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Creep of closed-cell aluminum foams: Effects of imperfections and predictive modeling

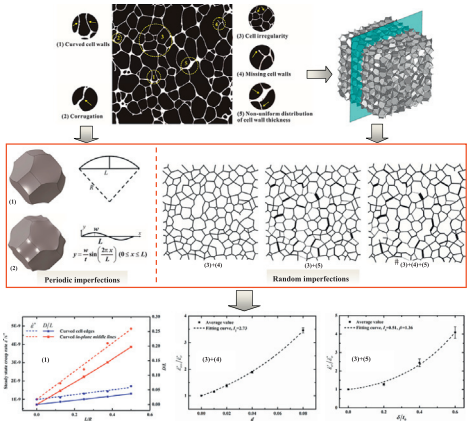
Bin Han [a,b,c], Run-Pei Yu [b,d], Qian-Cheng Zhang [b,d], Hua-Jian Gao [c], Qi Zhang [a,*], Tian Jian Lu [b,d,**], Bing-Heng Lu [a]

[a] School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] MOE Key Laboratory for Multifunctional Materials and Structures, Xi'an Jiaotong University, Xi'an 710049, China
[c] School of Engineering, Brown University, Providence, RI 02912, USA
[d] State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- Effects of five types of morphological imperfections on the creep of closed-cell foams are evaluated.
- A refined creep model of tetrakaidecahedral closed-cell foams is proposed.
- Cell-wall imperfections greatly speed up the creep rate of closed-cell foams.
- Interactions among different random imperfections are small and can be neglected.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of five different types of morphological imperfection – curved cell wall, corrugation, cell shape irregularity, missing cell walls and non-uniform distribution of cell wall thickness – on steady state creep of closed-cell aluminum foams is systematically studied under uniaxial compressive loading. A refined theoretical model is developed to predict the steady state creep rate of idealized tetrakaidecahedral (TKD) closed-cell foams. Based upon the TKD model, finite element modeling is also carried out. The presence of imperfections usually leads to significant increase in steady state creep rate. The creep rate increases linearly with the degree of cell shape irregularity and the curvature of curved cell walls, while increases as a power law function of the area fraction of missing cell walls and the dispersion degree of non-uniform distributed cell wall thickness. The combined effect of three different random defects—cell shape irregularity, missing cell walls and non-uniform distribution of cell wall thickness—causes more drastic increase in creep rate than any single or dual imperfections. Interactions among the three are small and can be neglected. Finally, an empirical formula of steady state creep rate is proposed to give a good prediction for closed-cell foams with random imperfections.

* Corresponding author.
** Correspondence to: T.J. Lu, MOE Key Laboratory for Multifunctional Materials and Structures, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail addresses: henryzhang@mail.xjtu.edu.cn, (Q. Zhang), tjlu@mail.xjtu.edu.cn (T.J. Lu).

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1. Introduction

Closed-cell metallic foams exhibit great performance in energy absorption, damping, acoustic and thermal insulation, as well as electromagnetic shielding [1–3]. They are also well suited for high temperature applications, such as the core of load-bearing sandwich structures in high temperature environments (e.g., gas reactor, combustion chamber and modern steam turbine), owing to their better resistance to oxidation than polymeric foams and much better toughness, thermal conductivity and thermal shock resistance than ceramic foams [4]. For long-term applications, however, the susceptibility to creep deformation must be taken into consideration in determining the service life when a metallic foam is loaded at temperature greater than about 1/3 to 1/2 of the melting point of its parent material. At present, whereas numerous investigations have been performed to study the creep behaviors of cellular metals, mainly focusing on honeycombs and open-cell foams [4–15], only a few studies have addressed the creep of closed-cell metallic foams.

Based upon an idealized cubic cell, Gibson and Ashby [16,17] developed a power-law creep model for both open-cell and closed-cell foams, assuming that the major contributions to macroscopic creep stem from the creep bending of transversely loaded struts and the creep stretching of cell membrane. To access the validity of this model, Andrews et al. [17,18] performed creep experiments on open-cell (Duocel) and closed-cell (Alporas) aluminum foams. While the experimental results for the open-cell foam were in excellent agreement with the model predictions, the creep resistance of the closed-cell foam was considerably lower than that predicted. It was argued that the inhomogeneous microstructure of the closed-cell foam led to a broad distribution of stresses within the sample, thus causing some cell walls to enter the power-law breakdown (PLB) regime [18]. Subsequently, Zhang et al. [19] examined the microstructure of an Alporas foam both before and after creep deformation, and found that the microstructure development was rather inhomogeneous during creep, due at least in part to the complicated distribution of the applied stress in the foam. They indicated that local stresses more than an order of magnitude higher than the average stress were present during creep. Haag et al. [20] found experimentally that closed-cell foams exhibited a higher creep strain rate and a higher stress exponent than those predicted by the Gibson-Ashby model for regular (idealized) foams, and suggested that the discrepancies were probably due to the combined effects of primary creep and localized PLB within the cell walls as well as geometric instabilities developing during the course of deformation.

