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Effects of cell size on compressive properties of aluminum foam

CAO Xiao-qing(曹晓卿)[1,2], WANG Zhi-hua(王志华)[2], MA Hong-wei(马宏伟)[2],
ZHAO Long-mao(赵隆茂)[2], YANG Gui-tong(杨桂通)[2]

1. College of Materials Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China;
2. Institute of Applied Mechanics, Taiyuan University of Technology, Taiyuan 030024, China

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Abstract: The effects of cell size on the quasi-static and dynamic compressive properties of open cell aluminum foams produced by infiltrating process were studied experimentally. The quasi-static and dynamic compressive tests were carried out on MTS 810 system and SHPB(split Hopkinson pressure bar) respectively. It is found that the elastic moduli and compressive strengths of the studied aluminum foam are not only dependent on the relative density but also dependent on the cell size of the foam under both quasi-static loading and dynamic loading. The foams studied show a significant strain rate sensitivity, the flow strength can be improved as much as 112%, and the cell size also has a sound influence on the strain rate sensitivity of the foams. The foams of middle cell size exhibit the highest elastic modulus, the highest flow strength and the most significant strain rate sensitivity.

Key words: aluminum foam; infiltrating process; cell size; compressive properties; strain rate sensitivity

1 Introduction

Metal foams are a relatively new class of structural materials and offer a variety of applications in fields such as lightmass construction or crash energy management. In view of potential applications, the mechanical properties of foamed metals are of paramount interest. It has been shown that, e.g. the compression strength is connected to the density of a foam[1−3], thus allowing to adjust this property within a certain range. However, because density cannot always be varied freely and in order to gain more control over the properties of metallic foams, adjustment of other variables seems desirable, namely alloy composition[4], foam morphology (size and shape of cells)[5−11] and the metallurgical state of the matrix metal[12, 13]. Both foam structures and cell morphologies depend on fabrication methods. Since there are a number of commercial fabrication methods, various foam structures and morphologies have been produced. There are a number of studies on the properties of aluminum alloy foams under quasi-static and dynamic loading, but limited reports[5, 7, 8, 11] on the effects of cell size on the mechanical properties of aluminum foams till now.

NIEH et al [5] studied the compressive properties of open-cell 6101 aluminum foams with different densities and morphologies and found that cell size has a negligible effect on the strength of foams, at a fixed density, whereas the cell shape affects the strength of foams. CHEN[14] studied the effect of cellular microstructure on the mechanical properties of open-cell aluminum foams produced by infiltrating process and found that cell size has a negligible effect on the compressive properties (modulus and strength). ONCK et al[7, 8] investigated the effect of specimen size (relative to the cell size) on the elastic modulus and plastic collapse strength of both the closed-cell and the open-cell aluminum foams analytically and experimentally. They drew a conclusion that the elastic modulus and plastic collapse strength of foams increased to a plateau level as the ratio of specimen size to cell size increased. But they did not study the size effects on the properties of foams at a fixed density and the specimen size satisfying the limit of L/d (6−8). However, recently PAN et al[11] reported their experimental results on AA6101 aluminum alloy foam produced by powder compact melting technique. They found in their experi-

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Corresponding author: CAO Xiao-qing; Tel: +86-351-4168773; Fax: +86-351-4139827; E-mail:cxqty@126.com

ments that cell-size has a significant effect not only on the crushing stress and plastic modulus of aluminum foam, but also on the strain-rate sensitivity of material of this kind. WANG et al[15] also studied the effect of cell size on the quasi-static compression and tension properties (strength and elastic modulus) of aluminum foam made by infiltrating process, and found that both the strength and elastic modulus were influenced by the cell size. We can easily find that the results obtained in Refs.[5,11,14,15] are contradictory to each other, and most of them have focused on the effect on the quasi-static properties of aluminum foams, therefore it is necessary to study the effects of cell size on the measured properties of foamed materials furthermore. Generally closed-cell foams are used as energy absorber for their high energy absorption efficiency, but their lower collapse strength results in lower energy absorption capacity, so studying the energy absorption characteristics of open-cell foams is of practical meaning. The purpose of this paper is to evaluate the effects of the cell size on the compressive properties of open cell aluminum foam produced by infiltrating process under uniaxial quasi-static and dynamic compression.

