ADVANCES IN MOTOR CONSTRUCTION ENABLED BY THERMALLY CONDUCTIVE THERMOPLASTIC

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Abstract: Thermoplastics have made steady gains in use in a wide variety of motor applications. Central to the development of these applications is an understanding of the heat transfer, harmonic damping and dimensional requirements of the applications and the cost/benefit relationships that exist. Discussion of the performance of thermally conductive, electrically insulative ceramic filled thermoplastics highlighting motor designs where these materials offer a competitive alternative to traditional construction techniques.

Key Search Words: Motor, encapsulation, thermal analysis, dimensional analysis, ceramic fill, thermal rise, CLTE

I. Introduction

In the past 20 years, engineering thermoplastics have been widely used in motor end brackets, brush holders, connectors, encapsulants, and stator and armature insulators. This has been accomplished despite the lower absolute properties of engineering thermoplastics versus the metals they typically replace. The ability to tailor material properties through the choice of resin and filler allows engineers to exploit the design flexibility inherent in thermoplastics to meet the performance requirements of a given application. The natural insulative properties and the ability to implement three-dimensional functionality allow for an integration of components and a robustness in design not allowed by metals.

Recently introduced products based on ceramic filler systems are demonstrating significant advances in meeting these market needs by enhancing thermal conductivity, reducing thermal expansion, and improving structural integrity by unitizing various components in the spindle/motor system.

In this paper, the design considerations and methodology for application of thermoplastic encapsulation techniques to a variety of brushless DC motors are reviewed, with the intent of improving the performance and reducing the cost of such devices.

II. Discussion

A. Design Considerations

The design considerations for a disk drive spindle, shown in a typical configuration in Figure 1, include efficiency, size, cost, dynamic stability, and acoustic noise. Redesign of a spindle to include encapsulation with a ceramic filled thermoplastic would ideally address each of these items for improvement.

Figure 2 demonstrates a technique which reduces the number of components in the spindle motor while at the same time simplifying the assembly process. The need to bond or press the stator onto the base plate has been eliminated, as

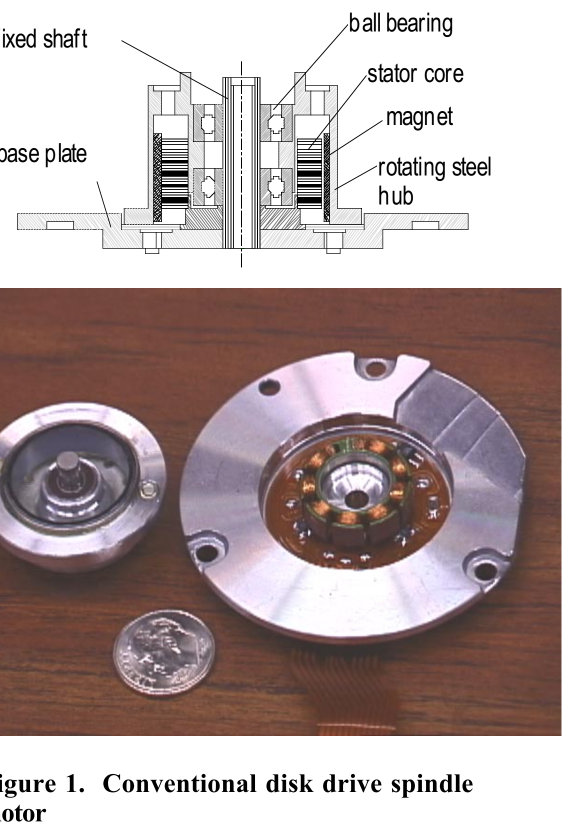


Figure 1. Conventional disk drive spindle motor

have issues with outgassing tied to this process. Post mold ultrasonic cleaning enables molding of the wound stator outside of the clean room in high volume injection molding

