320, and SC-324 Thermally Conductive Silicone Encapsulant are filled silicone potting materials with progressively higher thermal conductivities of 0.7, 1.0, 3.0, and 4.0 W/m·K, respectively. These materials are currently being used in numerous applications to protect sensitive electronic components from excess heat, including LED driver electronics, on-board chargers and inverters for electric vehicles, and electric motor stators.

A key differentiating property of Parker Lord thermally conductive silicone materials is their low viscosity compared to competitor materials with similar thermal conductivity. The lower viscosity allows Parker Lord materials to flow and fill voids more readily while providing excellent thermal conductivity. They are also easier to degas, meaning that parts can be potted that are essentially void-free if a vacuum potting process is used. Figure 1 shows thermal conductivity versus viscosity of Parker Lord silicone materials as compared to various competitor products. Technical data sheets for all commercial products can be found at www.parker.com.

Inductor Potting and Testing

The inductors used in this study were made from Micrometals T400-61D high-temperature, magnetic-powder toroid cores wrapped with 62 turns of 10-gauge insulated copper wire, which yield about 500 μH inductance at load. Inductors were potted in custom-made aluminum cooling plates fitted with liquid inlet and outlet ports for connection to an external circulating fluid bath. The five different materials were used to pot three inductors with each material, resulting in a total of 15 potted inductors. One set of potted inductors is shown in Figure 2. Before potting, each inductor was fitted with a thermocouple to measure its temperature during the test. (See Figure 3.)

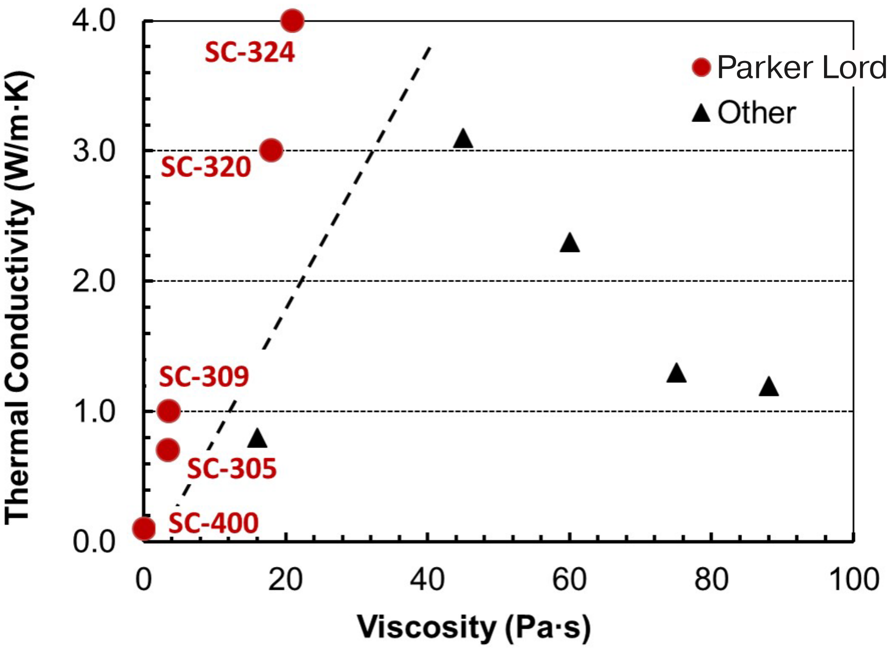

Figure 1: Thermal conductivity versus viscosity for various potting materials. Commercially-available Parker Lord materials are indicated as red circles.

Figure 2: Inductors potted in aluminum cooling plates with each of the Parker Lord potting materials.

