Reticulated Metal Foams Build Better Heatsinks

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An alternative to conventional finned heatsinks and coldplates, blocks of RMF material can provide greater cooling for power modules with high levels of power dissipation.

As power-component technology advances, thermal-management issues threaten to limit the performance of devices such as discrete semiconductors, hybrids and modules. As their power dissipation rises, it becomes increasingly difficult to cool these devices. In some cases, the inability to cool them may force designers to derate the devices' performance by reducing current or switching speed. Or designers may be forced to employ higher-voltage devices that are less efficient and more expensive.

Ultimately, these compromises in design may increase the size, weight or cost of the application. Although thermal-management techniques such as heat spreading may be applied to reduce high heat fluxes, this approach may increase the size of the thermal base on which the power devices are attached, resulting in increased [illegible]connect size and parasitics.

A better approach is to transfer higher heat fluxes to the ambient by improving the performance of the heatsink and by reducing or eliminating soft thermal interfaces. One of the new technologies capable of accomplishing these goals employs a class of materials known as reticulated metal foams (RMFs). Developed more than 20 years ago for structural applications, RMFs are now being applied effectively to thermal-management problems in electronic systems.

Unlike conventional finned heatsinks, RMF-based heatsinks consist of blocks of the RMF that are either brazed or soldered to a substrate material, which may be semiconductor, ceramic or metal-matrix composite. When compared with finned heatsinks, the RMF-based heatsinks offer improved thermal performance, smaller size, lighter weight, lower cost versus performance and other advantages.

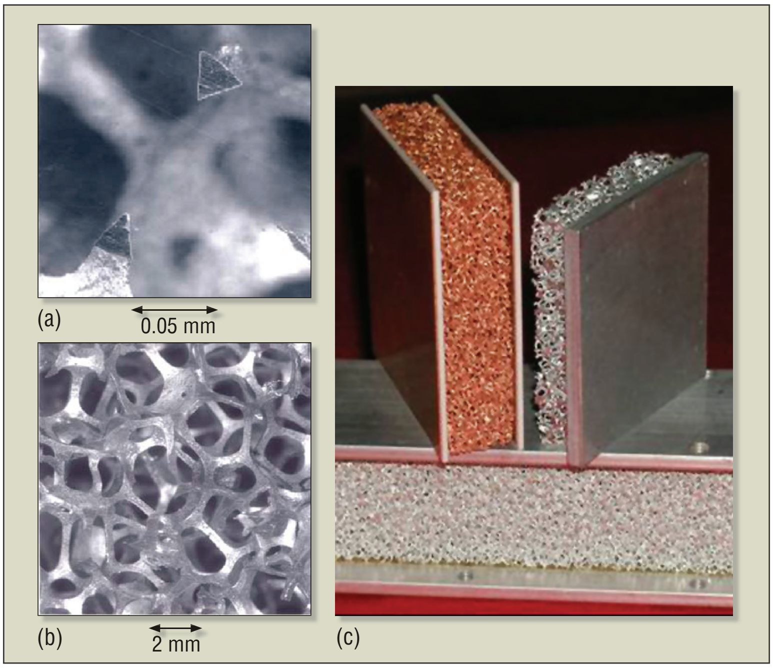

Fig. 1. *This 30-pores per inch (PPI) metal foam consists of nodes and ligaments that form a dodecahedron of 12 pentagon-shaped facets as can be seen when the material is viewed under magnification (a and b). Blocks of RMF are either brazed or soldered to a substrate to form heatsinks (c).*

Material Properties

RMFs are available, among others, in pure, highly conductive metals such as aluminum and copper (see **Fig. 1** for the physical structure of RMF).[1-2] The metal foam-based thermal technology is generic, flexible and scaleable. It is generic in terms of its compatibility with the cooling media, allowing it to be used with distilled water, inert fluoro-carbons, jet fuel, air, helium or argon.

