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Investigations on the yield behavior of metal foam under multiaxial loadings by an imaged-based mesoscopic model

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A R T I C L E I N F O

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A B S T R A C T

Metal foams are usually subjected to multiaxial loadings in applications. It is significant to investigate the yield behavior and mechanical mechanism of metal foam under multiaxial loadings. In this study, Firstly, the geometry of the metal foam sample was obtained via 3D reconstruction using micro-computer tomography images. Then, an imaged-based mesoscopic model numerical model is established based on Finite Element Method (FEM). From the uniaxial compression, it is noted that the initial crush randomly takes place at the weakest cells firstly, resulting in the plastic Poisson's ratio no longer to be constant in the metal foam. Therefore, the plastic Poisson's ratio at where localized deformation happens should be used in predicting the yield behavior metal foam. In this study, the plastic Poisson's ratio is determined by the imaged-based mesoscopic model. Two kinds of virtual experiments, i.e. triaxial compression based on a cubic model and biaxial compression based on a butterfly-shape model, were carried out to investigate the yield behavior of metal foam. Similarly, the foam cells crush randomly at the weakest region under triaxial compression. Meanwhile, the central section of the butterfly-shape model firstly collapses under biaxial compression. Based on the virtual experiments, the numerical yield points of metal foam under different stress state are obtained, and the yield surface is plotted in the mean-effective stress space. It is known that the Poisson's ratio has significant effect on the Miller's and Deshpande & Fleck's yield criterion. Based on the local plastic Poisson's ratio, more accurate prediction from Miller's yield criterion is obtained when compare with the numerical yield surface.

1. Introduction

Metal foams are widely used in various engineering applications due to their significant capability in energy absorbing and structure protecting [1,2]. In the applications, metal foams are usually subjected to multiaxial loadings, especially the multiaxial compression loadings.

Many investigations have been carried out to study the yield behavior of metal foam under multiaxial loadings. Gibson and Ashby proposed a theoretical model to describe the yield surface of metal foam,

$$\pm\frac{\sigma_e}{\sigma_y}+0.81\frac{\rho_0}{\rho_s}\left(\frac{\sigma_m}{\sigma_y}\right)^2=1 \tag{1}$$

Deshpande and Fleck [3] investigated the yield behavior of two aluminum alloy foams (Alporas and Duocel) for a range of axisymmetric compressive stress states. According to their experiment data, a phenomenological model is proposed to describe the yield surface of elliptical shape,

$$\varphi=\hat{\sigma}-Y\le 0 \tag{2}$$

$$\hat{\sigma}^2=\frac{1}{1+(\alpha/3)^2}\sigma_e^2+\alpha^2\sigma_m^2 \tag{3}$$

The yield surface shape is sufficiently simple for an analytical expression in Eq. (2) to be derivable for plastic Poisson's ratio ν^p in terms of α, giving

$$\alpha=3\left(\frac{\frac{1}{2}-\gamma^p}{1+\gamma^p}\right)^{\frac{1}{2}} \tag{4}$$

but this phenomenological model neglected the tension stress states. References [4–7] indicate that metal foams show the asymmetry of tension and compression yield stress. Miller [7] proposed a criterion, which concludes different states in the tension and compression loadings, based on the Drucker–Prager model [8]. It is given by

$$f=\sigma_e-\gamma\left(-\sigma_m\right)+\frac{\alpha}{d}\sigma_m^2-d \tag{5}$$

in which the constants γ, α, and d are closely related to plastic Poisson's ratio and two uniaxial compressive strength and tensile strength.

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Table 1
Properties of base material.

Base material: aluminum alloy (Al-Ca-Ti)				
Composition	Density (kg/m^3)	Young's modulus (GPa)	Yield strength (MPa)	Poisson's ratio
Al + 1.5%Ca + 1.5%Ti	2700	61.7	100–172.8	0.3