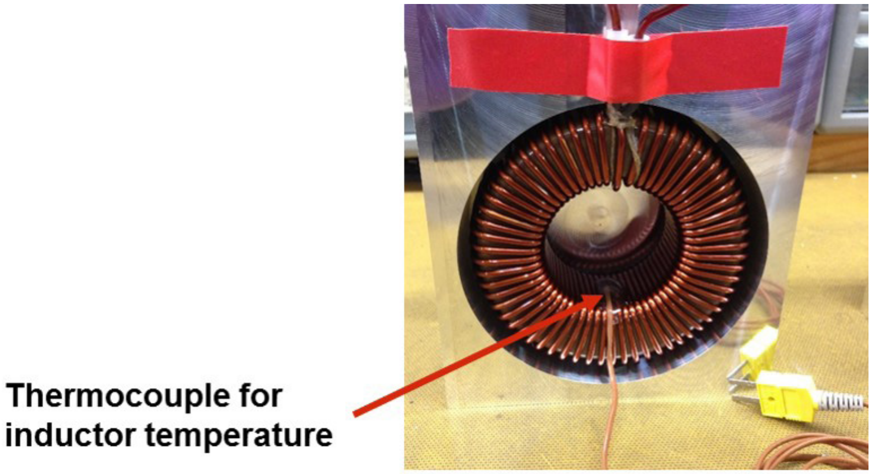

Figure 3: Detail showing the thermocouple location on the inductor, on the inner edge of the toroid opposite the wire leads.

The location of the thermocouple corresponds to the hottest location in the inductor as judged qualitatively from a thermal camera image of an unpotted inductor under load.

For the thermal tests, each inductor was connected to a Manzanita Micro PFC40X-188 charger passing 9.3 kW and 40 A at 240V input with 0.98 power factor. Power at the inductor was 30W. The aluminum cooling plate was connected to a temperature-controlled liquid bath; each inductor was tested at coolant temperature set points of 25°C, and the typical automotive coolant temperature of 50°C. A second thermocouple was attached to the exterior of the cooling plate to monitor temperature changes during the test; however, the temperature rise of the cooling plate was less than 2°C even in the most extreme cases and, accordingly, will not be considered further. The complete set-up is shown in Figure 4.

During each thermal test, the temperatures of the inductor and cooling plate were recorded using an Omega Soft data logger. The cooling plate and inductor temperatures were allowed to stabilize with no power. Power was then applied, and the temperature was monitored until the inductor temperature stabilized. The equilibration time was chosen at the point when the temperature reached steady state (no further temperature increase took place), and the reported temperature rise was calculated as the final temperature of the inductor minus the initial temperature. Figure 5 shows a representative plot for an inductor potted with Thermoset SC-400 encapsulant with the parameters indicated.

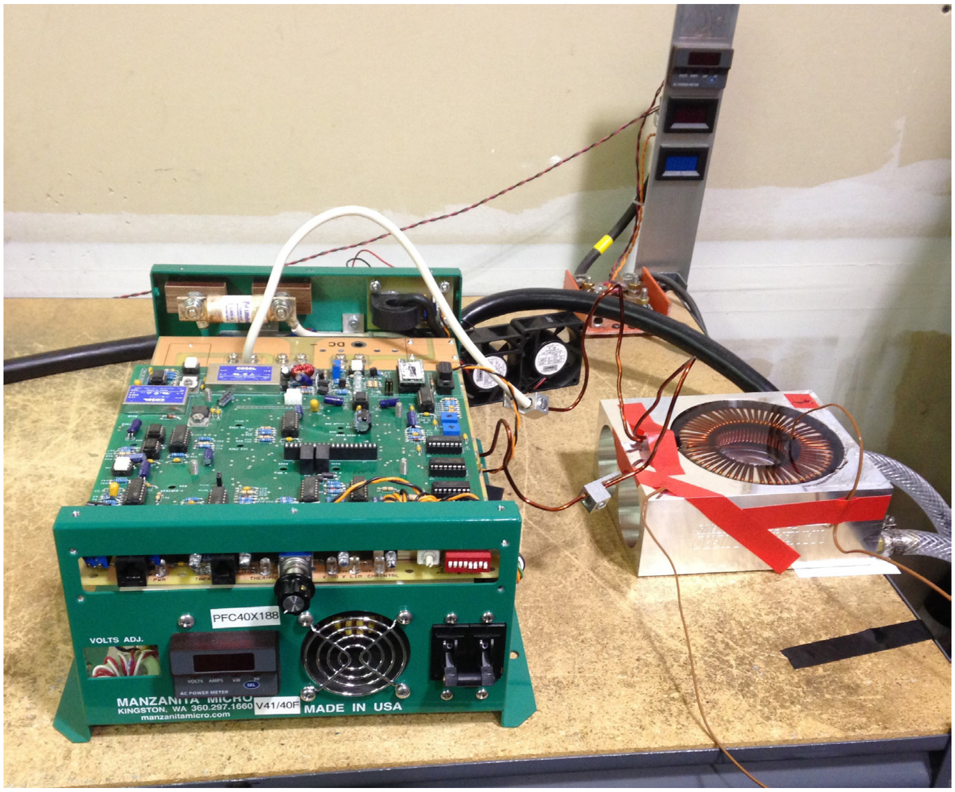

Figure 4: Test set-up for one inductor potted with Thermost SC-400 encapsulant showing the PFC40X-188 charger on the left, the potted inductor on the right, and the coolant inlet and outlet lines at the far right.