2 Experimental

The relative density ρ^*/ρ_s (defined as the density of the foam divided by the density of the solid it is made from) of the foams ranged from 0.33 to 0.50 and the cell diameter ranged from 0.75 mm to 2.5 mm. The foams were produced by the infiltrating process. In this process, the melted liquid metal was first poured into a bed of compacted sodium chloride particles, then after solidification of the metal, the salt was dissolved by water. The cell shape and size depend on the particles used. Commercial salt after thermal dehydration and decontamination was crushed and the fragments were sieved. Fig.1 shows the cross sections of typical material illustrating the cellular morphology in the as-received form of these foams by SEM. It can be seen that the foam structure in our case much differs from the ideal foam structure. The topology of foam is not the same as the GIBSON-ASHBY model[1]. The composition (analyzed using ICP-AES) of the foams was Al-1.31Mg-0.52Ca-0.21Ni (mass fraction, %).

An MTS810 material testing system was used for quasi-static compression tests. A constant cross-head speed of 1.2 mm/min was used for the test, corresponding to an initial strain rate of 10^{-3} s^{-1}, and the specimens were 35 mm in diameter and 20 mm in height.

The SHPB was used for dynamic compression test of aluminum alloy foams for strain rates above several hundred per second. The samples were 35 mm in diameter and 6−10 mm in height for dynamic compressive tests.

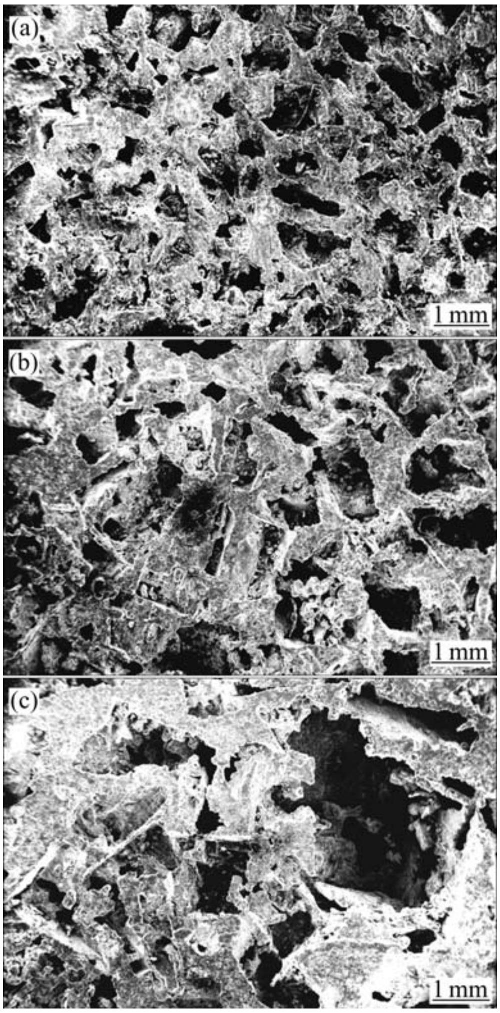

Fig.1 Microstructures of aluminum foams with different cell sizes: (a) 0.75 mm; (b) 1.50 mm; (c) 2.50 mm

The compression specimens were cut from a cast block by using electro-discharge machine to minimize cell edge damage. The specimen size was chosen 35 mm in diameter to ensure it was greater than 8 times the cell size of foams. To minimize the experimental discrepancy, three or more tests were conducted under each condition.

3 Results and discussion

In our case, the compressive behaviors of aluminum foams with ρ^*/ρ_s=0.33−0.50 have been studied. Fig.2 just shows the stress-strain curves for $\rho^*/\rho_s\approx$0.36, 0.41 under quasi-static and dynamic compression. The compressive stress-strain curves of aluminum foams investigated in this study, either quasi-static or dynamic compression, exhibit universal three deformation regions: an initial linear-elastic response; an extended plateau region with a nearly constant flow stress, sometimes an upper and lower yield point can be observed; and a final

