Experimental study of free convection in open-cell aluminum foam

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Abstract

Free convection in air-saturated open-cell aluminum foam was studied experimentally. The influence of pore density, foam height and bonding technologies are examined. For this research, the base plate temperature is varied between 55°C and 95°C. The ratio of the sample length-to-width is kept to a fixed value of 10. The investigated foams have a pore density of 10 and 20 PPI (Pores Per linear Inch) with a porosity of 93%. The foam height is varied between 6 and 40 mm. The bonding of the foam is done by either brazing, or by applying a single epoxy.

An effect of the bonding methods is observed. The brazed samples showed a higher heat transfer rate in all cases. The influence of the pore density is more pronounced. However, the strongest influence can be attributed to an increase in sample height.

Keywords: Open-cell foam, natural convection, electronic cooling, contact technology, foam height, PPI-value

1. Introduction

Open-cell aluminum foam is a rather new kind of material, popped-up recently for use in thermal applications. The foams used in this study are in-house casted, by replicating an organic preform. In a buoyancy-driven flow, open-cell metal foams has numerous opportunities: it has a high surface-to-volume ratio, small ligaments creating a lot of tortuous pathways keeping the boundary layers thin, it has a low weight and is shapeable in three dimensions (due to the manufacturing process). Only a few authors have studied open-cell metal foam experimentally in free convection. Bhattacharya and Mahajan (2006) have investigated influences of pore density and porosity for substrate...
temperatures up to 75°C for Al-foams. They found that the heat transfer rate increases with decreasing porosity. When the porosity is kept constant, the heat transfer rate increases for decreasing PPI-values. For copper foamed heat sinks, Qu et al. (2012) studied the influence of the inclination angle and the foam height. They have shown that the influence of the inclination angle for their cubic shaped heat sinks is not significant (6%).

In free convection, many parameters affect the heat transfer rate in foams. Therefore, the foam material & height, geometrical characteristics (PPI and porosity alone are not enough to describe a 3D material), substrate dimension, heat sink orientation, temperature of the substrate (or applied heat flux), bonding method, test constraints (thickness of the thermal paste, configuration of guard heaters etc.) and the box geometry should be reported. The objective of this study is to analyze aluminum foam heat sinks focusing on different heights, pore densities and bonding technologies, keeping a fixed length-to-width ratio of 10 for the heat sink. The PPI-value is varied between 10 and 20 PPI, both with a porosity of 93%. The height is varied between 40 and 6 mm for the 10 PPI foam and between 18 and 6 mm for the 20 PPI foam. The foam is bonded to the substrate either by brazing or by a single epoxy.

2. Test Rig and Foam Samples

The test rig and some foam samples are shown in Figure 1. The base plate measures 254x25.4x4 mm³ and is kept constant for all samples. The top surface of this plate is placed level with the surrounding insulation. On top of this plate, aluminum foam is bonded. This plate then acts as a substrate. The assembly is placed in an enclosed box, measuring 700x600x450mm³ (the box in Fig. 1 is closed at both sides with Plexiglas®). As it is a closed system, it is ensured that there is no momentum exchange with the environment. Different box geometries are tested, it was found that the used box is sufficiently large enough to induce no influence on the heat transfer rate.

![Fig. 1. (a) test assembly (b) some foam samples.](image-url)
The solid line in Figure 1(a) indicates where the cross-section, shown in Figure 2, is taken. Figure 2 shows two copper plates (245x25.4x5 mm$^3$) and the main heater, mounted underneath the substrate. The copper plates ensure a uniform heat flux from the main heater to the substrate. The bottommost copper plate is machined in order to be able to mount six flat K-type thermocouples. These thermocouples are then used to measure the substrate temperature ($T_s$). This substrate temperature is PID controlled.