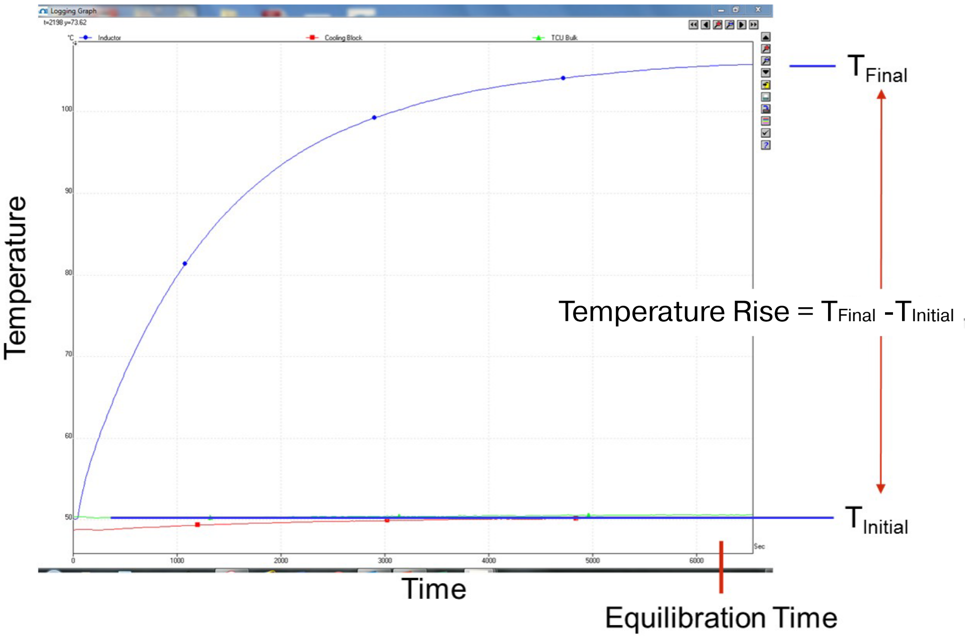

Figure 5: Temperature profile for a typical Thermoset SC-400 encapsulant potted inductor test, showing definitions of temperature rise and equilibration time. The blue line is the inductor, and the nearly-horizontal red line is the cooling plate.

Results of the Study

Each of the 15 inductors were tested at least one time, and several of the inductors were tested multiple times to determine repeatability. The average temperature rise and equilibration time data are summarized in Figures 6 and 7. Error bars are plus and minus one standard deviation of the data, which includes part-to-part variation and repeatability.

The data show that both the inductor temperature rise and the equilibration time are independent of the coolant temperature, as the data at 25°C and 50°C are nearly superimposable and within the test variation. It is important to note that the variation becomes much smaller as the thermal conductivity increases due to the more effective thermal connection to the aluminum cooling plate.

Dramatic reductions in both temperature rise and equilibration time are observed for inductors potted with thermally conductive materials. (See Figure 6.) The average temperature rise with Thermoset SC-400 encapsulant was about 55°C, and the average rise for the most thermally conductive materials, CoolTherm SC-320 and SC-324 encapsulants, was less than 10°C. Even the moderately conductive silicones, CoolTherm SC-305 and SC-309 encapsulants at 0.7 and 1.0 W/m·K, respectively, provided significant improvements. Under different test conditions that would generate a temperature rise much greater than 55°C, it is likely that the improvement would be even more pronounced.

Similarly, the equilibration time was also dramatically reduced with the higher thermally conductive materials. (See Figure 7.) With the non-conductive silicone, Thermoset SC-400 encapsulant, nearly two hours was required to reach steady state, whereas a stable temperature was achieved in less than 20 minutes for CoolTherm SC-320 and SC-324 encapsulants. This rapid temperature recovery means that heat is dissipated quickly and components will spend less time at elevated temperatures, thus increasing the lifetime of the components.

