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Experimental and multi-scale analyses of open-celled aluminum foam with hole under compressive quasi-static loading

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ABSTRACT

Compressive stress-strain behavior of open cell aluminum foam has been investigated using experimental and multiscale modeling methods. Mechanical behavior of cellular materials intensively depends on their microscopic structure and architecture which may degrade under loadings. To analyze the mechanical response of a full scale and complex aluminum foam component, one may develop multiscale modeling. In this way the degraded material properties are calculated through the analyses of a representative volume element (RVE) considering the micro-structural characteristic, architectural parameters and loading. In this study, open-celled AA6101-T6 aluminum foam is considered for the analyses. Geometrical characteristics of the foam using microscopic images are extracted, including thickness of cell walls, cell size, relative density and cross section of cell walls. The micro model is defined as RVE with nonlinear geometric and material behaviors considering the possible contacts between struts and it is conditioned on macroscopic quantity using appropriate boundary conditions. To validate the proposed model, different experiments have been performed for foam specimens with and without circular hole under compressive quasi-static loading. Finally, multiscale modeling has been proposed to analyze the foam components with complex and irregular shapes. It is shown that in order to model foams considering all the heterogeneities, even with larger size and having non-uniform stress field the use of currently existed finite-element and micro-structural models are not sufficient and the proposed multi-scale modeling which leads to acceptable results can be used for such analyses.

1. Introduction

Natural materials such as stone, wood and bone and man-made materials such as honeycomb, metallic and polymeric foams are examples of cellular materials. The micro-structure of these materials contain of continuous network of struts and plates [1]. Metallic foams are a new class of materials with low density and new physical, mechanical, thermal, and electrical properties. These characteristics make them a proper choice for light-weight structures, energy, and sound and vibration absorbers in car industries. They can be also used as core of sandwich structures, packing industries and thermal managements [2–4].

The mechanical behavior of cellular materials is important for their use in a wide variety of applications that take advantage of their capability to dissipate energy under compression loading. This property is affected by the cell structure of the foam and by the material of the cells walls. Because of the industrial importance of such material, the relationship between their structure and mechanical properties is an ongoing topic of intense researches [5].

Interests in metallic foams date from 1940s, when Sosnick filed a patent application for producing such foam [6]. Mechanical behavior of cellular material and their modeling have been investigated by Gipson and Ashbi [7]. Regarding the micro-mechanical modeling, the cellular materials can be divided into three groups of honeycomb, open-cell and closed-cell foams. All of these materials have limited elastic behavior. Their mechanical behavior is in the form of local deformations. The mechanism of these deformations can usually be in the form of bending, buckling, plastic yield and fracture of cell walls [7]. In recent years, low-priced aluminum foams have been widely used in several applications including the core of sandwich panels and different parts of cars. The goal is to extend light-weight structures with a high energy-absorb capacity which has proper stiffness and hardness

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properties. The successful usage of metallic foams requires developing design methods which are based on the structural engineering rules. As a result, developing of finite-element models for progressive damage analysis of metallic and nonmetallic foams and composite materials has been of a great interest [8–13].

The approaches used for modeling of cellular materials may be divided into two categories of phenomenological and micro-mechanical models. The goal in morphological modeling is to combine the microscopic phenomena with the model parameters. However, to determine the model parameters extensive experiments have to be performed. Therefore, the goal of phenomenological models is to best adapt the experimental mechanical behaviors without any direct relationship with the physics of phenomenon [14]. Since 1969, when Ruch proposed the first constitutive model for polymeric foam under compressive loading, several models have been proposed by researchers. In 2004, Liu and Sabhesh [15] proposed a constitutive model which can be used for compressive and tensile loads. In 2005, Liu [16] extended the previously developed model as a function of the density parameter.

In the micro-mechanical models, the microscopic phenomena are modeled with micro-structural and physical mechanisms considerations. As a result, micro-mechanical models present useful microscopic characteristic of ingredients and morphological micro-structures [14].

The most widely used micro-modeling for cellular materials is Gipson model [7]. In this model, the compressive stress-strain curve is divided into elastic, elastic-plastic and densification regions. Different analyses have been also proposed by several researchers including Kristensan in 1986 [17], Grenstand in 1998 [18], Varen and Krineik in 1987 [19–21], Wang in 2000 [22], Harderz [23] in 2005 and Kim et al. in 2001 [24,25]. In all proposed models, it was assumed that the micro-structure of the foam has ideal geometry without using the real 2D or 3D images.

