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Characterization of Mixed Metals Swaged Heat Sinks for Concentrated Heat Source

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ABSTRACT

The present experimental study investigates the thermal performance of four heatsink combinations based on the forced convection heat transfer mode. The four designs consist of an all Aluminum, all Copper, Copper baseplate/Aluminum fin and Aluminum baseplate/Copper fin heatsink. Each heat sink combination was tested in pairs of heatsinks placed within a vertical wind tunnel of Plexiglas walls such that the fins were positioned vertically and parallel to the airflow inside the tunnel. A block heater providing 800 watts and covering 10% of the baseplate was placed in between two identical heat sinks. Experiments were performed for Reynolds number ranging from 1000 to 4000, which corresponds to an approach velocity ranging from 2 m/s to 8 m/s. This Reynolds number was based on the fin spacing. The average rise in temperature of eight measured locations was used to calculate the thermal resistance. The all Copper heatsink provided the lowest thermal resistance of 22% compared to the all Aluminum heatsink thermal resistance. The Copper-Base/Aluminum-Fin and Aluminum-Base/Copper-Fin heatsinks showed very close thermal resistance results for identical approach velocities. The experiments show that there is an improvement of 11.4% in the performance of the Copper-Base/Aluminum-Fin heatsink due to the higher conductivity of the Copper base. The experiments show that the thermal performance can be improved 8.5% by increasing the thermal conductivity of the fin material, as in the case of the Aluminum-Base/Copper-Fin heatsink.

INTRODUCTION

High temperature and heat dissipation are the factors currently limiting electronic system capabilities. There are two primary applications that require heatsinks: the microprocessor at the PC board level and Power Electronics. With the trend of decreasing package size and increasing heat dissipation, the heat flux therefore also increases. In order to reduce the heatsink thermal resistance, designers use materials with higher thermal conductivity than Aluminum, such as Copper. The use of such metals as in Copper fin/ Aluminum baseplate, Aluminum fin/Copper baseplate and all Copper sinks, help to improve heat spreading.

For low power dissipation and low heat flux applications, extruded heatsinks are the most commonly used sinks due to its cost effectiveness. However, the extrusion process has limitations (H.W. Chu, C.L. Belady and C.D. Patel). When producing high aspect ratio fins, the extrusion die breaks more readily as the fin thickness and fin spacing decreases. For high power dissipation and high flux applications, bonded heat sinks with high aspect ratio can be used. For high volume applications, the die-casting manufacturing technique is an alternative due to its low averaged cost. It should be mentioned that high porosity and low purity alloys result in lower thermal conductivity products.

In heatsinks with bonded fins, the base is extruded with slots to allow the insertion of plates or extruded fins. Attaching the fins to the baseplate can be done using thermal epoxy, brazing or "swaging." Thermal epoxy is the common method used to bond high aspect ratio heatsinks. However, epoxy possesses a very low thermal conductivity as compared to Aluminum so that the thickness should be minimized in order to minimize its thermal impedance. Brazing is a subgroup of welding that takes place at temperatures above the liquid state of a filler material (450^{o}C) and below the solid state of the base materials. Capillary action plays a major role in filler flow through the joints.

The heatsinks tested in these experiments were bonded using a metal displacement process referred to as "Swaging" . The Swaging process, depicted in *Figure 1*, can be described as a cold forming process, which is used in the fabrication of high fin density heatsinks. Currently, this process involves the placement of fins with a tapered base into a slotted base plate and then the application of a rolling pressure on the opposite sides of each fin. This results in vertical and lateral pressure of the base unit material , which tends to push the fin toward the bottom of the groove in the base. This secure connection provides very good thermal contact between the fins and base and also prevents air and moisture from entering the grooves, thereby preventing corrosion and allowing the heatsink to be anodized.

EXPERIMENTAL APPARATUS AND PROCEDURE

Heatsink Description:

Four heatsink designs were tested. These were the Aluminum base/Aluminum fin (Al Base-Al Fins), Copper base/Aluminum fin (Cu Base-Al Fins), Aluminum base/Copper fin (Al Base-Cu Fins) and Copper base/Copper fin (Cu Base-Cu Fins) sinks.

