

THERMALLY CONDUCTIVE THERMOPLASTICS A VIABLE ALTERNATIVE FOR COIL WOUND DEVICE AND PASSIVE COMPONENT CONSTRUCTION

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Abstract: Thermoplastics have made steady gains in use in a wide variety of electrical applications. One of the few areas in which thermoplastics have not been effectively utilized are applications where thermal conductivity is required. Central to the development of these materials is an understanding of the heat transfer and electrical insulation 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 materials can be understood and their costs can be estimated. Various filler systems and their performance will be discussed highlighting opportunities where these materials offer a competitive alternative to existing construction techniques.

Introduction

In the past 20 years, engineering thermoplastics have replaced metal in numerous part designs in many industries by providing improvements in design flexibility, allowing greater part integration, and lowering system costs in manufacturing operations. This has been accomplished despite the lower absolute properties of engineering thermoplastics. 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. Furthermore, the ability to implement three dimensional functionality allows for an integration of components and a robustness in design not allowed by metal and ceramic materials.

One area that has received only limited attention has been the modification of the thermal properties of plastic materials. Typically, plastic materials are viewed as thermal insulators. However, the need for thermoplastic materials that are thermally conductive is rapidly growing in the marketplace. There are several factors which make thermally conductive thermoplastics attractive for different market segments.

Longer life The Arrhenius equation predicts that failure rate is directly proportional to component temperature. UL and the IEC use this principle as a cornerstone when defining raw material test specifications. In practicality,

most designers expect that a 10-15 °C increase in temperature halves the operating life of a device.

Higher power

Coil resistance specifications are given for an ambient temperature of 20 °C. The resistance of copper varies linearly with temperature so a lower copper temperature can be equated to a lower resistance. Assuming constant voltage, Ohms law predicts this lower resistance will result in a higher current. As power is the product of voltage and current, any increase in current at constant voltage leads to an increase in power.

Size reduction

As a general rule, as size is reduced, device temperature increases. Nowhere is this more evident than in the electronics market where there has been a continuing trend towards smaller, and faster integrated circuits. This trend has led to increasing challenges in thermal management for designers. In the case of processors, the amount of heat generated by the chip has become significantly larger. A typical 486 chip generates about 5 watts of power, while the newer Pentium II chips can generate over 30 watts. Similarly it is common to find power amplifiers generating over 5 watts of power. To enable this continued miniaturization, designers have been forced to integrate heat sinks and conductive substrates to dissipate heat.

Cost savings

Lower temperatures reduce the regulatory burden and in many cases allow the use of lower cost raw materials. Downsizing of components can reduce raw material content and shipping costs. Elimination of thermal management components such as heat sinks and conductive pastes reduce manufacturing steps and raw material costs.

Recently introduced thermally conductive thermoplastics meet all of these market needs. While redesign of existing components is in many cases necessary to realize the full potential of these materials, there are many avenues available to achieve the goals of electrical component manufacturers.

Discussion

Thermally Conductive Materials

In attempting to replace metals in thermally conductive applications, it is important to understand the performance of the current materials as well as the application requirements. Chart 1 shows the relative thermal conductivity of various materials. From this chart, it is clear that thermoplastics are insulators and in their unmodified state they do not possess the needed thermal conductivity to provide thermal solutions. However, there is a significant spread in the conductivity performance of the metals that are currently being used in thermal management applications. This observation suggests that in some applications metals may have more thermal conductivity than the application requires. Thus, the key to providing thermally conductive thermoplastic materials is to understand how much conductivity is needed.

To clarify the conductivity requirements for thermal management applications, we developed a simple model to help understand and quantify the balance between the conductive and convective elements involved in heat transfer. The model, shown in Figure 2, is based on a flat plate, in which a power source is placed on one side. Heat is transferred through the plate by conduction and removed from the external surface by convection. The temperature gradient across the plate is described by equation (1); the magnitude of the gradient across the plate is governed by the thermal conductivity of the material (K). The temperature of the external surface is described by equation (2); in this case the temperature gradient between the external surface and the ambient air is governed by the heat transfer coefficient (h). Two modes of convective transfer in air will be considered: first, *free convection*, in which the circulation is driven only by the temperature gradients at equilibrium - for this case, h is typically $5 \text{ W/m}^2\text{K}$; and, *forced convection*, in which the circulation is driven by an external means of air circulation - for this case, h is typically $50 \text{ W/m}^2\text{K}$.

