Selecting an encapsulant for an aerospace superconducting machine

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***Abstract*—Achieving larger benefits from electrified propulsion in single aisle aircraft (the largest commercial aircraft market segment) necessitates that a significant fraction of their 20 MW or greater propulsion system be electrified. 5 to possibly 20 of the MW-scale electric machines investigated by NASA would be required to meet this need. Approximately 10-20 of NASA's MW-scale electric machines would be required to reach the necessary power levels. Therefore, electric machines of 5 MW or greater are of interest. However, conventionally cooled high power density MW-scale electric machines still produce a significant amount of waste heat, which makes obtaining these power levels problematic. Highly efficient fully superconducting electric machines (or those with a cryogenically cooled, high purity copper or aluminum stator) are a possible solution but have multiple barriers to be overcome. One such barrier is the durability of superconducting windings. Superconductors are typically brittle, and encapsulants used to hold windings in place are a significant source of stress because of the mismatches in coefficient of thermal expansion at temperatures between room temperature and operational temperatures (20 to 77 K). These encapsulants also form a thermal barrier that can be detrimental to cooling the superconductors. This paper describes an initial study of commercially available encapsulants as it relates to superconducting machine applications along with initial modeling of thermal stress in superconducting windings for a superconducting or cryogenically cooled stator in a 5 MW electric machine.**

Keywords—electrified aircraft propulsion, EAP, superconducting, cryogenic, electric machine, motor, materials, epoxy, thermal modeling

I. INTRODUCTION

Electrified aircraft propulsion (EAP) is the next evolution of aircraft propulsion. Single aisle aircraft (the largest commercial passenger carrying market segment) requires roughly 20 MW of prolusion. NASA has been significantly involved in development of highly efficient, specific power dense components aimed at this application. Although progress has been made in the 1 to 2 MW regime, realizing greater benefits from electrification requires 10 MW or greater for the single aisle aircraft propulsion systems [1, 2]. When considering this level of electrification, superconducting machines, with their very low losses, become an interesting option for this application [3-5]. NASA is actively investigating this technology by engaging in design of a 5 MW motor with a cryogenically cooled metallic or superconducting stator. Part of the effort will be building a subscale stator, requiring several technical challenges to be solved. One issue of specific interest is the thermal stress on the stator turns caused by encapsulants. Because vehicle motors inherently experience vibrations, encapsulating stator turns will be necessary and are common practice in electric machines. However, at cryogenic temperatures, the differential thermal contraction between encapsulants and conductors can be substantial, leading to high stress and strain. This loading is a significant consideration because it can delaminate or fracture superconductors, which are notoriously brittle, and damage or significantly increase the low-temperature resistivity of high purity metals. This is a well-known issue that has been studied for other superconducting applications [6-9]. This stress is known to cause delamination of one superconductor from its substrate [9]. Furthermore, the design of the coils also has impact on the stress in the windings. Overall, stress in the windings increases with the number of turns but decreases as the winding's radius increases [7]. Stress in the windings is also non-isotropic as these windings are oval in shape and may be flat or contain a saddle-like feature depending on design. Moreover, these encapsulants will also have a strong influence on heat removal from the stator coils, therefore showcasing the importance of maximizing the thermal conductivity of the material.

This paper contains an initial look at commercially available encapsulants along with the pros and cons of the different solutions offered. The paper will consider these through the lens of preliminary modeling that will be used to direct detailed motor design.

II. INVESTIGATIONS, RESULTS, AND DISCUSSION

A. Encapsulants

For these investigations, seven different epoxies were examined as potential encapsulants. One of the epoxies was examined with and without filler while another was examined in combination with a different catalyst that altered the curing times and temperature. Coatings of epoxy (~0.3 to 0.7 mm) were applied to thin plates of Al (0.42 mm thick) and Cu (1.53 and 0.26 mm thick). Prior to application, the metal surfaces were cleaned with isopropanol, sanded with 240 grit sandpaper and cleaned again with isopropanol. Epoxies were mixed, applied to the surfaces and cured according to manufacturer specifications.