Generally, the heatsink base plate area, fin height and fin-center-to center distance were the same for all heatsinks as can be seen from *Figure 2 & Table 1*. The Aluminum serrated fins were extruded with an overall average thickness of 1.2 mm and an average base thickness of 1.33 mm. The thicker fin base helps to secure the connection between the fins and the baseplate and results in good thermal contact through the swaging process. The extrusion process used to produce the Aluminum serrated fins is flexible enough to allow for different fin body and fin base geometries. For the swaging process involving the flat Copper fins, the (constant)Copper fin thickness was selected to be equal to the Aluminum fin base thickness of 1.33 mm. Copper fins were sheared from 1.33 mm thick rolled flat sheets. The rolling process used to produce Copper plates only allowed for fixed flat sheet*s*.

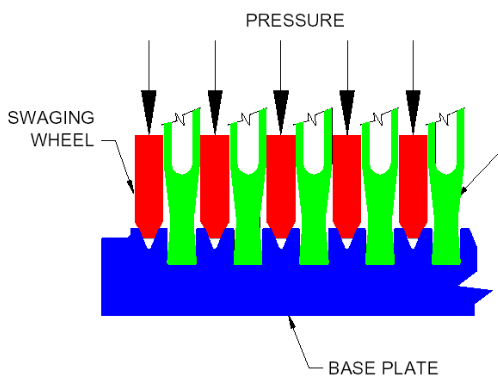

Figure 1: Swaging process

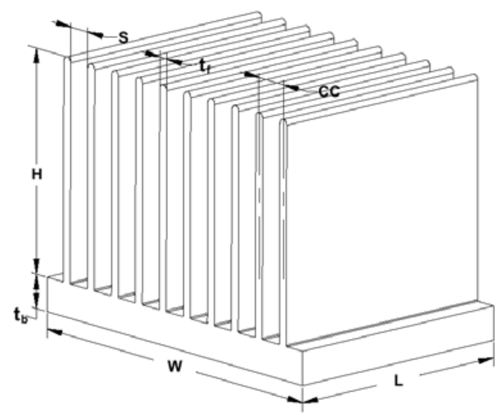

Figure 2: Heatsink geometry and dimensions

Table 1: Heatsinks geometries and dimensions

Heatsink Model	Al B- Al F	Cu B- Al F	Al B- Cu F	Cu B - Cu F
Baseplate Material	Aluminum	Copper	Aluminum	Copper
Fin Material	Aluminum	Aluminum	Copper	Copper
Fin Profile	Serrated	Serrated	Flat	Flat
Total Heat Transfer Area, A (mm^2)	472324	472324	472324	472324
X-Sectional Area of Fins, A_f (mm^2)	3786	3786	3786	3786
Base Length, L (mm)	127	127	127	127
Base Width, W (mm)	127	127	127	127
Base Thickness, t_b (mm)	12.7	12.7	12.7	12.7
Fin Height, H (mm)	49	49	49	49
Fin Thickness, t_f(mm)	1.2	1.2	1.33	1.33
Fin to Fin, C-C (mm)	3.43	3.43	3.43	3.43
Fin Spacing, S (mm)	2.23	2.23	2.1	2.1
Fin Height to Fin Spacing Ratio	22:1	22:1	23:1	23:1
Heatsink Weight, kg	1.3	2.5	3.2	4.4
Weight Ratio = (Heatsink Weight)/(Aluminum Heatsink Weight)	1	1.92	2.46	3.38

Heatsink Assembly

In order to minimize heat losses and accurately measure heat dissipation from the heat sink, matching pairs of each heat sinks were configured in a back-to-back configuration as shown in Fig. 3. The heat sinks were firmly bolted to heater plates using four countersunk machine screws at an equal distance from the center the schematic in Fig. 4. The surface area of each heater plate covers 10% of the heat sink baseplate.