We can now consider how changes in the thermal conductivity of the material affects the temperature gradient across the plate at equilibrium. For the purposes of this discussion, we will set: q at 5 watts; L at 1.27 cm (0.5 in); t_{H} at 21°C ; A will be 34.2 cm^2 (5.3 in^2) for the forced convection case and 342 cm^2 (53 in^2) for the free convection case - this is done to keep the absolute temperatures equivalent for both cases, this change does not affect the magnitude of the gradient across the plate.

Figure 3 shows the temperature gradient across the plate as a function of the material conductivity for both the free convection ($h = 5 \text{ W/m}^2\text{K}$) case and the forced convection ($h=50 \text{ W/m}^2\text{K}$) case. In order to maintain a small temperature gradient across the plate (ie. between 1°C and 10°C) the material should have a thermal conductivity in the $1\text{-}10 \text{ W/m}^2\text{K}$ range. For the free convection case, the material needs only a thermal conductivity of $1 \text{ W/m}^2\text{K}$ to maintain a 1 degree temperature gradient across the plate.

The key conclusion from considering this simple model is that convective heat transfer often governs the overall equilibrium temperature gradient. Further, convective heat transfer is not only dependent on the heat transfer coefficient, but also on surface area. The flexibility available with thermoplastic materials allows the design freedom to create larger surface areas and more efficient conductive geometries. Because of this, applications designed from thermoplastics with a conductivity of $1\text{-}10 \text{ watts/m}^2\text{K}$ may transfer as much, or even more, total heat than similar parts designed in metals with higher thermal conductivities.

Thermoplastic Solutions

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

- ⊙ 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.

Dielectric properties: 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.

Orientation: 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.

Loading: The fiber or flake fillers are generally more efficient than powdered fillers, in terms of the loadings needed to achieve conductivity.

Density: The 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%.

Coefficient of thermal expansion: The metallic fillers and ceramic powders reduce CLTE to levels very close to the base filler. Carbon fiber and powder have a negligible effect on performance.

Two thermally conductive materials, one using a ceramic filler and the other a carbon fiber filler, are shown in Table 1. 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.

The use of these fillers can be extended to other resin systems. This is demonstrated in Table 2, where examples of a ceramic filler compounded into nylon and polypropylene are shown. Again there is a five-fold increase in the thermal conductivity versus the base resin, without a significant effect on the physical properties of the resin.

Based upon the low density, orientation independence, low CLTE and dielectric properties, a conclusion of this paper is that powdered ceramic filler offers the most attractive blend of properties for manufacturers of electrical devices.

Cost Estimation

Although application performance is critical, if the total system cost is not competitive the application of thermally conductive thermoplastics will be constrained.

Central to this analysis is a comparison of the following:

- Cost of the resin
- Density of the resin
- Cost to mold the part
- Cost of other raw materials

Ceramic filled thermoplastic costs approximately US \$2.00 per pound more than the cost of the base resin. A 40% increase in resin density leads to a general assumption that resin cost will be 2.5 times higher than the corresponding base polymer. Since thermoplastic cost is a small percentage of total raw material costs, in many cases these increases can be offset by other savings.

Molding cost is determined by the process cycle time. Thermally conductive resins solidify significantly quicker than other resins and are generally considered to mold 30-50% faster than nonconductive resins. While potentially significant, cycle limitations due to insert loading and component testing can mitigate these benefits.

Raw material cost reduction enables the savings necessary to convert to a ceramic filled thermoplastic. Reduced coil temperatures allow the use of lower performance and less expensive magnet and lead wire. Increased power allows coil and steel downsizing. Regulatory testing such as UL

1446 and IEC-85 can be eliminated where temperatures can be driven below class B requirements.

To discuss the potential for savings further consider the natural gas valve solenoids pictured in Figure 1.

Figure 1



This component was manufactured using a glass reinforced PET polyester. The manufacturer had experienced problems meeting the UL class F temperature rating in high ambient temperature installations and decided to sample a ceramic powder filled nylon.

Table 3 contains a thermal analysis of the solenoid in manifold and co-axial valve configurations. Significant temperature reductions were achieved which allowed the manufacturer to alter other materials of construction and thus generate system wide cost savings.

