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Effect of dual-size cell mix on the stiffness and strength of open-cell aluminum foams

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Abstract

The mechanical properties of open-cell aluminum foams with dual-size cell distributions produced by infiltration method are measured. It is found that the relative density decreases when small cells (∼0.5 mm) are mixed into foams with large cells (∼2.5 mm). The open-cell aluminum foam mixed with small cells in low volume fraction show remarkable increase in stiffness and strength. However, the stiffness and strength of foams with high volume fraction of small cells degrade. The effect of multi-size cell mix on the performance of open-cell aluminum foams is investigated using finite element analysis of 2-D (hexagonal honeycomb) idealized cellular material models. The mechanism how cell size distribution influences the stiffness and strength is presented and discussed.

Keywords: Open-cell aluminum foam; Mechanical properties; Effect of multi-size cells; Honeycomb

1. Introduction

During the last two decades metallic foams have been developed and are growing in use as new engineering materials. These ultra-light metal materials possess unique mechanical properties, such as high rigidity and high impact energy absorption at low weight, equal properties in all directions giving tolerance to varying direction of loading, stable deformation mode and adaptation to loading condition during deformation, etc. [1]. There are many ways to manufacture cellular metallic materials [2]. Open-cell metallic foams can be produced by infiltrating compacted salt particles, as shown in Fig. 1. The maximum porosities achieved using this method are limited to values below 80%. Common foams display irregular microstructures. Homogeneous open-cell high-purity aluminum foams can be produced by replication from salt precursors [3]. It was found that density is the primary factor controlling the Young's modulus and yield strength of foams [1]. The cell size appeared to have a negligible effect on the strength at a fixed density, while the cell shape was shown to affect the strength of foams [4].

For real cellular materials, the distribution of solid and cells is uneven. Especially for open-cell foams made by infiltration method, a lot of solid is accumulated at nodes or so-called plateau borders, as shown in Fig. 2. A low-density ($\rho^*/\rho_s < 0.15$) honeycomb was analyzed by Warren and Kraynik [5]. The elastic modulus was found to increase when material was shifted away from the midspan of a member towards the nodes. They also gave analysis on open-cell foams with plateau borders along the edges [6]. It was found that changing the cross-section shape of the edge from circular or square to a plateau border configuration increased the stiffness of these foams by 60–70%. The effects of the distribution of solid on the stiffness and strength of metallic foams were studied by Simone and Gibson [7] using finite element analyses (FEA).

A few numerical studies of the effects of cell arrangement on the elastic properties were also performed [8,9]. It was shown that disorder induces an increase of Young's modulus and stabilization at large disorder. Highly irregular foams have a larger Young's modulus compared with a regular structure [10]. On the other hand, these numerical analyses

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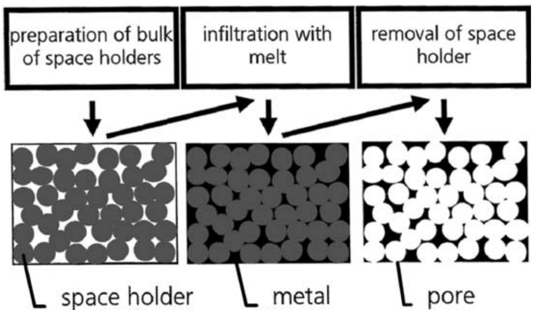

Fig. 1. Production of cellular metallic materials by infiltration method (Fig. 20 from Ref. [2]).

show that the yield strength of random structures is lower than that of the regular structure.

In this study, open-cell aluminum foams with dual-size cells are produced. The relative densities are about 36 % (~0.973 g cm^{-3}). The volume-fraction ratio of small-size cells (~0.5 mm) to large-size cells (~2.5 mm), η, is 0.25. The mechanical properties of these materials are compared with those with relatively homogeneous cell size at the relative density of 38% (~1.026 g cm^{-3}). Finite element analyses on idealized 2-D hexagonal honeycomb cellular materials, in which cells are considered as regularly distributed circular holes, are performed. Influences of the size and the fraction of small cells on the mechanical behavior of open-cell cellular materials are discussed. Qualitative accordance between the numerical results and the experimental results is obtained. It is shown that adding a small amount of small-size cells can reduce the relative density while improving the mechanical properties (the stiffness and the strength).

2. Experimental results

The open-cell aluminum foams are provided by the Institute of Solid State Physics, Chinese Academy of Sciences. Commercially pure aluminum is chosen as the matrix. The relative density of aluminum foam with uniform cell size is 0.38 and the average cell size is 0.75 mm. The relative density of aluminum foam with dual-cell size is 0.36, which contains 80% large-size (~2.5 mm) cells and 20% small-size (~0.75 mm) cells. The foams are made by infiltration method. In this method, melted liquid metal is first poured into a bed of compacted sodium chloride particles, and then, after solidification of the metal, the salt is dissolved by water. The cell shape and size depend on the particles used. To obtain foams with mixed cell sizes, salt of different sizes is used. Commercial salt after thermal dehydration and decontamination is crushed and the fragments are sieved. Two sieve-fractions, i.e. 0.5–1.0 and 2.0–3.0 mm, are used to produce average cell sizes of 0.75 and 2.5 mm, respectively. In our case, the *meso*-structure of the foam much differs from the ideal foam structure. The density is relatively high and the topology of foam is not the same as the Gibson–Ashby model [1]. An SEM photograph of undeformed aluminum foam material is given in Fig. 2. Unlike slender edges in regular open-cell foam, anomalous sheet edges were found. In multi-size cell aluminum foam, the small cells are congregated in the corner between large-size cells. When the volume-fraction ratio of small-size cells to large-size cells η is relatively low, small cells mostly occupy the nodal zone or the plateau zone, as shown in Fig. 2b. When η increases, more small cells occupy the midspans, as shown in Fig. 2c.