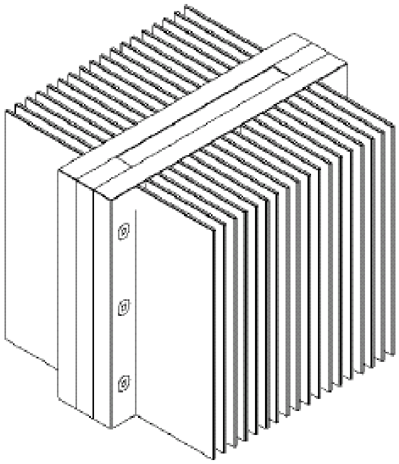

Figure 3: Heat Sink Back-to-Back Configuration

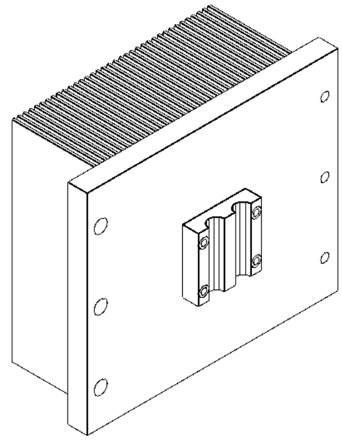

Figure 4: Heat Sink and Heater Plate

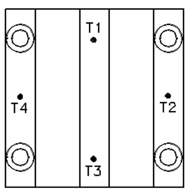

Figure 5: Thermocouple Locations on 10% Coverage Heater Plate

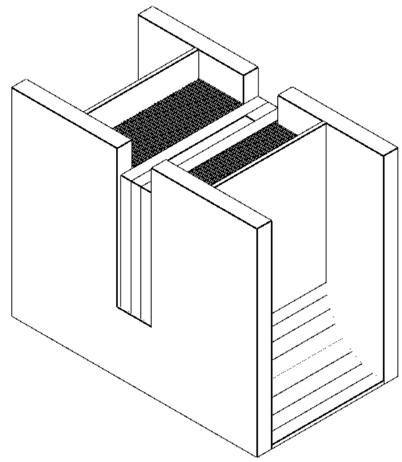

Figure 6: Testing Rig

Each of the bolts was torqued to 20 in-lbs using a consistent bolting pattern for all of the tests. The heat sinks were bolted together using six countersunk machine screws at equal intervals on the extruding edges of the assembly. A three-sided phonetic spacer was bolted between the heat sinks to minimize convection from the heater plates, as shown in Fig. 3. Two 400 W cartridge heaters were press fitted into four wells drilled into the heater plates, shown in Fig. 4.

Thermal grease was used in the interface between the heat sinks and the heater plates. Because of the symmetry of the assembly, it was assumed that the heat dissipated by the cartridge heaters was equally distributed between the two heat sinks. The heaters were powered using a Xantrex 150-7 DC power supply and typical line voltages of 120V at a current of approximately 6.6 A were supplied to the heaters. Temperature measurements were performed using 5 mil T-type copper-constantan thermocouples with Teflon coating connected to a Keithley 2700 data acquisition system (Leonard et al). Because of the small diameter of the thermocouple wires and the relatively large values of overall power dissipation, conductive losses through the leads were assumed to be negligible. Ambient temperatures in the test section were monitored using two thermocouples mounted just outside the main flow corridor. It was assumed that the spreading resistance between the heater plate and base plate was negligible and the heater plate temperature was taken as the base plate temperature. The heater plate temperature was measured in four interior locations on each of the heater plates indicated by locations T1-T4 in Fig. 5. The thermocouples were located on the heater plate so that an arithmetic average of their measured values would provide a representative value for the mean plate temperature.

The approach velocity to the heat sink assemblies was measured using a Dantec hot wire anemometer placed approximately 80 mm upstream of the leading edge of the heat sink assembly. The pressure drop across the heat sinks was measured from approximately 25 mm upstream from the leading edge to 25 mm downstream from the trailing edge using two Dwyer differential pressure transducers. The first transducer measured pressure drops between 0 and 250 Pa and the second measured pressure drops between 0 and 1250 Pa. The second transducer was only used when the pressure drop exceeded 250 Pa.

