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Critical Analysis of the Experimental Determination of the Thermal Resistance of Metal Foams

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Abstract This paper addresses experimental and numerical analysis of the thermal resistance of M-Pore[®] copper foam. The findings suggest a separation of the thermal resistance into two components: material resistance and contact resistance. Finite element analysis is used to calculate the thermal material resistance. Calculation models are based on micro-computed tomography data in order to account for the complex material geometry. The same samples are used for experimental analysis. A transient method is applied where a time-dependent temperature change is related to the thermal resistance. In addition to material resistance, experimental measurement values inevitably include thermal contact resistance. Although a thermally conducting paste is used in order to minimise this effect, a significant thermal contact resistance is found. As a result, the experimentally measured thermal resistance can no longer be considered as a material property but depends on the sample size and the particular shape of the contact surfaces. Furthermore, it is demonstrated that the traditional approach to experimentally obtain thermal contact resistance by changing the specimen size is impractical for cellular metals. Instead, the contact resistance is obtained by comparing experimental and numerical results.

Keywords thermal resistance, thermal conductivity, cellular metal, experimental measurement, finite element method, micro computed tomography.

1. Introduction

Cellular metals combine the properties of high strength, energy absorption and structural damping with low weight [1] making them attractive materials for lightweight applications. In addition, these multi-functional materials exhibit interesting thermal properties in conjunction with a large internal surface area. Potential thermal applications are heat exchangers [2,3], thermal conductivity enhancement [4,5] and fire retardants [6] where the high conductive metallic phase acts as a heat spreader and heat exchange occurs across the large internal surface area. The present paper addresses commercially available open-celled M-Pore[®] porous copper (see Fig. 1). Two different material densities are considered and, in the following, are referred to as low density (porosity $p = 90.5\%$) and high density ($p = 83.9\%$). Experimental and numerical experiments are conducted in order to investigate the thermal resistance.

Fig. 1 M-Pore® cellular copper: a) low density, b) high density

Thermal properties of cellular metals have been the focus of prior research. In [7] the effective thermal conductivity of open-celled steel alloy foams is investigated. Experimental analysis based on a steady-state method was applied in order to measure the effective thermal conductivity (i.e. the thermal material resistance). A distinct increase in thermal conductivity at elevated temperatures was related to an increase in radiation energy transfer. This effect was confirmed by Wang and Pan who used Lattice Boltzmann analysis to predict the conductivity of open-cell porous foams [8]. Solórzano *et al.* applied the transient plan source method to measure the thermal conductivity of aluminium foams [9] and hollow sphere structures [10]. These experimental measurements were shown to be very sensitive to inhomogeneities introduced by the manufacturing of cellular metals. In addition to experimental analysis, numerical studies on the thermal conductivity of cellular metals have been performed. A recent innovation is the use of micro-computed tomography (μ CT) data in order to achieve an accurate representation of the complex meso structure of cellular metals. In [11], μ CT data was used for the finite element analysis of the thermal conductivity of cellular metals. Calculation models were restricted to relatively small geometries. A distinct local scattering of the thermal conductivity was found. Thermal conduction in M-Pore® aluminium foam has been considered in [12]. The focus of that paper was the thermal anisotropy and an analytical model was developed that allows the complete characterisation of the thermal conductivity tensor based on a small number of directional measurements. Further numerical analysis were performed in [13] wherein Lattice Monte Carlo (LMC) analysis was undertaken on a range of different cellular metals. The numerical results were compared to analytical models and the three different categories of cellular metals: thick-walled, thin-walled and open-celled structures were introduced. M-Pore® cellular metal falls into the latter category. In [14], computed tomography data was combined with analytical analysis. Based on the detailed geometric data, a resistance network was developed in order to describe the effective material conductivity of Duocel® foam.

