Computational Materials Science 79 (2013) 45–51

Contents lists available at SciVerse ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Meso-mechanical study of collapse and fracture behaviors of closed-cell metallic foams

C.Y. Zhang [a,b], L.Q. Tang [a,*], B. Yang [a], L. Zhang [a], X.Q. Huang [a], D.N. Fang [a,c]

[a] Department of Engineering Mechanics, School of Civil Engineering & Transportation, South China University of Technology, Guangzhou, China
[b] Sino-French Institute of Nuclear Engineering & Technology, Sun Yat-Sen University, Zhuhai 519082, Guangdong, China
[c] College of Engineering, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 25 February 2013
Received in revised form 7 May 2013
Accepted 27 May 2013
Available online 29 June 2013

Keywords:
Metallic foams
Finite element
Meso-structure
Fracture
Plastic band
Pore irregularity

ABSTRACT

Metallic foam is a typical porous material with heterogeneous mesostructure. The complex influences of the porous structure on the mechanical properties of metallic foam are not well known yet and this remains a crucial problem in the ability to predict and optimize the mechanical properties of foam materials. Here we explored the three dimensional Voronoi structure to model the meso-structure of metallic foam. The average pore size was controlled by the number of seeding points used to construct the Voronoi structure and the porosity was controlled by calibrating the cell wall thickness. In addition, the concept of pore irregularity was introduced to try to further quantify the description of the heterogeneous structure. The correlation between the pore irregularity variation and the plastic response variation suggests inclusion of the measurable meso-structural parameter would improve the constitutive modeling of foam materials. The plastic and the cracking behavior of pores at the mesoscale under large compressive deformation and tensile deformation were studied and the excellent compressibility of metallic foams can be attributed to the formation of multiple plastic bands while the poor stretchability is due to that only one damaged plastic band can be formed.

1. Introduction

Metallic foams, as a new but yet imperfectly characterized class of materials, offer significant performance gains in light, stiff structures, for efficient absorption of energy, for thermal management and perhaps for acoustic control and other more specialized applications [1]. To achieve optimum structural performance, extensive studies have been made in understanding the mechanical behavior of metallic foams both experimentally and theoretically. Important scaling relationships, constitutive models and structure design guide can be found in comprehensive surveys [1,2]. At low densities, experimental results indicate the foams properties can be described by a simple scaling relationship,

$$\frac{P^*}{P^s} = \alpha\left(\frac{\rho^*}{\rho}\right)^n \tag{1}$$

where P^* and P^s are the properties (for example, Young's modulus, compressive strength, tensile strength, etc.) of the foam and the material to which the foam is made; ρ^* and ρ^s are the their densities, respectively. The constants α and n depend on the internal geometric structure of foam materials and their variations inevitably lead to a wide range of predicted properties at a given density [3]. However, the complex dependence is not well understood yet and this remains a crucial problem in the ability to predict and optimize the mechanical properties of foam materials.

To understand the mechanical properties of foam materials in terms of their mesostructures, many attempts have been made to describe the mechanical properties of cellular materials using unit cells, e.g., honeycombs [1,4], cubes [5,6], dodekahedra. [7], tetrakaidekahedra [8] and rod [9]. Analytical results based on these unit cell models provide invaluable insights into the correlation between the mechanical properties and the mesostructure in a concise and systematic way. However, negligence of random disorder of foam mesostructure by these idealized models usually leads to an over estimation of the mechanical properties of real materials [10]. Therefore, more realistic models which can depict the random irregularity are required to improve predictions for foam materials. Among the various stochastic models, Voronoi structure has been extensively used considering the structure approximately mimics the surface evolution during foam manufacturing [10–15]. To calculate the mechanical response of Voronoi foams, numerical method such as finite element method becomes necessary.

As an ideal energy-absorbing material, metallic foams usually undergo very large compressive deformation and a strain up to 60–80% is common. Under such large compression, very

* Corresponding author. Tel.: +86 020 87111030; fax: +86 020 87114460.
E-mail address: lqtang@scut.edu.cn (L.Q. Tang).

0927-0256/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.commatsci.2013.05.046

complicated contact behavior of cell walls due to cell collapse and excessive distortion make it difficult to successfully complete one large-deformation calculation [16]. Recently, Jang et al. [17] successfully reproduced the elastic moduli and strengths of open-cell aluminum foams by using Kelvin and random cell structures. Due to the compressive deformation adopted in the calculations is less than 15%, the hardening and the densification behaviors were not further discussed. Compared with the compressive behavior under large deformation, the tensile fracture behavior is even less understood and existing continuum constitutive models just simply assume the tensile behavior is similar with the compressive behavior [18]. To understand the mechanism of excellent compressibility and poor stretchability of metallic foams, investigation of the collapse and fracture of cells at mesoscale is necessary. Very recently, Mangipudi and Onck [19] studied the mesoscopic damage and failure mechanisms of metallic foams by using two-dimensional Voronoi structure.

