Applied Thermal Engineering 111 (2017) 884–893

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

A computational methodology for assessing the thermal behavior of metal foam heat sinks

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HIGHLIGHTS

- μ-CT scan is used to develop a detailed 3D metal foam solid model.
- The 3D solid model is used to develop a metal foam heat sink finite element model.
- A unique approach to calibrate h values between experiments and simulations.
- The calibrated FE model is used to assess the thermal performance of the heat sink.

ARTICLE INFO

Article history:
Received 20 April 2016
Revised 3 October 2016
Accepted 5 October 2016
Available online 6 October 2016

Keywords:
Metal foam
Heat sinks
Computational modeling
Micro-CT scan

ABSTRACT

In recent years, the use of open-cell meal foams in thermal applications have increased due to their random open pores nature that gives them an improved heat transfer performance. Most of the work done in the literature on metal foam heat sinks investigates their thermal behavior by means of experiments. These experiments are limited in the parameters that can be measured due to the complex geometrical nature of metal foams. This pushed for the use of advanced computational techniques to analyze their behavior. In this work, μ-CT scan is used to develop an accurate 3D representation of the metal foam fins used in the heat sinks. The model is used to create a computational FE model that is used to perform a wide range of simulations. The model is calibrated and validated against a range of experiments that are performed for the same metal foam sample. The 3D model is used to study the effect of assembly method between the heat sink base and the metal foam fin, by comparing the traditionally used thermal adhesives to a new technique utilizing thermal spraying. In addition, effect of forced convection, fin orientation, and number of fins on the efficiency, effectiveness, and thermal resistance. The model is also used to calibrate the heat transfer coefficient, which is very difficult to calculate analytically or experimentally due to the complex geometrical nature of metal foams.

1. Introduction

Metal foams have been utilized more in recent years after the huge jump in manufacturing technologies. A lot of research has been carried out testing their mechanical, thermal, and energy absorption behavior experimentally as well as computationally. Open-cell metal foams provide improved mechanical and thermal properties paralleled with a weight reduction. One of the main applications that benefit from the improved properties of open-cell metal foams is cooling of electronic packaging, specifically heat sinks.

The majority of the work in the literature is heavily based on experimental data coupled with analytical calculations [1,2], or with no experimental data as in the work of Lu et al. [3]. A relatively recent common approach to study the heat transfer behavior of metal foams is via computational techniques. Kopanidis et al. [4] constructed a 3D geometrical model of an open-cell metal foam via computational software while ensuring the PPI matches the real case. The model was used in a 3D CFD analysis to assess the thermal behavior. It is important to notice that the model was based on copying/repeating the geometry many times to build a larger model. This takes away the randomness and stochastic nature of foams. In addition, the foam struts in the model were straight links, with no curves in the model. A common simplified approach is to model the metal foam as a solid material (no cells) and use effective properties rather than the properties of the solid material [5]. While simple, this approach is limited in the range of results and cases that can be analyzed. Both approaches, geometrical construction/repetition and using effective properties, do provide an

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http://dx.doi.org/10.1016/j.applthermaleng.2016.10.014
1359-4311/

easy approach to obtain certain results but are limited based on the mentioned reasoning.

An innovative approach has been used recently in the literature that uses the μ-CT scan approach to obtain a more realistic 3D model of metal foams. Mendes et al. [6] utilized μ-CT scan to have an actual 3D representation of metal foams. The effective thermal conductivity was estimated based on simplified homogenous models while using the μ-CT model to extract the needed geometrical properties. Wulf et al. [7] used the same developed μ-CT models and extended the work with detailed numerical simulations using the Thermal Lattice Boltzmann Method (TLBM) to measure the effective thermal conductivity. Ranut et al. [8] developed a high resolution μ-CT metal foam model to study the flow and thermal behavior of metal foams at the pore level. A CFD analysis was performed to calculate the effective thermal conductivity and permeability.

In this work, an experimental-computational approach to assess the thermal behavior of metal foam heat sinks and calculate the heat transfer coefficient is presented in details. The methodology involves calibration and validation of the results in addition to a study on the effect of several process and geometrical parameters.

