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Determination of the thermal conductivity of periodic APM foam models

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ABSTRACT

Advanced pore morphology (APM) foam elements have a spherical outer skin and a porous inner structure. In this study, the method of Lattice Monte Carlo is applied to determining the thermal characterisation of periodic structures formed by spherical APM foam elements. Two diameters, i.e. 5 mm and 10 mm spheres, are considered. To this end, micro-computed tomography data of real samples is converted into numerical calculation models. This procedure allows the accurate geometric representation of the complex internal foam geometry. Lattice Monte Carlo is then used to obtain the effective thermal conductivity of partial and syntactic structures made up of APM foam elements. Samples are analysed for variation in absolute and directional (anisotropy) thermal conductivity.

1. Introduction

This work addresses the determination of the effective thermal conductivity of a periodic model of cellular metal assembled from advanced pore morphology (APM) foam elements. Cellular metals exhibit a number of attractive properties such as high specific strength [1], controlled energy absorption [2], damping [3] and versatile thermal properties [4,5]. Furthermore, large specific internal surface areas make them attractive candidates for application as heat exchanger or catalysts [6,7]. Cellular metals are formed from a metallic matrix with internal porosity. Structures with interconnected and mutually insulated pores are called open-celled and closed-celled, respectively. A major challenge that impedes the large scale industrial application of cellular metals is the inconsistency of physical properties [8]. Previous analyses have shown that changes in porosity [9,10], pore size and shapes [11] or even minor geometrical defects [12] can cause a significant variation in the effective properties. A promising solution is the assembly of cellular metals using pre-manufactured building elements. As an example, metallic hollow sphere structures [13] are made up from hollow spherical shells of sintered metal. More recently, APM foam elements have been introduced [14]. These are (approximately) spherical particles with a metallic skin and a stochastic internal foam structure. As such, they combine the controlled geometry of hollow sphere structures with the stochastic foam geometry of 'classical' cellular metals. APM foam elements are manufactured using a powder compaction process. AlSi7 powder and TiH2 foaming agent are rolled into wire-shaped precursor material. This precursor is then cut into small granulates that are expanded into sphere-like foam elements (see Fig. 1). Advanced pore morphology structures (APMS) are formed by joining APM foam elements using suitable joining technologies such as sintering, soldering or adhesive bonding.

Previous analyses of APMS have focused on their mechanical properties. Lehmhus et al. [15] investigated the influence of APM foam density in quasi-static and dynamic compressive testing. Vesenjak et al. [16] addressed the compressive behaviour of single APM foam elements and composite APM foam. They further introduced infrared thermal imaging to identify areas of plasticisation in experimental testing [17]. Hohe et al. [18] conducted experimental and numerical tests on graded APM foams for multi-functional aerospace applications. Their main focus of investigation was perforation resistance against bird strike events.

For the first time, the present paper investigates the thermal properties of APMS. Two different types of APM foam elements with diameters 5 mm and 10 mm are considered. Furthermore, two different morphologies (partial and syntactic APMS) are addressed. To this end, the complex geometry of single APM foam elements is captured using micro-computed tomography (μCT) imaging. Geometric data are then converted directly into Lattice

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Fig. 1. Light photograph of APM foam elements.

Monte Carlo (LMC) calculation models. Symmetric boundary conditions are used in the simulations and mimic an infinite APMS structure with foam elements arranged in a primitive cubic pattern. For each sample, the effective thermal conductivity tensor is obtained. APMS are tested for directional variation (anisotropy) and sample variation of their effective thermal conductivity.

2. APMS geometry

The APMS geometry is captured using micro-computed tomography imaging. An Xradia MicroXCT-400 machine with a Hamamatsu L8121-03 X-ray source was used for the scanning. Due to the size differences of the samples, the voxel resolutions were limited to 5.61 μm and 11.08 μm, respectively. A total of 1800 absorption radiographs (exposure time 16 s) was captured with 0.2° rotation for each projection. The selected acceleration voltage was 140 kV with a current of 70 μA. Segmentation of the μCT data allows material identification (in the case of APM foam elements this is either AlSi7 aluminium alloy or air). This material data is then mapped onto lattice models (see below *Lattice Monte Carlo Analysis*) where each lattice node corresponds to a voxel of the μCT data. A three-dimensional μCT reconstruction of a 10 mm APMS foam element is shown in Fig. 2. In order to visualise the internal pore structure, the foam element is cropped along one of its central planes.