Cylindrical specimens 35 mm in diameter and 20 mm in height were tested on an MTS810 testing system. The contact surfaces were coated with Vaseline to reduce friction. A constant cross-head speed of 0.02 mm s^{-1} was used for all tests, corresponding to an initial strain rate of 10^{-3} s^{-1}. Typical compressive stress–strain curves of foams with uniform cell size and dual cell size are shown in Fig. 3. The stiffness of the cellular material with mixed cell size is about 650 MPa, higher than that with uniform cell size, 260 MPa, though the relative density of the former is a little lower. On the other hand, the yield strength of the two materials shows little difference. Typical compressive stress–strain curves of foams with different small cell fraction are shown in Fig. 4. It indicates that the cellular material with lower small cell fraction has much higher stiffness and yield strength than that with higher small cell fraction.

3. Two-dimensional finite element analysis

Here, we use finite element analysis to explore the influence and mechanism of cell mix on the relative elastic modulus and relative plastic plateau strength of open-cell aluminum foams. For simplicity, ideal honeycomb model materials as a 2-D counterpart of the 3-D foams are used, as shown in Fig. 5. Though the cell shape is irregular in practice, a circular shape is assumed to ignore the cell shape effect and keep the configuration of the plateau border. Different small-cell sizes and thus different relative densities, ρ^*/ρ_s, are used to investigate the effects of the dual-size cell structure.

All finite element analyses are performed using the ABAQUS Analysis Package (Hibbit, Karlsson and Sorensen, Pawtucket, RI). CPS8 (8-node bi-quadratic plane stress elements) elements from the ABAQUS element library are used. Isotropic material model with elastic–perfectly plastic stress–strain behavior is assumed to eliminate any dependence of the results on a chosen strain-hardening exponent. Parameters used in the isotropic elastic–perfectly plastic model are $E_s = 70$ GPa, $\nu = 0.33$ and $\sigma_{ys} = 150$ MPa, the same as those used by Simone and Gibson [7].

Two solution procedures are used for each case. An applied loading and small deformation linear elastic analysis

