EXPERIMENTAL THERMAL PERFORMANCE STUDY OF BONDED HEAT SINKS COMPARING SWAGED, SOLDERED, AND BRAZED BONDING TECHNOLOGIES

POWER ELECTRONICS NOTE 2

BY CLIFF WEASNER AND AHMED ZAGHLOL

1. ABSTRACT

The experiment is to validate the thermal performance of the swaging bonding technique for a new tight fin spacing that is being developed to handle different fin configurations. Swaging is a form of bonding the fins to the base plate to manufacture a heat sink using a cold forming process. To gauge the performance of the swaging process, it will be tested against multiple heat sinks with different bonding techniques; such as thermal epoxy, soldering and dip brazing. The sample size for testing is two heat sinks for each bonding technique which are tested in a wind tunnel. Results indicate that swaged heat sinks have similar thermal performance to the dip brazing and soldering samples.

2. INTRODUCTION

It is well known that the useful life and reliability of semiconductors increases as operating temperatures decrease. The temperature of a semiconductor junction is the main criterion for its reliability and performance. The semiconductor manufacturer specifies the maximum allowable value. During the energy conversion in a semiconductor, part of the electrical energy transforms to heat, otherwise known as heat loss. Therefore, it is necessary to remove this heat loss and maintain the junction temperature at an allowable level. Ultimately, this heat ends up being dissipated by a heat sink to the cooler ambient air, which serves as an infinite sink or reservoir for heat dissipation. The temperature rise of the junction above ambient is dependent on the path of thermal resistance which the heat is required to take in order to reach its final destination - the ambient air. Reducing the thermal resistance of the heat sink contributes to the reduction of the thermal resistant path and thus decreases the junction temperature.

Currently, the heat sink that is most commonly used in the market are extrusions. Typically, extrusions have the lowest costs, however extrusions are limited by the amount of surface area available due

NOMENCLATURE:

T	temperature, K
Q	Heat transfer rate, W
R_θ	Heat sink thermal resistance, C/kW
W	Heat sink width, m
L	Heat sink length, m
t_b	Heat sink base plate thickness, m
H	Heat sink fin height, m
t_f	Fin thickness, m
C-C	Fin spacing, m
g	Gap between the fins
T_c	Thermocouple temperature, C
T_a	Ambient temperature, C
T_s	Average temperature of thermocouples, C
R_{avg}	Average thermal resistance, C/kW
R_{s1}	Thermal resistance of sample 1, C/kW
R_{s2}	Thermal resistance of sample 2, C/kW
R_{ref}	Reference thermal resistance, C/kW

to the maximum fin height to fin gap ratio which hinders their maximum cooling capabilities. The distance from the tip of the fin to the bottom of the fin at the base plate is the fin height while the fin gap is the distance between the inner surfaces of two fins placed side by side. Depending on the size and complexity of the heat sink, the fin height to fin gap ratio for extruded heat sinks can range up to 18:1. To have an increase in the thermal performance which extrusions can not acheive, bonded fin heat sinks are capable of a larger fin height to fin gap ratios of 60:1 and higher. With the increase in the surface area, the bonded heat sinks are capable of dissipating more energy for the same temperature rise at the cost of higher pressure drop. Bonded heat sinks are manufactured by attaching the fin to the base plate material using a bonding process. Since the heat sink's components are bonded together, the process allows higher fin densities, mixture of metal alloys and complex fin configurations that cannot be extruded or machined from a solid block of metal.

Depending on the bonding techniques used to join the fins to the base plate, the thermal resistance can be affected. The method of manufacturing bonded fin heat sinks is very important in order to achieve the best thermal performance in the Power Electronics field. Minimizing the resistance between the fins and the base plate will result in lower heat sink temperature and hence lower junction temperatures of the silicon chips in the electrical modules. The following experiment is to validate the thermal performance of the swaging bonding technique for a fin spacing that is being developed to handle different fin configurations.

Swaging is a continuous cold forming process at room temperature to bond the fins to the base plate. The material of the base plate between the fins is subjected to high pressure which results in a plastic deformation (see Figure 1). The resulting deformation provides a metal to metal contact between the fin and base plate that performs very close to a one piece extrusion.

