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Prediction of heat conduction in open-cell foams via the diffuse interface representation of the phase-field method

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ABSTRACT

We present a 3D simulation approach utilising the diffuse interface representation of the phase-field method combined with a heat transfer equation to analyse the thermal conductivity in air-filled aluminium foams with complex cellular structures of different porosity. Algorithmic methods are introduced to create synthetic open-cell foam structures and to compute the thermal conductivity by means of phase-field modelling. A material law for the effective thermal conductivity is derived by determining the appropriate exponent depending on the relative density in the system. The results are compared with the thermal conductivity in massive aluminium and in pure air.

1. Introduction

Open cell metal foams (see Fig. 1) are materials with exceptional properties. They evince extremely low density and at the same time outstanding mechanical [1], electrical [2], thermal [3–15] and acoustic [16] properties. For these reasons they are kindly regarded in machine tool building [17], machine construction [18], vehicle construction [19], architecture [20], orthopaedics [21] and other sectors: sports goods [22], heat exchangers [23], energy attics [24], catalytic converters [25], box radiators [26] and so on.

However, there are many limitations in the use of metal foams, due to the lack of sufficient regulations for construction, production/process parameters or simulation data. To enable foam models for a broader field of applications, an increased knowledge of material properties is required. In particular, heat transfer and residual stresses are important for production and joining technologies, which are related to the intricate morphology of the material. As an example for the structures considered in the following simulations, Fig. 2 shows the photographs of typical open-pore aluminium foams with different porosity.

A general review on the characteristics and properties of natural (e.g., bones or wood) and industrial cellular materials is given by Gibson and Ashby [27]. A comprehensive review on the potential applications of metal foams is given in [28]. The most comprehensive work on fluid flow and heat transfer in porous media is provided by Kaviany [29], who also provides a historical overview on contributions to the transport phenomenon of heat and mass transfer in porous media.

Early publications refer to the approximation of cellular solids in accordance to the methods used for packed beds [30,29,3]. As noted by Abramenko et al. [3], there exists a large number of models for the calculation of the thermophysical properties of porous media (cf. [29] with sometimes inconsistent and contrary results, because of which he argues, that the most resilient source of information are experimental measurements. There are several publications on the experimental determination of the thermal conductivity of cellular solids [4–6], but to our knowledge no particular analysis and articles on aluminium open cell foams. A recent study in [7] gives a clear review on the existing theories, divided into two major classes of models using correlations based on the combination of thermal resistances [29,8,4] and models based on ideal unit cells [9–11,5].

To put it in a nutshell, there are no unique experimental setups to particularly evaluate the effective physical properties of porous media, and foam materials. The thermal conductivity of the solid phase seems to play an important role in the overall effective thermal conductivity [9] as well as the strut connections [12]. Kanaun and Tkachenko report a minor effect of cell-size distributions on the effective thermal conductivity compared to their influence on the effective elastic properties, and no influence of the ligament cross-section (cf. [13]).

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There are different efforts to derive methods based on experimental setups as well as computational models [9,14,13,15,6,11,12]. The availability of modern numerical techniques and computational resources enables the application of sophisticated simulation methods. Quick turnaround times, lower costs and a deeper insight are some encouraging challenges for applying modern methods of computational material science to derive new material laws for effective physical quantities by means of homogenisation across the micro-structure.

In this project we adapt the simulation software Pace3D [31] based on phase-field modelling [32–41] to appropriately describe heat conduction in complex geometries on the centimetre scale and combine it with algorithmic fillings for the pore structure in aluminium foams. In the following simulation studies we analyse effective thermal conductivity properties of open-cell foams depending on the fineness and the shape of the pore structure. We concentrate on pure heat diffusion in the system and neglect effects like free convective flow or energy transport due to the phase change in the moisture possibly existing in the air.

In Section 2, we give a brief introduction into open cell metals foams. Section 3 describes the phase-field model as the fundamental method for the simulations and summarises the formulations for the volumetric heat capacities and for the thermal conductivities in the individual cells of the simulation domain, especially in the diffuse interface area. Section 4 explains the structured mesh generation algorithm to create synthetic open cell foam samples. In Section 5 we present the method to compute of the effective thermal conductivity by means of the simulation results. At last we discuss the results of the investigations in Sections 6 and 7.

2. Metal foams

Metal foams are usually produced by casting (e.g., m-pore, Dresden) and by powder metallurgical processes (e.g., Fraunhofer IFAM, Dresden). There also exist production processes according to Slip Reaction Foam Sintering procedures (e.g. [42,43], which produce foams with very high solid fractions (of about 40%).

