Choosing and Fabricating

a Heat Sink Design

For data and voice communications, speed is now the driving factor in the market. As a result, high frequency devices have become a major element for meeting consumer demands. Further, by combining higher packaging density and intelligent (software driven) PCBs, there is much more power dissipation at both the component and board levels.This situation creates great opportunities and significant challenges for thermal management and electronics packaging.

A first step in addressing thermal challenges is to consider heat sink choice and design. Looking at the market, we find a strong presence of extruded heat sinks which can provide only limited thermal performance. Old or off-the-shelf extruded heat sinks do not meet the stringent temperature requirements of today's ASICs. There's a sore need for high performance heat sinks that can expand the envelope of heat dissipation in current and near term electronics. With many different types of heat sinks available, the question is: what type of heat sink is suitable for my application?

Heat Sink Types

The general function of a heat sink is the same, irrespective of its fabrication process. Thus, we can distinguish between heat sinks by their manufacturing method.

Heat sinks fall into three broad categories:

1. Plate-fin: suitable for generally straight airflows
2. Pin-fin: suitable for omni-directional airflow
3. Foam-fin: suitable for ducted airflow (high pressure drop)

Excluding foam-fins, there are a number of high volume manufacturing processes for creating a heat sink fin field on a flat surface. Many articles are available that describe the details of such manufacturing techniques. Therefore, they are not covered here. Table 1 highlights the details of each manufacturing process.

Table 1. Definition of Different Heat Sink Manufacturing Processes [1].

Manufacturing Process	
Bonded	Individual fins are bonded with epoxy to a pre-grooved base
Convoluted (folded fin)	Fins are pre-folded and then brazed or soldered to a base plate
Die-Casting	Heat sinks are formed as a result of molten metal solidifying in a prefabricated die
Extruded	Molten metal is drawn through a die
Forged	Molten metal is pressed into a prefabricated mold to form the desired shape
Machining	Heat sinks are formed by the machining process
Single Fin Assembly	Individual pieces of fin and spacer material are stacked and then brazed to create the desired shape
Skived	Fins are "skived" from a solid piece of material
Stamped	Metal stamped to form a particular shape
Swaged	Individual fins are placed in a pre-grooved base, then a roller swages the sides of the fins to keep them in place

The pros and cons of each manufacturing technique are presented in Table 2.

Table 2. Pros and Cons of Different Heat Sink Manufacturing [1].

Type	Best for	Resistance	Pros	Cons
Bonded	Large applications	High	Close tolerances	Expensive
Convoluted (folded) fin	Ducted air	High at low flows and low at high flows	High heat-flux density	Expensive, needs ducting
Die-cast	Low power applications	High	Can be inexpensive	Low thermal conductivity and expensive die charge
Extruded	Most applications	Varies	Versatile	Limited size
Forged	Many applications	Moderate	Inexpensive	Limited in design and flow management
Machining	Prototypes	Design dependent	Quickly available for testing	High aspect ratio fins difficult to machine – inconsistent fin geometry
Single Fin Assembly (SFA)	All applications	Very low	Light weight and low profile with high degree of flow	Expensive
Skived	Many applications	Moderate	Close tolerance	Thick base, higher weight, directionally sensitive
Stamped	Low Power	High	Inexpensive	Low performance
Swaged	High power applications	Medium	Good for power devices	Heavy and bulky, limited ability for flow management

Figure 1 shows examples of heat sinks produced using some of these manufacturing methods.

