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Effect of pore combination on the mechanical properties of an open cell aluminum foam

Fusheng Han [a,*], Hefa Cheng [b], Jinxiang Wang [a], Qiang Wang [b]

[a] *Laboratory of Internal Friction and Defects in Solids, Institute of Solid State Physics, Chinese Academy of Sciences, Science Island, Hefei, Anhui 230031, China*
[b] *Department of Materials Engineering, Hefei University of Technology, Hefei, Anhui 230009, China*

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Abstract

The effect of secondary pores on the mechanical properties of an open cell aluminum foam was experimentally studied and simulated. It is found that introduction of smaller pores into the foam increases elastic modulus and yield strength, as a result of changes in the stress distribution and deformation mode.

Keywords: Aluminum foam; Mechanical property; Lightweight structure; Bimodal pores

1. Introduction

Metallic foams, particularly aluminum foams, have drawn more and more attention with the growing demand for lightweight components and the development of manufacturing technologies [1–7]. Although the relative density has long been believed to be the dominating factor on the mechanical properties of metallic foams [8–10], other parameters, such as pore size and pore distribution, should exert an influence over the mechanical behavior if the relative density is unchanged [11]. However, perhaps due to the difficulties in controlling the pore distribution in commercial aluminum foam products, there are very few studies addressing, both theoretically and experimentally, this topic.

In the present study, an open cell aluminum foam with varied pore size and pore combination was utilized with the objective of examining the effect of pore combination on the mechanical behavior of the foams.

2. Experimental procedure

The aluminum foams used in this study were made of commercially pure aluminum and fabricated by an infiltration process. The process mainly includes the preparation of the preform composed of NaCl particulates, penetration of the aluminum melt into it by application of high air pressure and dissolution of the NaCl particulates from the ingots after the aluminum melt has solidified. Cylindrical specimens were finally cut from the ingots to dimensions of $\varnothing 35 \times 20$ mm with either a single pore size or a combination of two pore sizes as listed in Table 1. The nominal density of the foam is determined by its mass and volume, and the nominal pore size characterized by the mean linear dimension of the pores. Uniaxial quasi-static compression tests were conducted on a MTS810 machine equipped with a data acquisition system with an error lower than 0.05. All the tests were carried out at a displacement rate of 0.02 mm/s, i.e. a strain rate of 10^{-3} s^{-1} in the specimens. The nominal compressive stress is defined as the load per area of the specimen, and the displacement or nominal strain of the specimen is determined from the crosshead displacement of the machine. At least three specimens were tested using the same aluminum foam in the same compressive condition to guarantee the reliability of the results.

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[*] Corresponding author. Tel.: +86-551-5591435; fax: +86-551-5591434.
E-mail address: fshan@issp.ac.cn (F. Han).

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Table 1
The pore combination of the specimens

Specimen no.	Nominal pore size (mm)	Relative density
1	0.75	0.393
2	1.75	0.394
3	2.50	0.433
A1	0.75 (20 vol%) + 2.5 (80 vol%)	0.360
A2	0.75 (40 vol%) + 2.5 (60 vol%)	0.312
A3	0.75 (60 vol%) + 2.5 (40 vol%)	0.291

3. Results and discussion

3.1. Compressive behavior of the foams

Typical compressive stress–strain curves of the specimens are shown in Fig. 1. If the linear part is taken as the Young's modulus of the foams, it is very obvious that specimens with combined pores have a relatively higher modulus although the flow stress is still dependent on the relative density. In order to examine the effect of pore combination on the compressive strength, the curves in Fig. 1 were normalized with the yield strength of the Al matrix and the relative densities of Al foams, i.e. $\frac{\sigma^*}{\sigma_s} / \left(\frac{\rho^*}{\rho_s}\right)^{3/2}$, where σ^* and σ_s are the flow stress of the foam and the yield strength of the Al matrix (22.5 MPa [12]), respectively, and ρ^* and ρ_s are the densities of the foam and the Al matrix (2.7 g/cm^3), respectively. As is seen in Fig. 2, the specimens with mixed pores exhibited increased strength except for specimen A3. It is therefore suggested that a certain combination of pores contribute higher specific rigid and strength to the foams, which is preferentially required in lightweight structures.