To gauge the performance of the swaging process, it will be tested against other heat sink bonding techniques such as thermal epoxy, soldering and dip brazing. Thermal epoxy is the most common method used in the electronic cooling market for bonded fins. Due to the process of using an epoxy to bond the fins to the base plate, there will be a significant thermal interface resistance at the joint of the fin and the base plate. Soldered joint will be used as the benchmark in this experimental comparison due to the low resistance in the joint. Both dip brazing and soldering use a metal filler material to bond the fins to the base plate. The filler is made of small particles of the bonding metal which will conduct heat through the joint. Soldering uses low melting temperature filler with a separate flux. Dip brazing is the process of joining two aluminum metals by dipping the completed assembly in a molten salt bath which acts as both the filler and flux. The dip brazing environment offers an oxygen-free environment to improve the bonding strength and occurs at a higher temperature.

To determine the thermal performance, each heat sink will be tested inside a wind tunnel (see Figure 2) for flow ranges from 2 to 6 m/s. The heat loss

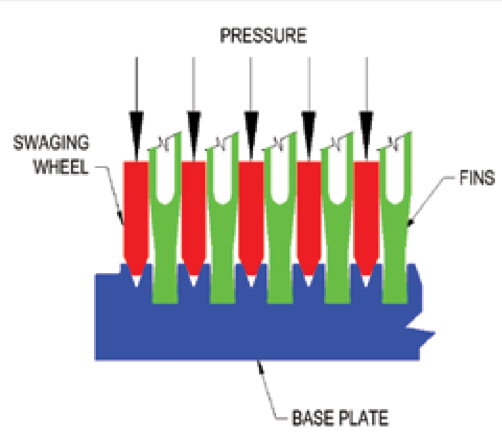

Fig. 1. Diagram of the swaging process of bonding the fins to the baseplate

Fig. 2. Picture of Wind tunnel

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will be supplied by a custom heater block that will replicate the power loss of an IGBT module. The thermal resistance for each bonding technique will be shown against a constant approach velocity. Each test sample will be compared versus one another to determine the relative performance.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

3.1. Heat sink Samples

Two heat sink samples are manufactured for each bonding technique. Each heat sink base plate is machined out of aluminum 6063-T5. The fin material is made aluminum alloy 1100. The fin material is made of sheet metal with no augmentations made to the surface or cross section. The heat sink dimensions are displayed in both Figure 3 and Table 1. Bonding techniques for the thermal epoxy, soldering and dip brazing are based on supplier instructions and recommendations. The tin silver based solder which will be used is difficult to bond an aluminum surface to another aluminum surface. In order to solder the aluminum fins to the aluminum base plate, the components had to be plated with electroless nickel with a thickness of 0.005 mm . It is assumed that there are no expected losses from the nickel plating as a potential resistance from the heat sink to the air.

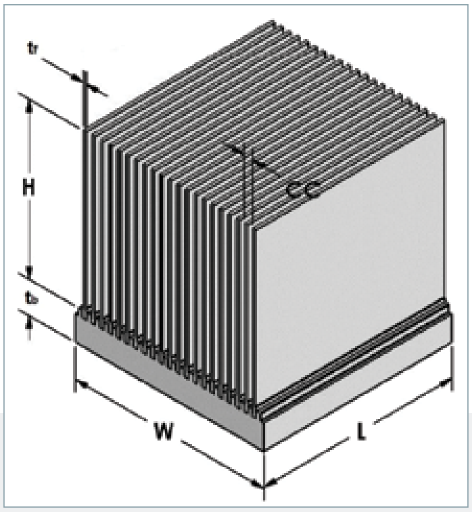

Fig. 3. Heat sink Dimensions Sketch

Fin Profile	Flat
Base Width, W	228.6 mm
Base Length, L	215.9 mm
Base Thickness, t_b	15.4 mm
Fin Height, H	48.9 mm
Fin thickness, t_f	2.03 mm
Fin to Fin, C-C	5.99 mm
Fin gap, g	3.96 mm

Table 1. Heat sink Physical Dimensions for the test samples using both fin configurations

3.2. Heater Block

The heater block is used to represent the IGBT modules. The dimension of the heater block is 149.86 mm wide by 165.1 mm long. It was designed to replicate the transistor and diode chip layout inside an IGBT module (see Figure 4). All the heat will be transfer through the twenty machine chip replicas. Each replica chip is 14.224 mm by 15.24 mm as shown in Figure 5. The heater block is machined from a C11000 copper block able to hold five 9.5 mm diameter cartridge heaters made from Omega Engineering (Omegalux CIR-5061/240V). The mounting plate is then soldered to the machine replica chips. The surface of the heater block is machined to 0.0254 mm / 25.4 mm. The heaters are pressed into the heater block using thermal grease to fill any voids between the two surfaces. The thermal grease utilized is Timtronics White Ice 510, with a thermal conductivity of 0.8 W/m.K. Type J thermocouples are positioned in the middle of the replica chips, 0.254 mm from the mounting surface and filled with epoxy to cover any holes.