The technology is flexible in terms of its compatibility with various semiconductor devices and substrates such as alumina, silicon carbide, aluminum nitride and beryllium oxide, as well as many other ceramic metallic or composite materials. RMF technology is also scaleable in size and performance so that it can be applied not only to discrete devices, but also to power electronics modules including hybrid multichip modules (HMCMs), as well as integrated photonic and electronic devices, and also to double-sided pc boards attached onto both sides of a hollow core section with built-in flow passages for thermal and structural purposes.

In the as-fabricated state, the isotropic RMF consists of randomly oriented polygon-shaped cells that can be approximated by a dodecahedron (**Fig. 1**).[3-5]

Notice that the cross sections of the ligaments are triangular. The small size of the ligaments of RMF does not allow boundary layers to grow and introduce enhanced mixing through eddies and turbulence. These features result in higher local convective heat transfer rates, since the thermal boundary layer is thinner. The thermal resistance to convective heat transfer remains low.

Thermal Characteristics

The as-fabricated specific density — which is the ratio of the weight of RMF foam to that of solid metal from which RMF is made — of RMF (5% to 10%) may be increased by successive compression and annealing steps. The compression increases the specific surface area, local convective heat transfer, effective thermal conductivity in the direction perpendicular to the plane of compression and flow resistance of the RMF matrix. The amount and direction of compression, as well as the initial pore size and relative density, are the variables that allow the properties of RMF to be tailored to a given application, creating a heatsink with performance optimized for the application.

The high-aspect ratio of the axial dimension to the radial dimension of RMF ligaments promotes linear and nonlinear buckling and the low-yield stress of pure metal ligaments. These effects reduce the effective elastic modulus of RMFs to a few kilo-pounds per square inch. Furthermore, an RMF block may be sliced to smaller sized pieces before brazing or soldering attachments to the heat-generating surfaces with low coefficients of thermal expansion (CTE). These surfaces may be semiconductors, ceramics or metal-matrix composites, and the ability to attach smaller blocks of RMF to these surfaces means that thermal stresses are further reduced.

The issue of mechanical stresses becomes important when considering the reliability of the attachment of the heatsink to the thermal base or substrate. The substrate is usually a metalized ceramic plate that directly attaches to semiconductor devices. Because RMFs limit their own material deformations and reduce thermal stresses associated with CTE mismatch from the heatsink to the substrate, the reliability of the heatsink attachment to the substrate is improved versus that of conventional heatsinks. Such reliability has been verified by testing RMF-based heatsinks over hundreds of thermal cycles.[6]