The most important parameters of open-cell metal foams are the solid fraction, which is usually 7–12% and the number of pores per (linear) inch (ppi), which is usually 7–40 ppi. Fig. 2 shows the photographs of typical open-pore aluminium foams.

The other parameters are pore and ligament size and shape, their distribution, the anisotropy of the pore shape as well as the appearance of closed faces and their preferential orientation. Jang, Kraynik and Kyriakides present pictures magnifying by X-ray tomography selected ligaments of the length 2.6 cm and 2.4 cm in an open-cell aluminium foam with 10 ppi [44, Fig. 11]. A pore of the same sample is shown in Fig. 3. The parameters h_1 and h_2 describe the shortest and the largest distance in the convex irregular polyhedron representing the cell. In this sample $h_{1,\min} = 4.013$ mm and $h_{2,\max} = 5.944$ mm and the mean value of h_1/h_2 is 1.27 (see [44]. The elongated shape is visible.

In Fig. 4, the preferred orientation of the elongated pores can be identified. Further the occurrence of closed faces can be seen.

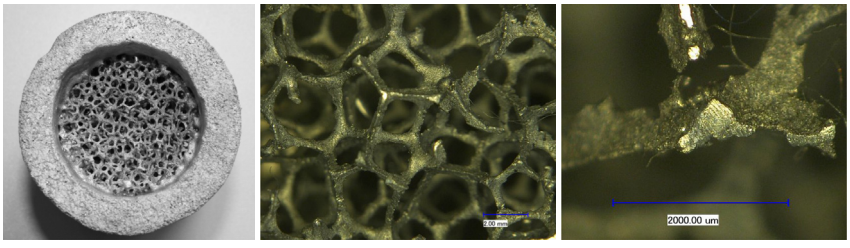
3. A diffuse interface model for heat diffusion in multiphase systems

We start with a justification for the use of the phase-field method as a method to represent the complex geometry of the foam structure by introducing a diffuse interface in order to simulate thermal processes in a porous foam system. The phase-field method is originally developed for the description of phase transformations, such as solidification and fusion of materials. We adapt this method in such a way (which is briefly described below) that it is used for the solution of the temperature equation in a complex system. But what is the decisive advantage of this method in this context? In energy storage systems, metallic foams are used in combination with phase change materials (PCM). Filled with paraffin, metal foams can be used in modern storage modules, to increase the thermal conductivity of the storage filling. Due to the paths of the foam, the heat diffuses faster into the filling, causes paraffin to melt and is thereby stored as latent heat. The adapted phase-field method is capable to describe both, the heat transfer as well as the phase transition of PCM as fill medium inside the non-changing metal phase. In this work we focus on the heat diffusion in complex porous system air–metal. As a further step towards the simulation of PCM-melting and solidification in a metal matrix, the modelling of phase transition during heat diffusion and convection has been planned. As an added benefit, the explicit solution of the diffusion equations (by means of the Euler method) benefits from the diffuse interface representation of the phase-field method causing a smooth transition between different thermal properties, such as the volumetric heat capacity C_V (for aluminium alloy: $2.34 \cdot 10^6$ J/m^3 K, for air: $1.16 \cdot 10^3$ J/m^3 K) and the thermal conductivity λ (for aluminium alloy: 150 W/mK, for air: 0.025 W/mK). The verification of the new method with the help of analytic solutions, as well as with the results of a finite volume-based method, is briefly described below.

The basic concept of the phase-field method is a partitioning of the simulation domain in sub-domains occupied by different phases and a construction of diffuse interface between the different distinct phases. A phase contains specific properties such as the aggregate state, an initial temperature, a specific composition, a particular crystal orientation and possibly a residual stress. Two separate phases differ from each other in at least one of these properties. The complete set of all phases is described by a vector-valued order parameter of the form

$$\vec{\phi}(\vec{x}, t) = (\phi_1(\vec{x}, t), \ldots, \phi_N(\vec{x}, t)), \tag{1}$$

where each component represents a particular phase and hence depends on space $\vec{x}$ and time t. ϕ_α equals 1 in regions, where the phase α is present and $\phi_\alpha = 0$ where the phase α is absent. An exception is the diffuse interface region which surrounds the phase



(a) (b) (c)

Fig. 1. Open-cell metal foam: (a) foam sample, (b) details of cell structure and topology, (c) details of ligament cross-section.