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Samples were then cold soaked in liquid nitrogen (77 K) for 3 hr, then allowed to return to room temperature.

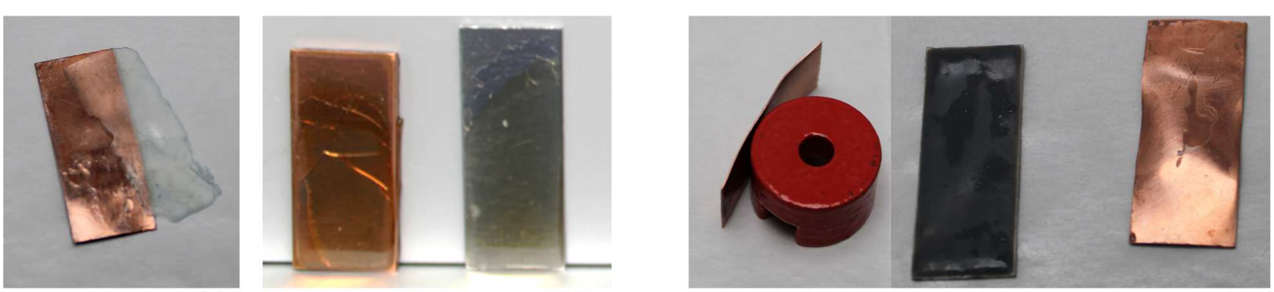
Three of the epoxies failed, Fig. 1, due to delamination, cracking and warping of the metal substrate. Warping of the substrate is considered undesirable, because it indicates stress induced on the substrate by the epoxy. One of the epoxies was tested in a filled and unfilled state; both variants caused the substrate to warp. The epoxies that did not fail are listed in Table 1 along with their viscosities (rheological analysis performed by parallel method), thermal conductivities (modified transient source plane method) and coefficients of thermal expansion (CTE, thermal machinal analysis). CTE is important as this characteristic will dictate stress as the material is cooled and heated. For simplicity at this time, the CTE of the epoxies are compared to Cu (16.6 ppm) [10] and Al (22.9 ppm) [10]. Viscosity is an important metric because it relates to how easily the epoxy can be used with a technique such as vacuum pressure impregnation [11] or other encapsulating methods that require the epoxy to flow into small spaces. Impregnation with an encapsulant is not only important to keep windings from moving relative to each other but also in terms of thermal properties of the system. Voids caused by higher viscosity, which limits impregnation, reduce the local thermal conductivity and create hotspots as a result and potentially cause other related electrical issues. In previous endeavors, viscosity during impregnation was kept under 1 kcp [11, 12].

Among all the kinds of epoxies, Epoxy 3 has the shortest shelf life, only 6 months while others have 1-year shelf life (important for staging the fabrication of complex parts). Epoxy 1a and 1b easily form crystals during storage and become hardened. When heated to 60 °C, Epoxy 1a and 1b become liquid again. Epoxy 2 shows the lowest viscosity at only 17 cp. During the viscosity testing using complex parallel plate rheometry, part B of Epoxy 3 can form a viscous layer around the testing plates higher measured viscosity (14 kcp—an artifact of our testing method). However, Epoxy 3 visually shows a much lower viscosity resembling the viscosity of motor oil (0.5 kcp), with a working time longer than 4 hr. Fillers in Epoxy 1a and 1b, and Epoxy 4 cause these to have higher viscosities than the unfilled epoxies. It was noticed that Epoxy 4 has the highest viscosity, and it was difficult to create a sample with a smooth surface.