All thermocouples are calibrated and the resulting uncertainty is assumed to be 0.1K conservatively. Special care is taken when manufacturing the copper plates in order to assure a good thermal contact. To further enhance this contact, silicon thermal conductive paste (V5312 from Assmann WSW-Components) is used with a thermal conductivity of 0.8 W/mK and good flow properties. The temperature of the surrounding air ($T_{env}$) in the closed box is measured with twelve thermocouples which are placed near the wall of the box (two on each side plane of the box). For all measurements, the difference between the thermocouple measurements to determine $T_s$ and $T_{env}$ was lower than 0.8°C.

To generate a one dimensional heat flux to the foam sample, three guard heaters were installed at the left, right and bottom side of the main heater. The purpose of the guard heater is to keep the temperature difference with the main heater as small as possible, which consequently minimizes heat losses to the surroundings. Separated power supplies are used for the main heater, bottom guard heater and both side guard heaters. All three of the supplies are voltage controlled to ensure that the average temperature on each copper plate matches its set point. To measure the power supplied to the main heater, the voltage as well as the current are measured. The overall accuracy of the measured power supplied to the heater is 3%.

The test rig is validated by comparing the results for a flat horizontal aluminum plate with the correlation found in Rohsenow et al. (1998). A very good agreement is found.

The foams used in this study are in-house manufactured and made of an AL1050 alloy. The bonding technologies, heights and PPI-values of the tested foams are shown in Table 1. The tested substrate temperatures are also reported. Furthermore, the cells are not spherical in shape but orthotropic. As a result, porosity and PPI value alone are insufficient to fully characterize the foam geometry. The cell shape resembles an ellipsoid rather than a sphere, which is due to the organic preform used in creating these foams. The foaming process which generates the organic preform occurs against gravity, resulting in stretched cells. To microscopically characterize a representative elementary volume for a foam, two cell diameters ($d_1$ and $d_2$) and the middle strut cross sectional area ($A_0$) can be used. These characteristics can be measured with sufficient accuracy (relative accuracy varies between 3% and 9%) and are reported in this work based on micro-computed tomography (µCT) data (Jaeger et al. (2011)), enabling the possibility to compare on a more profound way in the future (see Table 2).

For the epoxy contact, Bondmaster ESP110 (single part epoxy) is used. Epoxy is applied to the substrate and the foam is pressed onto it. By heating this assembly up to 150°C, the epoxy is allowed to cure (during 1 hour). For the brazed samples, the brazing is done on a substrate which consists of an AA3xxx Al-Mn alloy in the bulk with a lower melting point that the AA4xxx Al-Si alloy filler material on the brazing side. The assembly is heated to the
eutectic temperature of the filler material (577°C). Because the bulk and the foam consist of an aluminum alloy which melts at a higher temperature, the assembly does not distort. Together with a proper fluxing, a joint is achieved in a controlled nitrogen atmosphere brazing furnace. The brazing was done in cooperation with the company Solvay® in Germany.

Table 1. Used foam samples with the imposed substrate temperatures (set point)

| Foam (PPI) – bonding method | Heights [mm] | $T_s$ [°C] |
|-----------------------------|-------------|-------------|
| 10 – brazed                 | 40          | 55-60-65-70-75-80-85-90-95 |
| 10 – brazed                 | 25.4        | 60-67.5-75-82.5-90 |
| 10 – brazed                 | 18          | 60-65-67.5-70-75-80-82.5-90-95 |
| 10 – brazed                 | 12          | 60-65-70-75-80-85-90 |
| 10 – brazed                 | 6           | 60-65-70-75-80-85-90 |
| 10 – epoxy                  | 25.4        | 60-67.5-75-82.5-90 |
| 10 – epoxy                  | 18          | 60-65—67.5-70-75-80-85-89 |
| 10 – epoxy                  | 12          | 60-65-70-75-80-85-90 |
| 20 – brazed                 | 18          | 55-60-65-70-75-80-85-90-95 |
| 20 – brazed                 | 12          | 60-65-67.5-70-75-80-82.5-85-90 |
| 20 – brazed                 | 6           | 60-65-67.5-70-75-80-82.5-85-90 |

