Heat sink designs and properties: Opportunities for molders

Using PIM for the manufacture of heat sinks instead of extrusion or machining broadens geometry options and creates a dense structure.

Editor's note: A recognized expert in powder injection molding (PIM), Randall German is Brush Chair professor in materials at Penn State University. He coauthored this article with John Johnson, R&D manager of AMTellect Inc. (State College, PA), which is involved in the commercialization of PIM heat sinks. This column is part of an occasional series on understanding and applying PIM.

Increasing power requirements and decreasing size of high-performance microprocessors present heat-dissipation challenges to microelectronic package designers. These factors require the management of significant amounts of power over a small physical area, leading to high power densities. Current processors generate power densities in the range of 10 to 40 W/sq cm, with future Intel processors expected to be in the range of 20 to 60 W/sq cm. New heat sink designs will be needed to handle these increasing thermal loads and injection molding may be a big part of the solution.

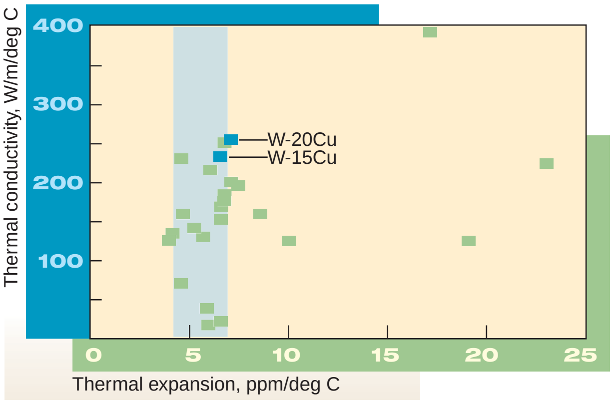

Figure 1. A plot of thermal conductivity vs. thermal expansion coefficient for several electronic materials. The band between 4 and 7 ppm/deg C thermal expansion represents the window of compatibility with semiconductors. The high relative performance of W-15Cu and W-20Cu are indicated, with the only competitors to powder injection molded tungsten copper being toxic beryllia and diamond.

A fundamental problem is maximizing the heat sink's thermal conductivity while matching the thermal expansion coefficient of silicon (about 4 ppm/deg C). Common and affordable metals with high thermal conductivity, like aluminum and copper, have a large mismatch in thermal expansion with respect to silicon. Consequently, every time the device turns on there is a stress generated between the silicon and heat sink. Eventually, the assembly delaminates and the circuit overheats. Thus, a major goal is to have a high thermal conductivity with a thermal expansion coefficient matched with typical semiconductor materials, generally in the 4- to 7-ppm/deg C range.

Why Mold Heat Sinks?

The most widely used method of extracting heat from a processor is to connect it to a heat sink, which is air cooled, either actively or passively. Heat sinks usually have fins to increase their surface area, which increases the amount of heat that they can release to the ambient air stream. Many heat sinks are extruded or machined from aluminum. Extrusion is a highly automated, low-cost, high-volume process but places limitations on the fin geometry. Machining or diecasting can produce denser fin arrays than extrusion, but still not dense enough to meet the power dissipation requirements of the latest personal computer processors.

These requirements have led to the development of folded-fin heat sinks and integrated heat pipes. Folded-fin heat sinks can give a twofold improvement over the performance of extruded heat sinks, but with a similar increase in cost. Integrated heat pipes can give additional performance improvement, but currently cost five to 10 times that of extruded heat sinks. New heat sink designs offer opportunities for injection molders to provide a low-cost, high-volume process that can meet the geometry and property requirements.

Aluminum was the early choice for a heat sink because of its relatively high thermal conductivity and ease of manufacturing. Increased needs for higher thermal conductivities led to consideration of copper. Still, both materials suffer from high thermal expansion, which provides challenges to mounting the heat sink to the silicon chip or ceramic substrate.

