Improved cooling technologies for both power-supply and motor-drive military applications

By Ralph Remsburg

Power dissipation problems are requiring increasingly complex design solutions. While designs that are more efficient make thermal management possible, current chips and systems still require sophisticated methods for dissipating heat. Several different fin geometries might be used to cool a three-chip, 1,080 W Insulated Gate Bipolar Transistor (IGBT) copper cold plate. The geometries are compared using maximum junction temperature and efficiency. One manufacturing method, Metal Injection Molding (MIM), appears to meet the thermal objectives and is examined more closely.

Insulated Gate Bipolar Transistors (IGBTs) generally are used as switching components in inverter circuits in both power-supply and motor-drive military applications. Although very efficient, these modules suffer from conduction and switching-power losses, which generate heat that must be conducted away from the power chips into the environment.

Previously, familiar air-cooled aluminum heat sinks were sufficient for this heat conduction. But as some military converter and inverter circuit applications reached multi-megawatt requirements, the more thermally effective approach of liquid cooling using copper cold plates has become more common. Cold plates have been improved with more capable designs that utilize lanced-offset fins to replace serpentine-tube cold plates. However, the space constraints of shrinking cold plates – and the strict demand to lower cost – have created a need for even more efficient heat-transfer surfaces within the cold plate.

Innovative designs utilizing impingement flow paths and microchannel surfaces are starting to be used. A manufacturing process called *Model Injection Molding* (MIM) makes highly efficient nonlinear fin arrays. A *fin*, technically referred to as an extended surface, is a protrusion from a heated surface that provides more surface area for heat dissipation. A fin array or fin pattern usually takes the form of a repeating series of identical fins with identical spacing between fins. The exact shape and spacing between fins can have a dramatic effect on the amount of heat that can be dissipated from a surface, and hence, the junction temperature of a device mounted to that surface.

Fin comparison

While there have been many studies of single cooling fin geometry parameters, the conclusions often conflict or can be applied only over a narrow range of variables. A review of the literature reveals that most studies of single-fin geometry neglect the importance of pressure drop, which for most real-world liquid-cooling systems is directly related to thermal performance by the pump flow curve. Even when the literature agrees on the relative performance of a single fin, these findings may become distorted when multiple, identical fin flow fields interact within a fin array.

Figure 1 shows a 50 mm x 50 mm IGBT module containing three IGBT chips dissipating 300 W each and three diodes dissipating 60 W each. The total power dissipation is 1,080 W. Simulations were run using seven different extended surfaces to find the best-performing surface in terms of heat transfer coefficient, volumetric efficiency, and use of minimum pumping power.

To simulate the cooling capability of the various fin patterns, Flomerics Inc. Flotherm v6.1 software was used. Flotherm is a Computational Fluid Dynamics (CFD) analysis tool widely used in the electronics-cooling industry. For each simulation, the ambient air temperature is 80 ˚C. Radiation effects are not included in the analysis. The steady-state temperature distribution, fluid velocity, and pressure drop were recorded as the volumetric flow rate was increased from 1 liter/minute to 20 liters/minute. The details of the seven cooling patterns are shown in Table 1. The *x*-axis is parallel to the fluid flow.