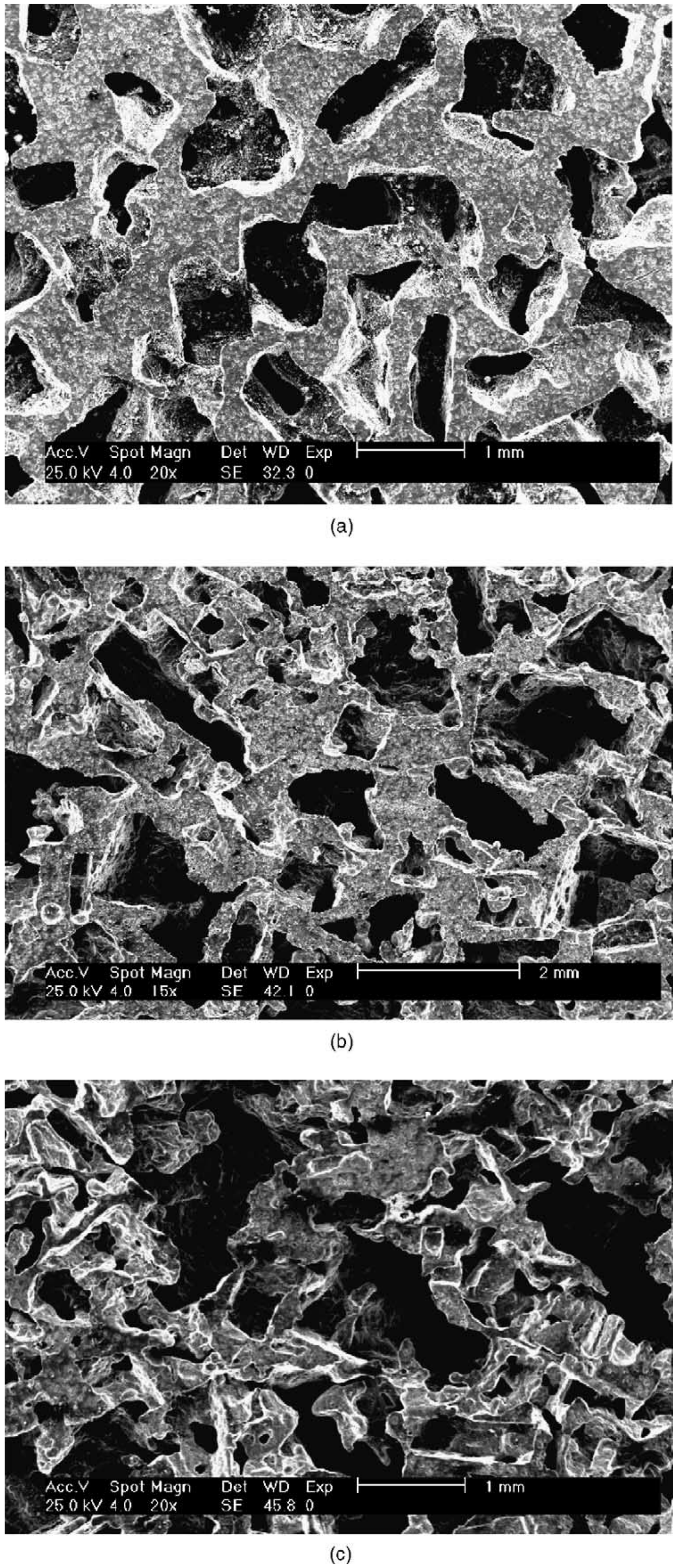

Fig. 2. SEM photograph of the undeformed aluminum foam material. The volume-fraction ratios are (a) $\eta = 0$ (with uniform cells), (b) $\eta = 0.25$, and (c) $\eta = 0.67$, respectively.

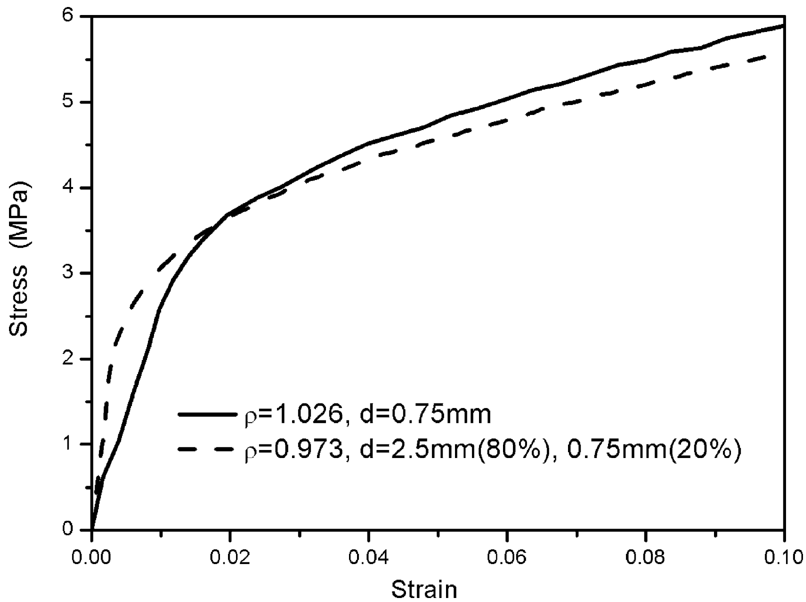

Fig. 3. The compressive response of pure aluminum foam with uniform cell size and with mixed cells while the small cell fraction is low.

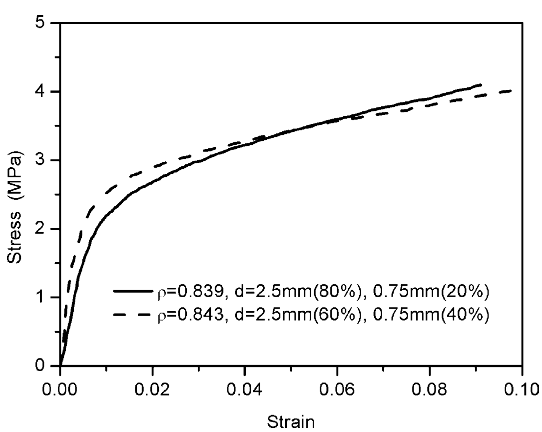

Fig. 4. The compressive response of pure aluminum foam with mixed cells while the small cell fraction is different.

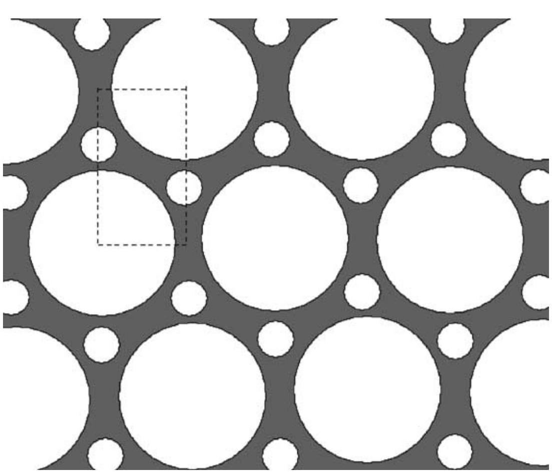

Fig. 5. Hexagonal honeycomb model considering mixed small cells, $r = 0.2d$, and $R = 0.8d$.

is first used to calculate the elastic modulus. Large deformation theory and an incremental, iterative solution method (the Newton's method [11]) are then used to calculate a stress–strain curve.