When compared with other types of compact heatsinks,

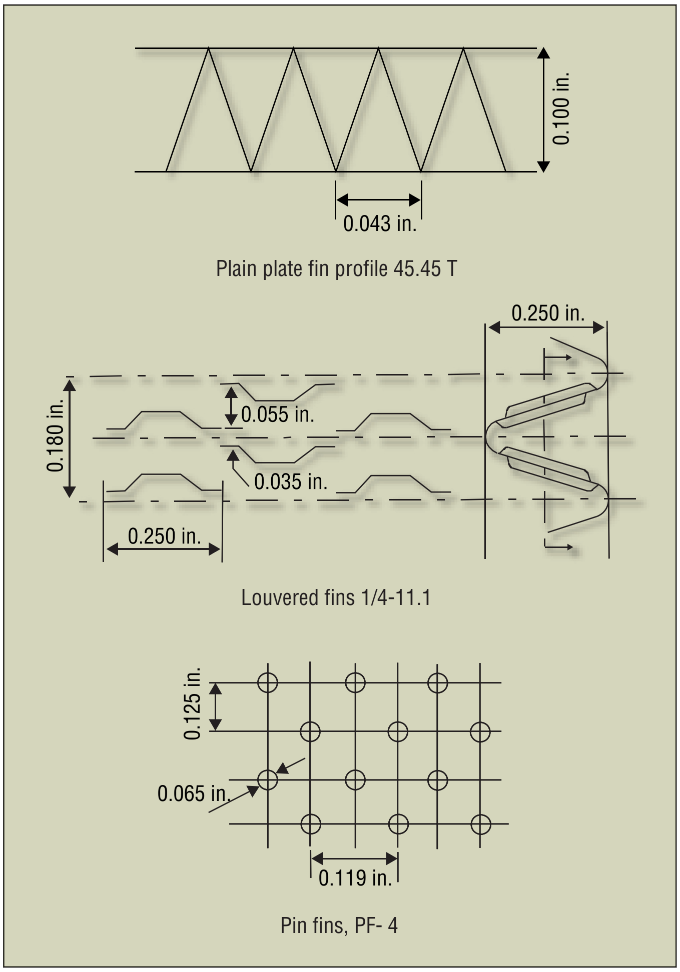

Fig. 2. *The performance of RMF-based heatsinks may be evaluated using three types of heatsink surfaces associated with conventional heatsinks.*

RMF-based heatsinks offer significant advantages including large specific surface areas (one cubic inch of a RMF may offer up to 400 in^2 extended surface area), superior and scalable thermal performance, and low weight, volume and cost per performance. Other benefits include compatibility with a wide range of coolants, high structural compliance and specific stiffness, and high resistance to corrosion.

RMF Performance Potential

The thermal performance of RMF-based heatsinks increases with the density and thickness of the RMF. The thickness effect levels off because of the fin efficiency considerations, and the density effect is limited by flow resistance. Convective film coefficients and the thermal conductivity of RMF also affect the thermal performance.[2] The maximum-possible (theoretical) thermal performance of RMF heatsinks was calculated using the maximum-attainable local film coefficients[7] of 0.01 W/(cm^2×°C) and 1 W/(cm^2×°C) for forced convection with air and water, respectively. The results[2] show that the maximum flat-plate-equivalent thermal performance of aluminum RMF heatsinks is 6 W/(cm^2×°C) and 48 W/(cm^2×°C) using air and water as the cooling