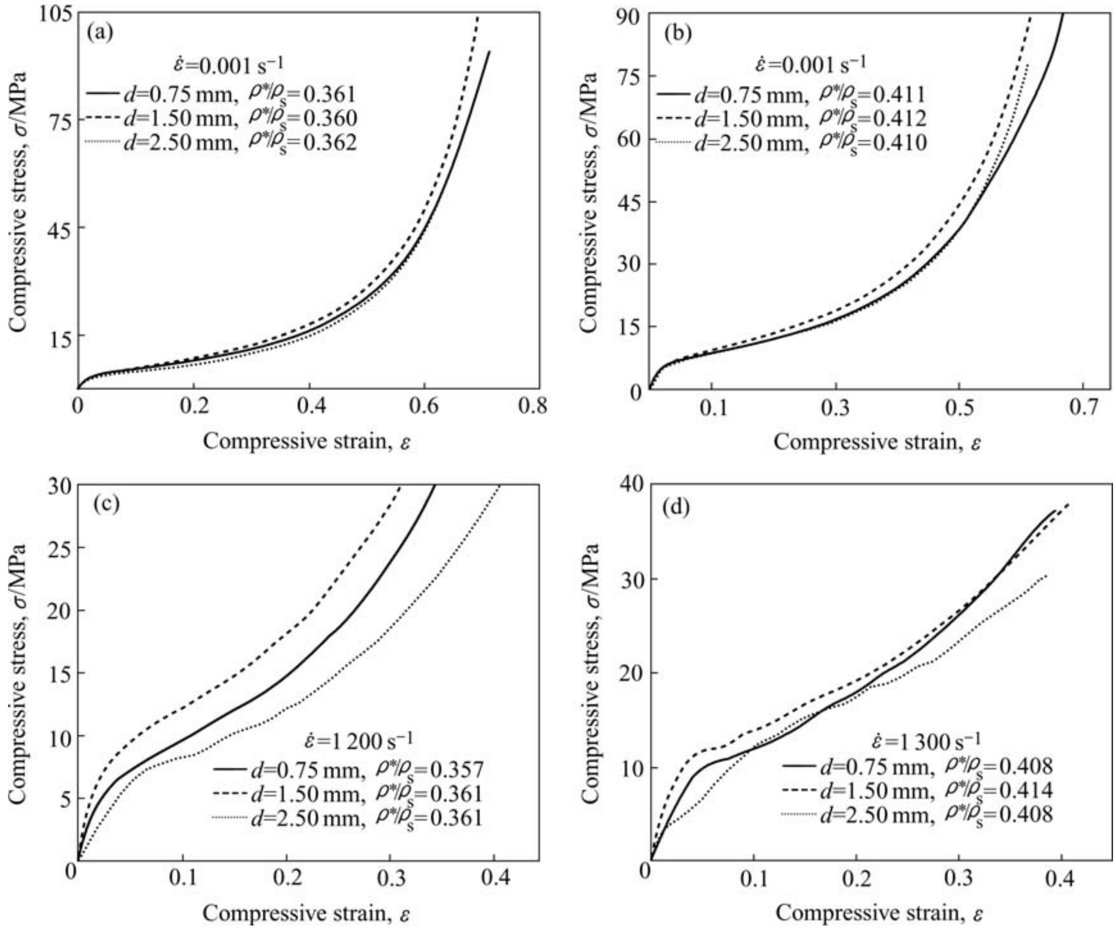

Fig.2 Compressive stress-strain curves of aluminum foams of different cell sizes under quasi-static((a) and (b)) and dynamic loading ((c) and (d)) conditions with $\rho^*/\rho_s\approx0.36$ and 0.41 respectively

densification as collapsed cells are compacted together. These deformation characteristics are similar to those of other aluminum alloy foams.

3.1 Elastic modulus

It can be seen in Fig.2 that for each of three cell sizes, the elastic moduli decrease initially and then increase with increasing compressive strain both under quasi-static and dynamic loading conditions. The initial decrease of the elastic moduli is associated with the increasing of strut's orientations with respect to the loading direction. The plastic bending of the struts leads to an increase in the orientation angles between individual struts and the loading axis. This makes it easier for elastic bending to occur, and thereby an initial reduction in the elastic moduli. The increase in the elastic moduli during later deformation stages is due to the densification of foam blocks at high strain levels, i.e. strain greater than 0.5 for quasi-static condition and 0.3 for dynamic condition.