Most commercially available metallic foams exhibit a variety of processing-induced morphological imperfections, including curved and wrinkled cell walls, non-uniform wall thickness, cell wall misalignments, broken cell walls, missing cells, and random dispersion of cell size [21–23]. These imperfections can have remarkable influence on the mechanical properties of the foams [24–27]. In particular, the effect of imperfections on the creep behavior has been investigated. For instance, Andrews and Gibson [6] studied the effect of cell shape variation, cell size distribution and cell wall curvature on the creep strain rate of 2D (two-dimensional) cellular solids, and found that the three types of imperfection can all accelerate creep. Huang and Gibson [7] investigated the creep behavior of 3D (three-dimensional) Voronoi open-cell foams with missing struts, and concluded that the removal of only a few percent of struts would increase the creep strain rate by one or two orders of magnitude. Lin and Huang [28] evaluated the effects of solid distribution along cell edges on the creep strain rates of 2D hexagonal honeycombs, and found that there existed an optimal distribution minimizing the creep strain rate. More recently, based 2D honeycomb and 3D tetrakaidecahedral strut models, Su et al. [13] studied the effect of missing cell struts on steady state creep of cellar materials and proposed a theoretical model to predict the creep rate. However, existing studies only addressed how the creep behavior of regular honeycombs and open-cell foams is influenced by the presence of imperfections. There is yet a study concerning the effects of imperfections on the creep response of 3D closed-cell metallic foams.

The present study aims to investigate the effects of a variety of morphological imperfections on uniaxial steady state creep of high porosity closed-cell aluminum foams. As clearly shown in Fig. 1, the imperfections considered include curved cell walls, corrugation, cell shape irregularity, missing cell walls, and non-uniform distribution of cell wall thickness, which are closed related to the liquid-state foaming process of Alporas foams [23,29]. Firstly, a theoretical model is developed with a semi-analytical formulation to predict the steady state creep rate of idealized tetrakaidecahedral (TKD) closed-cell foams. Subsequently, the effects of periodic imperfections on creep are quantified using finite element (FE) simulations. Lastly, the effects of random imperfections are also numerically investigated and their interactions are discussed, with the steady creep rate predicted by empirical equations.

2. Creep of closed-cell foams with TKD cells

According to their pore shapes, closed-cell aluminum (Al) foams fabricated via the method of melt-foaming may be classified into three categories: polygonal pores with high porosity (85%–95%), sphere-like pores with intermediate porosity (70%–80%), and spherical pores with relatively low porosity (<70%) [30]. Most of the commercially available closed-cell Al foams (e.g., Alporas foam) possess a low relative density <0.15 and hence their cellular morphology is dominated by polygonal pores.

Several space-filling unit cells, including cubic, tetrahedral, dodecahedral and TKD cells, have been employed to develop closed-form structure-property relations of 3D cellular solids [31]. Among these polyhedron cells, the TKD cell is known to be the only polyhedron that can be packed with identical units to fill space with nearly minimum surface energy [32–34], which is closest to the realistic pore shape of high porosity closed-cell aluminum foams. Therefore, in the present study, the TKD cell with uniform cell wall thickness is used as an idealized model to study the creep behavior of closed-cell foams.

2.1. Theoretical models for TKD closed-cell foams

Built upon the cubic unit cell, the Gibson-Ashby model [16,17] gave the following uniaxial steady state creep rate $\dot{\varepsilon}^*$ of closed-cell foams as a function of relative density $\overline{\rho}$:

$$\frac{\dot{\varepsilon}^*}{\dot{\varepsilon}_0} = f(\overline{\rho})\left(\frac{\sigma^*}{\sigma_0}\right)^n \tag{1}$$

where $\dot{\varepsilon}_0$, σ_0, n are the temperature-dependent creep constants of cell wall material, and σ^* is the uniaxial stress applied on the foam. The coefficient function $f(\overline{\rho})$ is expressed as:

$$f(\overline{\rho}) = \left\{\frac{1}{1.7}\left(\frac{n+2}{0.6}\right)^{\frac{1}{n}}\left(\frac{n}{2n+1}\right)(\phi\overline{\rho})^{\frac{3n+1}{2n}} + \frac{2}{3}(1-\phi)\overline{\rho}\right\}^{-n} \tag{2}$$

in which ϕ is the fraction of solid contained in cell edges/struts.

Different from the cubic-cell model, the representative volume element (RVE) of TKD closed-cell foams on a body-centered cubic (BCC) lattice consists of 6 square faces, 12 quarter-square (isosceles triangle) faces, 8 hexagonal faces and 36 struts, as shown in Fig. 2. Faces with thickness t_f constitute cell walls, while struts with thickness t_e and length L denote cell edges. In the current study, the cross-section of the struts is assumed to be square [7,13]. Due to the sharing of boundaries with neighboring RVEs, the thickness of the 6 square faces and the cross-sectional area of the corresponding 24 struts in the RVE model are both halved.

Since the bending of struts has been found to be the dominant creep mechanism for open-cell foams with low relative densities (<0.20) [10],