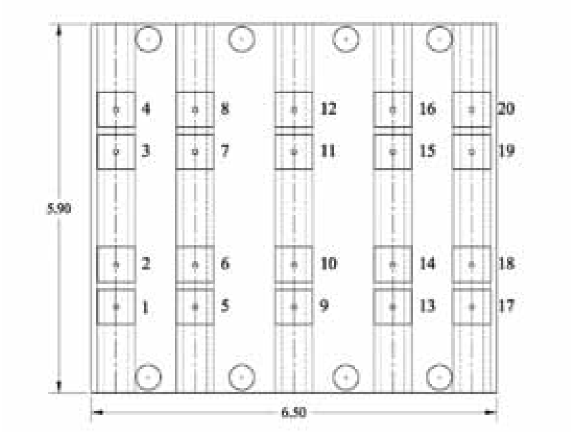

Fig. 4. Thermocouple layout and chip location on the heater block.

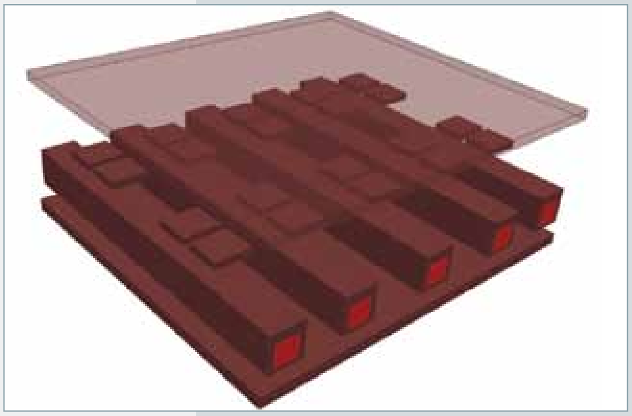

Fig. 5. IGBT replica heater block

3.3. Wind Tunnel

All tests are performed in a wind tunnel built to match the size of the heat sink as displayed in Figure 2. It is constructed with phenolic sheets and Plexiglas walls to limit the heat loss through conductivity from the heat sink. The wind tunnel has a cross section of 231.8 mm by 57.15 mm. The cross section dimensions of the working area of the wind tunnel are 1 fin gap larger than the cross section of the heat sink samples. The length of the wind tunnel is 121.9 cm with the heat sink positioned 51.8 cm from the air inlet of the wind tunnel. The flow rate is provided by a centrifugal blower capable of pushing 177 L/s at 0 Pa pressure drop from Delhi Industries Inc., part number D506. Due to the smaller cross sectional area of the blower than that of the wind tunnel; a diffuser is used to minimize any flow separation. The flow through the wind tunnel is not fully developed throughout the flow range. Power is supplied by a custom made test bench which is connected to a variable voltage power stat. The power stat is manufactured by Superior Electric Type SS150B-P2. The bench has a current source capacity up to 28A. The output voltage is 0-280 VAC with three phases. Measurements of the current are made with +/- 0.5% accuracy current transformer in conjunction with a Nicolet 310 Oscilloscope and a clamp on probe Hioki model #9008. In order to achieve 1000W of heat loss to the heat sink, the typical voltage is measured at 74.5V with the current measured at 13.4A. The voltage is recorded through the data acquisition unit measured at the cartridge heaters inside the heater block.

3.4. Measurements

All measurements taken in the test are recorded in a data acquisition and data switch unit Agilent 34972A using the software Agilent Benchlink on a desktop computer. The data acquisition unit is set to record data every 10 seconds. Due to the small diameter of the thermocouple wires and relative large values of heat dissipation, conductive and convective losses through the leads are assumed negligible. Type J thermocouples are placed in the heater block instead of the heat sink to improve repeatability between all the heat sink samples. An additional thermocouple is placed outside to record the ambient temperature. Air flow velocity is measure in front of the heat sink using an Omega FMA1005R-V1. The accuracy of the probe is 1.5% of the full scale for the velocity. The accuracy for velocity is +/- 0.15 m/s.