Tensile testing was performed on the epoxies listed in Table 1, both at room temperature (~293 K) and at 123 K. The tests were carried out using a commercially available tensile testing device according to D638-14, "Standard Test Method for Tensile Properties of Plastics". ASTM D638-14 type IV dog bone samples were made in molds and sanded flat to be gripped by the tensile testing device. The tensile testing device was also outfitted with a sample chamber capable of maintaining a 123 K temperature for the test. Although the cryogenic temperature used for this testing is not the 20 to 77 K expected for the final application, the data is sufficient to continue down selection of the encapsulants as the environment will only become more challenging. This data also demonstrates the general trends that will need to be accounted for in the design process. During the preparation of dog bone samples for testing, Epoxy 1.b sample broke easily. As such, only one sample survived and was tested at cryogenic temperatures. One important note about the tensile testing: Due to the challenges of preparing dog bone samples of Epoxy 1, only one sample of Epoxy 1.b was tensile tested and Epoxy 1.b was only tested once at each temperature. For the other samples only two samples of each epoxy were tested at a particular temperature. Typical mechanical testing requires repeating the test at least five times for a particular sample type and condition. While this data set falls short of that standard, this data is useful for discussing trends and understanding the design space. More testing is currently underway to ensure the data is properly supported (including error estimation in calculated Youngs' modulus) before material decisions are made.

Tensile testing results (Fig. 2) show a wide range of characteristics. Testing results at 123 K of Epoxy 1a did not produce a well-behaved result, therefore a Young's modulus could not be determined for that specimen (see inset). Three of the 4 samples exhibited a modulus over 7000 MPa and displayed sharp failure points at 123 K. Epoxy 3, however, started with the lowest modulus of 126 MPa at R.T. and only increased to 161 MPa at 123 K. Although the ultimate tensile strength of Epoxy 3 is significantly lower than Epoxy 2 (11 vs. 90 MPa), Also, because Epoxy 3 has a smaller modulus and retains more of its flexibility, stress in the Epoxy 3-stator coils systems should also be considerably less.

From the tensile testing results, Epoxy 3 would seem to be the clear candidate, however there are a number of complicating factors. First, the CTE is 62% larger than that of Cu (~16 ppm) at R.T [13]. If this ratio stays constant to 60 K (Cu drops to ~4 ppm at 60) there might be significant stress in the system caused by the epoxy despite its low modulus. Second, Epoxy 3 is still relatively viscous that makes infiltrating Litz wire or other systems with small tight spaces difficult. There may be routes to



(a) (b) (c)

Fig. 1. Cryogenic-cycling adhesion testing failures. (a) delamination (b) cracking and (c) warping of the substate.

TABLE I. EPOXY PARAMETERS. PROPERTIES ARE EXPERIMENTALLY MEASURED. *ARTIFACTS OF VISCOSITY MEASUREMENT CAUSED THIS VALUE TO BE SIGNIFICANTLY HIGHER THAN THE MATERIAL VISUALLY BEHAVES (VISUALLY BEHAVES MORE LIKE MOTOR OIL ~0.5 KCP)

Epoxy	Filler	Viscosity (kcp)	Thermal Conductivity, W/m-K (R.T.)	Coeff. of Thermal Expansion (ppm/°C ±1.5/°C ppm, 153 K to R.T.)	Cure Temperatures (°C)
1.a (catalyst 1)	Al_2O_3+C	14	1.26±0.02	16	R.T./45/65
1.b (catalyst 2)	Al_2O_3+C	25	1..48±0.25	33	80/100/120
2	None	0.02	0.28±0.01	62	65
3	None	14*	0.34±0.04	26	R.T./65
4	Al_2O_3	890	1.42±0.01	34	R.T.