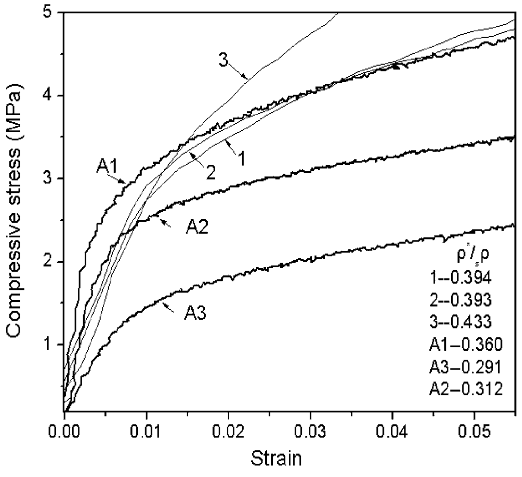

Fig. 1. Compressive stress–strain behavior of aluminum foams with varied pore combinations.

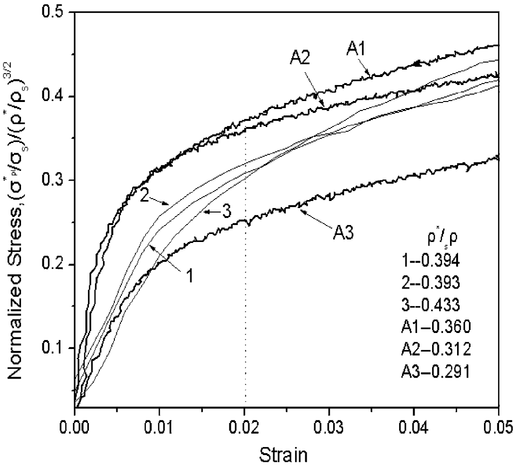

Fig. 2. Normalized stress–strain behavior of aluminum foams with varied pore combinations.

3.2. Simulation of the deformation mode

The aforementioned results demonstrate that some enhancement can be realized via the combination of big pores with small ones, which is most likely related to changes in load-bearing or deformation mode. Therefore, a simulation investigation was conducted with finite element (FE) analysis into the stress distribution and the failure mode of the pores to understand the correlated mechanisms.

For simplicity, a two dimensional model was used as shown in Fig. 3 with big and small circular cells and the small cells uniformly distributed at the nodes in the big cell walls. In consideration of the periodic feature of the model, a representative unit as shown in Fig. 4 was adopted for the FE analysis. The cell radii are represented by R for the big cells and r for the small ones. The distance between the centers of the neighbored big cells is defined as d, thus when the big cells contact the

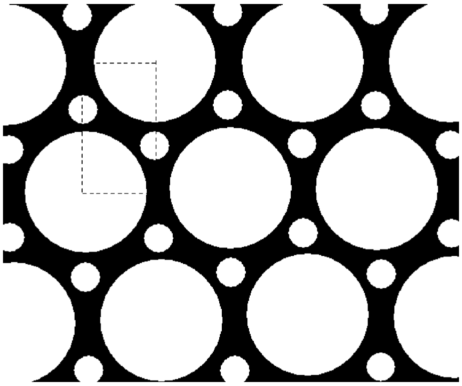

Fig. 3. Aluminum foam model used in finite element analysis with small pores distributed at the nodes of the cell walls.

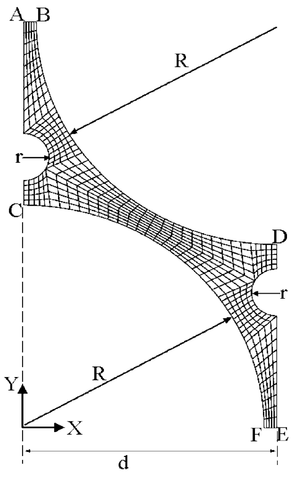

Fig. 4. A unit of the model.

maximum radius of the small cells is $\left(\frac{2\sqrt{3}}{3}-1\right)d$, roughly 0.15$d$. The case that r equals zero refers to single big cell structure. In addition, it is supposed that the model shows a stress–strain behavior with an isotropic elasticity and plasticity without dependence on the work hardening index. The FE analysis was carried out using Unit CPS8, i.e. a unit of 8 nodes with two-stage in-plane stress, with the ABAQUS software package. The modulus was firstly drawn in terms of the linear stage under low stress and then the stress–strain curves were obtained by displacement theory and the repeated increment method.

