Heat Transfer with Plastics versus Metals

Which Fillers Are Best Suited for Thermally Conductive Plastics, and How They Can Help Replace Metals

For many components, the use of metal-replacing plastics is an attractive possibility e.g. to save weight and benefit from enhanced design freedom. In various applications, however, the thermal conductivity of the polymers is of equal importance. There are different additives that can be used to enhance this property. In the development of two polyamide families, Domo Engineered Materials investigated which of those additives are especially useful to this end, and applied Light Flash Analysis to examine the materials.

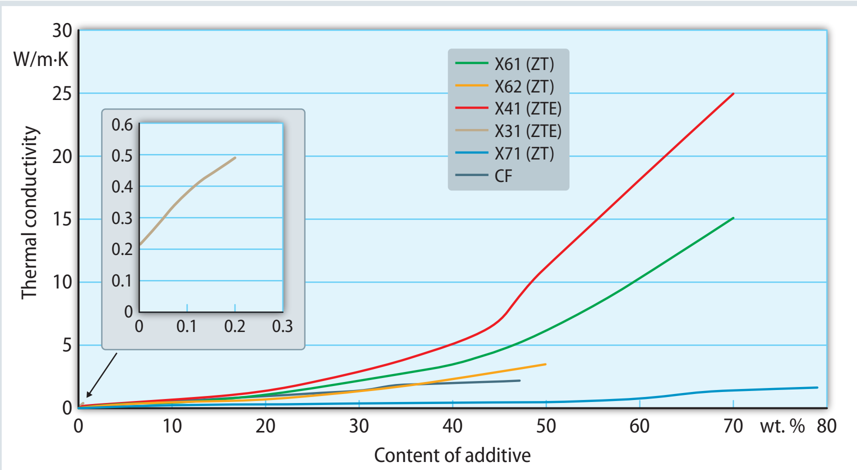

Fig. 1. In-plane thermal conductivity measuring of PA6 with various different fillers: the thermal conductivity (TC) depends on the additive. In some cases it rises considerably at an additive content of 40% or higher Source: Domo Engineered Materials; graphic: © Hanser

Thermal and electric conductivity are two important properties of engineering plastics targeted at replacing metal alloys in the design of components. For the study of the thermal conductivity of plastics and how it varies as a function of filler orientation, Light Flash Analysis (LFA) provides numerous advantages as a fast and reliable technology. Domo Engineered Materials has developed several thermally conductive polyamides (PA) for metal replacement in various components. The study of those formulations was performed in collaboration with Netzsch Gerätebau GmbH.

In the field of heat transfer there are two general options: thermally conductive and electrically insulating materials, or thermally as well as electrically conductive materials. Among its PA portfolio, Domo developed Domamid ZT for the former and Domamid ZTE for the latter category. Both product families comprise isotropic as well as anisotropic grades. Besides PA, the study also included compounds with polyphenylene sulphide (PPS) as matrix material

Conductive materials often demand a very high degree of customization, as the conductivity of the material depends as much on the additives used as on the geometry of the final application. Several additives were considered during the study, most of them carbon-based such as carbon black, graphene and graphite, but also inorganic materials such as aluminum oxide and boron nitride. Amongst others, measurements were performed on in-plane specimens, providing a good view on how the thermal conductivity (TC) of the PA varies depending on the specific filler and its content in the compound (**Fig. 1**). In most cases, a significant increase in conductivity is observed only at filler levels above 40%.

Two Additives ahead of the Rest

The maximum conductivity value depends on the characteristics of the filler, and indeed a significant variation in the composition of the overall filler can give rise to very different TC values. The fillers shown to be most effective are boron nitride and graphite. In addition, it was found that the TC values measured "in plane" (in flow direction) are generally the highest for anisotropic materials.

The TC was also measured using the "through-plane" method, indicating in general lower values for anisotropic materials than those obtained from in-plane measuring (**Fig. 2**). This is due to the different orientation of the filler within the sample as a result of the actual geometry of the particles. In isotropic materials, by contrast, the TC values are the same in all three spatial dimensions. Boron nitride and graphite proved to be the most effective fillers also in through-plane measuring. »