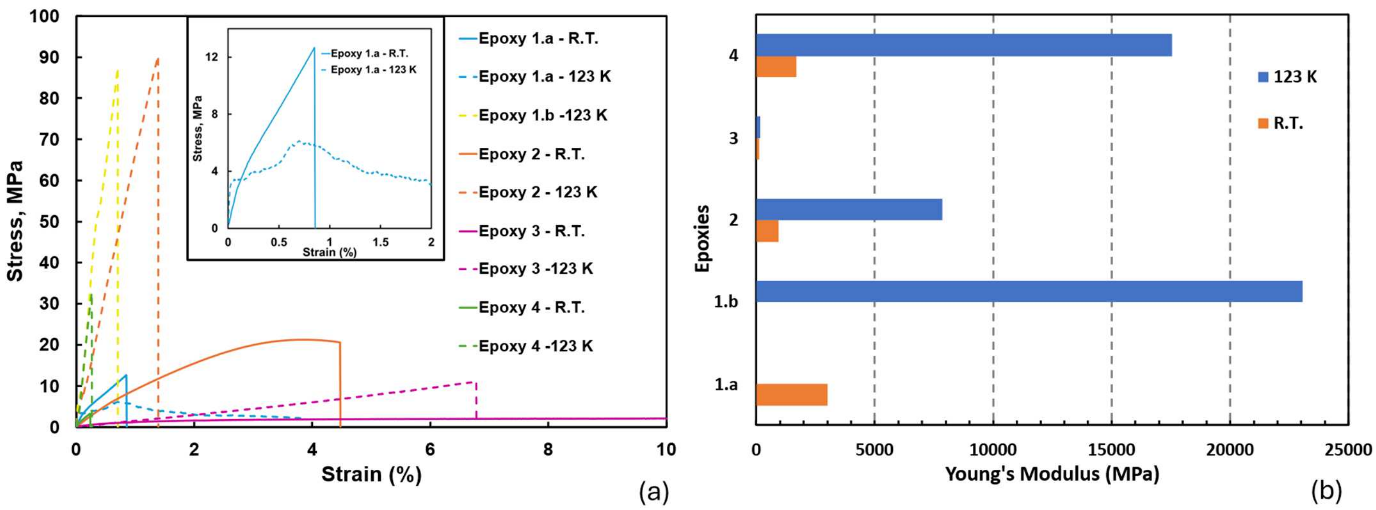


Fig. 2. Tensile testing of epoxy samples. (a) representative tensile testing (ASTM D638) results at R.T. and 123 K (engineering stress). (b) Young's Modulus as derived from tensile testing.

reducing this viscosity, but that will take experimentation and the impact to final cured epoxy will need to be assessed. Third, the thermal conductivity of Epoxy 3 is considerably lower than that of the filled epoxies. Fourth, although some of the epoxies were difficult to make bulk samples (dog bones) from, they will be applied in thin films in and around the windings and other structures. There is a significant difference in performance in this kind of application. Therefore, all the epoxies in Table 1 are currently being kept as candidates until more application like testing can be conducted.

B. Modeling

In a previous effort, a break-out conjugate computational fluid dynamics (CFD) model was created of a single slot of an oil cooled (60 °C) megawatt scale motor containing copper Litz wire [12]. The model was created to make rapid iterations of the model parameters for test data correlation. Since a new machine design is still in progress, this model is used here as an initial approximation. The purpose here is to understand the impact of thermal conductivity of the encapsulant on the system. Future iterations will need to include thermally-induced stresses and better reflect the machine designed to operate at cryogenic temperatures (e.g., no back iron in the cryogenic environment, radially thinner winding, and reduced heat generation in the winding).

For the purposes of this paper, the temperature dependent thermal conductivities of the material systems in the Litz wire were approximated from values found in literature [13-15] and the working fluid was changed to gaseous He at a temperature of 60 K. The modeled geometry is of two American wire gauge (AWG) 3 equivalent Type 8 Litz wires constructed of six thousand 40 AWG strands coated with a ~10 µm thick polyimide coating. Each slot was populated with two Litz wires in an up and down configuration. Fluid passes over the side of the Litz wire facing the rotor and then passes back again through the back iron (a laminated Co-Fe alloyed material) that surrounds the Litz wires on 3 sides. For more specifics on the model, including more detailed diagrams please refer to [12]. For the purposes of this effort, the model is started from a 60 K state as if the system had been precooled before operation. The model was run with 500 A of direct current (an approximation of the final conditions) passing through the Litz wire until thermal equilibrium was reached. This model does not account for alternating current losses the full motor will experience. Future models will need to properly account for all loss mechanisms.