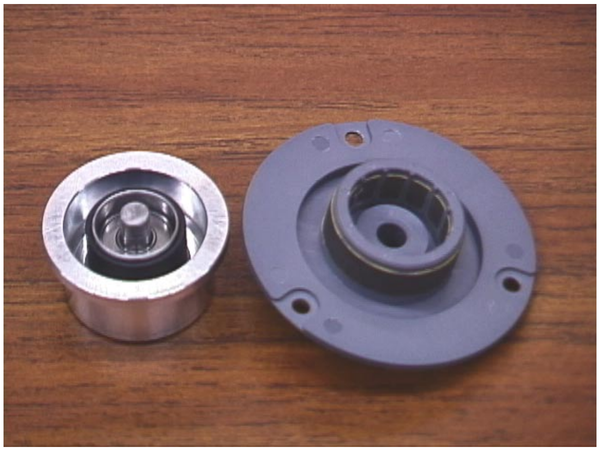


Figure 2. Unitized stator/baseplate assembly

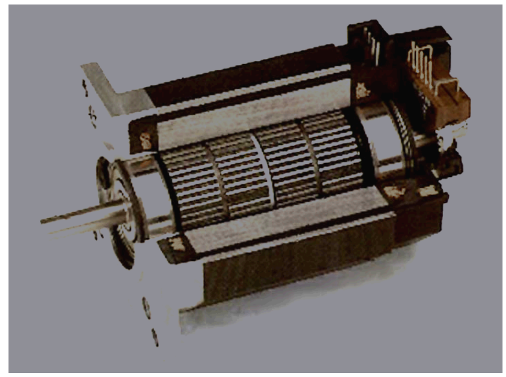
facilities. The thermoplastic flange may be reinforced with metal inserts to provide additional mechanical stability, or selectively plated to provide EMI protection of the read/write process. The dimensional stability and net shape molding eliminate the need for machining operations to create the mounting and locating features.

B. Dimensional Considerations

Thermal compatibility is a major issue in motor construction. Plastic materials typically expand at a rate 5 to 10 times that of metals. In applications where direct encapsulation of wire is implemented, the expansion differential between the copper and the plastic leads to wire stress and potentially open failures. Also, bearing performance can be significantly affected by raceway stress. Vibration induced by raceway deformation is a major cause of runout in spindle motors. The associated frictional losses are also a source of heat in a hard drive. When a Coefficient of Linear Thermal Expansion (CLTE) differential exists between the case and mounting material, the stress level will change with temperature. Furthermore, bearing pre-loads used to reduce run-out will be altered as materials expand at different rates. When mounting a spindle motor to an aluminum drive body, the need to match rates for dimension consistency with respect to the head stack is also important.

Typically, CLTE rates in plastic increase exponentially with temperature. A unique benefit of ceramic filler is the relative linearity of CLTE with temperature. Table 2, in the Appendix, highlights the CLTE performance of a variety of motor construction materials at both room temperature and 100C. Steel and Aluminum have CLTE's at room temperature of approximately $0.8x10^{-5}$ in./in./°F and $1.3x10^{-5}$ in./in./°F respectively. By comparison Nylon and Polyphenylene Sulfide have CLTE's of $4.5x10^{-5}$ in./in./°F at room temperature. The addition of glass to thermoplastic can reduce these levels but a differential in expansion rates develops. The glass exhibits an orientation dependence generating minimum CLTE's of roughly $1.3x10^{-5}$ in./in./°F. in the fiber direction but $3.8x10^{-5}$ in./in./°F in the cross fiber direction. With their inherently lower expansion rates, ceramic fillers offer the ability to reduce CLTE to levels approaching the base filler. A ceramic filled PPS manufactured by LNP Engineering Plastics trade name Konduit OTF-212 exhibits a CLTE of $1.1x10^{-5}$ in./in./°F in the flow direction and $1.3x10^{-5}$ in./in./°F cross flow at room temperature.

Figure 3 expands upon this principle. The manufacturer of this step motor maintains a radial air gap of 70 to 80 microns. When using a ceramic filled alternative to their glass reinforced PET they were able to demonstrate a 30-40°C increase in winding temperature before the onset of rotor seizure.