Compressive load is applied in the *y*-direction. Considering the periodicity and the symmetry of the honeycomb structures, a typical mesh for the unit cell is shown in Fig. 6. Assuming small cells and large cells are mixed together, the radius of the large cells is *R*, and the distance of two adjacent large cells is 2*d*. In the representative volume element, symmetric boundary conditions in the *x*-direction are applied to line AC, symmetric boundary conditions in the *y*-direction

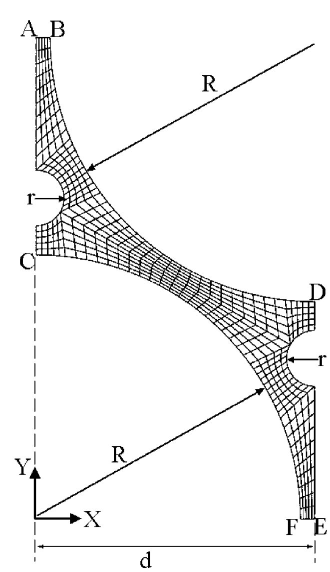

Fig. 6. Sample finite element mesh for the unit cell used in calculation, $r = 0.1d$, and $R = 0.94d$.

are applied to line FE. The periodic boundary condition in the x-direction is applied to line DE, and the displacement boundary condition in the y-direction is applied to line AB. The reaction forces on the nodes of the displaced boundary are recorded and summed in order to compute the overall stress at each increment of displacement. The stress of 2% strain or the maximum stress (if the maximum stress is reached before the strain of 2%) is chosen as the yield strength.

It is obvious that the critical value of R is d, i.e. $R < d$. The small cells with radius of r are located in the plateau borders. If the large cell size reaches the critical value d ($R = d$), the maximum radius of the small cells is $(2/\sqrt{3} - 1)d \approx 0.15d$. However, if $R < d$ is chosen, r may be larger. Changing the values of R and r, different relative densities are acquired. In our numerical simulation, we consider four values of r, i.e. $r = 0.10d$, $r = 0.15d$, $r = 0.20d$, and $r = 0$ which corresponds to single-size cells. Different values of R are used, given a relative density ranging from about 0.19 to 0.42. In all these cases, the small cells are assumed located regularly, as shown in Fig. 5.

For the case when the volume fraction of the small cells are large, similar analysis are performed with small cells located both in the plateau borders and in the weak midspans between two large cells.

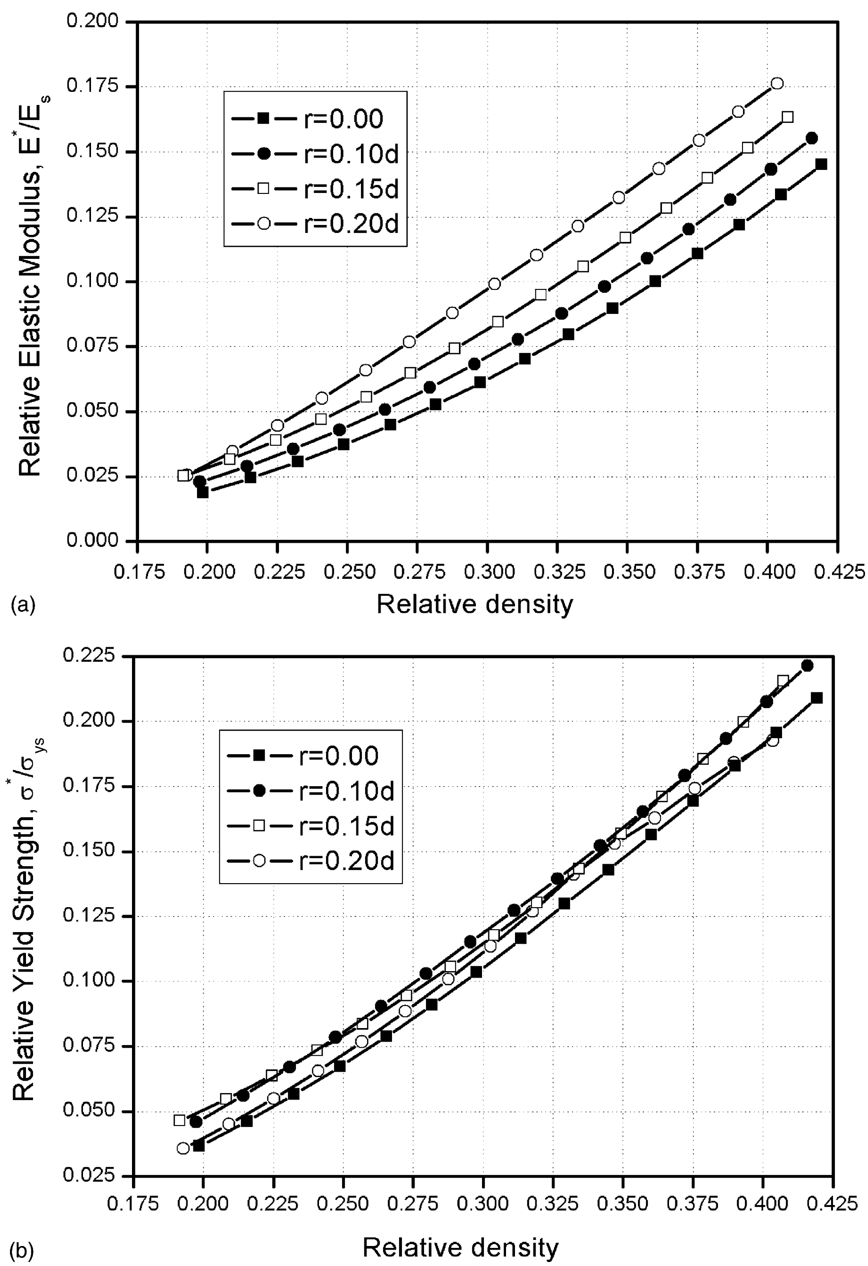

Fig. 7. Mechanical behavior of honeycomb with mixed cells: (a) relative modulus vs. relative density and (b) relative strength vs. relative density.