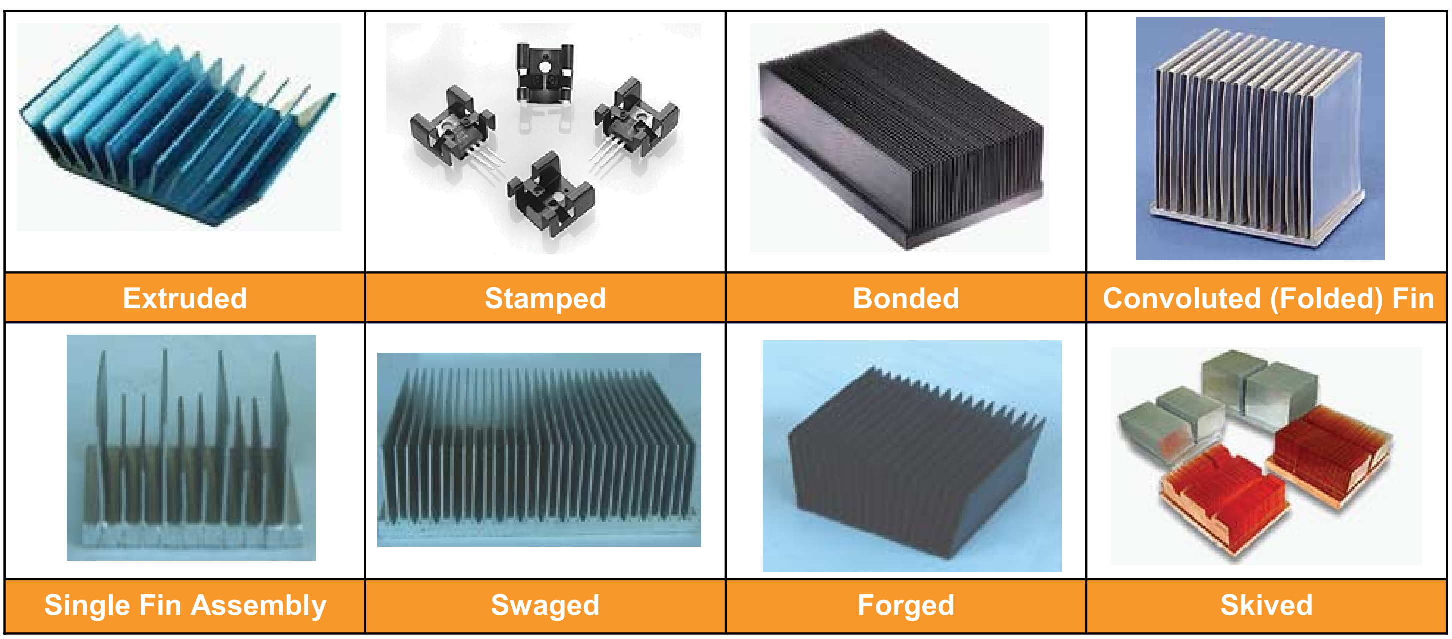

Figure 1. Heat Sinks Fabricated Using Different Manufacturing Processes [1].

Figure 2 shows some of the details of these manufacturing processes, e.g. skiving and bonding fins.