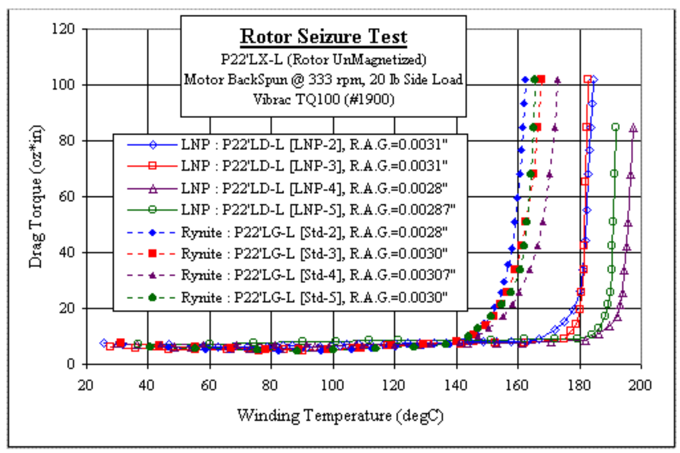


Figure 3. Rotor seizure comparison

C. Thermal Considerations

In the spindle motor we have been discussing, there are various heat sources such as hysteresis losses or eddy current losses in the magnetic steel [2], but the most important heat source is the resistive loss in the coil [3]. From a heat transfer standpoint, the ability to predict accurately the temperature rise in a coil when the copper losses are given is essential. A single parameter, then, which is the thermal resistance from winding to ambient air, can be used to represent the thermal performance of the whole motor. These values may be obtained from experiments, from the past experiences with similar motors, or from simple design rules of thumb. In order to evaluate various design configurations in the design stage, as well as the variations of thermal conductivity owing to specific choice of certain materials, a more refined analysis that can take into account detailed geometry should be performed [4]. Finite-element (FE) thermal analysis is one method that can be used for this purpose.

There have been several studies on the FE thermal analysis of motors; much of the research assumed that the heat sources are distributed uniformly along the circumference, i.e., axi-symmetric conditions. This is a good approximation in most cases when the thermal conditions are not too severe, but essentially lacks the capability of considering the case where encapsulation material is filled in the slots between the stator poles. Other studies assume two-dimensional planar models that usually have only a symmetric portion of stator and rotor together. The incapability mentioned in the axi-symmetric models may be partly resolved. However, this modeling scheme can be justified only when radial heat flux dominates. On the other hand, it is difficult to assess how much heat is, in fact, dissipated in radial and axial directions respectively before completing the analyses.

In many cases, as will be shown, both paths of heat removal are equally important, although there might be some exceptional cases. Thus, it is natural to develop a three-dimensional FE model which takes into account material selection variations in the slots as well as all the heat transfer paths at the same time.

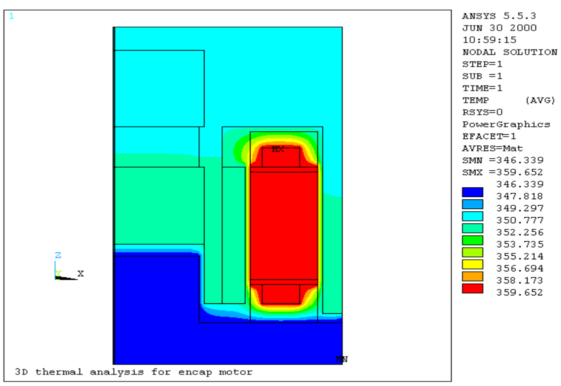


Figure 4. Predicted coil temperature when encapsulation is not used

Figures 4 & 5 are Ansys models of the thermal rise of the spindle motor in figure 2

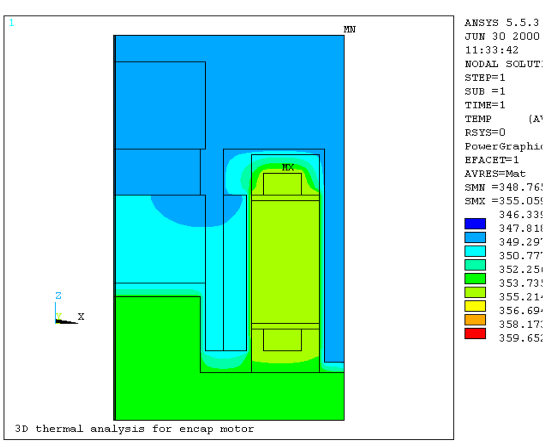


Figure 5. Temperature when thermoplastic encapsulation of k=1

The concept of thermal resistance also helps to understand the overall heat transfer mechanisms. Upon close examination of a typical spindle motor as shown in Figure 1, the heat producing coils are mainly surrounded by the air in any direction, while also contacting the stator. Since the thermal conductivity of the air is far less than that of any other materials in the motor, and the conduction path from the stator to the base plate is small, the other parts of the heat path are less significant. Thus it is possible for a small change in thermal conductivity of those regions to result in a significant temperature drop at the coil, rather than other design modifications.