As the complexity grows, there is a need to develop new models. Even obtaining an analytical closed form solution for completely random micro-structures is impossible. For this reason, numerical models have been developed. Using micro-structural finite element models, several researches have been conducted to predict compressive mechanical behavior of open-cell aluminum foams. The stress-strain response of foams is varied with variations in the cell arrangement, relative foam density, loading speed, and cross-section area of constituent cell walls struts. Therefore, researchers such as Jang et al. in 2010 [26], Maheo in 2013 [27], Li in 2014 [28], Gaitanaros in 2012 [29] and Barbier in 2013 [30] investigated the effects of these parameters on the stress-strain response using micro-structural finite element modeling.

The main goal of this research is to propose a practical method in order to analyze the metal foams with complex-shaped micro structures and made components with non-uniform stress field.

Due to the randomness of the micro-structure of foams, analytical models cannot be used to analyze mechanical behavior of foams with complex, irregular and large shapes. Also, micro-structural finite element models are usually used for small and plain configurations and RVEs. Morphological models can be used for material models and large-scale continuum finite element analyses. However, in this type of models one still requires performing several expensive experiments in order to obtain the model parameters. Therefore, to investigate the mechanical response of aluminum foam components with complex and large sizes, a multi-scale modeling can be used so that the effects of variations in the micro-structure specifications and architectural parameters can be transferred from the micro scale in to the macro scale model. In this paper, open-celled AA6101-T6 aluminum foam is considered for the analyses and geometrical characteristics of the foam using microscopic images are extracted, including thickness of cell walls, cell size, relative density and cross section of cell walls. The micro model is defined as RVE with nonlinear geometric and material behaviors and is conditioned on the macroscopic quantity using appropriate boundary conditions. To validate the proposed model, different experiments have been performed for foam specimens with and without circular hole under compressive quasi-static loading. Finally, the multiscale modeling is performed to analyze the foam components with complex and irregular shapes.

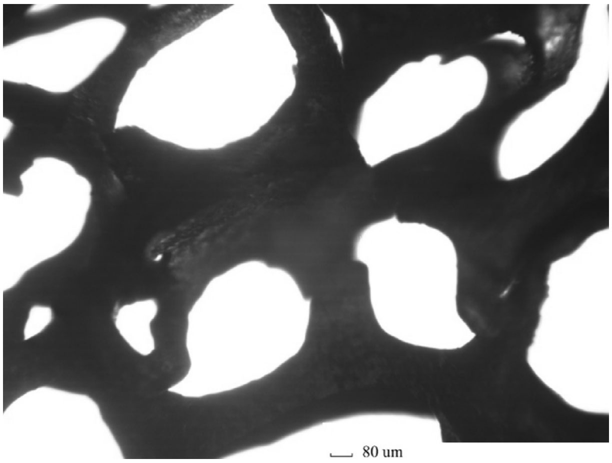

Fig. 1. Typical image of wall for open celled AA6101–T6 aluminum foam.

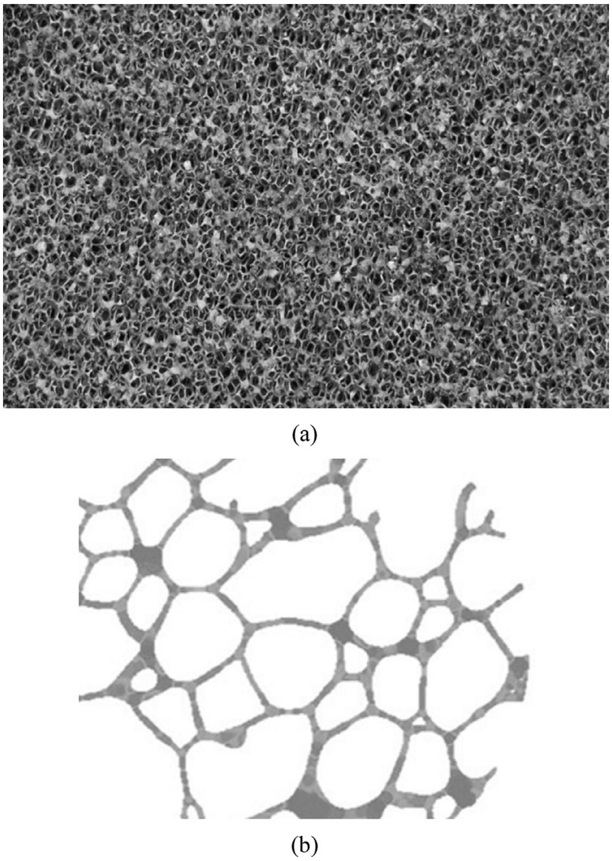

Fig. 2. a): Typical image of open celled AA6101–T6 aluminum foam b): Micrograph of open-celled AA6101–T6 aluminum foam.