Accordingly, new tailored composite materials have emerged, such as W-Cu, Mo-Cu, and SiC-Al, which combine high thermal conductivity with thermal expansion coefficients suitable for many packaging applications. These materials, especially W-Cu with 15 to 20 wt-%, are formed by mixing powders and can be injection molded into complex geometries and sintered to meet heat sink design requirements.

Figure 1 (opposite) plots the thermal conductivity vs. thermal expansion coefficient for several electronic alloys (silicon, indium phosphide, alumina, copper, gallium arsenide, kovar, beryllia, aluminum, and the new composites). The shaded region shows the materials that fit between 4 and 7 ppm/deg C in thermal expansion coefficient, and the unique high thermal conductivity of W-15Cu and W-20Cu are marked. The only other matches are either very expensive (diamond) or toxic (beryllia), making these composites natural choices for most consumer electronic applications such as personal computers.

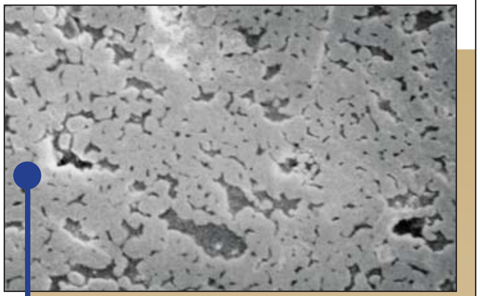

Figure 2. A scanning electron micrograph of a tungsten-copper sample prepared with inhomogeneous distribution of the tungsten (light gray) and copper (dark gray), leading to degraded heat-dissipation properties. The picture is about 50 µm across.

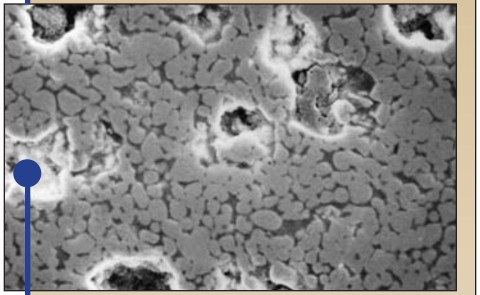

Figure 3. A porous sintered tungsten-copper sample with large pores and oxides. Both forms of microstructure defects degrade the thermal conductivity and are common difficulties with poorly processed material. The picture represents roughly 50 µm in width.

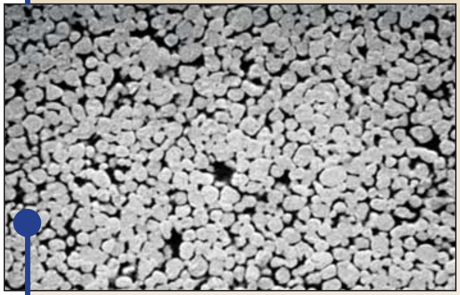

Figure 4. A scanning electron micrograph of a sintered tungsten-copper heat sink after debinding and sintering, showing homogeneous grains of pure tungsten (white rounded phase) and an interwoven network of copper (dark phase) with a few dark spots where tungsten grains were pulled out during polishing. The picture is approximately 50 µm across.

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Small powders are needed to achieve a high sintered density for W-Cu, since copper is poor at promoting sintering densification even well above its melting point of 1083C. The use of elemental tungsten and copper powders leads to problems such as inhomogeneous microstructures, residual porosity, and copper bleedout.