4. Results

4.1. Effects of small cells with small fraction

Fig. 7a and b show the dependence of the relative modulus E^*/E_s and the relative strength σ^*/σ_{ys} to the relative density of the honeycomb for different small-cell sizes, respectively. The numerical results indicate that both the stiffness and the yield strength increase if small cells are added at constant density. With small cells 0.20*d* in radius, the honeycomb shows the largest increase in stiffness; while with smaller cells 0.10*d* or 0.15*d* in radius, the honeycomb shows the largest increase in yield strength. This suggests that both the stiffness and the strength can be increased

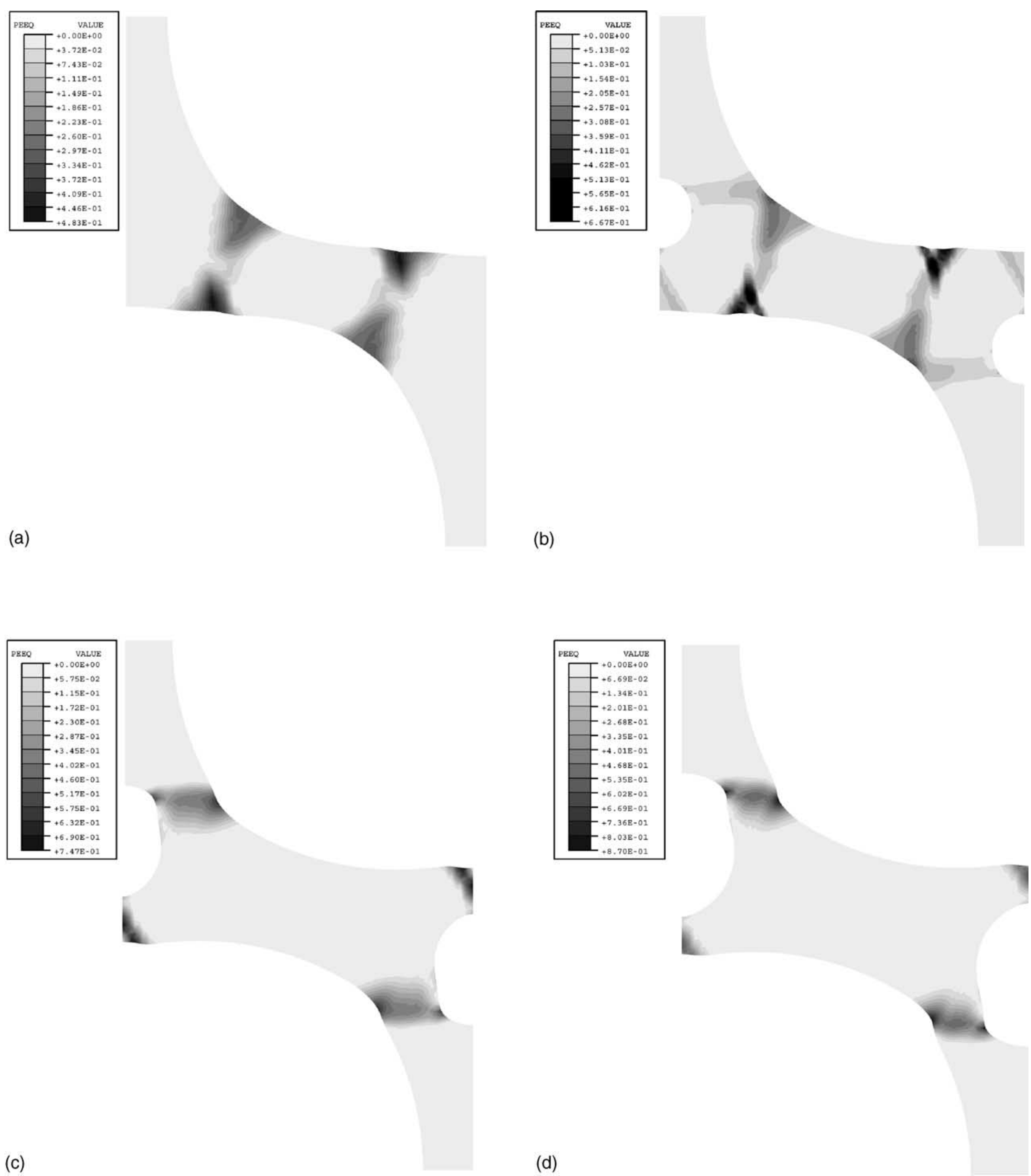

Fig. 8. The equivalent plastic strain distribution in honeycombs when the compression strain is 0.1 and the relative density is 0.30: (a) $r = 0.0$ (single size cells), (b) $r = 0.10d$, (c) $r = 0.15d$, and (d) $r = 0.20d$.