Table 3

Convection only (hung in free air)	Coil Resistance		delta Temp (F)
	Start	Stabilized	
Manifold valve, standard coil	9.784	14.014	198.3
	9.698	13.908	199.1
Manifold valve, conductive coil	9.718	13.450	176.2
	9.646	13.394	178.2
			177.2
			avg
Co-axial valve, standard coil	9.942	14.776	223.0
Co-axial valve, conductive coil	9.696	14.124	209.5
Conduction and convection, heat sinked (clamped in vice)			
Manifold valve, standard coil	9.736	12.553	132.7
Manifold valve, conductive coil	9.711	12.186	116.9
Co-axial valve, standard coil	9.908	12.846	136.0
Co-axial valve, conductive coil	9.723	12.086	111.5
Heatrise summary			
convection	manifold valve	co-axial valve	
standard encapsulant	198.7	223.0	
heat conductive encapsulant	177.2	209.5	
improvement	21.5	13.5	
conduction and convection			
standard encapsulant	132.7	136.0	
heat conductive encapsulant	116.9	111.5	
improvement	15.8	24.5	

In the convective limited configuration, the manifold valve showed a 12% reduction in coil temperature. Similarly the

co-axial valve showed a 7% lower operating temperature. When each solenoid was mounted to a heat sink, the manifold valve showed a 14% lower coil temperature and the co-axial valve showed a 22% lower temperature.

When assembled into valves the increased thermal conductivity allowed the manufacturer to realize cost savings by moving from a 180 °C MW-78 to a 155 °C MW-80 magnet wire. Since a nylon meets the new temperature standards, the manufacturer was able to eliminate the costly and problematic PET bobbin. Additional savings were generated when the molder reduced its processing fee because of the faster molding cycle and lower costs associated with nylon versus PET encapsulation.

Conclusions

Through the development of a simple heat transfer model, the thermal performance of materials in air cooled applications has been outlined. The model has shown that convective heat transfer often governs the overall equilibrium temperature gradient. Because convective heat transfer becomes the limiting factor, thermoplastics with a conductivity of 1-10 watts/m²K can transfer as much heat as a metal with a higher thermal conductivity.

Ceramic powder has the best balance of properties as a thermoplastic filler for electrical component applications. Significant potential exists to increase component power and extend operating life while reducing device size. Thermoplastic composite materials based on PPS, nylon, and polypropylene have been formulated which meet the targeted thermal performance of 1-10 watts/m²K.

The cost of these materials are typically 2.5 times that of the base polymer. These cost increases can be offset through the use of less expensive polymers enabled by lower operating temperatures. Savings in molding offer an additional chance to recoup some of these costs. When magnet and lead wire, as well as other raw materials, are downgraded to accommodate the lower operating temperatures, further benefit can be gained. 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 conductivity.

References

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Griffith Neal received his BS in Chemical Engineering from the University of Michigan. His professional career began with Du Pont where he held a variety of positions in sales, marketing and product management in both North America and Asia. After leaving Du Pont he founded Encap Technologies, an engineering consultancy which designs and prototypes thermoplastic encapsulation systems for electro-mechanical devices.

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Chart 1: Thermal Conductivity of Various Materials