The simulated results show that small pores can uniformly distribute at the nodes only when their volume fraction is below 40%. On this condition, the size of small pores was found to have a singular effect on the relative elastic modulus and the relative yield strength. As presented in Fig. 5(a) and (b), when combined with relatively small pores, e.g. with a pore size of 0.1 – 0.15d, the yield strength was increased with insignificant enhancement in the elastic modulus. However, with combined relatively big pores, e.g. with a pore size of 0.20d, the strengthening effect in the elastic modulus was more significant than that in the yield strength. These tendencies agree well with the experiment results, as can be seen in Fig. 1, and with the simulation results of reference [11].

The effect of pore combination can be understood by the failure modes of the foams. Fig. 6 shows the distribution of stress in the cell walls of different pore combinations at a strain of 0.1, in which the denser the color, the higher the stress-concentrated degree. Significant stress concentration occurs in the weak locations of the cell walls when no small pores are included (Fig. 6a). By introducing small pores into the nodes, a part of the concentrated stress shifts to cell walls between the big pores and small pores, making the premature failure at originally stress-concentrated locations to be reduced (Fig. 6b). As the size of combined pores increases, the concentrated stress moves completely from the cell walls between big pores to those between big and small pores (Fig. 6c and d). The stress is then dispersed over a more extensive zone and thus yield of the cell walls is delayed, exhibiting an increased elastic modulus.

When the volume fraction of combined small pores exceeds 40%, a part of them will randomly distribute at the cell walls in addition to the nodes, behaving like a defect because of the weakening effect on the cell walls. The deformation and fracture preferentially arise at these sections due to the stress concentration caused most likely by the additional small pore defect. The overall mechanical properties were therefore reduced, as shown in Figs. 2 and 7.

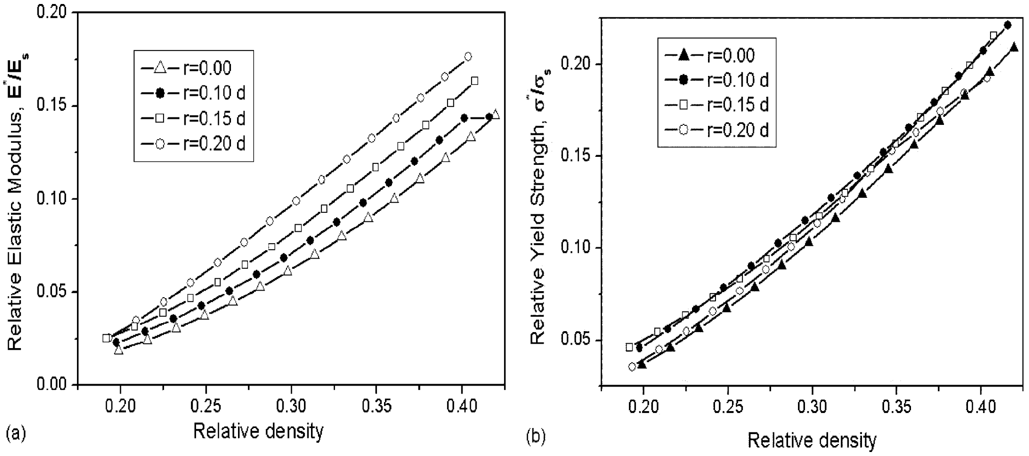

Fig. 5. Simulated results: (a) dependence of the relative elastic modulus on the relative density; (b) dependence of the relative yield strength on the relative density.

