Thermally Conductive Thermoplastics

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An area in which thermoplastics have not been effective in replacing metals has been in applications requiring thermal conductivity. Recently, however, through the use of various filler systems, thermoplastic materials have been developed with thermal conductivities from 1 to 10 W/m°K.

During the past two decades, 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.

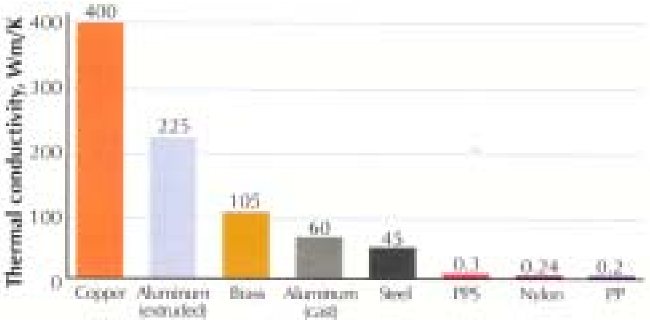
An area that has received only sporadic attention has been the modification of the thermal properties of plastic materials. Typically, plastic materials are viewed as thermal insulators. However, the need for thermoplastic materials that are thermally conductive is rapidly growing in the marketplace.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

In the electronics market, the trend is toward smaller, lighter, faster computers, which has led to increasing challenges in thermal management for designers. As processors become faster, the amount of heat generated by the chip increases; a typical 486 chip generates about 5 watts of power, while the newer Pentium 11 chips can generate more than 30 watts. The inability to remove the heat generated by these chips greatly reduces their operating life. The design flexibility afforded by thermally conductive thermoplastics could provide attractive solutions to increased demands on chip cooling systems.

The lighting market is another area in which thermally conductive plastics could be useful. Here, improving the thermal management capabilities of a thermoplastic, coupled with part integration and lower manufacturing costs, could significantly improve the operating life span of fluorescent fixtures. Thus, improvements in thermal performance could drive the replacement of traditional metals in these applications.

THERMALLY CONDUCTIVE MATERIALS

Figure 1. Thermal conductivity of various materials.



In the attempt to replace metals in thermally conductive applications, an understanding of the performance of the current materials and their application requirements is important. Figure 1, which shows the relative thermal conductivity of various materials, makes it clear that thermoplastics are insulators, and in their unmodified state, do not possess the needed thermal conductivity to provide thermal solutions. However, a significant spread exists in the conductivity performance of the metals currently being used in thermal management applications, suggesting 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.

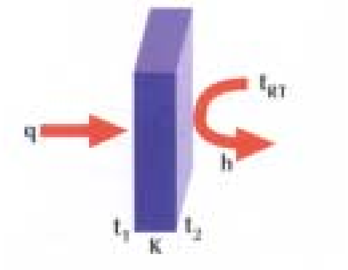


Figure 2. Flat plate model for heat transfer.

Conduction:
t_1-t_2=(qL)/(AK) (eqn 1)

Convection:
t_1-t_2=(qL)/(Ah)) (eqn 1)

Where:
K=thermal conducivity of the material (W/mK)
h=heat transfer coefficient (W/m^2K)
Q=power input (w)
A=surface area of the plate (m^2)
L=thickness of the plate (m)

To clarify the conductivity requirements for thermal management applications, a simple model has been developed to aid in understanding and quantifying 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* (in Fig. 2); 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* (Fig. 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. The first is free convection, in which the circulation is driven only by the temperature gradients at equilibrium. For this case, h is typically 5 W/m^2°K. The second mode is forced convection, in which the circulation is driven by an external means of air circulation. For this case, *h* is typically 50 W/m^2°K.

How changes in the thermal conductivity of the material affect the temperature gradient across the plate at equilibrium can now be considered.

For the purposes of this discussion, the following will be set: *q* at 5 watts, *L* at 1.27 cm (0.5 in), t_{rt} at 21°C; A will be 34.2 cm2 (5.3 in2) for the forced convection case and 342 cm2 (53 in2) 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 W/m^2°K) case and the forced convection (h=50 W/m^2°K) case. In order to maintain a small temperature gradient across the plate (i.e., between 1°C and 10°C) the material should have a thermal conductivity in the 1 to 10 W/m^2°K range. For the free convection case, the material needs only a thermal conductivity of 1 W/m^2°K to maintain a 1° temperature gradient across the plate.

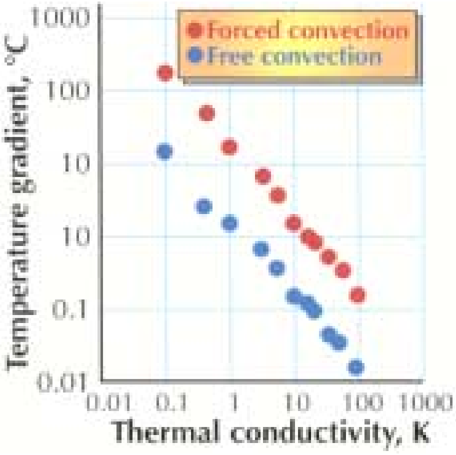


Figure 3. Model predictions for temperature gradient across the plate.