The important innovation of the present paper is the systematic separation of thermal resistance into thermal contact resistance R_C and thermal material resistance R_M . The experimental setup used in this analysis is shown in Fig. 2 and it becomes clear that experimental measurements inevitably include the contact resistance between the specimen and heat source R_{C1} as well as specimen and the temperature sensor R_{C2} . As a result, the material thermal resistance R_M cannot be directly obtained. In the following, the thermal resistance measured in experiments is referred to as the total resistance R_T :

$$R_T = R_{C1} + R_M + R_{C2}. \quad (1)$$

The usual correction method applied for *solid* materials is to calculate the thermal contact resistance using samples of different thickness of the same material. Measurement of the thermal contact resistance R_C are then plotted versus the specimen thickness and extrapolated to zero thickness in order to obtain the thermal contact resistance. However, this extrapolation is only valid if the contact resistance is constant for all samples. This is not the case for cellular metals where we show that the

thermal contact resistance is a function of the conducting surface area A_C , i.e. $R_C = R_{C1} + R_{C2} = f(A_C)$ and, accordingly, the standard correction method cannot generally be applied. Comparison of finite element data and experimental measurements reveals an approximately linear dependence of contact resistance and conducting contact area.

Fig. 2 Thermal resistance in experiment and simulation.

2. Finite Element Analysis

Finite element analysis was used to calculate the thermal material resistance R_M . In contrast to the experimental measurements, contact resistance can be completely eliminated (see Fig. 1). The material resistance is related to the more commonly used material parameter effective thermal conductivity k according to:

$$R_M = l / k, \quad (2)$$

where l is the thickness of the specimen. A total of six cuboid specimens was considered and the effective thermal conductivity was determined in the three surface normal directions. The samples can be classified according to low density (3 samples, average density $\rho = 840 \text{ kg m}^{-3}$) and high density (3 samples, average density $\rho = 1470 \text{ kg m}^{-3}$). The outer dimensions of the samples were 20 mm x 25 mm x 40 mm and each direction contains 6, 8 and 12 cells, respectively. This exceeds the required number of at least 4 cells that can be considered as a representative volume for the determination of the thermal conductivity. This has been demonstrated in [15] where different specimen sizes of M-Pore[®] aluminium foam have been investigated. It was found that samples smaller than 4 cells are too small to be properly representative of the foam and their corresponding material properties are no longer effective ones. In order to capture the complex geometry of the cellular structure, calculation models were based on μ CT data of real samples. The 3D computed tomography image acquisition was performed using a Xradia MicroXCT-400 CT system. An accelerating voltage of 140 kV and a current of 70 μ A were applied for the radiography of the M-Pore[®] copper samples. All measurements were conducted using the Hamamatsu L8121-03 X-ray source. During the radiation of the samples 1801 2D-projections were acquired using an exposure time of 2 seconds and a resolution of 50.13 μm / voxel. The 3D volume processing was applied on the projections of the 2D radiography images. For the 3D-reconstruction the software XMReconstructor from Xradia was used. For better contrast conditions between metal and pores a prior image processing based on a median filtering was performed. The base material properties of the copper are as follows: thermal conductivity $k_{\text{Cu}} = 380$

$\text{W m}^{-1} \text{K}^{-1}$, density $\rho_{\text{Cu}} = 8900 \text{ kg m}^{-3}$ and specific heat $C_{\text{Cu}} = 385 \text{ J kg}^{-1} \text{K}^{-1}$. Because of the low thermal conductivity of air ($k_{\text{Air}} = 0.025 \text{ W m}^{-1} \text{K}^{-1}$ [16]), the pore space of cellular metals is usually considered not to contribute significantly to thermal heat transfer. In addition, numerical results are to be compared with experimental findings that are obtained in a vacuum without the occurrence of convective heat transfer. Furthermore, temperatures below 400 K are considered and accordingly the contribution of radiation heat transfer can also be disregarded [6]. As a consequence, within the numerical analysis, the thermal conductivity of the pore space is zero.

Fig. 3 Numerical model.