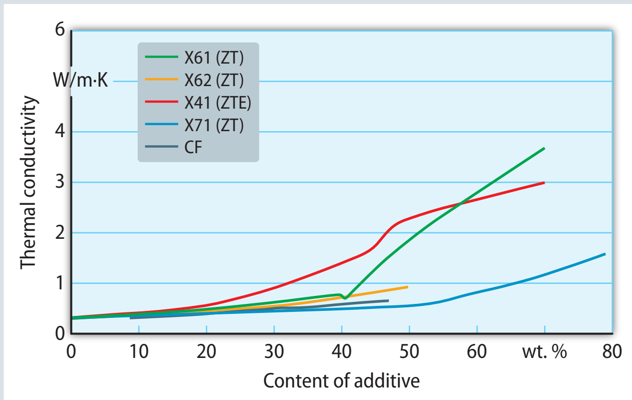

Fig. 2. Through-plane thermal conductivity measuring of PA6 with various different fillers: boron nitride and graphite deliver the best values Source: Domo Engineered Materials; graphic: © Hanser

Part Geometry Determines Thermal Conductivity

Figure 3 summarizes the results of both aforementioned measuring methods. As can be seen, isotropic materials show TC values close to the bisector of the quadrant, whereas anisotropic materials show values far from the axis. The more the values deviate from the x=y axis, the more the material has anisotropic behavior. This confirms that the choice of material and filler to use will therefore depend largely on the design and geometry of the final part. The actual thermal conductivity of the material cannot be the only selection criteria.

Two Measuring Methods, One Device

The LFA examinations were performed with Netzsch LFA 467 HyperFlash measuring equipment (**Fig. 4**). The device was chosen because of the simplicity it offers to measure both through-plane and in-plane thermal conductivity. In fact, the measurement is always taken in the same way. For through-plane values, the square sample is cut into strips, which are rotated by 90°, rearranged to a square and placed back into the special sample holder for laminates. Physically, the measurement will always be through-plane with respect to the sample holder, but the rotation of the plates inside the instrument enables us to obtain data relative to the in-plane conductivity.

Based on the results of these examinations, Domo has decided to use a mix of boron nitride and aluminum oxide in various different ratios as additives for thermally conductive and electrically insulating materials. For thermally as well as electrically conductive solutions, on the other hand, the primary additive is graphite.

Metals Often Over-Designed

Next to these findings on the conductivity provided by different additives, it was also substantiated that thermally conductive plastics in many cases are well suitable for metal replacement. The study has shown that the metals used to provide applications with a certain degree of thermal conductivity are often over engineered, and that the same required effect can be achieved with a material of much lower thermal conductivity (**Table 1**).

If in the case of an LED, for example (**Fig. 5**), the temperature limit to be reached at free convection is approx. 120.5 °C, aluminum with a conductivity of 100 W/m·K is clearly over engineered, although a predominant metal in such applications. In order to ensure the same level of protection and temperature control, a plastic material with 10 W/m·K would produce a very similar result. In this case, even a material with a thermal conductivity of just 2 W/m·K would suffice. At other applications with higher energy dissipation requirements and forced convection, however, the thermal conductivity would have to be higher, and we would also have to reconsider the part geometry and resulting requirements.

Thermally conductive engineering plastics have many advantages over metals. The most important ones are greater flexibility and efficiency. Plastic materials offer more freedom of design, reduce production cycle times and avoid much of the post-processing associated with metals. Also, they do not cause the typical corrosion problems of metals, and their lower density reduces the weight of the final application. A PA material, for instance, weighs up to 33 % less than aluminum. Especially in automotive applications, this contributes to the lightweighting of vehicles, with subsequent lower fuel consumption and fewer CO_2 emissions.

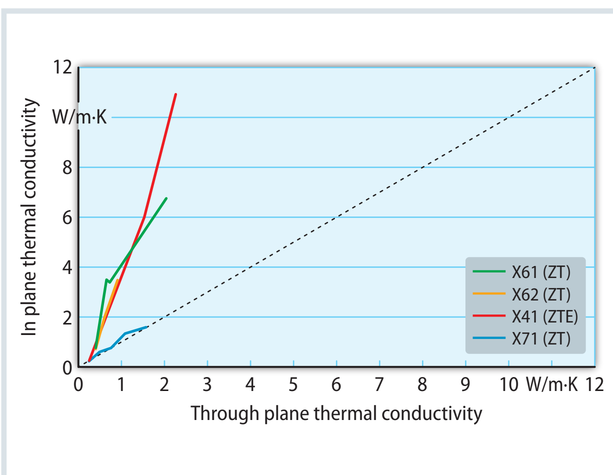

Fig. 3. Combined results of in-plane and through-plane thermal conductivity measuring: isotropic materials show TC values on the bisector of the quadrant. The TC values of anisotropic materials are far away from the axis. Therefore, proper material selection must not only take the TC value in consideration, but also the part geometry
Source: Domo Engineered Materials; graphic: © Hanser

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In addition, a plastic component can significantly reduce vibrations compared to metal parts. The use of different raw materials can also meet further requirements such as good processability, chemical resistance, flame retardancy (e.g. in compliance with automotive standards such as FMVSS 302) and adequate mechanical properties. Furthermore, plastics can relative easily be colored, enable the integration of functions into molded parts, and can be electrically insulating as well as conductive. Typical target applications of thermally conductive plastics include heat sinks, coolant management systems, LED lighting systems, parts for miniaturization in electronic systems and a wide range of automotive applications.