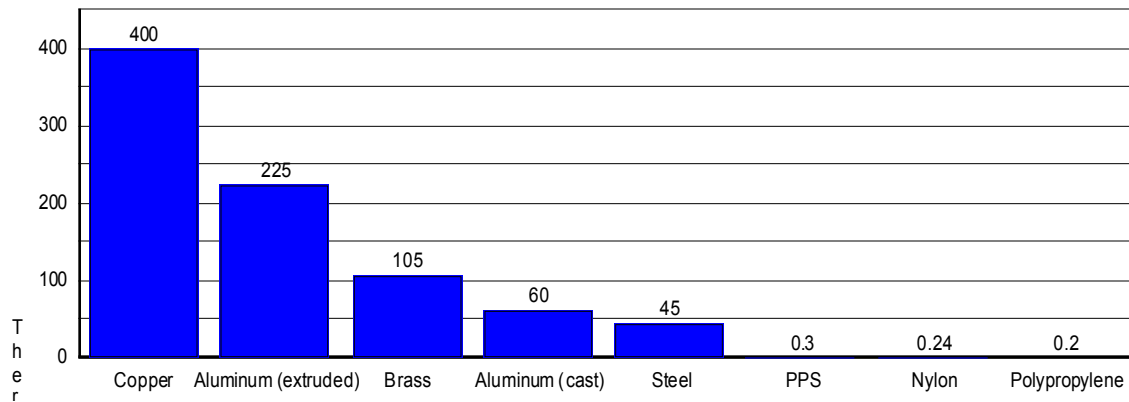


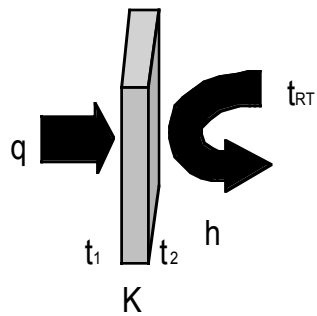
Figure 2: Flat Plate Model for Heat Transfer

Conduction:

$$t_1 - t_2 = (qL) / (AK) \text{ (eqn 1)}$$

Convection:

$$t_2 - t_{RT} = (q) / (Ah) \text{ (eqn 2)}$$



Where: K = thermal conductivity of the material (W/mK)
 h = heat transfer coefficient (W/mK)
 q = power input (w)
 A = surface area of the plate (m²)
 L = thickness of the plate (m)

Figure 3: Model Predictions for Temperature Gradient across the Plate

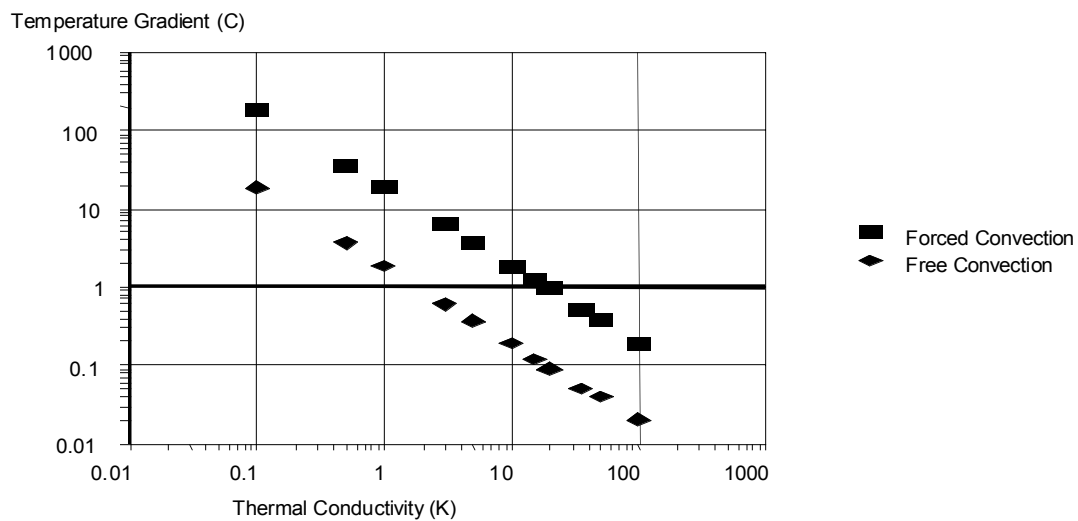


Table 1: Material Properties for PPS Composites

	PPS (10% glass)	PPS (10% glass) w/ ceramic filler	PPS (10% glass) w/ carbon fiber
Thermal Conductivity (W/m °K) <i>through plane</i>	0.3	1.0	2.2
Thermal Conductivity (W/m °K) <i>in plane</i>	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

Table 2: Physical Properties for Nylon and Polypropylene Materials

	Nylon (10% glass)	Nylon (10% glass) w/ ceramic filler	Polypropylene	Polypropylene w/ ceramic filler
Thermal Conductivity (W/m °K)	0.2	1.0	0.2	1.2
Tensile Strength (MPa)	93.2	93.1	34.5	17.3
Tensile Elongation (%)	3.0	2.3	>200	1.5
Flexural Strength (MPa)	117.0	152.5	48.3	36.6
Flexural Modulus (MPa)	4,485	9,246	1,242	4,278
Notched Izod (J/m)	53.4	53.4	21.4	16.0