Ceramic Filled Thermoplastic Encapsulation as a Design Feature for a BLDC Motor in a Disk Drive

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***Abstract:* Thermoplastics have made steady gains in use in a wide variety of motor applications. One of the few areas in which thermoplastics have not been effectively utilized are spindle motors. Central to the development of these applications is an understanding of the heat transfer and harmonic damping requirements of the applications and the cost/benefit relationships that exist. A simple model will be presented in which the heat transfer requirements for thermally conductive plastics can be understood and their costs can be estimated. Various filler systems and their performance will be discussed highlighting motor designs where these materials offer a competitive alternative to traditional construction techniques.**

***Index Terms* – Disk drive, motor, encapsulation, thermal analysis, ceramic fill.**

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.

Manufacturers of spindle motors have had little success emulating these approaches because of the dimensional constraints and concentricity requirements of most end uses. 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 encapsulation techniques to a prototype spindle motor intended for disk drive application are reviewed, with the intent of improving the performance of such devices, and reduction of their cost.

DESIGN CONSIDERATIONS

Typically, plastic materials are viewed as thermal insulators. However, the need for thermoplastic materials that are thermally conductive is rapidly growing in the marketplace. Several factors make thermally conductive thermoplastics attractive for spindle motors. 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 would ideally address each of these items for improvement.

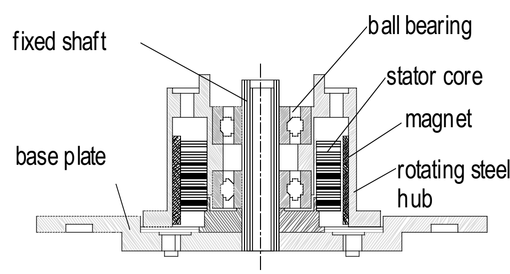

Figure 1. Conventional disk drive spindle motor

The resistance of copper varies linearly with temperature so a reduction in copper temperature can be equated to a reduction in resistance. Ideally, any design changes, outside of the magnetic design, should also lead to a reduction in coil temperature. This would reduce the resistive losses in the copper, and thereby improve the efficiency of the motor [1]. The thermal conductivity of the encapsulation material is thus very important since this would determine whether the coil temperature would increase of decrease.

Encapsulation techniques have also been used successfully in the past to reduce the number of components in other motor application, and at the same time, reduce the size of components such as locating, connecting, and holding features. In a disk drive spindle, it may be possible to incorporate features for locating items such as the stator, bearings and electrical connections as part of the encapsulation process. This may eliminate the need for parts or precision machined surfaces that currently perform these functions. Further, reduction of the volume consumed by extraneous parts and features would leave more volume for the functional components in the spindle, such as the motor and bearings. Thermal compatibility is a major consideration in the design. Plastic materials typically expand at a rate 5 to 10 times that of metals. Glass or mineral fillers can be added to some polymers to reduce the effect but as temperature rises this differential increases. In applications where direct encapsulation of wire is implemented the differential between the plastic and copper 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 RRO and NRRO in the spindle. The associated frictional losses are also a source of heat in a hard drive. When a CLTE differential exists between the case and mounting material the stress level will change with temperature. Furthermore pre-loads used to reduce run-out will be altered as materials expand at differential rates. When mounting the spindle motor to an aluminum drive body, the need to match rates for dimension consistency with respect to the head stack is also important.

Finally encapsulation of the stator winding has been shown in many past applications to be a very effective method for vibration and noise reduction. Proper selection of the encapsulation material would need to include an analysis of the vibration frequencies that need to be damped, so that the thermoplastic can be formulated accordingly.

There are three general classes of fillers that can be compounded into conventional thermoplastic to increase the thermal conductivity:

- Carbon Fillers: carbon fibers, carbon powder
- Metallic Fillers: copper powder, steel, aluminum powder, aluminum flake
- Ceramic Fillers: boron nitride, aluminum nitride, aluminum oxide

Each filler type has advantages and disadvantages. The ceramic fillers will have a negligible affect on electrical properties and are well suited for insulation applications. The carbon and metallic fillers will be electrically conductive, therefore limiting applicability to enclosures. Because of their aspect ratio, fiber and flake fillers will tend to exhibit differential conductivity based on filler orientation. This orientation also manifests itself in differential shrinkage in molded components. This affect causes warpage and may increase the difficulty in achieving dimensional requirements. Powdered fillers typically do not show an orientation dependence. The fiber or flake fillers are generally more efficient than powdered fillers, in terms of the loading needed to achieve conductivity. Metallic fillers have high density, which can lead to weight disadvantages in many applications. Depending on loading, ceramic fillers having a specific gravity of 3.6 to 3.9 increase resin specific gravity from 30 to 50%. Carbon powder and fibers having the lowest density tend to increase specific gravity by 20-30%.