Fig 4. By way of adapting the specimen, the LFA 467 HyperFlash device from Netzsch enables both through-plane and in-plane TC measuring © Netzsch

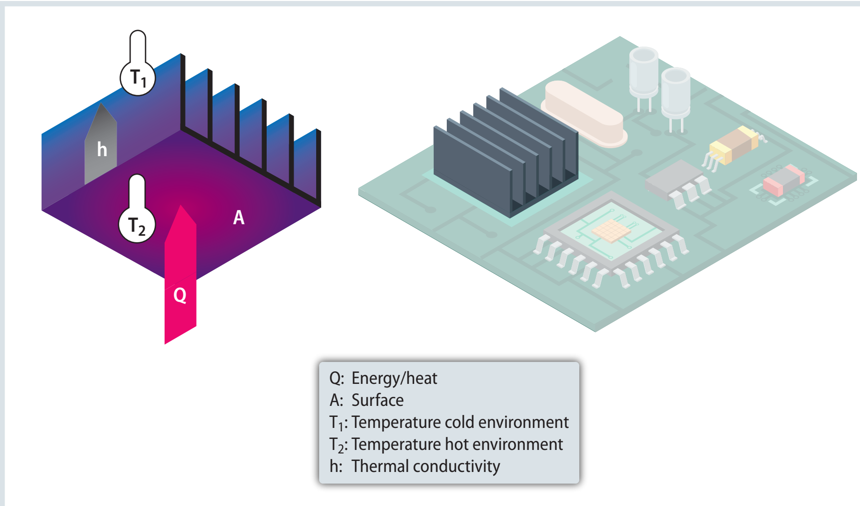

Fig. 5. Example of heat transfer through the heat sink of an LED: the heat (T_2) on surface A passes through the heat sink (heat flow Q) and can then dissipate to the environment. The difference between T_1 and T_2 results in the thermal conductivity (h) Source: Domo Engineered Materials; graphic: © Hanser

Two Case Stories

Both of Domo's new thermally conductive PA material families are already used in the automotive industry. Two examples highlight their potential for metal replacement. In the first case, a solution was needed for manufacturing the engine cover of an electric vehicle. The defined material specifications were long-term heat resistance, chemical resistance, excellent processability and thermal conductivity. The material finally approved by the tier 1 supplier was Domamid ZT 6X70H1 X71 NC91, a PA6-based, heat-stabilized material with a thermal conductivity of 1.2 W/m·K through-plane.

The second case is an under-bonnet application serving as part of the cooling circuit for an electric motor, which demanded a thermally and electrically conductive material. The customer expected a through-plane thermal conductivity 2 W/m·K or greater. The application also required high flowability due to the reduced wall-thickness of the part and the dimensions of the mold (component thickness 1 mm and length 50 mm), as well as heat stabilization for peak temperatures around 210 °C and good mechanical properties, including a maximum tensile stress at break of about 70 MPa. The material finally selected for this particular application was Domamid ZTE 66X50H1 X41 NC99, a PA66-based, heat-stabilized grade with a through-plane TC of 2 W/m·K and an in-plane TC of 12 W/m·K. ■

	Free convection				Forced convection			
	Standard plastics	Thermal conductive plastics		Metal	Standard plastics	Thermal conductive plastics		Metal
Energy/heat [W]	3	3	3	3	15	15	15	15
Thermal transmittance [W/m²·K]	7	7	7	7	50	50	50	50
Thermal conductivity [W/m·K]	0.1	2	10	100	0.1	2	25	100
Temperature cold environment T_1 [°C]	120.5	120.5	120.5	120.5	118.4	118.4	118.4	118.4
Temperature hot environment T_2 [°C]	142	122.9	120.9	120.5	264.1	134.3	121	118.5
Temperature difference ΔT [°C]	21.5	2.4	0.4	0	145.7	15.9	2.6	0.1

Table 1. Comparison of thermal conductivities of plastics and metal: the higher the thermal conductivity of the material, the smaller the difference in temperature between both points Source: Domo Engineered Materials