The commercial software package MSC.Marc was used for the finite element analysis. Mixed meshes containing linear hexahedral, linear tetrahedral and linear pentahedral elements have been shown to yield superior accuracy [17] and are used in the subsequent analysis. The corresponding MSC.Marc element numbers are 43, 135 and 137. A multi-frontal sparse solver was used for the solution of the equation system. Post-processing was automated using a Fortran subroutine that calculates the rate of heat transfer $\dot{Q}$ as the sum of nodal reaction heat flux within either the top or bottom surface. Mesh refinement analysis ensures geometric and numerical convergence of the calculation results and indicated a minimum number of 10^6 elements for each calculation model. High numbers of finite elements enable a more precise representation of the target geometry thereby improving geometric convergence. Numerical convergence requires a sufficient number of integration points (i.e. elements) in order to accurately calculate the temperature field. Thermal steady state analysis was performed and the thermal material resistance R_M was obtained by evaluating Fourier's law:

$$R_M = \frac{\Delta T \cdot A}{\dot{Q}} \quad (3)$$

The temperature difference ΔT is defined by constant temperature boundary conditions prescribed at the top ($T_1 = 400 \text{ K}$) and bottom ($T_2 = 300 \text{ K}$) of the calculation model (see Fig. 3). All remaining surfaces are adiabatic. Assuming that no temperature dependence exists, the temperatures may be chosen arbitrarily as long as $T_1 \neq T_2$. The variable A is the total contact area of the sample (i.e. projected area of conducting phase A_C + area of voids) and the rate of heat transfer $\dot{Q}$ is a result of the

steady state analysis. Area A must not be confused with the *conductive* contact area A_C of the metallic phase that is considered in the discussion section below. The main sources of inaccuracy in the finite element analysis are as follows. Geometric inaccuracy is introduced by the limited resolution of the computed tomography scans that cannot detect geometrical details below its resolution (i.e. 50.13 μm). In addition, the geometry can be slightly changed during the transformation from volume data to finite element mesh; however, great care is taken to minimise this effect by ensuring geometric convergence. Furthermore, material properties for copper were taken from the literature and may deviate slightly from the actual base material properties of the cast copper in the cell walls. Finally, the numerical multi-frontal sparse solver of the finite element analysis has a limited accuracy that is mainly governed by the mesh density. This effect was carefully minimised by the mesh refinement analysis described above. Finally, numerical analysis disregards thermal radiation that within the considered temperature range (below 400 K) constitutes a very small contribution to the overall heat transfer. It should be mentioned here that it is not possible to quantify the error of the numerical simulation. Based on the results of the finite element simulation and using Equations (2) and (3) the effective thermal conductivity k was calculated. Figure 4a shows a plot of the material parameter versus the material density. Markers are plotted for the perpendicular x , y and z directions (i.e. normal vectors to the sample surfaces). Linear regression models for each orientation are plotted as lines and yield a good fit to the experimental data. Weak anisotropy is identified with a slightly reduced conductivity in the x direction. This observation can be explained by the manufacturing procedure and is in agreement with previous findings on M-Pore[®] aluminium foam [12]. The temperature distribution inside the central cross section of a high density copper foam sample is shown in Fig. 4b. Due to the complex geometry of the struts, isotherms are not perpendicular to the macroscopic temperature gradient as it would be expected in a solid sample.

Fig. 4 Finite element results: a) Effective thermal conductivity plotted versus density. b) temperature distribution inside high density copper foam sample.

3. Experimental Measurements

The components of the experimental setup (see Fig. 5) can be categorized into three different categories: temperature control, thermal insulation and measurement. The temperature control consists of a flat copper heating plate with an embedded heater wire. A temperature control unit regulates the electrical energy input into the heating wire. Thermal insulation is achieved in three different ways. First, thermal conduction to the surroundings is minimised by supporting the heating element on low thermally conducting ceramic stands and enclosing the whole setup in polystyrol foam insulation. Thermal convection is eliminated by evacuating the specimen and the heat source inside the vacuum chamber. Finally, uncontrolled energy loss due to thermal radiation is minimised by the use of thermal radiation shields and restricting experiments to temperatures between 300 and 400 K. Measurement includes time-dependent temperature curves of the heating element and a sensor located on top of the sample (see Fig. 2)