3.5. Procedure

Thermal paste is applied to the heater block before installation. Timtronics White Ice 510 is applied at a thickness of 0.076 mm using a scrapper tool as shown in Figure 6. Thermal paste application guidelines set by Timtronics during the process. The heater block is bolted to the heat sink. Using a recommended torque pattern by Infineon to insure the gap between the heater block and heat sink is minimized. All bolts are torque to 6.8 Nm using the recommended pattern and repeated again for 13.6 Nm. The resulting outcome of the grease spread after each test was shown to be repeatable for all the test samples.

The heat sink with the heater block mounted is positioned into the wind tunnel. The data

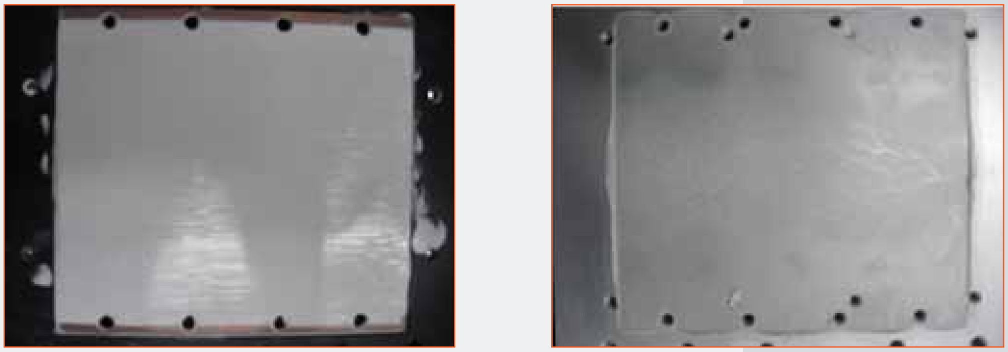

Fig. 6. Showing the application of the thermal epoxy on the heater block before testing (a) and on the heat sink after testing (b).

acquisition unit is turned on with the fan. Using the flow probe, the velocity is set at 2 m/s by adjusting the power of the fan. The power supply for the heater was turned and set to read at 74.8V at the heater block. The constant heat loss is applied to the heater block set at 1000W +/- 10W throughout the experiment. All measurements are recorded for each velocity point in until the test samples reach steady state for 10 minutes. Steady state is considered when there is less than 0.2C variation in the temperature in 30 subsequent readings. The procedure will be repeated for a flow range of 2 to 6 m/s for all heat sink test samples.

4. THERMAL MODELING

The test results will also be compared to the simulation using Qfin software modeling the replica of the wind tunnel, thermal grease, heater block and heat sink samples as per Figure 7. The diffuser and fan are not modeled. Qfin is a flow network solver which uses 3D conduction while excluding radiation heat transfer. The software's accuracy for the temperature rise of the thermal model is +/- 10%. The model assumes that the flow entering the wind tunnel is evenly distributed at a specific velocity and there are no losses through conduction to the wind tunnel from the heat sink. All heat is transferred through convection of the moving air mass. The heat sink is modeled as per the dimensions of the heat sink displayed in Table 1. The heat sink was modeled with perfect contact between the fins and the base plate with zero resistance in the joint to use as basis for comparison. The material of the heat sinks is aluminum alloy 6063-T5. The heater block is modeled as a single copper block with the heat generated by 5 cartridge heaters. Twenty temperature probes are placed in the heater block and positioned as per Figure 4 which will be used for the calculations and analysis for the simulation results. Thermocouples are placed there to show the temperature under the silicon chips replicas of the heater block as shown in Figure 5. The thermal grease is applied between the surface of the heat sink and heater block by using a set thermal resistance. It would take a large amount of cells to effectively model the thermal interface therefore both the heat sink and heater block are modeled with a mesh of 50,000 cells. The focus was made on making sure there are an effective number of meshed cells near each thermocouple.