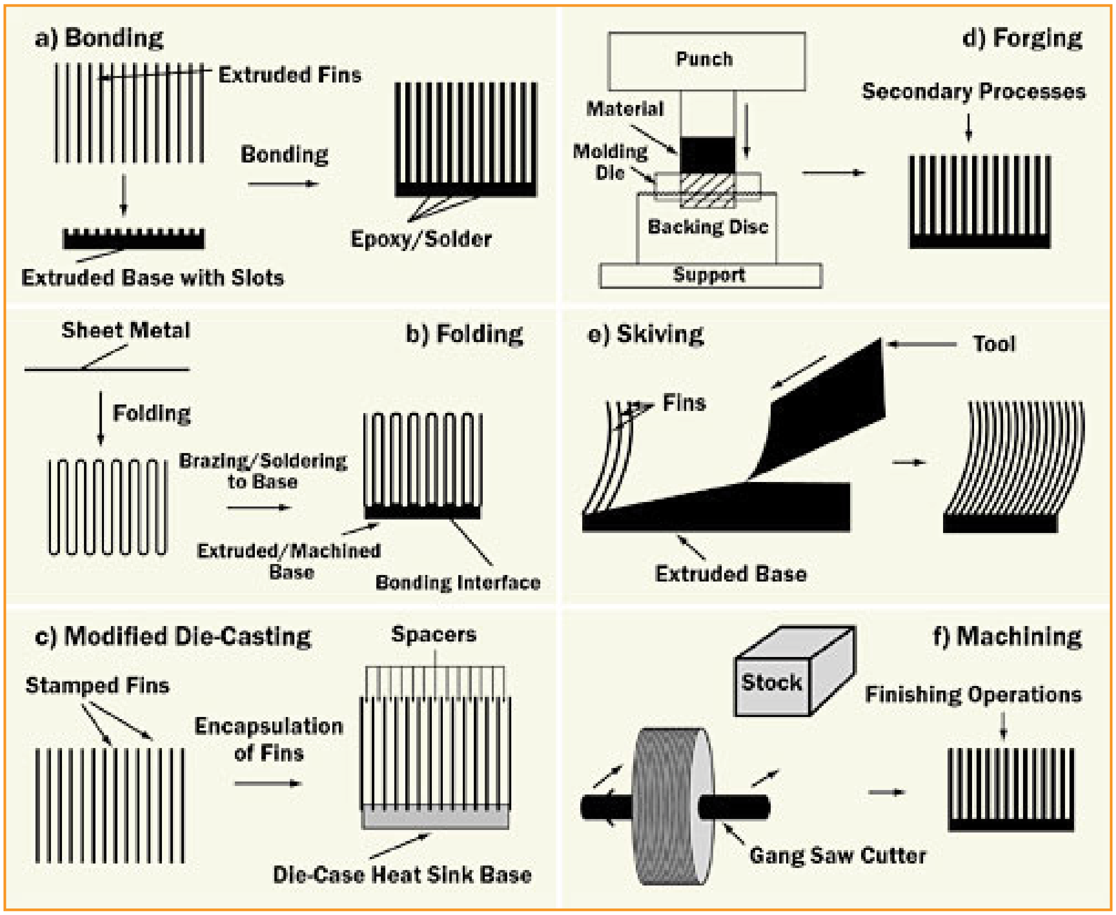

Figure 2. Details of Some of Heat Sink Manufacturing Processes [2].

The manufacturing process has a direct impact on a heat sink's thermal performance. This stems from the number of fins that can be produced by a given manufacturing technique and from the interfacial resistances created when using that process. Bonded fin and swaging assembly techniques introduce a third material between the fins and the base. Single-fin assembly (SFA) places a third material in between the fins. Although SFA is a brazing process and the metallurgical joints very close to solid, nevertheless, all three of these techniques are impacted by the presence of the third material. Among other methods, stamped, extrusion and die-casting are perhaps the oldest technologies for high volume production. Most heat sinks on the market are made by such processes.

More recent heat sink fabricating methods were developed to meet the need for more fins on a flat surface. SFA, micro die-casting and forging produce higher performing heat sinks suitable for high power application. Of the three, SFA can produce the highest number of fins per linear length because of its manufacturing process. (Advanced Thermal Solutions has made SFA heat sinks with 26 fins per cm, or 67 fins per inch.). Manufacturing technology has advanced enough to produce high aspect ratio as well as high fin count heat sinks.

Salient Features of High Performance Heat Sinks

A desirable cooling solution for modern electronics is a lightweight heat sink with low thermal resistance at low air velocities. Because the noise from moving the air through electronics enclosures is an issue, the low thermal resistance at low air velocities is an attractive feature. Hence, two parameters are key when considering a heat sink: high fin count and management of air flow movement through the fin field.

As the number of fins increase, the air flow resistance of the heat sink also increases. This implies that by managing the flow through the fin field, significantly higher thermal performance (lower case-to-ambient resistance) can be attained. Figure 3 shows the impact of design on flow through a fin field for three heat sinks with the same geometrical volume but different fin structures: the ATS maxiFLOW™, straight fin and folded fin.