Fig. 5 Experimental setup

An equivalent thermal conductivity k' is obtained by fitting finite element data to experimentally measured temperature curves [18]. It is important to note that this value is not a material parameter since the experimental measurement includes thermal material resistance R_M as well as contact resistance R_C . In order to calculate the thermal conductivity k , only the material resistance R_M must be used (see Eq. 2). Finite element replicas of the specimen and temperature sensor are generated. The finite element evaluation of the experiment is a wholly independent calculation from the previous analysis where an exact representation of the material meso-structure was analysed. In contrast, the sample is modelled as a solid cuboid with the outer dimensions of the sample and all assigned material properties are effective values. On the corresponding surface of the specimen, a temperature boundary condition simulates the heating element. In an iterative process, the equivalent thermal conductivity k' (i.e. total thermal resistance R_T) of the finite element model is adjusted until the numerical temperature profile can be overlaid on the experimental data. Potential measurement errors in the experimental analysis are discussed next. The used RTD 100 Class A sensors exhibit a measurement error specified below 0.41 K for temperature up to 403 K. An additional error is introduced by the measurement of specimen lengths required for the numerical evaluation with a maximum error of 0.1 mm. Based on these quantifiable inaccuracies the measurement error of the thermal conductivity is $< 1.7\%$. Additional non-quantifiable inaccuracies are residual convective and radiation heat transfer. However, great care was taken in the design of the experimental setup to minimise these effects. Finally, the finite element evaluation introduces a small inaccuracy due to limited numerical accuracy.

Preliminary measurements were performed for calibration and in order to showcase the standard experimental procedure for determining the thermal contact resistance of solid materials. To this end,

CNC-machined aluminium blocks were analysed with direct contact as well as using a thermal conducting foil and paste. Due to the machining, the surface of the samples exhibits distinct grooves shown in Fig. 5b. Three samples with the surface areas 20 mm x 50 mm and heights $h = 20, 30, 40$ mm are tested. The results of the analysis are shown in Fig 5a. The thermal contact resistance is obtained by plotting the total resistance versus the specimen thickness l . Extrapolation to $l \rightarrow 0$ yields the thermal contact resistance for each system. It is important to note that this procedure is only valid for a constant contact resistance and, as will be demonstrated later, can therefore generally not be applied for cellular metals. The highest contact resistance is found for direct contact. The application of a thermally conducting foil slightly decreases the contact resistance and minimum values are found using thermally conducting paste.

Fig. 6 Measurements of Al3005: a) Thermal resistance, b) Magnification of the contact surface.

After obtaining the contact resistance, the thermal material resistance can be calculated $R_M = R_T - R_C$. The effective thermal conductivity is determined by $k = l / R_M$. The final results are listed in Table 1 and can be compared to the reference value for Al3005: $160 \text{ W m}^{-1} \text{ K}^{-1}$ [19].

Sample	Direct	Foil	Paste
#1	158.0 W m ⁻¹ K ⁻¹	164.7 W m ⁻¹ K ⁻¹	158.9 W m ⁻¹ K ⁻¹
#2	150.0 W m ⁻¹ K ⁻¹	163.1 W m ⁻¹ K ⁻¹	159.2 W m ⁻¹ K ⁻¹
#3	155.9 W m ⁻¹ K ⁻¹	158.5 W m ⁻¹ K ⁻¹	159.1 W m ⁻¹ K ⁻¹

Table1: Conductivity measurements of Al3005.

It can be seen that a large thermal contact resistance decreases the accuracy of the measurement. The explanation for this phenomenon lies within the assumption of constant contact resistances. Let us assume that the contact resistance of one sample exhibits a deviation ε from the average value R_C . The effective conductivity is calculated by subtracting the average contact resistance from the measured total thermal resistance of the sample, i.e. $k = l / [R_T - (R_C + \varepsilon)]$. It can be seen that for $R_C \gg R_M$ (i.e. $R_C \rightarrow R_T$), even a small deviation ε will distinctly change the calculated conductivity k . As a consequence, all subsequent measurements with M-Pore[®] copper were performed using thermal conducting paste in order to minimise the thermal contact resistance.