Figures 2 and 3 show examples ▶

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***Figure 5.* An early design of a PIM tungsten-copper package for encapsulation of microelectronic circuits. This design was successfully used in the Penn State research program to demonstrate how W-Cu composites could be produced by PIM.**

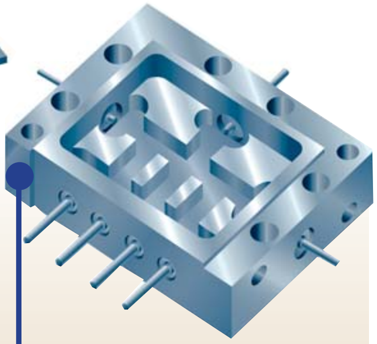

***Figure 6.* An example of the shapes under discussion for PIM where glass-sealed feedthroughs are included in the package design.**

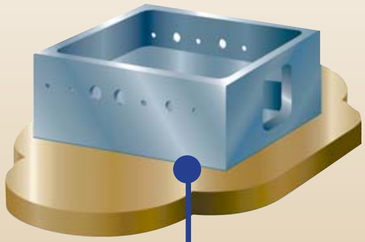

***Figure 7.* An example of a new-wave microelectronic package where the glass-to-metal sealing is accomplished using a PIM package (light blue-gray color) bonded to an injection molded tungsten-copper base (bronze color) for heat dissipation.**

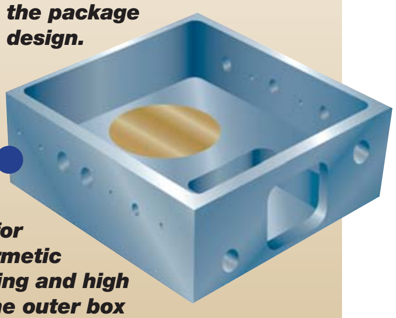

***Figure 8.* A new microelectronic package designed for PIM to combine hermetic glass-to-metal sealing and high heat dissipation. The outer box (light blue-gray color) is formed from a glass-metal sealing alloy, such as Kovar, while the inner sweet spot is formed from tungsten copper (bronze color). The combination allows for the semiconductor circuit to be positioned for excellent heat extraction. The holes are penetrated by lead wires that are sealed into place by glass.**

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of poor sintered microstructures. New composite powders have demonstrated the ability to solve these problems and significantly reduce sintering temperatures. Such powders tailored for injection molding are commercially available—for example, Osram Sylvania's Tungstar W-Cu powders, which are produced from coreduced copper and tungsten oxides. The use of composite powders also eliminates the need for a blending or milling operation prior to compounding, giving molders one less thing to worry about.

Molding pressures and temperatures for W-Cu are similar to those for injection molding of stainless steel powders. However, the small particle size and low solids loading make components more prone to flash. Also, the high tungsten content makes the feedstock more abrasive, with possible long-term wear problems. The mold, insert, injection screw, and screw tip must be replaced due to wear during high-volume production.

Sintering can be performed in various atmospheres including hydrogen, partial pressure, and cracked ammonia, but the use of graphite vacuum furnaces is not recommended. Toll sintering is commercially available for molders to thermally process W-Cu without investing in a special furnace. When properly performed, the sintered microstructure is homogeneous, as shown in Figure 4 (p. 109).

Development of the infrastructure for powder production and sintering has enabled W-Cu to become increasingly used for chip submounts and stem heat sinks for optoelectronic devices, basemetals and fin-shaped heat sinks for integrated circuits, and bases for multichipped boards. Up to now the early designs were for microelectronic packages, such as those shown in Figures 5 and 6.

One of the fresh options possible via powder injection molding is to custom design microelectronic packages with tailored functions. Figure 7 is a graphical illustration of a glass-to-metal sealing alloy designed for ▶

heat dissipation using a tungsten-copper base. Figure 8 (p. 110) is an alternative design, which includes the tungsten copper as an insert in the base. Such devices are just going into production for high-performance electronics. The continued evolution of heat sink designs provides an exciting opportunity for molders to provide new solutions for the thermal management problems facing the electronics industry.

The Center for Innovative Sintered Products at Penn State has been active in commercializing thermal management materials formed by powder injection molding and sintering. Several commercial products have emerged that include variants based on invar silver, molybdenum copper, aluminum nitride, and now tungsten copper in conjunction with AMTellect. From the standpoint of affordability and price, the W-15Cu and W-20Cu composites appear to be clear winners, suffering only from a high density. ◆

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