DATA REDUCTION

The thermal resistance, R_θ, was calculated as

$$R_\theta = \frac{\overline{T}_S - T_{amb}}{Q} \quad \textbf{(1)}$$

where

$\overline{T_S}$ *:* average temperature of the heatsink baseplate based on measurement of four thermocouples [K], shown in *Figure 8,*

$$\overline{T_S} = \left(\sum T\right)/4 \quad \textbf{(2)}$$

T_{amb}*:* ambient air temperature[K],
Q: heat transfer from a single heatsink rate [W],

The reduction in heatsink thermal resistance as compared to the thermal resistance of the all Aluminum heatsink was measured as follows:

$$\%R_\theta = \frac{R_\theta - R_\theta\big|_{Al\,B-Al\,F}}{R_\theta\big|_{Al\,B-Al\,F}} \times 100 \quad \textbf{(3)}$$

$R_\theta\big|_{Al\,B-Al\,F}$: thermal resistance of all Aluminum heatsink (Al B-Al F),

The Reynolds number of the fin channels' airflow, Re_S, was defined as

$$\mathrm{Re}_S = \frac{V_S \cdot 2S}{\nu} \quad \textbf{(4)}$$

ν*:* kinematic viscosity of air, [m^2/s]

V_S*:* air velocity in fin spacing,[m/s], $V_S = \overset{o}{V}\Big/(A_{WT} - A_f)$

$\overset{o}{V}$: Volumetric flow rate in the wind tunnel, [m^3/s]
A_{WT}: Wind Tunnel cross sectional Area, [m^2]
A_f*:* cross sectional area of the fins, see Table 1, [m^2]
S: width of fin channel i.e. fin spacing, see Table 1, [m]

RESULTS AND DISCUSSIONS

Performance of Heatsinks

The performance curves of all the bonded (via swaging) heat sinks are shown in *Figures 7 and 8*. Table 2 shows the percentage reduction in thermal resistance for the alternative metal heat sinks with respect to the thermal resistance of the all Aluminum heat sink for the full range of Reynolds number. As expected, the all Copper (Cu B-Cu F) heatsink possessed the lowest thermal resistance while the all Aluminum (Al B-Al F) had the highest. As shown in Table 2, the all copper heat sink can reduce the thermal resistance by 22%. This behavior is explained by the higher thermal conductivity of the Copper as compared to the Aluminum. This results in lower thermal spreading resistance in the baseplate, better heat conduction through the fins and higher over all heat transfer to the ambient air. It is worth mentioning that the all Copper and all Aluminum sinks represented the limiting cases of performance for these metal combinations.

Figure 7 shows the thermal resistance, R_θ, versus the fin channel Reynolds number, Re_S. For the Cu Base-Al Fin heatsink, the Copper baseplate decreases the thermal spreading resistance in the baseplate, which in turn helps to decrease the over all thermal resistance of the heatsink. Table 2 shows an improvement of 11.4% in the thermal performance in the Cu B-Al F due to the Low coverage (10%) of the heat source. With the Al Base–Cu Fin heatsink, the over all thermal resistance of the heatsink is decreased by 8.5% as the Copper used in the fins helps to increase the fins' efficiency. For Low source coverage, it can be concluded that the high conductive material is more efficient when it is used as base material than using it as fin material.

Table 2: Thermal resistance comparison of alternative metal heat sinks performance with respect to an all Aluminum heatsink.

Cu Base-Al Fins		Al Base – Cu Fins		Cu Base – Cu Fins	
Re_S	$\%R_\theta$	Re_S	$\%R_\theta$	Re_S	$\%R_\theta$
960	7.7	900	6.2	910	18.2
1460	9.9	1370	7.6	1390	20.7
1980	11.2	1850	7.9	1880	21.7
2490	12.0	2330	8.4	2370	22.6
3010	12.8	2810	9.1	2860	23.4
3530	12.8	3300	9.5	3350	23.3
4050	13.5	3790	11.1	3850	24.0
Average	11.4	Average	8.5	Average	22.0

