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Fabrication, modelling and evaluation of microstructured materials in a digital framework

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ABSTRACT

Microstructured materials are inhomogeneous at small length scales, where different constituents or phases can be distinguished and the evaluation on their material properties and mechanical behaviours is critical for the applications of such material in engineering. In this study, we develop a systematic digital framework for material representation, fabrication, modelling and characterisation to evaluate the material properties of microstructured multi-phase materials. As the core of this digital framework, a 2-/3-D finite element model generator is developed to create finite element (FE) models for microstructured materials and their meshes with self-developed codes and available scientific engineering software and packages, which can describe the microstructures in detail. For characterisation and evaluation purposes, the generated FE models are further equipped with appropriate boundary conditions based on practical experiments in laboratory. Then the well-established FE models can be run using commercial finite element analysis packages, i.e., Abaqus, to extract the information and data for material property evaluation for the materials of interest. As a case study, the proposed digital framework is applied to evaluate a typical closed-cell metal foam material and the results obtained show clearly cell size effect of foams on their mechanical behaviours which is validated by experimental data available.

1. Introduction

Microstructured materials are regarded as inhomogeneous at small length scales, where different constituents or phases can be distinguished. As a guideline, a random microstructure in such materials can be characterised by several parameters of each phase existing in the materials, such as their size, shape, distribution, compactness (space occupied by phases regarding the total space), and arrangement (random or regular), [1–4]. In order to incorporate the spatial arrangement of phase components in a numerical modelling and simulation, it is essential to quantitatively characterise the normally random microstructures in such materials. From digital representation reconstruction and fabrication's point of view by computer graphics, accompanying with the understanding on material microstructures in practical, several numerical methods have been developed and employed to generate such material structures [5–13], i.e., Voronoi tessellation method, cellular automata grain growth algorithm, sphere growth algorithm, and image analysis methods for further numerically characterising the material properties and mechanical behaviours of the materials of interest. Image analysis methods [12,13] include the X-ray Computed Tomography (CT), serial sectioning method, etc., which largely reply on the expensive scanning of the real material samples and thus they are not the focus in present study. In comparison with other methods and considering metal foam materials as case study here, the sphere growth algorithm is very fast and enables to create large structures with high dispersion of cell size distribution and random spatial distribution of cells. Metal foams have the interesting properties, such as high stiffness in conjunction with very low specific weight, or high compression strength combined with good energy absorption characteristics [14,15] and thus up to now these materials still attract a lot of research interests for material optimization design purpose and a lot of numerical modelling and simulations have been reported in literature [9,10,16–20]. Recently the studies on foam materials show their investigation on cell size effect on material properties of metal foams [19–22].

In this paper, being motivated by the idea of digital material representation, we further develop this idea to a systematic digit framework for microstructured and multiphase materials, which includes digital material representation and fabrication, finite element model generation and digital testing on characterization and evaluation of material properties and mechanical behaviours of such materials by continuing the topic of cell size effect. The whole paper is structured with seven main sections. In Section 2 we expose the digital

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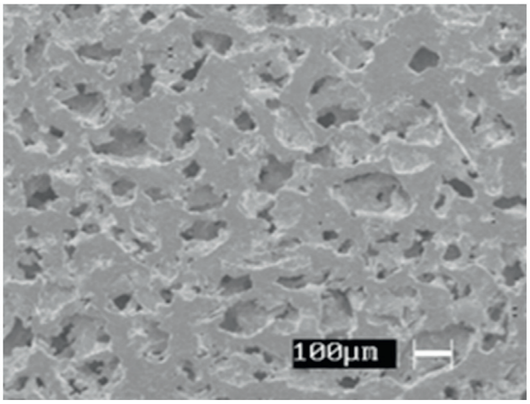
representation and fabrication of the microstructured materials using the sphere growth algorithm for the existing multiple phases from both direct and inverse problems' point of view and the 2-/3-D geometries of characteristic material structures can be fabricated using the foam materials as a case study. Section 3 describes the generation of the 2-/3-D finite element models and their meshes based on the geometries obtained in Section 2 by using the free mesh generator – Gmsh and the commercial finite element analysis package – Abaqus. In the following Section 4 we focus on the case study of two-phase materials – metal foams, starting with the in-depth discussion on their material models defined in Abaqus. Section 5 gives the whole idea and procedure of the digital testing for the evaluation of material properties and mechanical behaviours of titanium foams including hydrostatic tension, hydrostatic compression, and uniaxial compression test, etc. Then we focus on the recently-found cell size effect on the material properties and mechanical behaviours of this typical metal foam material in the Section 6 by looking at the stress–strain curves obtained in three digital tests. Lastly we summarize our conclusion and outlook the future work in the Section 7.