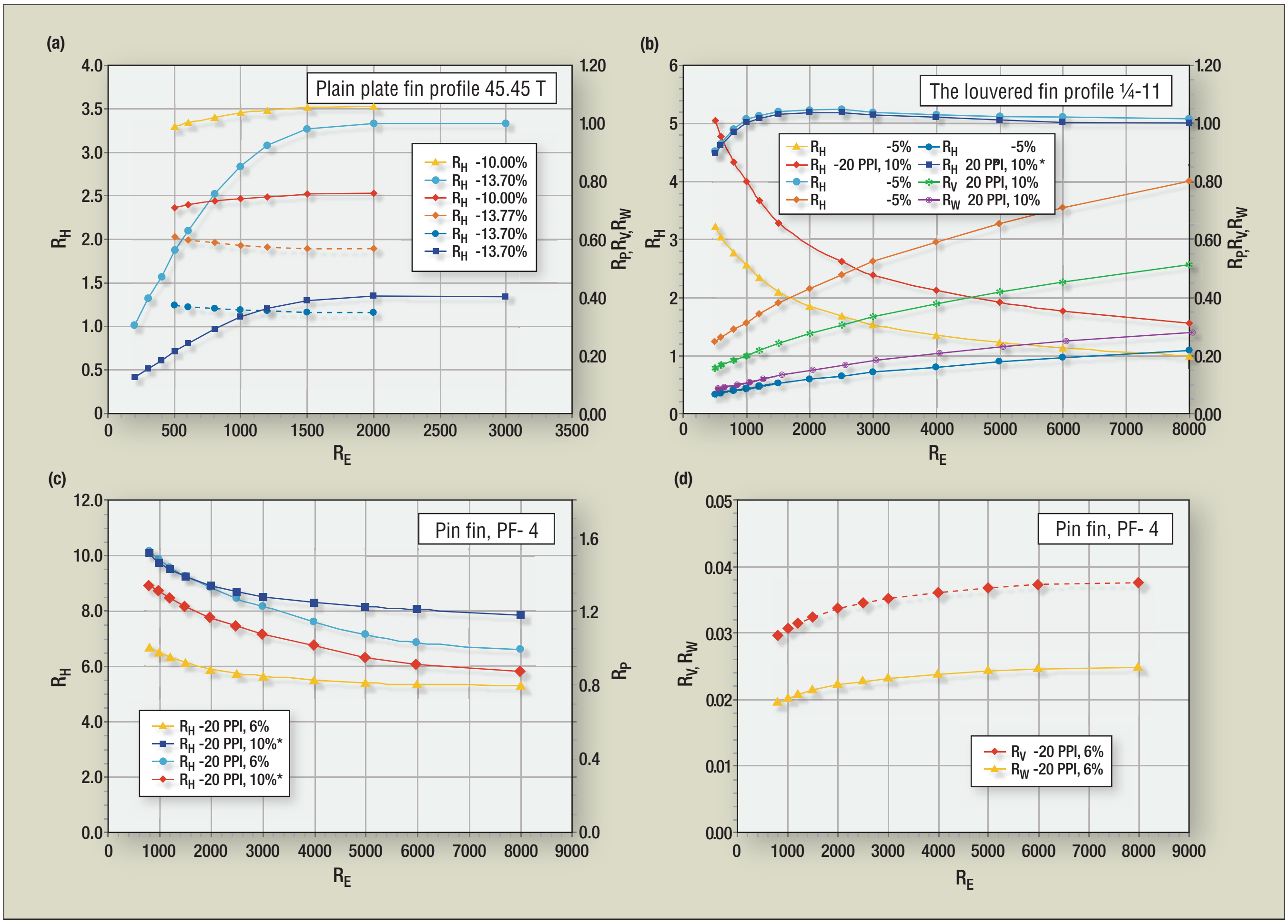

Fig. 3. *The performance of RMF-based heatsinks is compared with that of conventional heatsinks for four fin profiles.*

media, respectively. These performance numbers are rather conservative since the actual values of local film coefficients as measured with RMF-based heatsinks may be up to four times higher than those reported in the literature.[7]

Comparisons

At this point, it is important to know how the performance of RMF-based heatsinks compares with that of heatsinks built using conventional materials. Let's consider a few of the high-end commercially available heatsink options using either plated fins or pin fins.

Fig. 2 depicts three types of extended heatsink surfaces (fin geometries)[8] that provide a basis for measuring the performance of RMF-based heatsinks with conventional types. Comparisons are based on the R_H, R_P, R_V and R_W ratios, which are defined in the **table**.

For all comparisons, the friction factor (f) and the Colburn factor (j) were taken from test data reported by Kays & London[8] for pin-fin and plate-fin heatsinks, and from similar tests conducted in the ~~ERG~~ and Northrop Grumman laboratories for the RMF-based heatsinks.[1] Although the thickness of pin-fin and plate-fin profiles are different for each geometry, the thickness of RMF for all cases is 0.200 in.

In **Fig. 3a**, the comparison of RMF-based heatsinks with plain plate-fin profile shows that the relative performance of RMF slowly increases with Reynolds number (R_E) for the

Term	Definition
h_{EFF}	Effective film coefficent (scaled for the coldplate area of the heatsinks). This is the amount of heat per unit area (W/cm²) transferred for a 1°C difference in temperature between the heatsink and cooling medium. $h_{EFF} = h_L \times \eta_F \times (A_{HT}/A_B)$.
h_L	Local film coefficient
A_{HT}	Total heat-transfer area
A_B	Base area
η_F	Fin efficiency factor
R_H	Ratio of the effective film coefficient of foam to fin
R_P	Ratio of the pressure drop (psid) of foam to fin
R_V	Ratio of the core volumes of the aluminum RMF-based heatsink to fin-based heatsink, both dissipating 1 W. Heatsinks use the same mass flow rate and have the same temperature difference (ΔT=1°C) between the base and the coolant (air).
R_W	Ratio of the weights of the aluminum RMF-based heatsink to fin-based heatsink.

