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Numerical homogenization of hybrid metal foams using the finite cell method

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Dedicated to Professor Dr.rer.nat. Ernst Rank on the occasion of his 60th birthday

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ABSTRACT

We present a numerical homogenization approach for hybrid metal foams, i.e. foams that are electrocoated to improve their mechanical properties. Based on the finite cell method, a spatial discretization of a μCT-scan of the microstructure of the hybrid metal foam under investigation is derived and the window method is applied to compute effective material properties. We demonstrate that this method offers the possibility to efficiently compute and study the influence of the coating thickness of hybrid metal foams.

1. Introduction

Cellular and foam-like metals represent a class of light-weight materials that are of increasing interest in many different engineering disciplines [1,2]. Thanks to their low density, metal foams are used in light-weight structures such as sandwich plates or integral foams. In addition, they exhibit other appealing properties such as a high kinetic energy absorption capacity, mechanical damping, acoustic absorption, and heat transfer ability, just to name a few. These properties demonstrate the potential of metal foams for many different applications in engineering [3] and can thus account for the increasing research invested in these materials. In addition to the manufacturing technology of foamed materials [4], many researchers are investigating the modeling and simulation of the complex microstructured material — see, for example, [5,6].

Hybrid metal foams constitute a new class of cellular materials. In order to further improve the mechanical properties of open cell aluminum foams, electrodeposition is applied to strengthen the foam by means of a nanocrystalline nickel layer, see [7–10]. As proven by experiments, the coating increases the stiffness and energy absorption capacity of the foam significantly. Similar results have been obtained in the case of open cell aluminum foam coated with nanocrystalline copper [11].

Encouraged by these promising results, a new method to simulate the mechanical behavior of hybrid metal foams is being developed. To this end, the microstructure of the foam obtained by μCT-scans is discretized, and the effective elastic material properties are computed by numerical homogenization. In this way, it is possible to study the influence of the coating thickness on the mechanical behavior of the foam numerically, i.e. without carrying out experiments. Furthermore, this approach allows to optimize the hybrid metal foam in such a way that the layer-thickness can be customized to meet required material properties. This can be helpful for designing hybrid metal foams, as it reduces the number of necessary trials during production and experimental testing.

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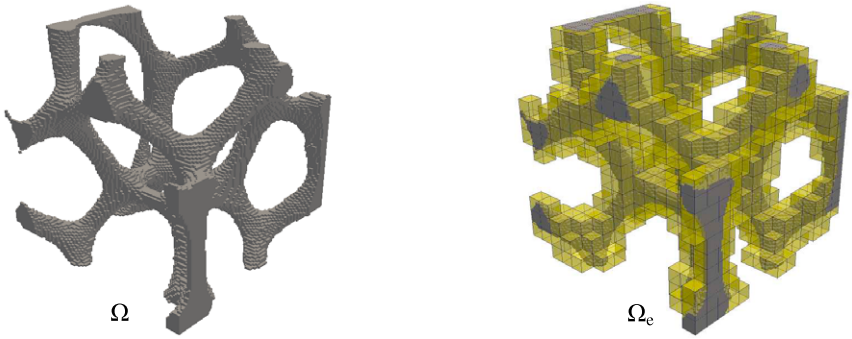

Fig. 1. (a) A μCT-scan of a foam structure and (b) the corresponding FCM mesh.

Due to the complex microstructure of the foams and the additional difficulty of modeling the thin coating layer, standard discretization methods such as the finite element method are difficult to be applied in a straightforward way. This is due to the fact that the pre-processing, i.e. the generation of the corresponding finite element models, would be very labor-intensive — and the resulting models would be very large and therefore costly to compute. In order to overcome the meshing problem, several remedies based on the partition of unity approach [12] such as X-FEM [13–16] and GFEM [17,18] have been proposed. These methods have also been applied to the homogenization of problems where the geometry is described by voxels or by means of the level-set function [19–21]. Alternatively, we propose to apply and further develop the finite cell method (FCM) [22,23], which has been demonstrated to be an efficient numerical tool to simulate problems with complex geometries. The FCM was successfully applied to different linear [24,25] and nonlinear problems [26,27] in structural mechanics and extended to numerical homogenization in [28,29]. In this paper, we will apply and further extend the FCM to the homogenization of hybrid metal foams, allowing to study the influence of the coating thickness.

The outline of this paper is as follows: In Section 2, we will briefly recall the FCM — with a special emphasis on the numerical integration which is a key factor and responsible for accuracy and efficiency. In Section 3, the overall numerical homogenization approach will be presented. In this section, we will also summarize the window method which is a variant of the self-consistency approach known from homogenization methods. Additionally, an acceleration procedure based on Aitken's method will be proposed in order to reduce the number of iterations within the window method. In Section 4, we will present the results of several numerical studies. Based on an extensive parameter study, we will make a suggestion on how to discretize the microstructure of the foam before we study the influence of the coating thickness. Finally, Section 5 will summarize the most important results and give an outlook on future work.

2. The finite cell method applied to voxel models obtained from μCT-scans

2.1. Basic formulation

Since a detailed description of the FCM can be found in [22,23], a brief overview of the most important basics of the method for problems in linear elasticity will suffice. The FCM is very similar to the standard FEM, except for the definition of the mesh discretizing the physical domain Ω. In the FCM, the mesh does not represent the geometry accurately, which is why elements (referred to as *cells* in this method) do not necessarily conform to the boundaries of the physical domain. As the FCM mesh embeds the geometry of the problem, the extended domain Ω_e spanned by finite cells is bigger than the physical domain Ω; see Fig. 1. One of the main benefits of the FCM is that it allows for a straightforward mesh generation at hardly any cost. This is of advantage for problems that exhibit very complicated geometrical features such as in cellular materials. Since the finite cell mesh does not represent the geometry accurately, we introduce an indicator function

$$\alpha(\mathbf{x}) = \begin{cases} 1 & \forall \mathbf{x} \in \Omega \\ \alpha_0 = 10^{-q} & \forall \mathbf{x} \in \Omega_e \setminus \Omega. \end{cases} \tag{1}$$

By introducing the indicator function α in the integration of the stiffness matrix and the load vector of the overall system, the geometry can be accounted for during the numerical quadrature. The exponent q is chosen to penalize the void domain during the integration. In order to balance the accuracy of the geometry representation and possible conditioning problems, since α is very close to zero, we choose q in the range of $q = 4, \ldots, 15$. In this paper, we use $q = 12$. Correspondingly, the stiffness matrix $\mathbf{K}_c$ and the load vector $\mathbf{F}_c$ of each cell reads,

$$\mathbf{K}_c = \int_{\Omega_c} \mathbf{B}^T \alpha \mathbf{C} \mathbf{B} \, d\Omega, \tag{2}$$

$$\mathbf{F}_c = \int_{\Omega_c} \mathbf{N}^T \alpha \mathbf{f} \, d\Omega + \int_{\Gamma_N} \mathbf{N}^T \bar{\mathbf{t}} \, d\Gamma, \tag{3}$$