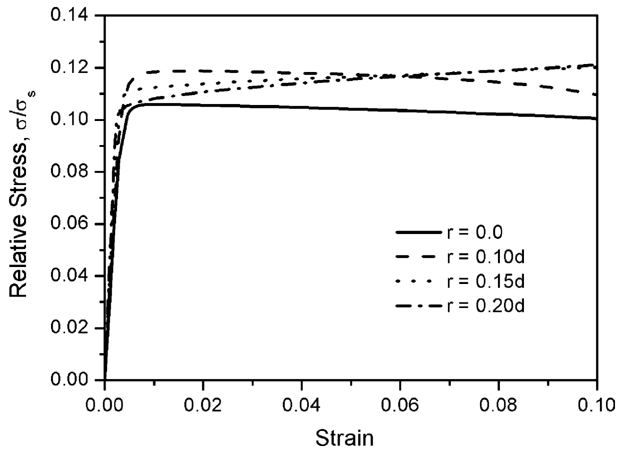

Fig. 9. Stress–strain curves of dual-size cell honeycombs with different *r*, the relative density is 0.30.

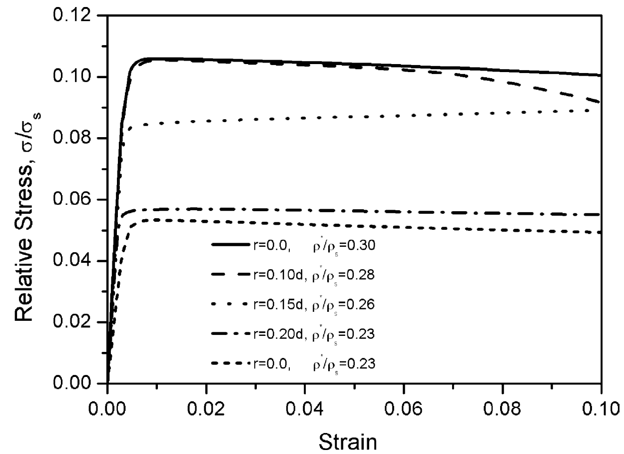

Fig. 10. The stress–strain curves of honeycombs with different relative densities.

if small cells with proper size and volume fraction are added.

Fig. 8 shows the equivalent plastic strain distribution of the four models with the same relative density of 0.30 when the compressive strain in the *y*-direction is 0.10. For the cases of uniform cell size and dual cell size with small cells 0.10*d* in radius, the equivalent plastic strain occurs in the weak edge between two large cells, and two plastic hinges are formed near the plateau borders, as shown in Fig. 8a and b, respectively. For the cases of dual cell size with small cells 0.15*d* and 0.20*d* in radius, the equivalent plastic strain occurs in between the small cells and the large cells, and the plastic hinges are formed there, as shown in Fig. 8c and d. It is obvious that the deformation mode changes with the increase of the small-cell size. When the small-cell size is below a critical value, plastic deformation mainly occurs in the edges between large cells. However, when the small-cell size exceeds a critical value, plastic deformation occurs in the edges between the small cells and the large cells. Fig. 9 shows the stress–strain curves of the four models with the same relative density of 0.30. It is shown that uniform cell size honeycomb exhibits the lowest stiffness and strength, while dual cell size honeycomb with small cells 0.20*d* in radius shows the highest stiffness, though its strength is relatively low. The dual cell size honeycomb with small cells 0.10*d* in radius shows the highest strength, while its stiffness