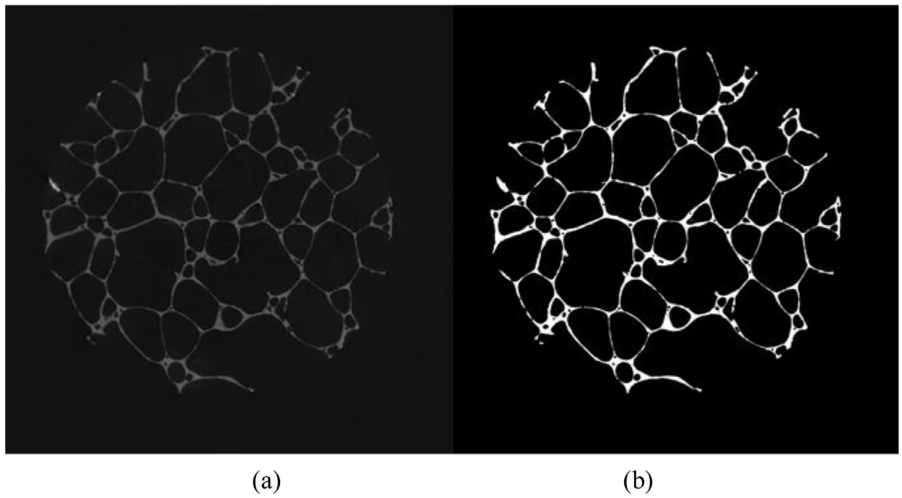

Fig. 1. X-ray microtomography images of (a) raw image and (b) after greyscale-based thresholding.

In the above yield criterions, the plastic Poisson's ratio is an important parameter in the constitutive models of metal foam. However, it is difficult to be measured by experiment due to the localized deformation. Metal foam deforms uniformly under loading. The cells collapse progressively during deformation. This feature leads to the scattered experimental data of plastic Poisson's ratio. For example, the plastic Poisson's ratio of Alporas foam with relative density of 8% was 0.024 as obtained by Gioux and Gibson [9], but it was 0.33 by Motz and Pippan [10]. Different Poisson's ratio will result in the prediction deviation of the yield behavior of metal foams. Describing the Poisson's ratio for foam material with uniform deformation feature is still ambiguous currently.

In addition to the theoretical work, many experimental investigations have been conducted to study the yield behavior of metal foam. Deshpande and Fleck [3] used a high pressure triaxial system to probe the yield surface for Alporas (closed-cell) and Duocel (open-cell) foams. In their experiments, the stress versus strain response along several proportional stress paths was measured. Doyoyo and Wierzbicki [11] conducted an extensive study on yield behavior for Alporas and Hydro closed-cell aluminum foams using butterfly-shaped specimens subjected to plane stress in an Arcan apparatus. The yield stresses in effective stress-mean stress space could be fitted with a quadratic function. Similar experiments were performed by Zhou et al. [4], and roughly identical results were obtained. Ruan et al. [6] tested the closed-cell CYMAT foams under axisymmetric compression using a high-pressure triaxial test system. Reasonable agreement of experimental and various published phenomenological yield surface has been observed. Combaz et al. [5] experimentally attained the yield data under a very wide range of triaxial loading paths, including compression and tension. Although many attempts have been made to acquire sufficient data to describe a complete yield surface of metal foam, the yield behavior under combinations of triaxial loadings are very limited. It is important to probe the yield stress of metal foam under various stress states. Under this consideration, the numerical solution can be a good option.

Numerical approach can simulate the complex stress state which cannot be achieved in tests, based on reliable finite element model. Generally, the mesoscopic models of metal foam can be mainly divided into two types, i.e. the Voronoi model [12–14], and the model based on the X-ray computed tomography (CT) [15–19]. Researchers [15,16] believe that the Voronoi FE model cannot be used to simulate the elastic stage of metal foam precisely, because they may not be able to sufficiently capture the complexity of real cell structures. Computed tomography has recently proved to be a good way in modeling the 3D microstructure of foams or the architecture of cellular materials. Recently, numerical models based on cell structures obtained from computed tomography images [15] have been used to capture the actual meso-scale geometry to investigate the strain-rate sensitivity of open-cell foams. Similar modeling techniques have also been employed to investigate the quasi-static compressive properties of closed-cell foams [16].

This study aims at investigating the yield behavior of metal foam, especially the compressive yield properties, of metal foam. Three-dimensional (3D) finite element models (FEM) of Alporas foam based on the mesoscopic geometrically realistic modeling is developed. Uniaxial loadings are simulated in order to investigate the compression/tension properties of metal foam. The local plastic Poisson's ratio is determined by the numerical method. Visual experiments, i.e. triaxial and biaxial compressions, are implemented to investigate the yield properties of metal foam, and the yield surface is obtained. A developed yield criterion based on the plastic Poisson's ratio is proposed.

2. 3D image-based FM model

2.1. Material

The closed-cell aluminum Alporas foam used in this study was supplied by Gleich Ltd., Kaltenkirchen, Germany. The average cell size is 2.88 mm, and the nominal density is 230 kg/m^3. The properties of Alporas foam are listed in Table 1 [20].

2.2. Reconstruction of geometrical model and FE model

An Alporas closed-cell foam specimen with dimensions Φ25*20 mm was scanned by a CT system housed in Northwestern Polytechnical University (NWPU, Xi'an, China). The images (total 1271 images) were captured and the interval between every two images was 0.0145 mm. The