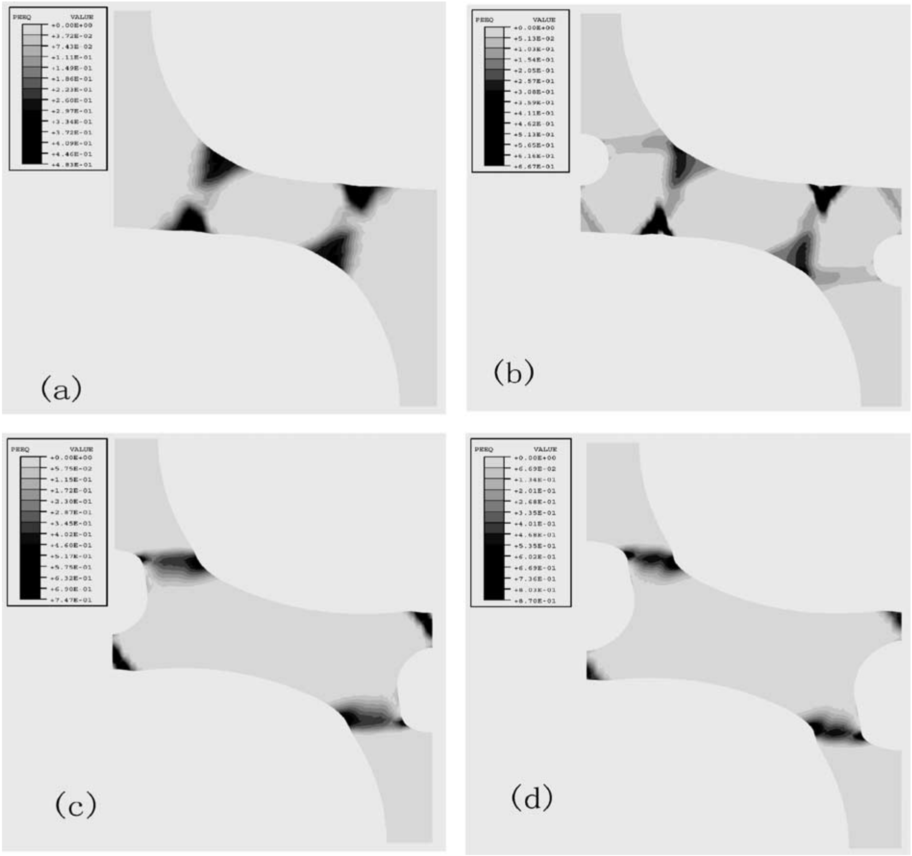

Fig. 6. Stress distribution at a strain 0.1 in the cell walls of the foam with a relative density of 0.30; the sizes of the combined small pores are (a) 0; (b) 0.10*d*; (c) 0.15*d*; (d) 0.20*d*.

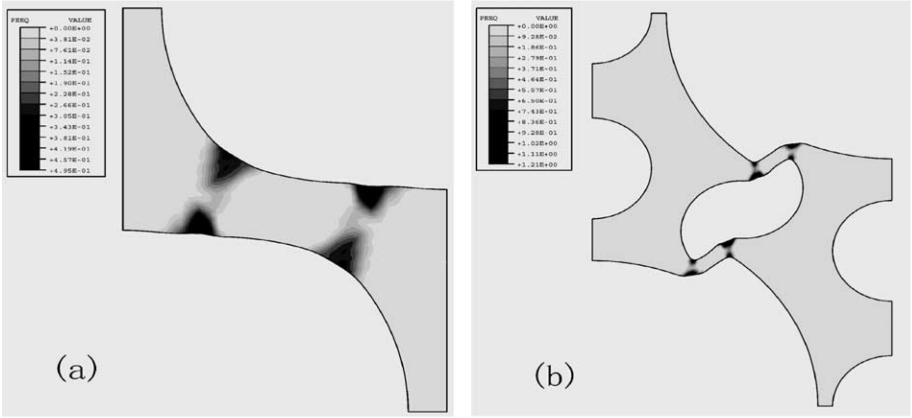

Fig. 7. The deformation mode of the foams with: (a) single pore size; (b) combination of big pores (0.70*d*) and small pores (0.20*d*) in the volume fraction of 55%.

4. Conclusions

An open cell aluminum foam can be enhanced by introducing secondary small pores into the cell walls in comparison to those with single pore size. A combination of large pores with relatively smaller pores contributes to relatively higher specific yield strength, while with relatively bigger pores makes the elastic modulus increase. However, excessively high volume fraction of the combined small pores will decay the mechanical properties. The simulation results suggest that the enhancement arises from the changes in the stress distribution and deformation fashion.

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