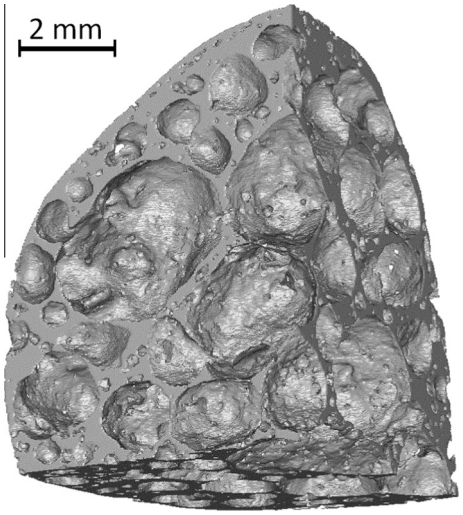

Fig. 2. Micro-computed CT data: three-dimensional reconstruction (cropped to 1/8 of the spherical element).

The internal pores of APMS foam elements are predominantly closed, i.e. enclosed by a solid cell wall. However, the micro-computed tomography data indicates small openings within these cell walls connecting the majority of neighbouring pores. This observation can be confirmed using electron-beam microscopy of the same material. Fig. 3 shows a micrograph of an APM foam element cross section and small holes within the cell walls can easily be identified.

The geometric properties of the scanned foam elements #1–10 are summarized in Table 1.

3. Lattice Monte Carlo analysis

Numerical analysis of the effective thermal conductivity of APMS is performed using Lattice Monte Carlo (LMC) analysis. This versatile finite difference method has been successfully applied to determine the effective thermal conductivity of cellular metals such as sintered fibre structures [19], hollow sphere structures [20], Alporas® aluminium foam and M-Pore® metal sponge [21]. The LMC method is based on probing particles that are inserted into a lattice model to explore the effective diffusivity of composite materials. Geometry data is usually derived from μCT imaging. Alternatively simplified model structures can also be utilised.

Probing particles perform random walks within the primitive cubic lattice model and are directed by jump probabilities. These probabilities are the thermal diffusivities of each material (normalised by the maximum thermal diffusivity of all components present in the model). Whilst simulating APMS, the effective thermal conductivity of the cell wall material AlSi7 is 167 W/(m K) [22]. The thermal conductivity of air enclosed within the pores is only 0.027 W/(m K) [23] and thus can be assumed to be zero to a good approximation. This minor simplification allows decreasing the required computation times for each calculation. The accuracy of LMC analyses is determined by the number n of probing particles

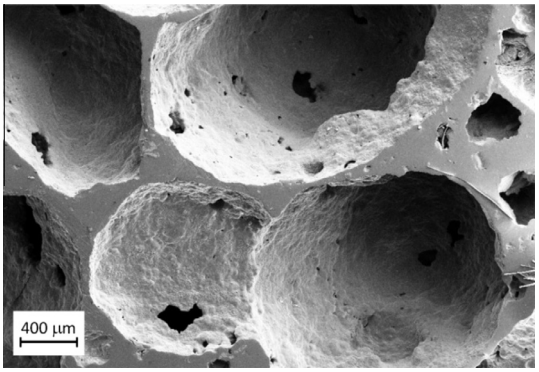

Fig. 3. Electron beam microscopy of APM foam element.

Table 1
Geometric properties of APM foam elements.

Sample	Nominal outer diameter (mm)	Porosity (%)	Mass (g)
#1	5	81.0	0.064
#2	5	85.3	0.050
#3	5	80.5	0.066
#4	5	82.0	0.061
#5	5	83.7	0.055
#6	10	84.1	0.43
#7	10	84.6	0.42
#8	10	82.3	0.48
#9	10	81.6	0.50
#10	10	82.3	0.48