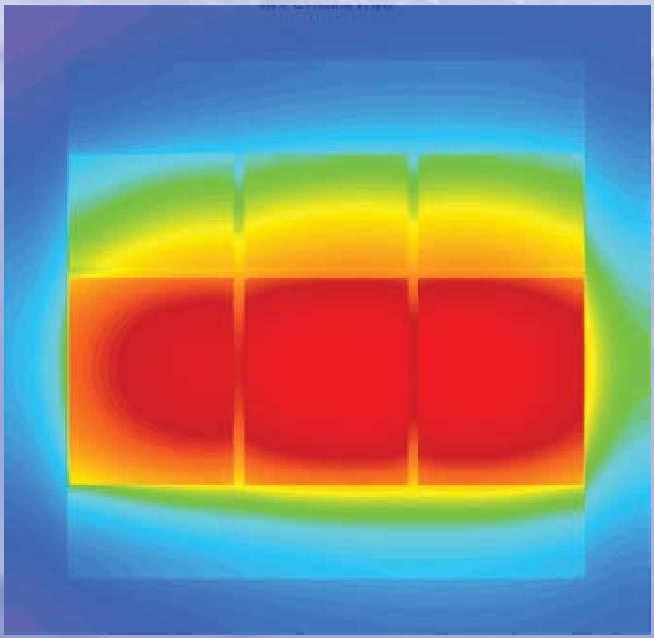


Figure 1

Pattern	# Fins in x	# Fins in y	Diameter or thickness (mm)	Fin area (cm^2)
Single tube	-	-	10.0	15.7
Double tube	-	-	10.0	31.4
Stacked fins	49	-	0.20	245
Square in-line	31	31	0.785	151
Square staggered	31	31	0.785	151
Lanced-offset	49	8	0.20 x 3.5	137
Nonlinear	-	-	0.5	135

Table 1

Figure 2 shows a thermal comparison of the various fin geometries. The curves represent the maximum semiconductor junction temperature when using a 30 percent EGW mixture having an inlet temperature of 80 ˚C to cool the 1,080 W IGBT module described.

Note that using the double-pass tube has roughly the same temperature result at 20 liters/minute as the staggered square pin pattern has at 1 liter/minute. The nonlinear array shows a lower junction temperature at all simulated flow rates. The single and double pass tubes would probably have unacceptable results in a cooling system unless the system could supply a large volume of coolant at low pressure. In this 1,080 W application, the nonlinear array has an 11.2 ˚C lower junction temperature at 1 liter/minute than the next best performing geometry, which is the lanced-offset fin pattern. At 20 liters/minute, the nonlinear array maintains a 2.0 ˚C lower junction temperature.

Figure 3 shows a com-parison of pressure drop results for the simulation series.

The staggered square pins, although producing a good result in terms of temperature rise (second to the nonlinear array), have a high-pressure requirement. At 20 liters/minute, the staggered square pins have nearly 4.3x the fluid resistance as the nonlinear array.

Figure 4 shows the relative efficiency of the fin patterns when compared using a metric of θP_p, which is the product of ˚C/W and watts of pumping power. The lower the value, the more efficient the fin pattern. As noted previously, the staggered pin pattern has good thermal performance but a very high-pressure drop. Therefore, efficiency is low.

According to data presented in Figure 4, the best surface in terms of efficiency is the single-pass tube. Although the efficiency is high, the lack of surface area and the resulting high junction temperature may preclude the use of this type of cold plate for cooling high-power modules. The nonlinear array performs better than all the other tested configurations in terms of junction temperature and has a relatively low pressure drop and, therefore, high efficiency. Because of the high efficiency, the nonlinear array may have advantages when it's used in low- and high-power applications.

Nonlinear fin arrays

In a nonlinear fin array, extensive CFD analysis ensures that each fin is optimized for maximum performance while simultaneously accounting for the performance flow fields of the fins adjacent to it in the array.

