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On the thermal properties of expanded perlite – Metallic syntactic foam

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ABSTRACT

This paper addresses the thermal properties of syntactic metal foam made by embedding expanded perlite particles in A356 aluminium matrix. Lattice Monte Carlo (LMC) analyses are conducted to determine the thermal characterisation of the foam. For increased accuracy, the complex geometry of the metallic foam is captured by micro-computed tomography imaging. Using the resulting detailed geometric models, the effective thermal conductivity tensor is computed with possible thermal anisotropy taken into consideration. The numerical results are verified by comparison with experimental measurements. To this end, an improved steady-state method is used to correct for thermal contact resistance. Furthermore, the effective heat capacity, average density and thermal diffusivity of perlite – metal syntactic foam are determined.

1. Introduction

Materials with metallic matrix and internal porosity are commonly referred to as cellular metals. They are multi-functional and they typically show high strength to weight ratio [1], damping [2], and controlled energy absorption [3] combined with versatile thermal properties. Due to the high thermal conductivity of the metallic phase, cellular metals can be used for conductivity enhancement of energy storage composites [4,5] and as heat exchangers [6–8].

The present paper addresses the thermal properties of novel metallic syntactic foam (MSF). This subclass of cellular metals is created by combining hollow particles with a continuous metallic matrix [9]. For the material considered the hollow particles are expanded perlite and the matrix is A356 aluminium alloy. Syntactic metal foams have been previously fabricated by embedding metallic [10,11] glass [12] or ceramic spheres [13,14] into a metallic matrix. Due to their closed cell porosity MSFs are not usually suitable for conductivity enhancement or for use in heat exchangers. However, the novel expanded perlite MSF overcomes this limitation. Due to its low strength, the perlite, which is volcanic glass, can be readily removed (e.g. using a high pressure water jet) resulting in a porous aluminium structure with an interconnecting pore network. Such a material is referred to as a metallic sponge and is attractive for thermal applications due to its large accessible surface area and relatively high thermal conductivity.

There has been a strong focus on structural applications of MSFs but previous work on the *thermal* properties is surprisingly scarce. In [15,16] the effective thermal conductivity of syntactic steel foams containing hollow spheres was predicted using numerical analysis. Conductivities were found to decrease from 35 W/m K to 20 W/m K with increasing filler particle fraction. This work was extended for advanced pore morphology (APM) filler particles [17] in an aluminium matrix. Due to the higher intrinsic conductivity of aluminium, relatively high conductivities of the syntactic foam, between 32 W/m K and 41 W/m K, were found. Furthermore, the thermal expansion coefficient of MSF was studied for hollow SiC filler particles [18] and cenospheres [19]. This somewhat limited literature on thermal properties is dwarfed by research focusing on the thermal characterisation of metallic sponges that consider thermal energy transfer by conduction [20,21], convection [22,23] and radiation [24,25]. A thorough review thereof is far beyond the scope of this paper. This difference in research intensity is easily explained by the large field of thermal applications for cellular metals with interconnected porosity.

The present paper addresses for the first time the thermal properties of MSF containing expanded perlite particles. Analytical and numerical approaches are combined with experimental measurements to determine the material density, specific heat capacity, effective thermal conductivity, and effective thermal diffusivity.

2. Methodology

2.1. Sample manufacturing

Perlite aluminium syntactic foams were manufactured using infiltration casting. The expanded perlite particles (particle density 0.18 g/cm^3 [26]) were approximately spherical in shape and

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Nomenclature

Symbol	Description (Dimension)
C_{A356}	specific heat capacity of A356 alloy (J/kg K)
C_{MSF}	specific heat capacity of MSF (J/kg K)
D^*	dimensionless diffusivity (–)
D_{eff}	effective thermal diffusivity (m^2/s)
h_S	sample height (m)
k_{A356}	thermal conductivity of A356 alloy (W/m K)
k_{eff}	effective thermal conductivity (W/m K)
k_{EP}	thermal conductivity of expanded perlite (W/m K)
k_R	thermal conductivity of reference body (W/m K)
l_R	distance between temperature measurement locations (m)
m_{Al}	mass of aluminium (kg)
m_{PE}	mass of perlite (kg)
m_S	mass of sample (kg)
N_{JA}	number of jump attempts per particle (–)
N_P	number of probing particles (–)
p	porosity (i.e. volume fraction of perlite particles) (–)
$\dot{q}$	heat flux (W)
R	particle displacement (voxel)
$R_{C,HE}$	thermal contact resistance (m^2 K/W)
$R_{C,R}$	thermal contact resistance (m^2 K/W)
R_S	thermal material resistance of the sample (K/W)
R_{tot}	total thermal resistance (K/W)
t	LMC temp (i.e. total number of jump attempts) (–)
T_{IF}	extrapolated temperature (K)
T_{HE}	temperature of the heating element (K)
T_{R1}, T_{R2}	temperatures of the reference body (K)
V_{Al}	volume of aluminium (m^3)
χ	anisotropy ratio (–)
Φ_{Al}	aluminium volume fraction (–)
ρ	density of MSF samples (kg/m^3)
ρ_{Al}	density of aluminium (kg/m^3)