Table 2. Properties of the studied foams, determined through a μCT scan.

| Foam (PPI) | $\phi$ [-] | $d_1$ [mm] | $d_2$ [mm] | $A_0$ [$10^{-1}mm^2$] | $\sigma_0$ [m$^{-1}$] |
|------------|------------|------------|------------|------------------------|------------------------|
| 10         | 0.933      | 4.22       | 6.23       | 0.998                  | 462                    |
| 20         | 0.937      | 2.77       | 4.15       | 0.377                  | 720                    |

3. Data Reduction

Both $T_s$ and $T_{env}$ are determined with thermocouples in resp. in the bottommost copper plate in Figure 2 and by averaging 12 thermocouples in the box. $\dot{Q}$ is determined by measuring the current and voltage. All measurements were performed in steady state condition. This stage is reached when all temperatures vary less than 1% during a period of 5 minutes. Every test sample is measured twice in a random sequence.

A modified Nusselt number is proposed, based on the product of the convection coefficient with the foam efficiency (as defined by Ghosh et al. (2009) for a channel flow), where the foam efficiency is not separated from the convection coefficient as indicated by Moffat et al. (1988). With no numerical data available, it is impossible to separate the foam efficiency from the convection coefficient in a 3D flow pattern. Only for a channel flow, Ghosh et al. (2009) were able to separate both.

By reporting a modified Nusselt number, a better comparison with literature data is possible; as a lot of authors now report a lumped Nusselt number (Bhattacharya and Mahajan (2006), Qu et al. (2012)). Such a lumped Nusselt number is defined with $\eta h$ directly determined out of $R_{tot}$. The modified Nusselt number is determined through:

$$ Nu^* = \frac{\eta h \cdot L}{k_{air}} $$  \hspace{1cm} (1)

where $\eta h^*$ is defined as:

$$ \eta h^* = \frac{R_{conv}}{A_s} $$  \hspace{1cm} (2)

The convective resistance is defined as the total thermal resistance minus the contact resistance between the foam and the substrate, the conductive resistance (over the copper and the substrate) and resistance over the thermal paste (taken 1.5 mm thick, with the uncertainty conservatively estimated to be 1 mm).
\[ R_{\text{conv}} = R_{\text{tot}} \left( \frac{\dot{Q}}{\Delta T} \right) - R_{\text{cond, cu + al}} - R_{\text{thermal paste}} - R_{\text{contact}} \] (3)

The thermal contact resistance is determined based on literature, for the same in-house foam with the same bonding technologies (curing times, brazing technique etc.) (Jaeger (2012)). This modified Nusselt number (Eq. (1)) is plotted against the Rayleigh number, given by:

\[ Ra = \frac{g \beta (T_s - T_{\text{env}})}{\alpha_{\text{air}} \nu_{\text{air}}} \] (4)

where \( \beta \) represents the thermal expansion coefficient for an ideal gas and \( \alpha \) the thermal diffusivity (both determined with at \( T_{\text{avg}} \)).

For all measurements performed in this study, the relative uncertainty on Ra ranges from 3.5 to 4.5%, on \( \dot{Q} \) from 1.2% to 2.9%, on \( R_{\text{tot}} \) from 1.7% to 3.3%, on \( R_{\text{conv}} \) from 3.5% and 8.9% and on \( N\nu^* \) from 4.1% to 9.3%.

Fig. 3. The modified Nusselt number is plotted against the Rayleigh number for 10 PPI foam of 12 mm height for two bonding methods.

Figure 3 plots the modified Nusselt number against Ra for a brazed and for an epoxy bonded 10 PPI foam with a height of 12 mm. It is noticeable that the data for the epoxy and brazed samples show statistically the same result, indicating the good quality of the data reduction. However, the modified Nusselt number for the brazed sample is systematically higher than for the epoxy sample. This is related to the fact that the epoxy layer covers the complete substrate. This results in an additional thermal resistance near the substrate and between the strut (which is not the case for the brazed samples where there is a metal-metal contact).