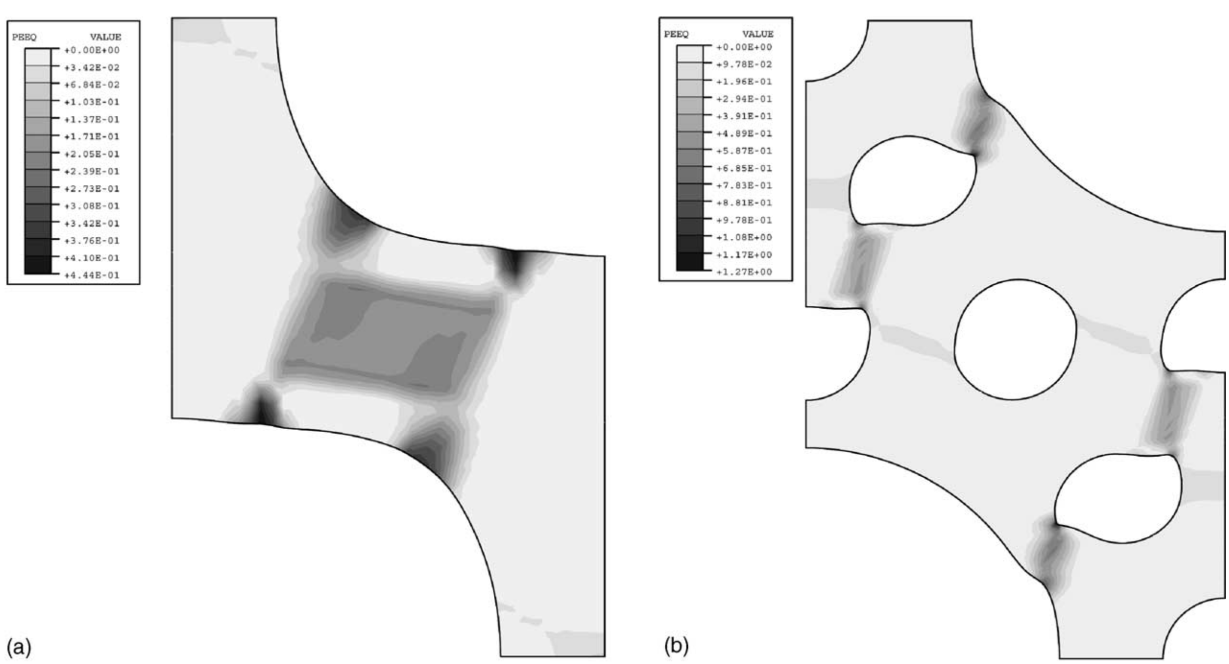

Fig. 11. The equivalent plastic strain distribution in (a) a single-size cell honeycomb with the relative density of 0.49 and the radius of cells is 0.75*d*; (b) a dual-size cell honeycomb with the relative density of 0.49, the radius of large cells is 0.6*d* and that of small cells is 0.15*d*.

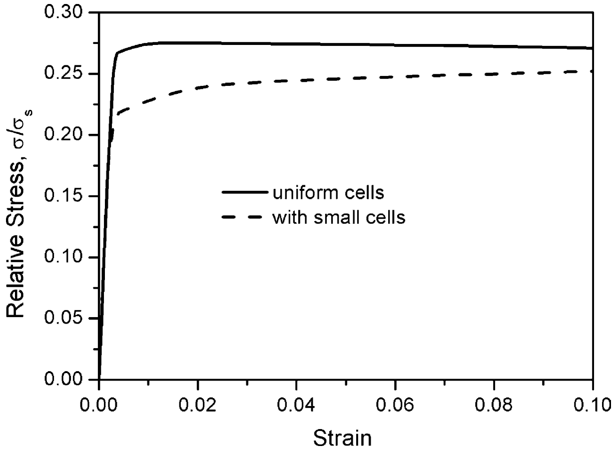

Fig. 12. The stress–strain curves of the cellular materials with the relative density of 0.49.

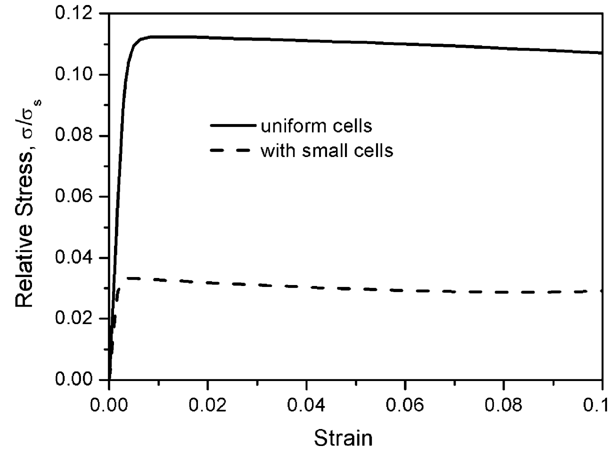

Fig. 14. The stress–strain curves of the cellular materials when the relative density is 0.31.

is relatively low. Fig. 10 shows the stress–strain curves of these four models with identical large cells but with small cells of different radii, respectively. For comparison, the stress–strain curve of a uniform cell size honeycomb with relative density of 0.23, the same as that of the dual cell size honeycomb with small cells 0.20*d* in radius, is also shown in the figure.

4.2. Results of dual cell size honeycomb with large fraction of small cells

In the above analysis, small cells are assumed embedded in the plateau borders among the large cells. In this case, the fraction of small cells is low. Now we consider the instance that the fraction of small cells is relatively high. As an idealization, small cells are assumed distributed not only in the plateau borders but also in the weak midspan between two large cells.

Fig. 11 shows the equivalent plastic strain distribution of two models with the same relative density of 0.49 while one is with uniform cells and the other is with both small cells with the radius of 0.15*d*, and large cells with the radius of 0.6*d*. Fig. 12 shows the stress–strain curves of the two models. It is obvious that the yield strength of the model with dual-size cells is lower than that of the model with uniform cells.

Fig. 13 shows the equivalent plastic strain distribution of another two models with the same relative density of