5. DATA REDUCTION

The thermal resistance R_θ [C/kW] is calculated:

$$R_\theta = (T_s - T_a) / Q \quad (1)$$

where T_s is the average temperature of the twenty thermocouples mounted in the heater block [K], as shown in Figure 4.

$$T_s = (\Sigma T_c)/N \quad (2)$$

N is the number of thermocouples used to measure the heater block temperature which is 20

T_c is the temperature of the thermocouple in the heater block [K]

T_a is the ambient temperature [K]

Q is the heat transfer rate [W]

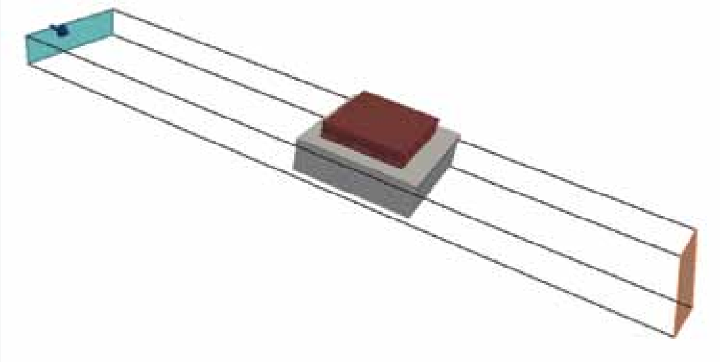

Fig. 7. Thermal model

$$R_{avg} = (R_{s1} + R_{s2})/2 \qquad (3)$$

R_{avg} is the average of the thermal resistance of the two heat sinks with the same bonding technique.

R_{s1} is the thermal resistance of sample 1

R_{s2} is the thermal resistance of sample 2

$$\%R_{ref} = (R_{avg\text{-}sold} - R_{avg\text{-}other}) / (R_{avg\text{-}sold}) \times 100 \qquad (4)$$

$\%R_{ref}$ is the performance comparison of the average thermal resistance of the test samples compared to the soldered based heat sink samples when comparing the same fin type.

$R_{avg\text{-}sold}$ is the average thermal resistance of the two soldered samples for a single fin type.

$R_{avg\text{-}other}$ is the average thermal resistance for the other bonding techniques.

6. RESULTS

The test results for the flat finned heat sinks are recorded in Table 2. The table shows the thermal resistance of each sample and the average of the two samples with respect to velocity (Eq. 1 and Eq. 3, respectively). Testing of the thermal epoxy at a velocity of 2 m/s were not able to be recorded as the heater block temperatures in the test were rising above the set limit of 100C. Thus the test samples with the thermal epoxy were limited to a flow range of 3 to 6 m/s. The test results for each pair heat sink samples show good repeatability for every flow rate except for the glued heat sink samples as displayed in Figure 8. There is a large difference in the performance between both glued samples. The difference will have to be investigated to determine what are the possible causes. The expected performance difference between thermal epoxy and swaging is determined to be 14% on average as per Zaghlol et al [3]. As expected, the glued samples have the highest thermal resistance. The thermal barrier is noticeable between the glued fins as they performed much more poorly than the other type of bonded heat sinks. In Figure 9, the measurements displays very small difference between the soldered, dip brazed and swaged results. Table 3 displays the performance in respect to the average heat sink sample using Eq. (4) in comparison to the solder samples. Swaged over the average of the flow performs slightly better than soldering with an increase in performance of 0.658% thermal resistance. Dip brazing performs with an average 0.916% lower thermal resistance over the flow range. The results in the difference between swage, dip braze and solder falls within the determined experimental error. Glued bonded heats sinks performs the worst with an average of 27.146% higher thermal resistance.

Bonding Technique	Flow Rate m/s	Sample 1 R_{s1} (C/kW)	Sample 2 R_{s2} (C/kW)	R_{avg} (C/kW)
Soldered	1.93	67.80	66.24	67.02
	2.99	55.67	55.97	55.82
	3.97	48.13	49.71	48.92
	4.99	42.60	41.58	42.09
	6.04	35.35	35.17	35.26
Dip Brazing	2.03	65.81	67.33	66.57
	2.96	55.49	55.72	55.61
	4.01	47.25	48.02	47.63
	5.00	41.24	41.51	41.37
	6.01	35.90	35.19	35.55
Thermal Epoxy	2.95	63.20	70.40	66.80
	3.97	56.77	63.94	60.36
	5.02	50.49	57.82	54.15
	6.02	43.54	52.99	48.26
	1.98	67.95	66.30	67.13
Swaged	2.99	55.77	55.50	55.63
	4.02	47.81	47.43	47.62
	5.03	41.11	40.87	40.99
	5.91	36.44	35.60	36.02