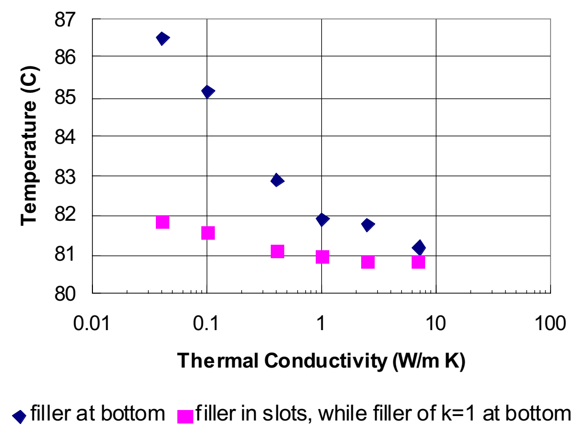


Figure 6. Temperature at coil vs thermal conductivity of the filler material.

Figure 6. shows the temperature at coil as a function of the thermal conductivity of the filler material for two different design variations when 1 W of copper loss is given. Assuming that the ambient air temperature is 30 °C, the temperature drop by using the filler of k=1 W/m·K at bottom between the stator and the base plate is 4.6 °C, which leads to the 7.7% of reduction in the total thermal resistance. Further increase in the thermal conductivity over 1 W/m·K does not seem to contribute to the temperature drop very much. Once the filler is used at bottom, the effect of filling the slots with thermally conductive materials is less significant; only a 1 °C of extra reduction in temperature is gained.

The analysis shows that the design change of filling the air gaps with a thermoplastic material with a thermal conductivity of 1 W/m·K or higher may reduce the total thermal resistance by 9.2% for this design geometry. The geometry of the stator and its mounting to the baseplate is paramount when using the encapsulation for thermal improvement. The main mechanism of heat transfer appears to be conduction. In the case of conduction, the contact area between the encapsulated stator and the baseplate is almost directly proportional to the heat dissipation. In the case of the design shown in Figure 2, this contact area would provide a noticeable change in the coil temperature. In other designs, where the contact area is much greater, such as with hub underslung motors, there would be expected a much greater gain in thermal transfer.

D. Dampening Considerations

Encapsulation of the stator winding has been shown in many past applications to be a very effective method for achieving vibration and noise reduction. Proper selection of the encapsulation material must include an analysis of the vibration frequencies that need to be damped, so that the thermoplastic can be formulated accordingly. The mechanical performance of the encapsulated spindle motor was tested using laser Doppler vibrometry. The axial runout was measured and compared to that of a commercially available 10 KRPM drive from a major disk drive manufacturer, shown in Figure 7. Although radial runout is a more direct measurement of spindle quality, axial runout is a much more convenient measurement, and the relative radial runout of a disk drive spindle can usually be inferred from its axial runout. The measurement of the computer spindle was made while spinning in its own enclosure. In this case, the peak-to-peak axial NRR was approximately 2 microns.

The NRR testing of the encapsulated spindle design was made in open air, as shown in Figure 8, which tends to increase the spindle runout due to aerodynamically induced disk vibration. In spite of this handicap, the encapsulated spindle showed NRR results that were comparable to that of the commercial disk drive. The peak-to-peak NRR measurement was also approximately 2 microns.

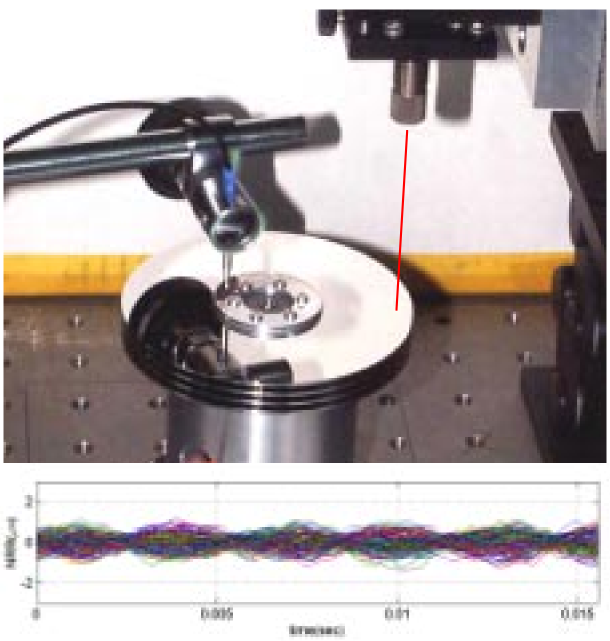


Figure 8. Testing of encapsulated spindle design with aluminum baseplate for NRR at 10 KRPM.