Steel and Aluminum have CLTE's at room temperature of approximately $.8\text{x}10^{-5}$ in./in./°F and $1.3\text{x}10^{-5}$ in./in./°F respectively. By comparison Nylon and Polyphenylene Sulfide have CLTE's of $4.5\text{x}10^{-5}$ 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 $1.3\text{x}10^{-5}$ in./in./°F. in the fiber direction but $3.8\text{x}10^{-5}$ in./in./°F in the cross fiber direction. With their inherently lower expansion rates, metallic and 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 $1.1\text{x}10^{-5}$ in./in./°F in the flow direction and $1.3\text{x}10^{-5}$ in./in./°F cross flow at room temperature.

Typically, CLTE rates increase exponentially with temperature. This change magnifies differentials and accelerates the aforementioned problems. 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 250°F. Only the ceramic filled resin maintains performance similar to metals.

Two thermally conductive materials, one using a ceramic filler and the other a carbon fiber filler, are shown in Table 3, in the Appendix. These materials contain PPS with 10% fiberglass as the base resin system. Both materials show significant improvements in thermal conductivity. These materials also illustrate several of the advantages and disadvantages of the different filler types. The carbon fiber system is electrically conductive and exhibits orientation effects: note the difference in the thermal conductivity measured in the plane of the plate versus through the plane. The ceramic filler is a powder, is not electrically conductive, and has the same thermal conductivity in all directions.

The physical properties of these two thermally conductive materials are normal for the type of fillers used. The particulate filler (ie. the powdered ceramic) has no reinforcing properties but does increase stiffness. The carbon fiber filler will add additional reinforcement - this is reflected in the increase in the tensile and flexural strength. Based upon the low density, orientation independence, low CLTE and dielectric properties, a conclusion of this paper is that powdered ceramic filled thermoplastic offers the most attractive blend of properties for manufacturers of spindle motors.

Although application performance is critical, if the total system cost is not competitive, the application of thermoplastic will not occur. Central to this analysis is a comparison of the following:

- Cost of all the raw materials
- Cost to mold the component
- Cost of assembly
- Cost of the complete system

The density-adjusted cost of ceramic filled thermoplastic is approximately three times more than aluminum. Since the thermoplastic cost is still a small percentage of total raw material cost in a spindle motor the increase versus aluminum in many cases is offset by other savings.

Fabrication cost is determined by the process cycle time and equipment costs. Thermally conductive resins solidify significantly quicker than other resins and are generally considered to mold 60-70% faster than aluminum casting. Injection molding equipment is significantly less costly than die casting lines and the higher productivity generates savings in total tool cost through reductions in cavitation requirements. Furthermore the net shape capability of injection molding eliminates many costly post casting machining steps. Most importantly the electrical insulative properties of thermoplastic and the ability to encapsulate wound stators offers the potential to eliminate components and simplify the manufacturing process.

A Redesigned Spindle Motor

To discuss these system savings further, consider the spindle motors pictured in Figures 2 and 3. Figure 1 shows an old style configuration with heat-bonded coils and a stator pressed into a locating feature on the aluminum baseplate.

Figure 2. Encapsulated stator on aluminum baseplate.

The application in Figure 2 uses plastic encapsulation to unitize the stator. The bonding to the aluminum flange, connector, and coil insulation are all accomplished in one operation. The need to bond or press the stator onto the base plate has been eliminated, as 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 facilities. The version shown in Figure 3 takes the process one step further by creating the flange itself in the same molding operation. The flange in this case may be reinforced with metal inserts to provide additional mechanical stability, or selectively plated to provide EMI protection of the read/write process. In this case, the mounting and locating features no longer need to be created by machining operations.