The results of the experimental analysis on M-Pore[®] copper are shown in Fig. 7. Measurements were conducted on six samples and three perpendicular directions each. Analogous to Fig. 6a the total thermal resistance R_T is plotted versus the specimen thickness l . In contrast to solid Al3005, a linear regression of the data points yields poor correlation. In particular, for the high density copper foam (filled dot markers), the estimated contact resistance R_C exceeds the total thermal resistance of two specimens, theoretically indicating a negative (!) thermal material resistance R_M . It can be concluded that the contact resistance of this material is no longer constant but changes for different samples. As a consequence, the described procedure above to calculate the contact resistance by extrapolation is no longer applicable.

Fig. 7 Total thermal resistance plotted versus specimen thickness.

4. Discussion

In the previous sections, results of finite element and numerical analysis were presented. Finite element analysis yields the thermal material resistance R_M that can easily be converted into the

effective thermal conductivity k . Experimental measurements allow the determination of total thermal resistance R_T , i.e. the sum of material and contact resistances. Both results can be combined in order to conduct a systematic study of the contact resistance. This is achieved by subtracting the material resistance from the total resistance according to $R_C = R_T - R_M$.

A likely explanation for the varying contact resistance indicated in the previous Section is the changing copper contact area. Even so, the investigated samples are representative volume elements as far as porosity and thermal conductivity are concerned, the two-dimensional conductive copper surface area (see darkened geometry in Fig. 8b) comprises only a small fraction of the geometry and thus varies between specimens. In the following, this area A_C is determined for each specimen and orientation. Exact values are obtained using the μ CT data of the samples tested in numerical and experimental analysis. The total contact area for each measurement is the sum of the two opposing surfaces perpendicular to the measurement direction. Figure 8a shows the thermal contact resistance plotted versus the contact area. In addition, a linear regression line is plotted and the function given in the Figure. It can be observed that this linear function provides a good estimate of the contact resistance within the considered contact area range. It should be mentioned here that according to theoretical prediction the thermal contact resistance is expected to be proportional to the inverse square root of the contact area [20]. Accordingly, a non-linear regression $R_T = 0.0522 / A_C^{0.5}$ is shown as a dashed line (inverse regression) and might be more appropriate for the extrapolation of results.

Fig. 8 Thermal contact resistance: a) plotted versus contact area
b) graphical representation of the contact area

An important implication of these findings is the minimum specimen size for experimental measurements of cellular metals. In order to obtain the thermal contact resistance, the previously described extrapolation technique needs to be applied. However, this method is only valid for constant thermal contact resistance requiring large representative volumes. In the case of density or thermal material resistance, the representative volume is the complete three-dimensional geometry resulting in smaller specimen sizes. In contrast, for the copper contact area, only a small two-dimensional fraction can be considered. As a consequence, large specimen sizes are required in order to obtain representative copper contact areas and thus constant thermal contact resistances.

5. Conclusion

Numerical and experimental analyses on the thermal resistance of M-Pore[®] copper foam were conducted. In order to account for the complex meso-structure of the material, numerical calculation models were based on μ CT data. Numerical results indicate a thermal conductivity of $10\text{--}15\text{ W m}^{-1}\text{ K}^{-1}$ (low density material) and $24\text{--}30\text{ W m}^{-1}\text{ K}^{-1}$ (high density material) which are high values for cellular metals. In addition, weak thermal anisotropy was observed with a slightly decreased conductivity in one direction. Experimental analysis was first conducted on an Al3005 reference material and thermal contact resistance was analysed using a standard extrapolation method. Experimental measurements were continued on M-Pore[®] copper. Thermal resistances were obtained for a total of six samples. Measured resistances include thermal contact resistances and must therefore be corrected before the thermal conductivity can be calculated. However, the standard extrapolation method to determine contact resistance could not be applied since the contact resistance of the M-Pore[®] samples is not constant. Instead, numerical and experimental results were combined to calculate thermal contact resistances. Geometric analysis of computed tomography data indicates a linear dependence of these contact resistances and the conductive copper contact area within the considered range. It can be concluded that the application of the extrapolation technique for experimental data requires large specimens in order to achieve similar conductive contact areas and thus constant contact resistances. The application of the transient experimental procedure to different types of cellular materials will require additional numerical analysis in order to distinguish thermal material and thermal contact resistance.

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