There are only a few processes that can economically produce a nonlinear

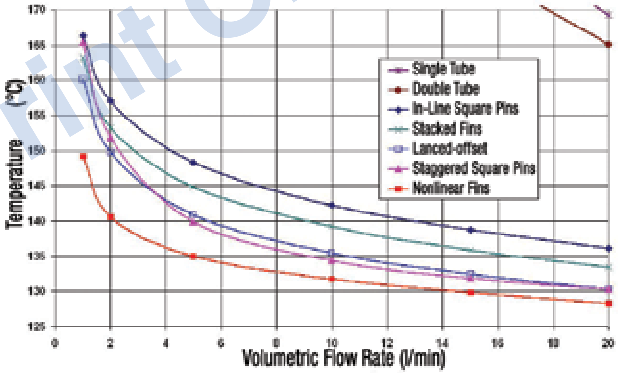


Figure 2

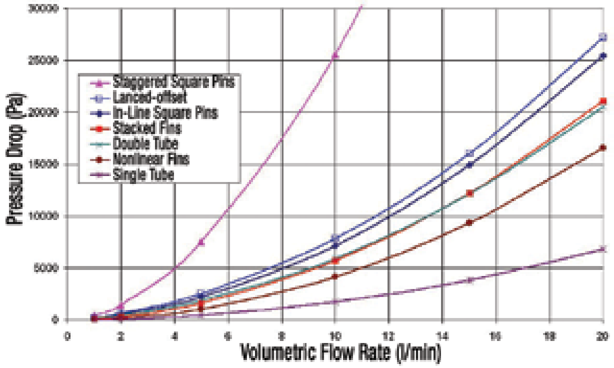


Figure 3

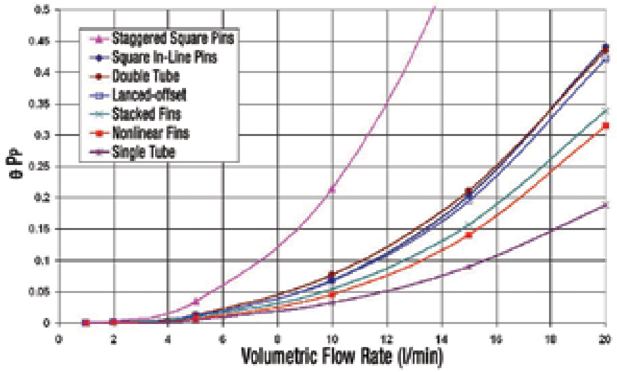


Figure 4

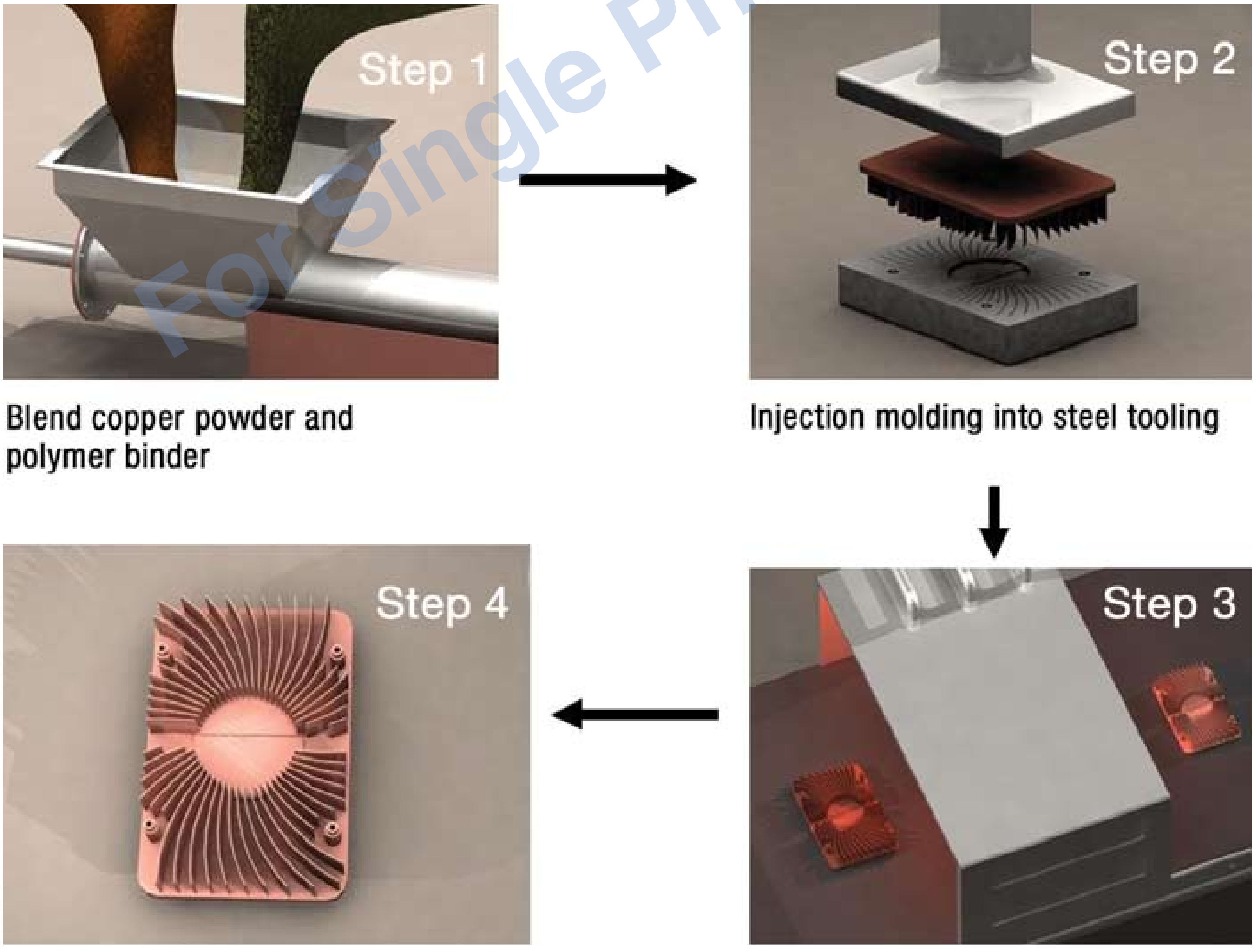
fin array. MIM is one of the most flexible. Using combined patented and proprietary technology to address thermal management challenges in the computing and other industries, MIM injection-molding technology was developed by Amulaire Thermal Technology.