E. Processing Considerations

The 7.5 kilowatt submersible motor shown in Figure 9 powers a remote operable vehicle (R.O.V.). It is designed for use at depths in excess of 11,000 feet, and is capable of withstanding 5,000 psi of pressure. The unique hydrodynamic bearing scheme accommodates the more than three quarter inch reduction in radial diameter which occurs under maximum pressure.

Stress cracking during mold cooling is a common issue in this type of large overmold. The CLTE mismatch between the materials more than offsets the plastic elongation, causing failure typically in proximity to weld lines. This submersible motor faced the additional issue of in use thermal stress. The 21” outer diameter creates the potential for significant stress between the external water temperature and the coil “hot spot” temperature. Furthermore, the ROV can operate in proximity to underwater volcanoes and steam vents which cause dramatic temperature variations. Without CLTE management stress cracking would be an issue.

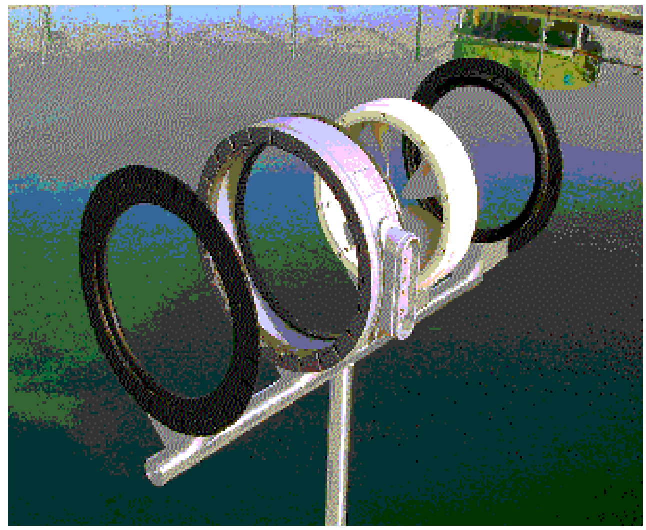


Figure 9. Submersible motor components.

To achieve a complete hermetic encapsulation, sixteen 2.5” pins are used to position the motor in the mold cavity. When the cavity is 94% filled with resin the pins are withdrawn hydraulically. To understand this process better consider Figure 10. Note the hydraulic curve (red) and the transition point B where the process moves from high pressure cavity fill to cavitypacking. Shortly after transition the pins are retracted, causing an instantaneous drop in cavity pressure (blue) over the 0.3 second retraction time. If the resin solidifies prematurely the recess the pins have created will not fully pack. A benefit of thermally conductive resin is it’s uniform temperature profile in the molding cavity. Most plastic begins to solidify as soon as it enters the cavity. An outer skin of material forms and insulates a molten core which solidifies more slowly. In traditional thermoplastics this varied crystallization rate is generally accompanied by differential shrinkage and voids.

Ceramic filler overcomes this processing limitation by creating a more uniform temperature profile in the resin. Additionally the large inherent surface area and spiracle aspect ratio of the filler leads to high levels of nucleation, significantly lower resin shrinkage, and almost instantaneous solidification throughout the wall section. For this manufacturer it offered a way to pull the pins, pack the vestige and then solidify the whole motor in under 1 second as shown in the area between points C & D.