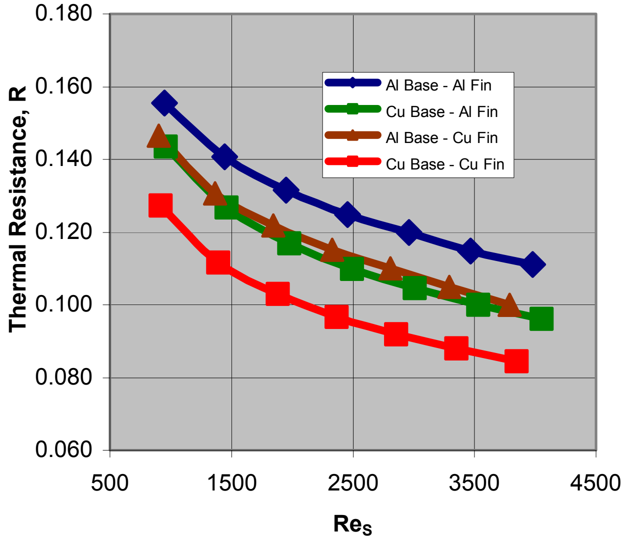

Figure 7: Thermal resistance vs. fin spacing Reynolds Number.

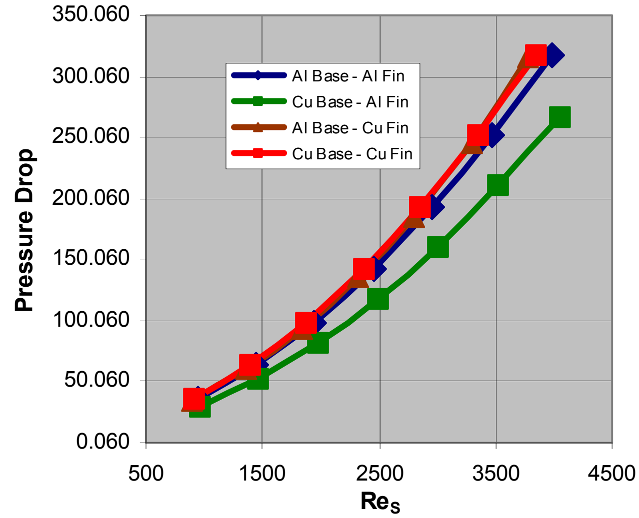

Figure 8: Pressure drop vs. fin spacing Reynolds Number

Figure 8 shows that the pressure drop through the Copper fin heatsinks (Al Base – Cu Fin & Cu Base-Cu Fin) is higher than the one going through the serrated Aluminum fin heat sinks (Al Base-Al Fin & Cu Base-Al Fin). From Table 1, the average thickness of the flat Copper fins is 1.33 mm while the average thickness of the serrated Aluminum fins is 1.2 mm. Due to this difference in fin thickness, the fin spacing, S, of the Copper fins is 2.1mm while that of the serrated Aluminum fins is 2.23 mm., which results in this higher pressure drop through the copper fins.

CONCLUSIONS

The thermal performances of the four-heatsink combinations under forced convective heat transfer mode have been performed for high source coverage of 10% of the baseplate surface area. The four designs comprise an Aluminum base/Aluminum fin (Al Base-Al Fin), Copper base/Aluminum fin (Cu Base-Al Fin), Aluminum base/Copper fin (Al Base-Cu Fin) and Copper base/Copper fin (Cu Base-Cu Fin) heatsinks. As expected, the all Copper (Cu Base-Cu Fin) heatsink had the lowest thermal resistance with 22% average reduction in thermal resistance as compared to the all Aluminum sink. However, the Copper heatsink possessed 3.4 times the weight of the Aluminum heatsink. Up to 8.5% reduction in thermal resistance was achieved by using an Aluminum base/Copper fin (Al Base-Cu Fin) sink with 2.5 times the weight. The Cu B-Al F heatsink had the lowest weight increase being only twice as heavy as the all Aluminum heatsink with a reduction in thermal resistance of 11.4% compared to the all Aluminum sink. For Low source coverage, it can be concluded that the high conductive material is more efficient when it is used as base material rather than using it as fin material.

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