Figure 5 shows the sequence used to make a MIM part. First, a mixture of powdered metal and polymer binders is molded into the desired shape. The part is removed from the mold and sintered at high temperatures to remove the polymer binders so that no extraneous material remains in the final product. Sintering also bonds the metal particles. During sintering, while the polymer binder debinds and vaporizes, the parts shrink in a uniform and controlled manner. Usually a net shape is achieved with no need of further processing.

Cold plates made using this MIM process can have more pin fins to increase the surface area of the cold plate, and they can have highly complex nonlinear fin patterns. One recently developed cold plate, for example, contained 5,000 pin fins in a 5 x 5 inch area. Amulaire has also designed compact and unique fin pattern solutions for dissipating nearly 6,000 W, utilizing the MIM process, as shown in Figure 6.

Figure 7 shows a top view of the flow field of the optimized nonlinear fin array utilizing an impingement flow pattern used in this simulation. Each fin is individually designed to take advantage of the existing direction of fluid flow, minimizing pressure drop while offering an optimized heat transfer surface area. The inlet coolant flow impinges at the center of the fin pattern. Round pins at the center transfer heat directly from the hottest part of the IGBT module into the fluid area of the cold plate having the highest fluid velocity and highest heat-transfer coefficient.

As the fluid moves outward from the point of impingement and the velocity decreases, the round fins change shape to ellipses to take advantage of the direction of fluid flow and offer more



Blend copper powder and polymer binder

Injection molding into steel tooling

Take “green” part and send through sintering over

Polymer binder burns off, part shrinks 20%, and only copper remains

Figure 5

surface area. Although the surface area of each fin is greater in this area, the pressure drop does not increase greatly because the fluid is moving slower.

As the fluid approaches the exit ports, velocity starts to increase. Again the fins change shape, but from elliptical to round. At the same flow rate, this nonlinear design results in a significant reduction in maximum temperature from the lanced offset fin pattern of Table 1, which would be the typical choice used to cool the module. Because the objective of thermal management specialists is to eliminate problems in heat transfer at the component and system levels, these results show that a properly designed heat sink using a nonlinear fin array can make an important contribution to that goal.