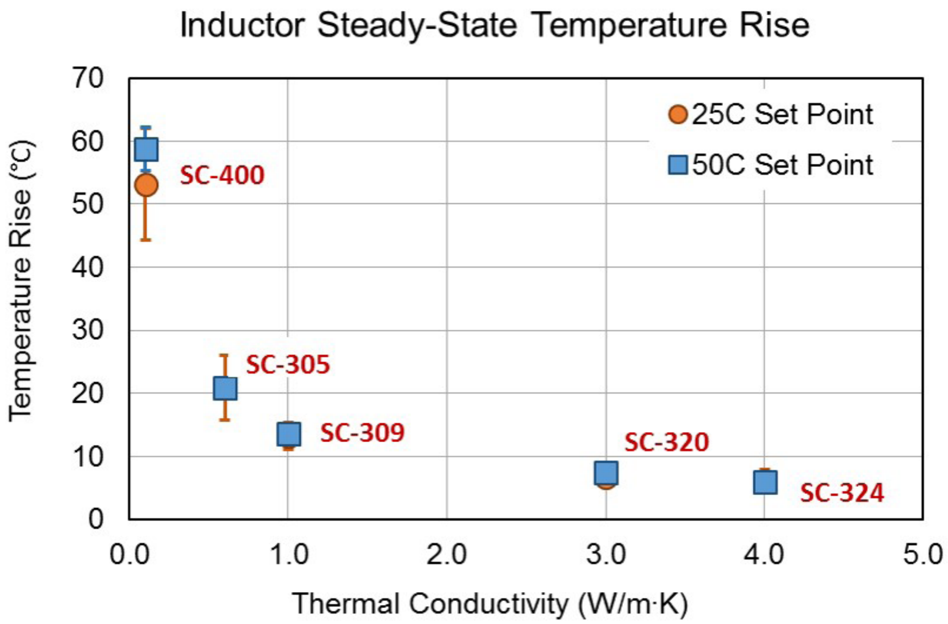

Figure 6: Average temperature rise for inductors in the study at both 25°C and 50°C set points of the liquid coolant.

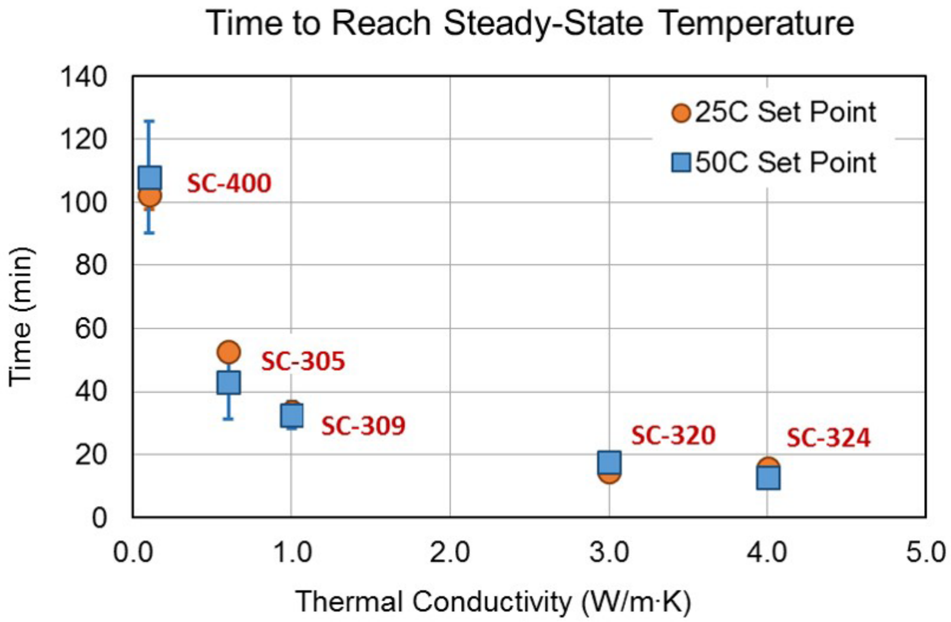

Figure 7: Average time to reach steady-state temperature (equilibration time) for inductors in the study at both 25°C and 50°C set points of the liquid coolant.

Conclusions

Proper thermal management is essential for developing power electronics that are smaller and lighter, and smaller and lighter means higher power density. Using Parker Lord thermal management materials that provide the unique combination of high thermal conductivity and low viscosity, we have demonstrated substantial reductions in both maximum temperature rise and the time to reach a stable temperature. Both of these benefits bring about improvements in efficiency and component lifetime, thereby enabling high-performance power electronics.

Acknowledgement

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