2. Digital representation and fabrication of microstructured materials

In current work, we employ the sphere growth algorithm to generate 2-/3-D microstructured materials and use closed-cell metal foam materials to show the whole development and application of the proposed digital framework. The codes with implementation of the sphere growth algorithm were programmed by using Matlab codes.

For closed-cell metal foams, there are only two phases existing in the materials: (a) hollow cells, which can be treated with a circular shape for 2-D and a spherical shape for 3-D, respectively; and (b) cell walls made of base materials, i.e., steel, aluminium, magnesium, and titanium, etc. Fig. 1a and b show two typical closed-cell material structures: aluminium foam with a porosity of 88% manufactured via the powder compact melting method and titanium foam with a porosity of 70% fabricated via the powder metallurgy technique. The cells of the aluminium foam sample are large enough to be recognized even in the photo taken by using a digital camera because of its cell sizes at 2–5 mm. The microstructure of the titanium foam must be characterised through SEM due to its cell sizes at 50–150 μm as shown in Fig. 1b.

(a) Aluminium foam with a porosity of 88%

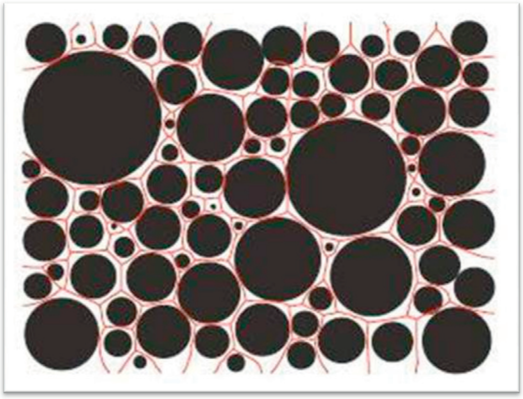


(b) Titanium foam with a porosity of 70%

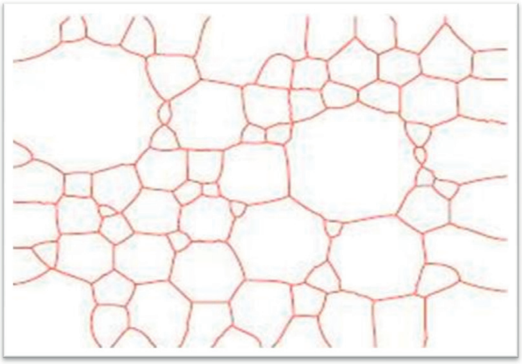
Fig. 1. Structures of typical metal foams.

For the basic algorithm of the digital representation and fabrication of the foam structure used in present study, Fig. 2 shows the basic algorithm of the sphere growth method in a two-dimensional case as a direct problem. According to the spatial distribution and actual size of the cells, the centres of the circular cells can be firstly located based on the actual structure of a metallic foam material as shown in Fig. 2a and then each cell can be grown to the appropriate size as depicted in Fig. 2b and finally the 2-D digitally representative model can be fabricated accordingly.

As we know the porosity of a metal foam material as well as the other characteristics of its microstructure, i.e., cell size and distribution, we also can treat the fabrication as an inverse problem. In such a case, we can randomly define the centres of cells with different sizes but make the cells to follow the appropriate relative positions between the neighboured cells' centres due to the existence of cell walls. In the developed Matlab codes, the main control and input parameters include the dimensional type of the problem (2-D or 3-D), the sizes of the 2-/3-D materials model which can be shaped as circle, square, and rectangle in 2-D cases, and cylinder, cube, and brick for 3-D cases, the total type numbers of cell size, the total numbers of cells at each size, and the radius of cells at each cell, etc. for such an inverse problem. By this way, the dimension and the position of the elementary cell could be easily defined using an algorithm for the generation of a set of random real



(a) The 2-D circular cell model



(b) The representative structure of metallic foam

Fig. 2. 2-D circular-cell model of metal foam.