Table. *Definition of terms.*

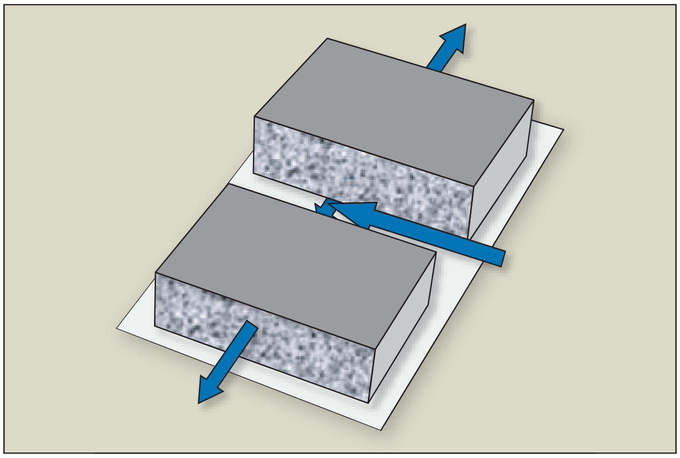

Fig. 4. *Dividing a large foam block into two reduces the drop in air pressure across the heatsink.*

final compressed densities (ρf) of RMF, which are 13.7% and 10%, respectively. The initial as-fabricated density (ρi) of RMF is 5%.

As **Fig. 3a** reveals, the RMF thermal performance approaches 3.5 times and 2.5 times that of fin profile 45.45T at R_E = 1000 and above. The pressure drop approaches 100% and 40% of that of 45.45T for the same foam densities, respectively. The volume and the weight ratios are 60% and 40%, respectively, at R_E of 500. Both these ratios are slightly reduced at higher Reynolds numbers (R_E) as shown in **Fig. 3a**.

The louvered fin profile ¼-11 comparisons of **Fig. 3b** use 20-pores per inch (PPI) and 30-PPI RMFs. The densities of RMFs are 5% and 10% for the 30-PPI and 20-PPI foams, respectively. The 20-PPI foam has somewhat lower thermal performance and lower flow resistance compared to the 30-PPI RMF as shown in **Fig. 3b**.

The unit extended area densities are 6.9 in^2/in^3-% and 5.3 in^2/in^3-% for 30-PPI and 20-PPI foams, respectively.[1] Therefore, the surface densities of RMF used in this comparison are 34.5 in^2/in^3 and 53 in^2/in^3 for the 30-PPI and 20-PPI foams, respectively. The thermal performance ratios are 5.1 times and 3.2 times at R_E = 500, and they approach 1.5 times and 1 time at R_E = 8000 for 20-PPI and 30-PPI foams, respectively.

The relative thermal performance of the louvered-fin profile increases with the R_E number and asymptotically approaches the values given previously. The flow-resistance comparisons show that at R_E = 500, the RMF heatsink design has 90% of the flow resistance of louvered fins, but this ratio steadily increases and reaches up to 120% at R_E = 2000. Meanwhile, the R_P ratio is reduced to 100% at higher R_E numbers.

The RMF heatsinks employed a single block and two parallel blocks of foams (**Fig. 4**) for 30-PPI and 20-PPI foams, respectively. This approach demonstrates the design flexibility of RMFs. The flow resistance of RMF heatsinks may be reduced using the flow-partitioning technique to meet design requirements where high performance and a low-pressure drop are needed.

For the 30-PPI foam, the volume and weight ratios are 22% and 10%, respectively, at R_E = 500, and they increase to 80% and 22% at R_E = 8000. The same ratios are 18% and 23% at low R_E number, and 50% and 28% at high R_E number for the 20-PPI foam-based heatsinks.

Comparisons of the RMF-based heatsinks with pin-fin heatsinks show that the foam-based heatsinks have 10 times and 6.5 times the thermal performance of pin fins at R_E = 1000 as shown in **Fig. 3c**. However, the relative performance of the pin-fin geometry steadily increases with the R_E number, and the R_H ratios reduce to 8 times and 5 times at R_E = 8000 for the 10% and 6% dense 20-PPI foams, respectively.