The encapsulation process in this design has also eliminated the need to special mounting features required to affix the stator to the baseplate. This removes the cost associated with the former mounting features. Also the volume saved by the removal of these features (as well as from optimization of the magnetics) has permitted an enhancement to the bearings and motor configuration in the spindle. The bearings, for example are 5x13 mm, instead of the usual 5x11 mm bearing typically used in a desktop disk drive spindle. The larger bearing promotes better dynamic stability and better bearing life at higher spin speeds. The magnet is mounted on

Figure 3. Encapsulated stator on molded baseplate.

a steel tube that serves as the back-iron and also the mounting of the outer bearing raceways. This configuration, where the airgap is located closer to the bearings, which is stiffest location in the hub, should also result in improved hub stability.

Thermal Analysis

There are various heat sources in a spindle motor such as hysteresis losses or eddy current losses in the magnetic steel [2], but the most important one is the resistive loss in 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 the experiments, the past experiences with similar ones, or simple design rules of thumb. In order to evaluate various design configurations in the design stage, and the variations of thermal conductivity owing to specific choice of some materials, a more refined analysis that can take into account of 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 that some encapsulation material is filled in the slots between the stator poles. Others are basically the study on the 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 is dominate. 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 ways of heat removal are equally important, although there might be some exceptional cases. Thus, it is so natural to develop a three-dimensional FE model so to take into account material selection variations in the slots as well as all the heat transfer paths at the same time.

The concept of thermal resistance also helps to figure out the overall heat transfer mechanisms. Upon close examination of a typical spindle motor 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 4 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 analyses shows that the design change of filling the air gaps with some thermoplastic materials with a thermal conductivity of 1 W/m·K or more may accomplish the reduction of 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 heat transfer.

Spindle Mechanical Performance

The mechanical performance of the encapsulated stator design 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, 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.

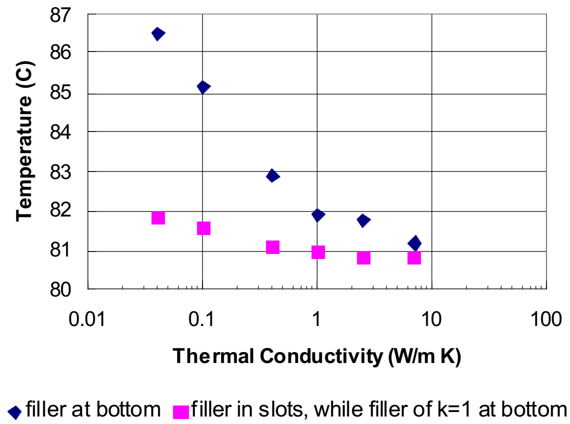

Figure 4. Temperature at coil vs thermal conductivity of the filler material.

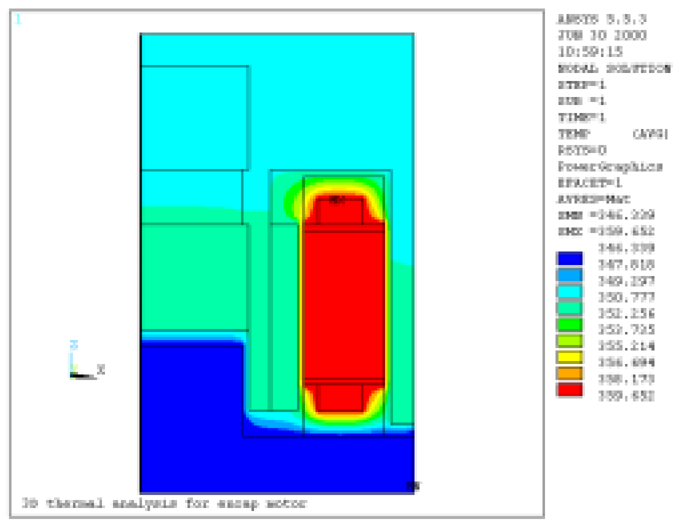

Figure 5. Predicted coil temperature when encapsulation is not used

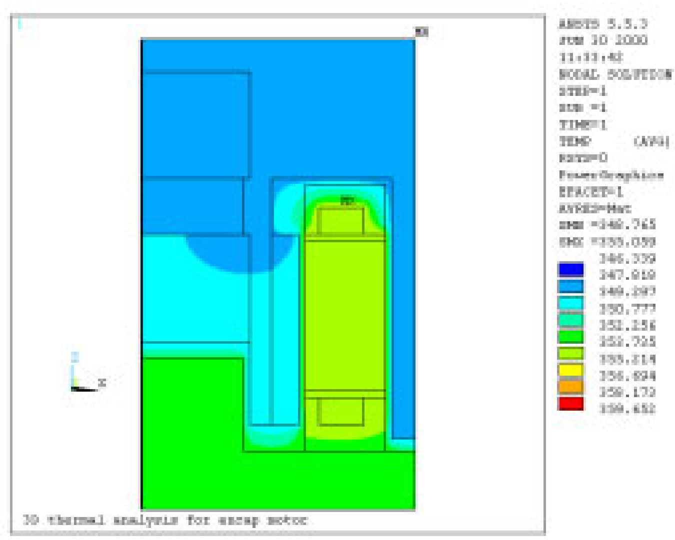

Figure 6. Temperature when thermoplastic encapsulation of k=1 W/m·K used at bottom