particles with diameters between 2 and 2.8 mm were separated by sieving. These particles were filled into a mould and the resulting packed bed was infiltrated with liquid A356 aluminium alloy. A subsequent thermal T6 treatment enhances the mechanical properties of the syntactic foam [27]. A detailed description of the manufacturing procedure can be found in [26]. The resulting samples were of cylindrical shape as depicted in Fig. 1a. The three-dimensional reconstruction of micro-computed tomography (μCT) data shown in Fig. 1b only considers the metallic phase of the foam material. It can be seen that pores (i.e. the volume occupied by the expanded perlite particles) percolate as neighbouring particles touch during the infiltration casting.

2.2. Lattice Monte Carlo analysis

Lattice Monte Carlo (LMC) is a finite difference based method that simulates diffusion in virtual models by random walks of probing particles [28,29]. The method is frequently used for the analysis of thermal [29–31] and mass diffusion problems [32,33]. Its major advantage over finite element methods is memory efficiency allowing the computation of a 10^9 voxel model on a standard desktop system (8 GB RAM). Further benefits are the simple model generation from µCT data and its high numerical stability.

In the first step of the LMC analyses, virtual models of the MSF are created. Due to the complex meso-structure of the foam material, geometric models are derived from µCT scans of samples. A high voxel resolution (voxel side length 35.32 µm) ensures an accurate geometric representation. In the present study, a total of six µCT data scans were obtained and their physical properties are summarised in Table 1. The result of the µCT scans is primitive cubic voxel data where the greyscale level of each voxel indicates the average density within its volume. Thus, segmentation allows the distinction between the high density aluminium and low density expanded perlite particles or pores. For this segmentation, the aluminium volume fraction Φ_{Al} of the scanned MSF samples is determined. To this end, the sample is weighed on a precision scale to measure the sample mass m_S (see Table 1). This value is corrected by the perlite mass m_{PE} that had been determined prior to casting in order to obtain the aluminium mass $m_{Al} = m_S - m_{PE}$. Using the density of A356 aluminium alloy ($\rho_{Al} = 2520\ kg/m^3$ [34]) the aluminium volume V_{Al} is calculated using $V_{Al} = m_{Al}/\rho_{Al}$. The aluminium volume fraction is then determined by the division of the aluminium volume with the cylindrical sample volume V_S (see Table 1), i.e. $\Phi_{Al} = V_{Al}/V_S$. During the segmentation of the µCT data the greyscale threshold is iteratively adjusted until the segmented volume fraction Φ_{Al} in the numerical model coincides with this calculated value. In the next step, the cylindrical µCT data is truncated to make the largest possible prism and the geometry is mirrored relative to three perpendicular surfaces. This step is required in order to prescribe periodic boundary conditions on all surfaces of the numerical model. The truncated voxel data is converted into a primitive cubic lattice model by substituting each voxel with a lattice node located at its centre. The segmented material information (i.e. A356 aluminium or expanded perlite)

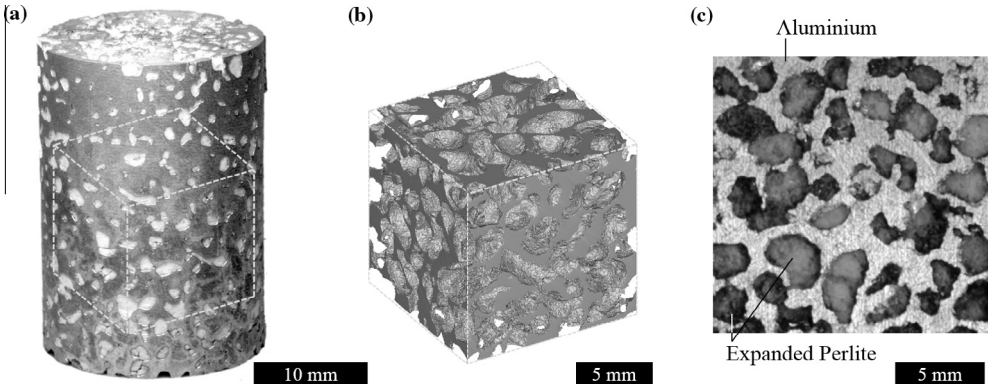

Fig. 1. Perlite metal syntactic foam (PMF): (a) cylindrical sample, (b) μCT reconstruction, (c) detailed view of the foam structure.