Table 2. Thermal Resistance test results and thermal resistance calculations

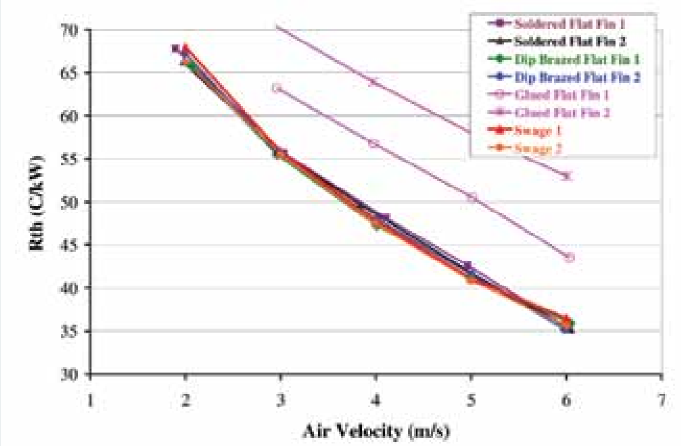

Fig. 8. Test results for all samples.

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Flow Rate	Simulation	Dip Brazed	Glued	Swaged
m/s	$\%R_{ref}$	$\%R_{ref}$	$\%R_{ref}$	$\%R_{ref}$
2	-5.211%	0.674%	N/A	-0.160%
3	-5.919%	0.386%	-19.672%	0.334%
4	-7.400%	2.628%	-23.384%	2.652%
5	-13.760%	1.704%	-28.654%	2.617%
6	-26.538%	-0.813%	-36.873%	-2.156%

Table 3. Thermal resistance comparison of the test samples with respect to the soldered heat sink samples.

7. CONCLUSION

The test results prove that the swaging process is capable of matching the performance of the soldered and dip brazed processes for bonded heat sinks. Glued heat sinks perform worse than all three other options by an average of 27.146%. The simulation results under estimate the performance of the soldered heat sinks by 11.8%.

Swaging matches the performance of soldering and dip brazing while offering more capabilities. Soldering is expensive for aluminum due to the need of nickel plating the the entire surface area of the heat sink. Dip brazing is a time consuming process which is the most expensive method of all four bonding techniques. Swaging offers similar costing to the thermal epoxy bonded fin heat sinks while offering better thermal performance. Swaging is also capable mixing different metals, such as copper and aluminum, which helps increase the thermal performance of the heat sink. This is something that cannot be done easily with thermal epoxy or dip brazing.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Incropera, F. and DeWitt, D. *Introduction to Heat Transfer.* 3rd Edition. John Wiley & Sons. 1996.
2. Timtronics.com
3. A. Zaghlol, K. Hermann, J. Butler, P. Teertstra, and J.R. Culham, "Forced Convection Heat Transfer for Swaged Mixed Metal Heat sinks," Proceedings of Itherm2002 IEEE Symposium, May 29-June1, 2002, San Diego, California, USA.
4. A. Zaghlol, W. Leonard, and J.R. Culham, "Characterization of Swaged Mixed Metal Heat Sinks," Presented in APEC 2003, Miami Beach, Florida, USA, February 2003.
5. A. Zaghlol, W. Leonard, and J.R. Culham, "Characterization of Swaged Mixed Metal Heat sinks for Concentrated Heat Source," Presented in InterPack'03, Maui, Hawaii, USA, July 2003.
6. A. Zaghlol, "Thermal Characterization of Aluminum Heat sink with Bonded Copper Inlays," Presented in PCIM Europe, May 2003, Nuremberg, Germany.

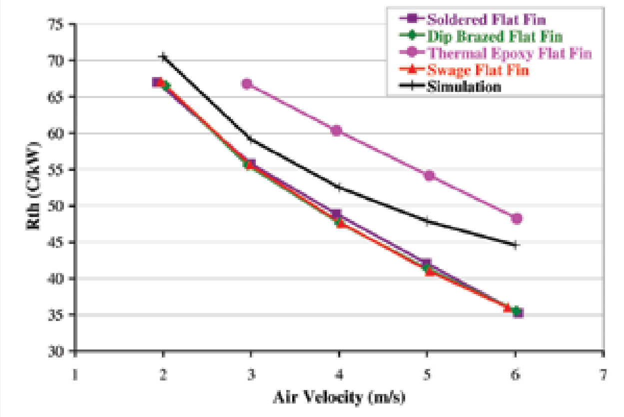

Fig. 9. Test results and simulations results.

CONTACT

USA
374 Merrimac Street, Newburyport, MA 01950
T 978 462 6662 | F 978 462 0181
info.nby@mersen.com

CANADA
6200 Kestrel Road, Mississauga, ON L5T 1Z1
T 905 795 0077 | F 905 795 2508
technicalservices.mis@mersen.com