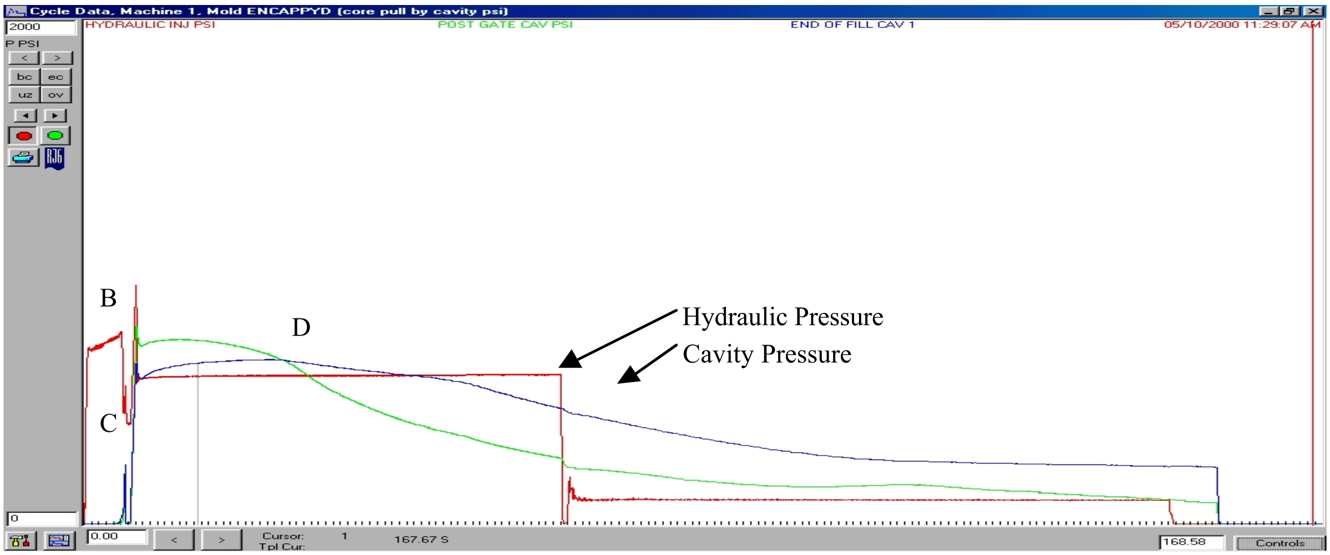


Figure 10. Process pressures for encapsulated ROV stator (time vs pressure)

III. CONCLUSIONS

Designs that use ceramic filled thermoplastics are just gaining acceptance in the market. A variety of applications have been developed which are showing performance unachievable with conventional thermoplastics. Improvements in heat transfer, dimensional consistency, processing latitude, and the ability to modify dampening characteristics offer designers new avenues for component integration Through the development of a simple heat transfer model, it has been shown that conductive heat transfer seems to govern the overall equilibrium temperature gradient. Because of limiting factors in the heat transfer mechanism, thermoplastics with a conductivity of approximately 1 watt/m°K can transfer as much heat as a metal with a higher thermal conductivity.

Currently, the cost of these materials are comparable to thermally conductive thermosets and typically two to three times those of epoxy potting or aluminum casting. These cost increases can be offset through the integration of components and the simplification of manufacturing techniques.

The most significant opportunity for cost reduction will always come when a component can be redesigned into a smaller platform enabled by the improvements in all of these areas.

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APPENDIX

Table 1: Thermal Conductivity of Various Materials

	Thermal Conductivity W-m/°K
Copper	400
Aluminum (extruded)	225
Brass	105
Aluminum (cast)	60
Steels	45
PPS	0.3
Nylon	0.24
Polypropylene	0.2

Table 2: CLTE for Various Materials

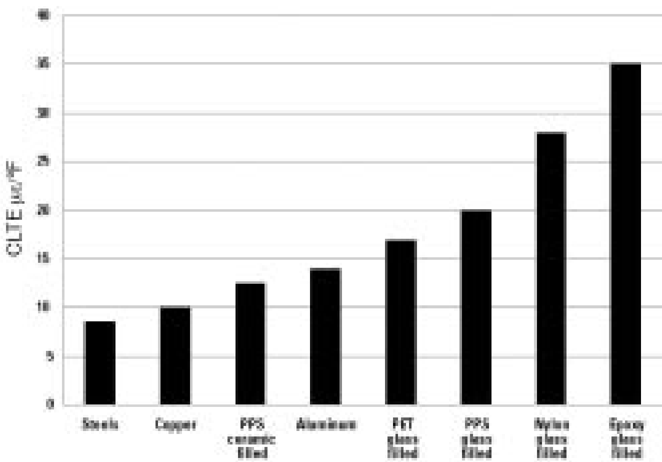

Table 3: Material Properties for PPS Composites

	PPS 10% glass	PPS 10% glass w/ ceramic	PPS 10% glass
Thermal Conductivity (W/m °K) *through plane*	0.3	1.0	2.2
Thermal Conductivity (W/m °K) *in plane*	No Data	1.0	7.0
Surface Resistivity (ohms/sq)	$>10^{13}$	$>10^{13}$	5.4×10^{2}
Tensile Strength (MPa)	79.4	52.4	138.7
Tensile Elongation (%)	3.0	0.5	1.0
Flexural Strength (MPa)	103.5	80.0	179.4
Flexural Modulus (MPa)	6,210	14,835	27,600
Notched Izod (J/m)	48.0	16.0	32.0