Fig. 3 shows temperature of the modeled profile. The cool fluid flows in from the bottom right along the windings to the left, around the end windings and then over the back iron. Finally, the fluid emerges on the top right. The profile indicates that the fluid temperature increases to 93 K between inlet and outlet and most of that temperature increase happens after the fluid passes along the wires (53 K). This increase in helium temperature is more than the fluid temperate increase in the previous investigation (< 5 K when oil was used with an inlet temperature of 333 K). The drastic increase in fluid temperature decreases the effectiveness of the fluid to remove heat from the end turns furthest from the inlet, back iron and top side of the

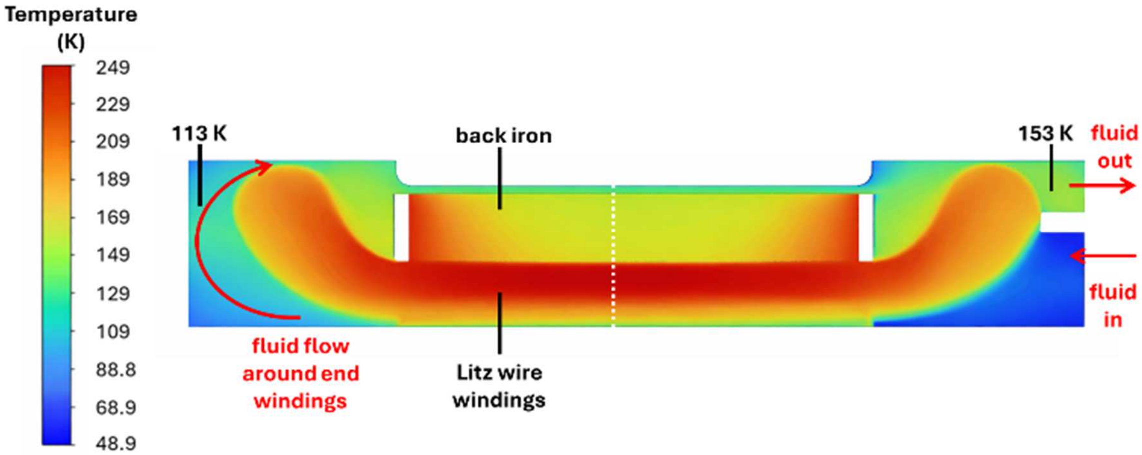


Fig. 3. Profile view of thermal model results for the thermal conductivity of the epoxy and wire insulation equal to 0.05 W/m-K.