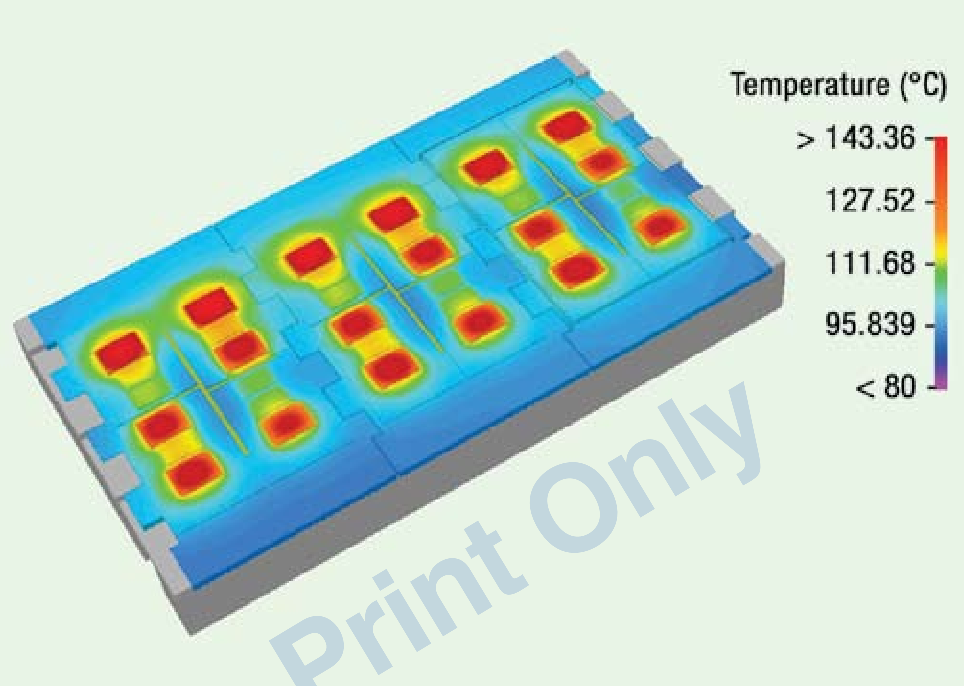


Figure 6

Increased reliability and performance

A recently developed MIM technology enables the development of cold plates for IGBTs with superior heat-dissipation capabilities. This new approach to IGBT cold plates has implications for both power-supply and motor-drive military applications.

As component designers work to in-crease the power capabilities of IGBT modules, it becomes more difficult for system designers to stay below the maximum temperatures specified in the manufacturer's data sheets. As temperatures are reduced, reliability and available performance increase. For example, some data shows that reducing the junction temperature 50 ˚C can lead to a 33x life extension (6,000 cycles at 100 ˚C, 200,000 cycles at 50 ˚C). Increasing the level of fin sophistication from standard machined fins to nonlinear fins can put these levels of performance and reliability within the reach of system designers at a competitive price point.

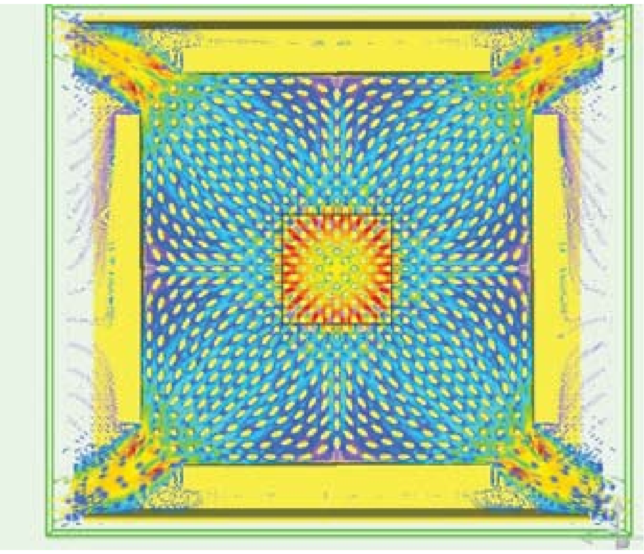


Figure 7

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