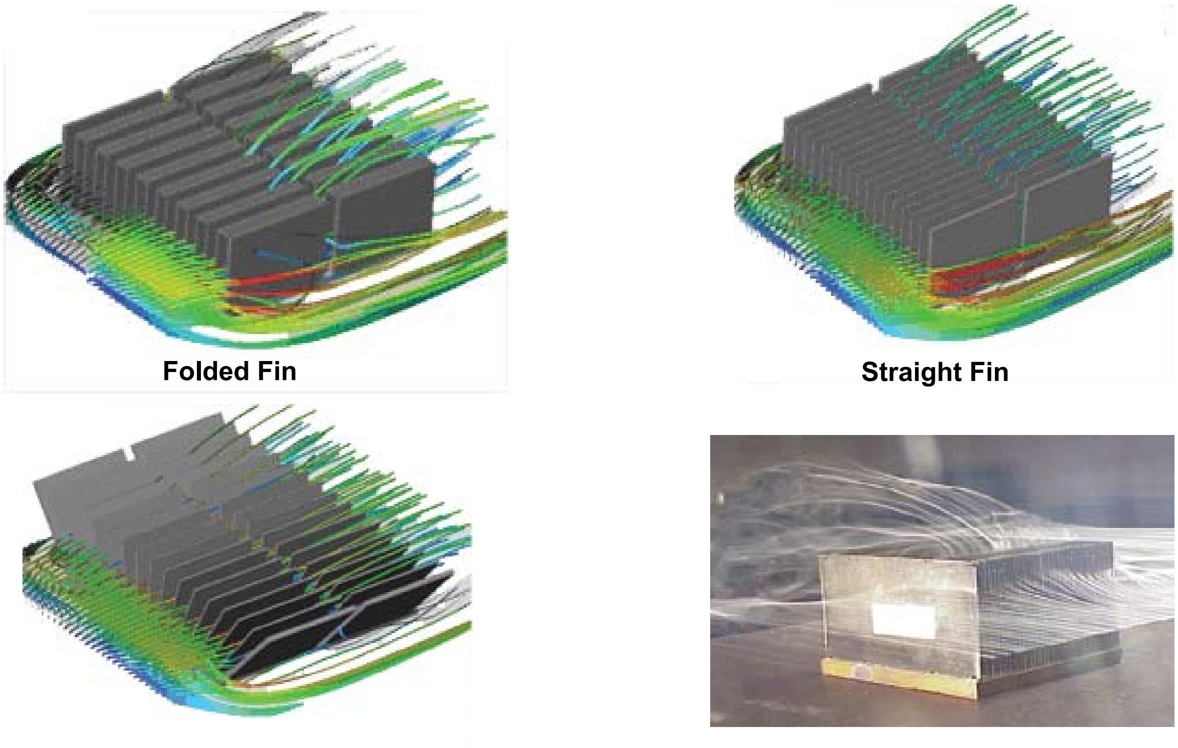

Figure 3. Computational Air Flow Visualization of an Unducted Heat Sink Showing the Premature Egress of Flow from the Fin Field, and Smoke Flow Visualization for the Straight Fin Heat Sink. The maxiFLOW™ Heat Sink Has the Least Egress and the Best Thermal Performance [1].

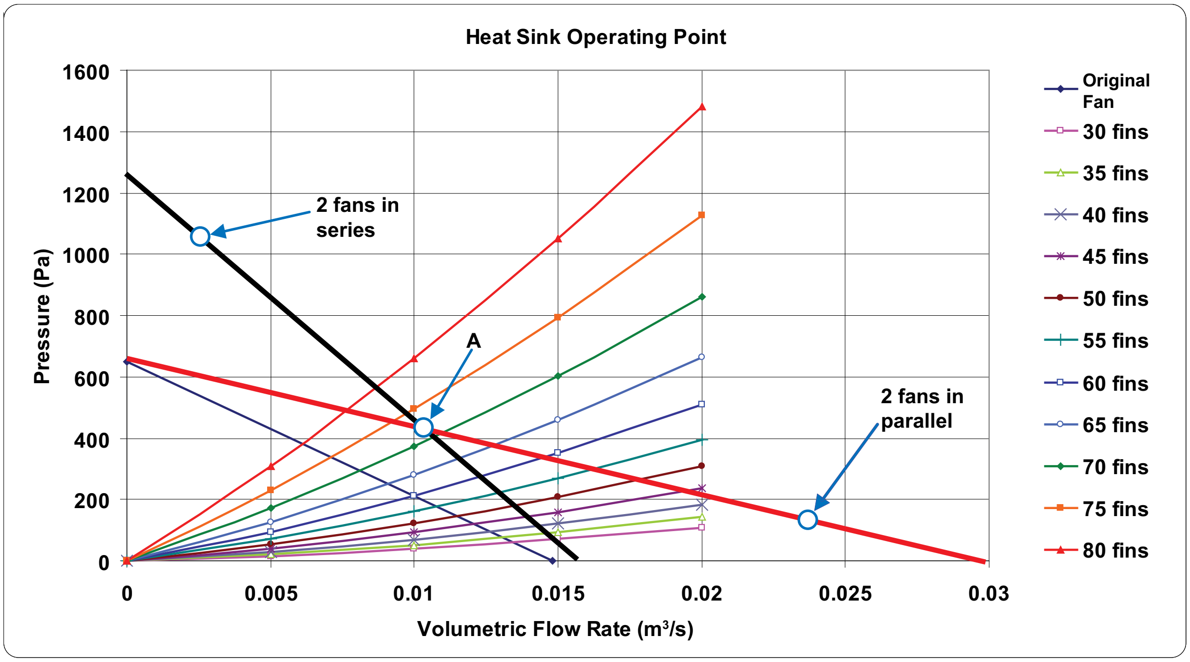

Figure 4. Thermal Resistance of an 80 x 80 mm Heat Sink as a Function of Number of Fins [3].

With a wide variety of heat sinks available, the question of which is the best is always daunting for an application engineer trying to solve the thermal issue. Figure 4, [3], shows that by just adding fins, one is not going to get a better performing heat sink. The selection is application dependent.

The figure clearly shows that even in a system with a fan tray (fans in parallel or series), as the number of fins increases, the pressure drop and subsequently the air flow through the fin field diminishes accordingly. Therefore, it is always best to calculate the base temperature of a heat sink in a given application to see whether the device thermal requirements are satisfied. Below, we show an analytical model for calculating the case temperature of a heat sink base. A control volume is placed on a single fin of a heat sink that resides on a component in a PCB channel with an adjacent PCB on top.