2. Methodology

The first step of this work is run metal foam heat sink experiments in a wind tunnel in order to build data for the temperature distribution profile for a variety of cases. These experiments will have different fan speed, heat sink orientation angle, and different assembly methods between the metal foam fin and the heat sink plate. Then, a μ-CT scan is used to build a detailed 3D model of the metal foam. The model is used in a finite element frame of work to perform computational analysis of metal foam heat sinks. The temperature profile from the experiments is used to validate the computational model. The value of the heat transfer coefficient is calibrated during this step as well. Finally, the 3D heat sink computational model is used to assess the thermal behavior and to calculate some of the quantitative values such as the thermal resistance and temperature drop between natural and forced convection.

3. Metal foam heat sink experiments

For all experiments, aluminum 6101 alloy foam [9] was used with 93% porosity and pore-density of 4PPC (4 pores-per-cm, approx. 10 pores-per-inch). Samples of 25 × 25 × 6.35 mm were used with base plates of the same material with dimensions 20 × 14.35 × 3 mm as shown in Fig. 1. Some of the experiments presented in this work were presented in the literature in a previous work by the author [10], in addition to several new ones, with a detailed description of the experimental setup and conditions.

Table 1 lists all experimental cases investigated in this work and Fig. 2 shows a schematic of the experimental setup. The temperature profiles for each case taken at the heat source, base plate, and top of the fin are shown in Figs. 3 and 4. The results of the temperature profiles will be used as the basis for the computational analysis, which will be used to evaluate variables and parameters such as the heat transfer coefficient, thermal resistance, effectiveness, and efficiency.

3.1. Uncertainty analysis

In order to be able to use the experimental results shown in Figs. 3 and 4 in the calibration of the numerical model to be presented in the subsequent sections, the error from the experimental readings must be checked to be within a suitable range. Uncertainty in the experiments performed in this study comes from three aspects: error in power measurements, thermocouple input, and metal foam dimensions. The data sheet of the digital multimeter gives a maximum error of 1% in voltage and resistance reading, hence giving a relative error of 3% in power input (Q) measurements. The data acquisition card was set to get temperature readings for every 0.01 °C for up to 60 °C. This gives a relative uncertainty of 0.0167%. The dimensions of the metal foam were calculated using Vernier caliper with approximately 1% uncertainty. The total relative uncertainty is then calculated as:

$$\frac{\delta h}{h} = \sqrt{\frac{\delta Q}{Q} + \frac{\delta A}{A} + \frac{\delta T}{T}} \quad (1)$$

giving a total uncertainty of ±3.16%.

4. μ-CT scan and geometrical modeling

It is very difficult, if not impossible, to model the highly complex and irregular structure of open-cell metal foams directly using a CAD or an FE software. In this work, reverse engineering technique using computed tomography (CT) scan is utilized to generate the actual 3D model of the metal foam. The metal foam sample shown in Fig. 1 [9], is used during this process. CT scan was performed on Skyscan 1172 and the sample size was 25 × 25 × 6.35 mm. The sample size covers the minimum requirement of 1 PPC unit length (1 cm) by having more than twice the PPC unit length (2.5 cm), both horizontally and vertically. X-ray source was set at 40 kV and 250 μA. By keeping the step size of 0.7° (deg), total 512 slices were captured. Scanning trajectory was complete 360° for thorough capture of sample. No filter was

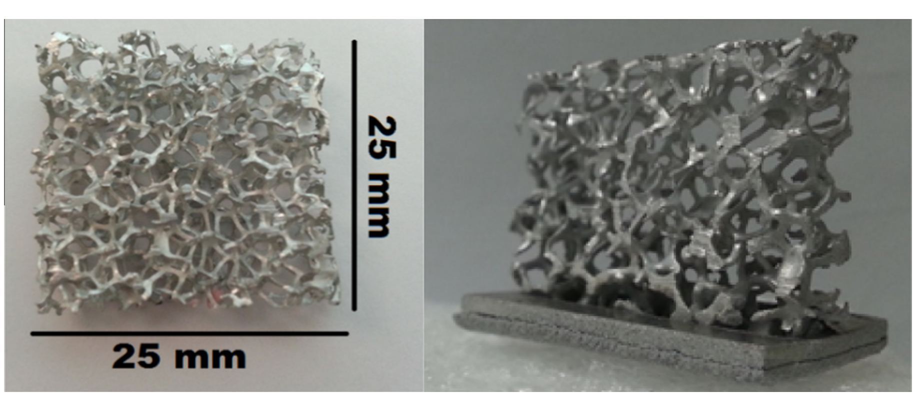

Fig. 1. Original aluminum 6101 alloy metal foam sample (left), and metal foam heat sink (right).