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 dependent not only on the heat transfer coefficient, but also on surface area. The flexibility available with thermoplastic materials allows the design freedom to create more efficient geometries.

Because of this, applications designed from thermoplastics with a conductivity of 1 to 10 W/m^2°K may transfer as much, or even more, total heat than similar parts designed in metals with higher thermal conductivities.

THERMOPLASTIC SOLUTIONS

The following three general classes of fillers can be used to increase the thermal conductivity of thermoplastics:
* 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 the following advantages and disadvantages:

* The carbon fillers and metallic fillers will be electrically conductive as well as thermally conductive. The ceramic fillers will provide materials that are electrical insulators.
* The fiber or flake fillers are generally more efficient fillers, in terms of the loadings needed to achieve conductivity. However, because of their aspect ratio, injection molded parts may have an orientation dependence. Powdered fillers may require higher loadings, but will not show an orientation dependence.
* The metallic fillers often have high specific gravities, which can lead to a weight disadvantage in some applications.

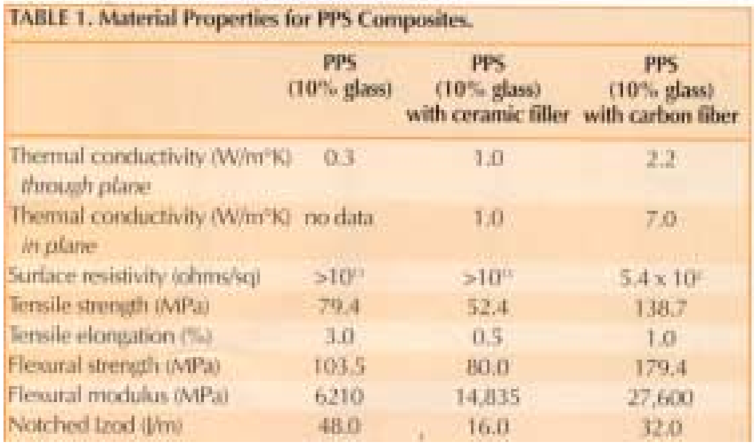


TABLE 1. Material Properties for PPS Composites.

	PPS (10% glass)	PPS (10% glass) with ceramic filler	PPS (10% glass) with carbon fiber
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)	$>10^{13}$	$>10^{15}$	5.4×10^{6}
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)	6210	14,835	27,600
Notched Izod (J/m)	48.0	16.0	32.0

Two thermally conductive materials, me using a ceramic filler and the other a carbon fiber filler, are listed in Table 1. These materials contain polyphenylene sulfide (PPS) with 10% fiberglass as the base resin system. Both materials show significant improvements in thermal conductivity, and 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.

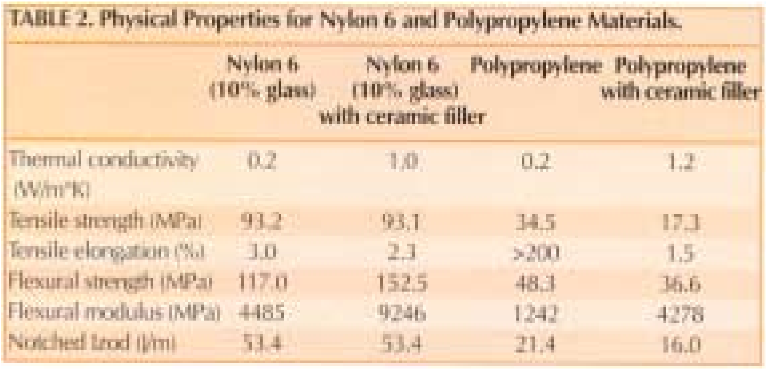


TABLE 2. Physical Properties for Nylon 6 and Polypropylene Materials.

	Nylon 6 (10% glass)	Nylon 6 (10% glass) with ceramic filler	Polypropylene	Polypropylene with 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)	4485	9246	1242	4278
Notched Izod (J/m)	53.4	53.4	21.4	16.0

The physical properties of these two thermally conductive materials are normal for the type of fillers used. The particulate filler (i.e., the powdered ceramic) has no reinforcing properties and serves to lower the tensile and flexural strength. The carbon fiber filler will add additional reinforcement, which 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 6 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.

CONCLUSIONS

By means of a simple heat transfer model, the thermal performance of materials in air-cooled applications has been outlined. The model shows 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 to 10 W/m°K can transfer as much heat as a metal with a higher thermal conductivity. Through the use of thermally conductive fillers, thermoplastic composite materials based on PPS, nylon 6, and polypropylene have been formulated that meet the targeted thermal performance of 1 to 10 W/m°K.