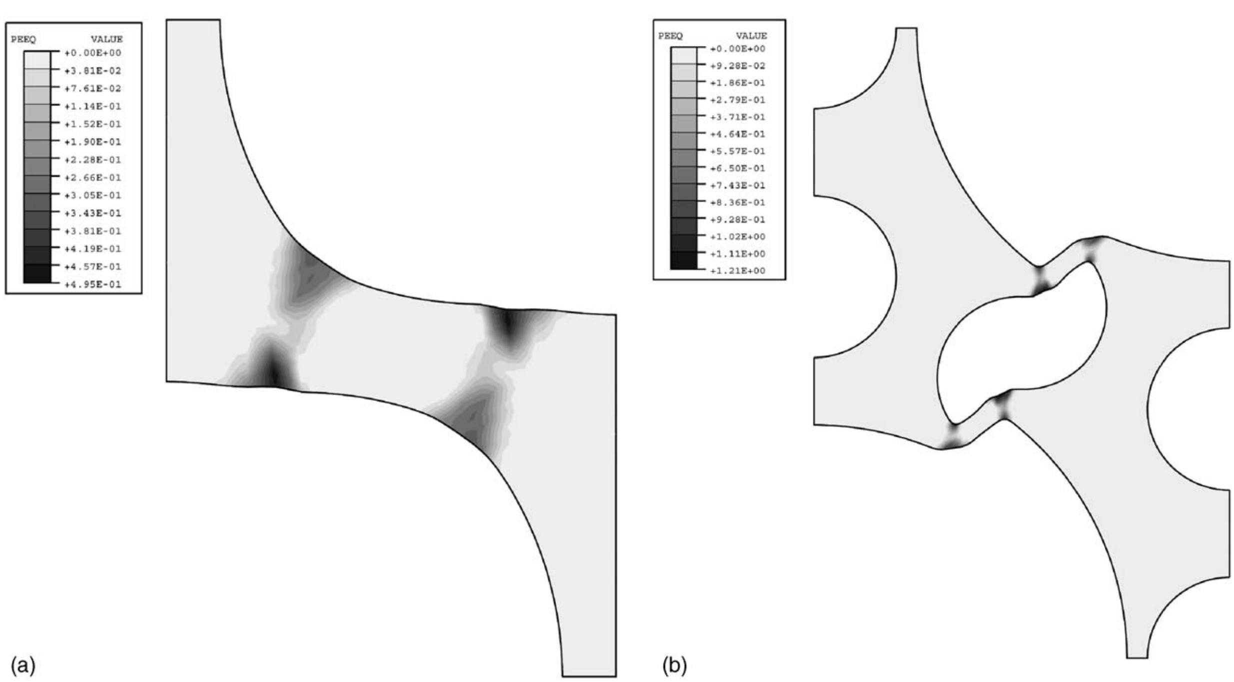

Fig. 13. The equivalent plastic strain distribution in (a) a single-size cell honeycomb with the relative density of 0.31 and the radius of cells is 0.872*d*; (b) a dual-size cell honeycomb with the relative density of 0.31, the radius of large cells is 0.7*d* and that of small cells is 0.2*d*.

0.31, similar to those shown in Fig. 11 but has a lower relative density ($R = 0.7d$ and $r = 0.2d$). Fig. 14 shows the stress–strain curves of the two models. The Young's modulus of the model with dual-size cells is 2.65 GPa, much lower than that of the model with uniform cells whose modulus is 4.95 GPa.

5. Conclusions

In order to increase the porosity, small-size cells are introduced in the open-cell aluminum foams made by infiltration method. It is found that the stiffness and the strength of foams with multi-size cells but identical relative density increase when a small quantity of small-size cells is added. An idealized 2-D honeycomb model with small cells embedded in the plateau borders is used to analyze the effect of the small cells. It is found that the center parts of the plateau borders contribute little to the stiffness and the strength of the honeycombs. The volume fraction of solid is shifted from the center parts of the plateau borders to the midspan edges after mixing small cells. Thus material has been redistributed according to the structural optimization and its stiffness and strength can been improved. In the ideal case, with dual cell sizes and the small cells are located at the plateau borders, there exists an optimal small-cell size with an optimal volume fraction. However, when the volume fraction of small cells becomes relative higher, some small cells will be distributed in the midspans of the honeycomb, leading to a degradation of the mechanical properties.

From the experimental results and the finite element simulations, it is obvious that multi-size cell structure will decrease the relative density of the open-cell foams while, in some cases, maintain their mechanical properties, i.e. stiffness and strength.

Acknowledgements

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References

[1] L.J. Gibson, M.F. Ashby, Cellular Solids, Cambridge University Press, Cambridge, UK, 1997.
[2] J. Banhart, Progr. Mater. Sci. 46 (2001) 559–632.
[3] C.S. Marchi, A. Mortensen, Acta Mater. 49 (2001) 3959–3969.
[4] T.G. Nieh, K. Hogashi, J. Wadsworth, Mater. Sci. Eng. A 283 (2000) 105–110.
[5] W.E. Warren, A.M. Kraynik, Mech. Mater. 6 (1987) 27–37.
[6] W.E. Warren, A.M. Kraynik, J. Appl. Mech. 55 (1988) 341–346.
[7] A.E. Simone, L.J. Gibson, Acta Mater. 46 (1998) 2139–2150.
[8] H.X. Zhu, J.R. Hobdell, A.H. Windle, J. Mech. Phys. Solids 49 (2001) 857–870.
[9] H.X. Zhu, J.R. Hobdell, A.H. Windle, Acta Mater. 48 (2000) 4893–4900.
[10] A. Fazekas, R. Dendievel, L. Salvo, Y. Bréchet, Int. J. Mech. Sci. 44 (2002) 2047–2066.
[11] ABAQUS Theory Manual Version 5.7, Hibbitt, Karlsson and Sorenson Inc., Pawtucket, RI, 1997.