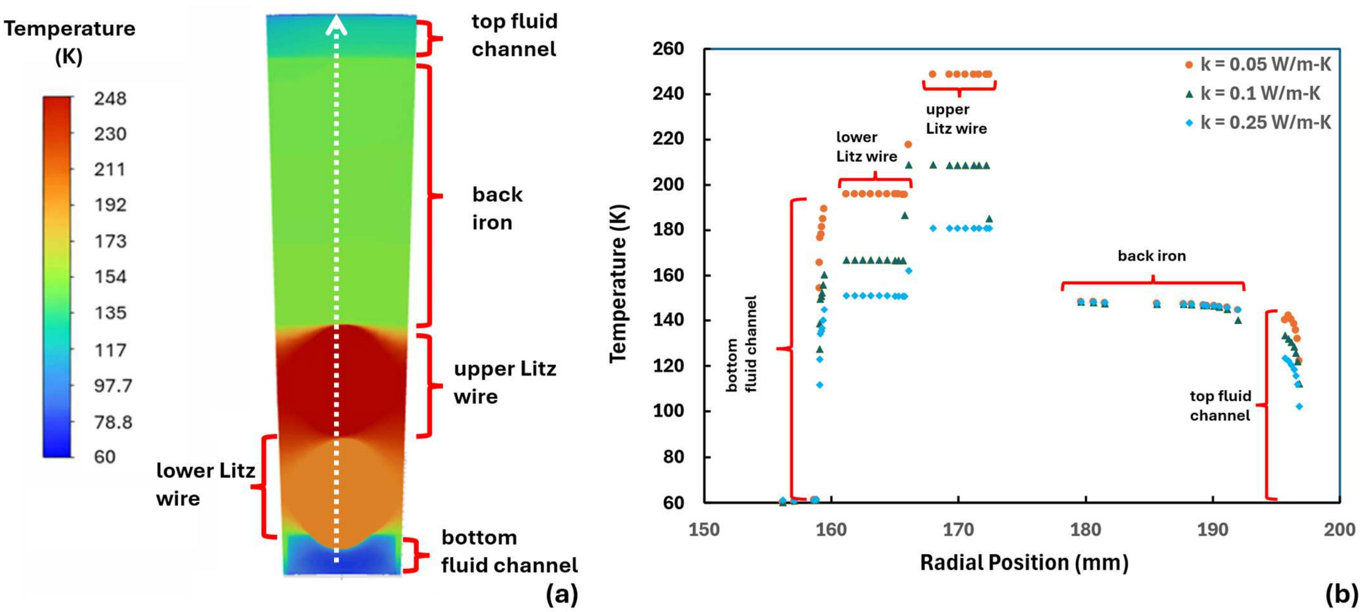


Fig. 4. (a) Cross section taken at dashed line in Fig. 3. (b) Temperature profiles taken along dashed line in (a) for thermal conductivities (k) set for both epoxy and wire insulation.

end turns nearest to the fluid outlet. Therefore, future designs will need to avoid such scenarios.

Fig. 4(a) show a representative cross section of the Litz wire with thermal conductivity of the encapsulant (epoxy) and wire insulation both set to 0.05 W/m-K. From the literature, this is approximately the observed thermal conductivity of epoxies and polyimides at 60 K. The first observation is the ~60 K difference in temperature between the round Litz wires. At these temperatures, loss in copper is logarithmic with temperature, so this temperature difference cannot be tolerated in the final motor design. The second observation is that there is a difference of ~120 K between the cooling fluid and bottom conductor and ~110 K between the upper conductor and back iron. This indicates that the low thermal conductivity is likely restricting the flow of heat out of the conductors. Third, the lack of a significant temperature gradient across the back iron reveals that the heat capacity of the back iron is not conducive to promoting thermal transport to the fluid. This will need to also be considered in the future design of the system.

To understand the sensitivity of the system to potting and wire insulation, the model was run with the thermal conductivity of the encapsulant (epoxy) and wire insulation both set to 0.05, 0.1, and 0.25 W/m-K. The sensitivity of the system is important to set both targets for the material system and expectations for the motor design. A plot of the resultant temperatures is shown in Fig. 4(b). These plots reveal that the thermal conductivity can bring the temperature of this poorly designed system down by 45 K (lower Litz wire) to 68 K (upper Litz wire). The results also reveal that a point of diminishing return has been reached when the thermal conductivity of the system reaches ~0.1 W/m-K. The increase to 0.25 W/m-K (2.5x increase in thermal conductivity compared to the 2X increase in between 0.05 W/m-K and 0.1 W/m-K) results in much smaller decrease in temperature. Therefore there this bounds the usefulness of increasing thermal conductivity. For the purposes of implementing a material solution in this application, a 2x increase in thermal conductivity is more realistic to achieve than a 5x increase. The final observation worth noting is that a ~50 K temperature difference between the Litz wires is maintained at the higher thermal conductivities. Thus, this difference must be reduced through design rather than changes to the encapsulant and potting materials.

III. Conclusions

An initial, but not final assessment was made for a number of epoxies that may be used as encapsulants. Several epoxies were removed from the candidate list and the remaining candidates have gone through tensile testing at room temperature and 123 K. While not conclusive, the testing does give insight to how these epoxies will behave in the application. Additional testing will be conducted in the near future, including room temperature compression testing as well as compression testing, thermal conductivity, and coefficient of thermal expansion at relevant cryogenic temperatures.

While not a surprise, the modeling results revealed several points where attempting to run a stator designed for 333 to 433 K operation fails to meet the requirements of a cryogenic stator. However, the results did indicate a need to push thermal conductivity of the Litz wire-encapsulant-insulation system to 0.1 W/m-K. Above this thermal conductivity a point of diminishing returns was identified. This same evaluation will need to be made with a model closer to the final geometry, but this result can be used as a worst-case scenario and guide the initial selection of materials.

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