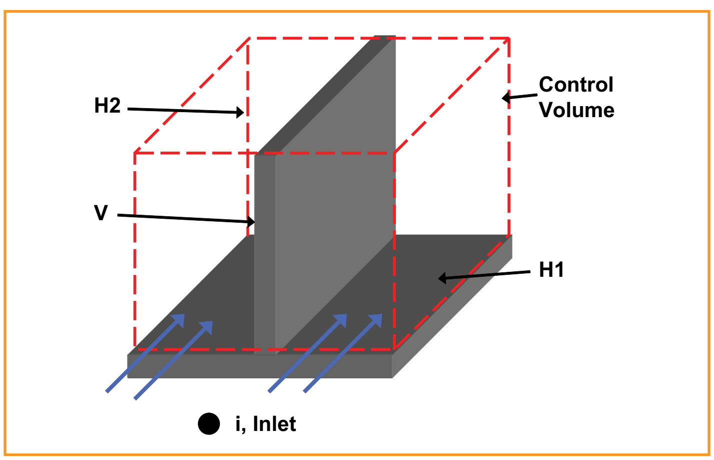

Figure 5. Control Volume on a Single Fin of a Heat Sink Where H and V refer to Horizontal and Vertical Surfaces, Respectively.

Let us apply conservation of energy to this control volume and place the appropriate heat transfer terms in this equation with P referring to the power coming to the heat sink from its base.

$$\dot{Q}_{in} = \dot{Q}_{out}$$

$$P = h_{H1}A_{H1}(T_c - T_m) + 2h_v A_v (T_{fin} - T_i) + h_{H2}A_{H2}(T_{f,t} - T_i) + R_r(T_{fin} - T_{ref})$$

Assume a high efficiency fin, hence, $T_{fin} = T_{f,t} = T_b = T_c$, and R_r is the radiation resistance. To calculate T_{ref}, assume that the heat sink is facing the adjacent board with power dissipation of $P_{adjacent}$

$$T_{ref} = T_{board} = \frac{P_{adjacent}}{hA_{board}} + T_i$$

And

$$Q_{H2} = R_2(T_c - T_i)$$

Where, T_m and T_c are defined by

$$T_m = T_i + \frac{P - R_2(T_c - T_i)}{2\dot{m}C_p}$$

And

$$T_c = \tfrac{1}{\gamma}(P + R_1 T_m + \zeta T_i + R_r T_{ref})$$

Where,

$$R_3 = h_V A_V \qquad R_1 = h_{H1} A_{H1} \qquad R_2 = h_{H2} A_{H2}$$

$$\zeta = R_2 - 2R_3 \qquad \gamma = R_l + R_2 + 2R_3 + R_r$$

Solve for T_c,

$$T_c = \left(\gamma + \frac{R_2}{2\dot{m}C_p}\right)^{-1}\left[P + \frac{R_l}{2\dot{m}C_p}\left(2\dot{m}C_pT_i + P - R_2T_i\right) + \zeta T_i + R_r T_{ref}\right]$$

The above equation provides an analytical expression for calculating a heat sink's base temperature per its in-situ boundary condition. As shown in Figure 4, the air velocity, V, approaching the heat sink is not only affected by the number of fins, but also by the system and PCB configuration. Once V is obtained, T_c can be calculated to ascertain whether the device thermal performance meets the stated objectives.

Summary

Thermal management of today's and tomorrow's electronics requires superior performance to meet the operational needs of a successful product. Combining innovation in both design and manufacturing has led to the development of next generation heat sinks. Despite the availability and high volume production of unique and exceptionally performing heat sinks, the thermal requirements of the component and the respective heat sink at the in-situ level must first be addressed before a heat sink or its fabrication is considered. The combination of analytical and computational tools has enabled engineers to assess this need before they consider a heat sink solution.

References

1. Advanced Thermal Solutions, Inc. Heat Sink Design and Characterization, Tutorial Notes, 2008.
2. Iyengar, M. and Bar-Cohen, A., Design for Manufacturability of SISE Parallel Plate Forced Convection Heat Sinks, IEEE Transactions on Components and Packaging Technologies, Vol. 24, No. 2, 2001.
3. Advanced Thermal Solutions, Inc., Qpedia eMagazine, November 2008, Limit of Heat Sink Thermal Resistance for a Ducted Flow.