The flow resistance of RMF heatsinks is higher at low Reynolds numbers: 1.5 times and 1.3 times for 6% and 10% dense 20-PPI foams, respectively. The relative flow resistance of RMF reduces with the R_E number, and the R_P ratio reaches 100% and 70% (100% at R_E = 4000) at R_E = 8000. The 20-PPI 10% dense foam-based heatsink uses two parallel blocks for flow portioning, which reduces both the

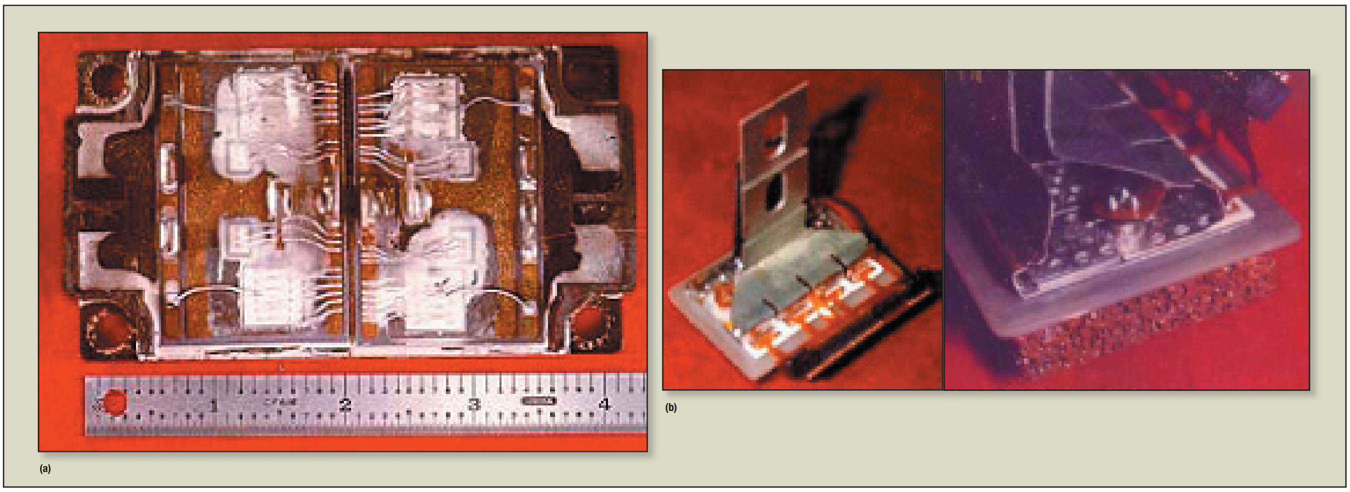

Fig. 5. *A half-bridge power module cooled by an external coldplate (a) is outperformed by a higher-power half-bridge cooled by an integral RMF-based coldplate (b). (Courtesy of SPCO).*

thermal performance and the flow resistance at any given value of R_E number. However, the volume and weight ratios are extremely low for both the 10% and 6% dense 20-PPI foam-based heatsinks as shown in **Fig. 3d**.

Application Example

The application of RMF-based heatsinks to commercial and military power modules such as those used in battery-power converter (BPC), inverter-converter control (ICC), etc., may offer significant advantages with respect to cost versus performance, and volume and weight. For example, in **Fig. 5** there are two ~~BPCs~~ — one is cooled by a standard, off-the shelf plate-fin coldplate (part a) and another is cooled by an integral, RMF-based coldplate (part b).

In **Fig. 5a**, the ~~BPC~~ consists of a state-of-the-art half-bridge 600-V, 200-A IGBT power module that dissipates 300 W. The unit has a coldplate area of 10.5 in^2, resulting in a packaging efficiency of 15%, which means only 15 % of the coldplate area is used for power devices. The weight of the power module is 4.5 lbs without the coldplate and 12 lbs with the coldplate.

Compare those values with those of the 1200-V, 400-A half-bridge power module mounted to an RMF-based heatsink (**Fig. 5b**). This unit dissipates 800 W continuous, or more than twice the rated power of the first half bridge. Moreover, it has a peak power dissipation of 2.5 kW. In this design, the base area is 3.5 in^2 for a packaging efficiency of 45%. This unit weighs just 1.2 lbs with the coldplate attached. In addition, the RMF-based coldplate also supports wireless interconnect technologies (that do not use wire bonds for power-module interconnections) to further reduce parasitics.[2] **PETech**

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