Conclusions

Designs that use encapsulation in disk drive spindles are at a very early stage in development. With very little engineering effort, other that in the encapsulation process, a prototype spindle was fabricated which showed excellent dynamic performance. With addition effort direct toward a fine tuning of the design, the dynamic performance will likely exceed that of currently available spindles. The primary advantages of such designs are through the improved heat transfer, vibration and noise damping, and packaging improvements inherent in the encapsulation material and process.

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. Because of its dielectric properties, orientation independence and low CLTE ceramic powder has the best balance of properties as thermoplastic filler for spindle motors. Currently, the cost of these materials is typically three times that of aluminum. 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.

References

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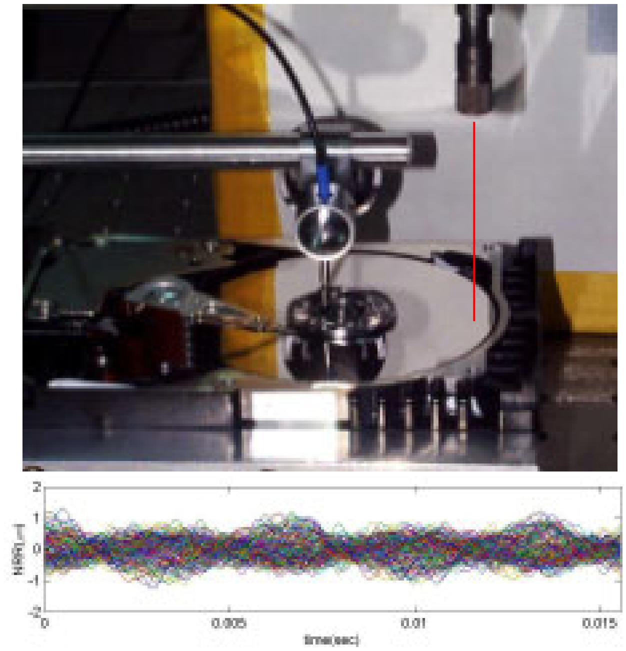

Figure 7. Testing of a commercial 10 KRPM drive for NRR

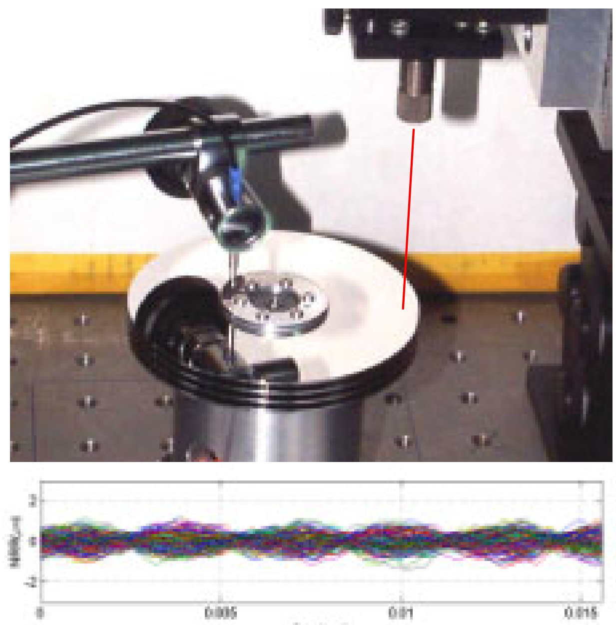

Figure 8. Testing of encapsulated spindle design with aluminum baseplate for NRR at 10 KRPM.

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
Polypropylen e	0.2

Table 2: CLTE for Various Materials

	CLTE με/°F
Steels	8.5
Copper	10
PPS, ceramic filled	12.5
Aluminum	14
PET, glass filled	17
PPS, glass filled	20
Nylon, glass filled	28
Epoxy, glass filled	35

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