The present study does not aim to derive new scaling relationships through parametric studies. Rather, emphasis of the work is put on investigating the mesostructural behavior of metallic foams under realistically large deformation and further linking the mechanical responses at meso-scale and macro-scale. The mesostructural behaviors in compression and in tension are compared. In addition, variation of the mechanical properties at a fixed density due to the randomness of mesostructure is explored. The results suggest that there is an important correlation between the pore irregularity variation and the plastic response variation. Both experimental measurements and numerical simulations were conducted. And in the numerical simulations, three dimensional Voronoi structures were chosen to model the inner geometric structure of closed-cell metallic foams.

2. Experimental measurements

Compressive tests were carried out on a universal test machine (INSTRON 5567). The material used for the tests was commercially available closed-cell aluminum foam with a relative density of 0.13(AoShenTe metallic materials technology Co., Ltd., Shanghai, PR China). There is a large variation in pore size, with some cells less than 0.3 mm in diameter and others as large as 2.4 mm (Fig. 1a). Statistics was made on the distribution of pore size by using the image processing software developed in-house (Fig. 1b). The measured elastic modulus, the yield strength and the densification strain are 0.82 ± 0.04 GPa, 4.7 ± 1 MPa and 0.62 ± 0.04 respectively. The solid making up the foam is aluminum consisting of 0.6% Mg as well as 0.3% Si by wt. The mechanical property of the solid material was measured by using the dual indentation method [20] and the typical derived stress–strain curve was shown in Fig. 2.

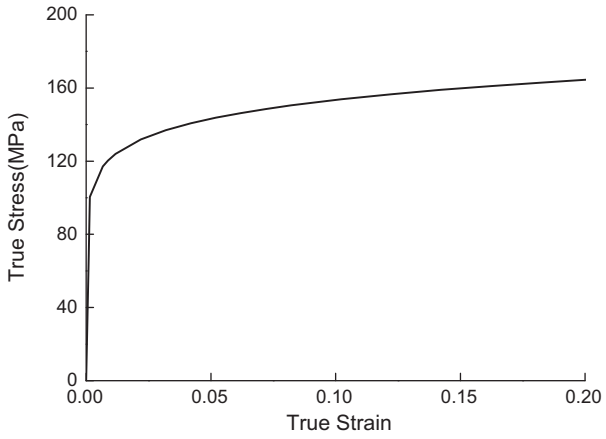


Fig. 2. Derived tensile curve of the solid material.

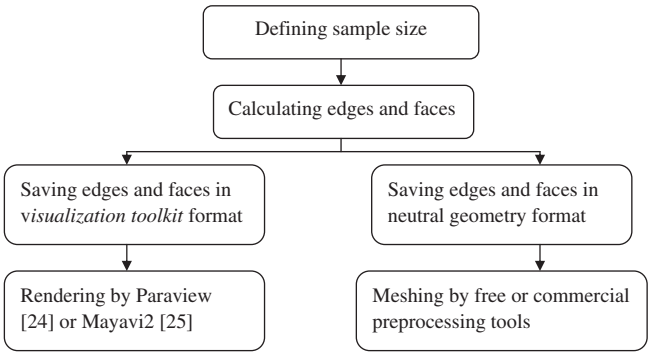
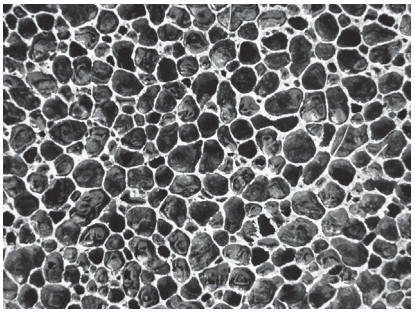


Fig. 3. Method constructing and displaying three dimensional Voronoi structures.

3. Finite element simulations

3.1. Construction of three dimensional Voronoi foams

Constructing and displaying a three dimensional Voronoi structure is not a trivial task. Here a relatively general method is proposed (Fig. 3): random seeding points are generated in an enclosed volume representing the material sample. The program



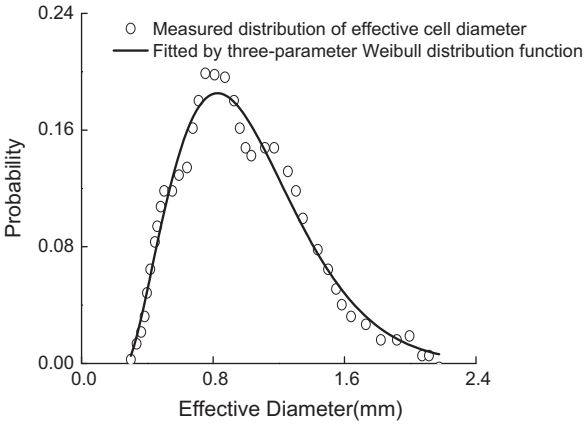


Fig. 1. (a) Cross section of the foam material; and (b) distribution of effective cell diameter.