4. Results

Figure 4 shows an overview of the performed measurements, where the modified Nusselt number is plotted against the Rayleigh number. It is shown that a foamed heat sink shows a significant improvement when compared to a horizontal blank aluminum plate. This increment depends on the used bonding technology, pore density and foam height. A 10 PPI brazed heat sink with a same space constraint as a 20 PPI sample (18 mm high) performs e.g. on average 3.69 times better against a blank plate in comparison with a 20 PPI sample (only 3.18 times better). An epoxy bonded 10 PPI sample with the same space constraint as a brazed 10 PPI sample (12 mm), performs 3.16 times better compared to a blank plate, whereas the epoxy bonded sample performs only 2.89 times better.

Compared with the measured blank aluminum plate, the heat transfer rate of the studied sample with the highest heat transfer rate (10 PPI sample with 40 mm foam height) is 4.95 times higher. This result is comparable with the one found by Bhattacharya and Mahajan (2006).

These large differences in heat transfer rate indicate that, the influences of bonding technology, pore density and height have to be studied into more detail.
The contact technology has – of all studied parameters – the lowest impact on the heat transfer: up to 15%. The higher the foam sample, the lower the overall thermal resistance and the higher the relative impact of the bonding technology. The brazed foam has a higher Nusselt number because of the more qualitative thermal contact between struts and substrate. The contribution of the thermal contact resistance to the overall thermal resistance is lower than in forced convective applications (up to 5%).

The PPI-value has a higher impact on the Nusselt number. 10 PPI foam performs up to 25% better when compared to a 20 PPI foam sample with the same dimensions.

However, the most important parameter studied here is the foam height. The difference in heat transfer between a 6 and 12 mm 10 PPI foam is already 32%. However this increment in heat transfer rate decreases for larger foam heights. Furthermore, the foam height is a parameter that is highly restricted due to the space constraints around the heat sink.

Fig. 4. An overview of the performed measurements, compared with literature data of a blank plate. (e) stands for epoxy contact (other samples are brazed).

5. Conclusions

A validated test rig is built to study horizontal-orientated heat sinks with metal foam. Three parameters were varied: contact technology, PPI-value of the foam and the height of the foam.

The contact technology has the lowest influence on the heat transfer (up to 15%), the PPI-value has a higher impact on the Nusselt number. 10 PPI performs up to 25% better when compared to a 20 PPI foam with the same dimensions. The most important parameter is the foam height. The difference between a 6 and 12 mm 10 PPI foam is already 32%.

References

A. Bhattacharya and R.L. Mahajan, Metal foam and finned metal foam heat sinks for electronics cooling in buoyancy-induced convection, J Electron Packaging, vol. 128, pp. 259-266, 2006.
I. Ghosh, Heat transfer correlation for high-porosity open-cell foam, Int J Heat Mass Tran, vol. 52, pp. 1488-1494, 2009.
P. De Jaeger, C. T’Joen, H. Huisseune, B. Ameel, M. De Paepe, An experimentally validated and parameterized periodic unit-cell reconstruction of open-cell foams, Journal of Applied Physics 109 (2011) 10.
P. De Jaeger, C. T’Joen, H. Huisseune, B. Ameel, S. De Schampheleire, M. De Paepe, Assessing the influence of four bonding methods on the thermal contact resistance of open-cell aluminum foam, Int J Heat Mass Tran, vol. 55, pp. 6200-6210, 2012
R.J. Moffat, describing the uncertainties in experimental results, Exp Therm Fluid Sci, vol. 1, pp. 3-17, 1988.
W.M. Rohsenow, J.P. Hartnett, Y.I. Cho, Handbook of heat transfer, McGraw-Hill, New York, United States, 1998.
Z. Qu, T. Wang, W. Tao, T. Lu, Experimental study of air natural convection on metallic foam-sintered plate, Int J Heat Fluid Fl, vol. 38, pp. 126.132, 2012.