The cell size of foams influences the elastic moduli in elastic region, plastic plateau region and densification region, and the influence becomes more significant under dynamic loading than under quasi-static loading, especially the elastic moduli in elastic region. Table 1 lists the elastic moduli of foams with cell size 0.75 mm, 1.50 mm and 2.50 mm, and $\rho^*/\rho_s\approx0.36$, 0.41 under quasi-static and dynamic compression. The elastic moduli in densification stage under dynamic loading are not listed in Table 1 because the foams are not fully dense under dynamic loading. Fig.3 shows the SEM images of foams after quasi-static and dynamic compression, respectively. In our experiment, when the average cell size is about 1.5 mm, the foam exhibits larger modulus. This is in agreement with the result reported in Ref.[15].

PAN et al[11] made use of a cuboid model with constant density presumption to illustrate that the elastic modulus is not affected by the cell size of foams. In fact the foams are not equal in density everywhere, and there exists micro-imperfection in cell walls or struts, thus arising the difference of elastic modulus for foams with different cell sizes and resulting in the values of moduli being much lower than those predicted using the formula $E^*/E_s=(\rho^*/\rho_s)^2$ given by GIBSON and ASHBY[1], where E^* and E_s are the elastic moduli of foam and material from which foam is made, respectively. The contradictory results obtained till now about the effect of cell size on the elastic modulus may be caused by the different method by which foams are made or the different morphology of foam structures. But the mechanism how cell size influences the modulus is not clear, and further exploration will be needed in future by theoretical modeling and numerical methods.

3.2 Strength and strain rate sensitivity

The definition of compression strength is somewhat

Table 1 Elastic moduli of aluminum foams in three stages of deformation

ρ^*/ρ_s	$\overline{d}$ /mm	$\dot{\varepsilon}$ /s^{-1}	E_e/MPa	E_p/MPa	E_d/MPa
0.361	0.75	0.001	218	22	492
0.360	1.50	0.001	228	26	700
0.362	2.50	0.001	280	20	492
0.357	0.75	1 185	417	47	
0.361	1.50	1 171	626	56	
0.361	2.50	1 190	241	32	
0.411	0.75	0.001	409	32	586
0.412	1.50	0.001	427	40	567
0.410	2.50	0.001	368	32	531
0.408	0.75	1 310	557	60	
0.414	1.50	1 361	929	66	
0.408	2.50	1 317	557	60	

ρ^*/ρ_s is the relative density of foams; $\overline{d}$ is the average cell size of foams as-received; $\dot{\varepsilon}$ is the initial strain rate for quasi-static compression, and average strain rate for dynamic compression; E_e, E_p and E_d are the elastic moduli in initial elastic deformation stage, plastic deformation stage (plateau region) and densification area, respectively.

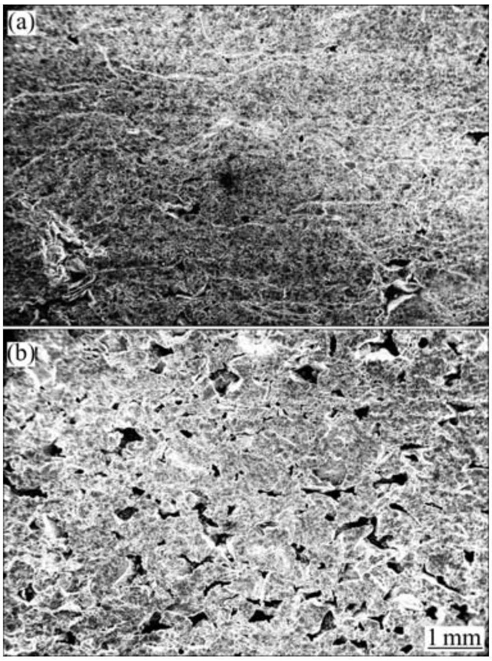

Fig.3 SEM images of vertical section of foams compressed: (a) Quasi-static loading; (b) Dynamic loading

ambiguous for metal foams. As one observes a different stress-strain behavior depending on the type of alloy used, varying definitions for strength can be adequate[16]. An upper and lower yield point can be observed in few compressive strain-stress curves in our study, so the stresses at 5%, 10% and 20% total deformation are taken to examine the effect of cell size on the compressive strength of foamed aluminum. These values are listed in Table 2. It is found that the stress values at 5%, 10% and 20% total deformation are the largest when the cell size is about 1.50 mm. The effect of cell size on the strength of foam becomes significant when the strain rate is increased from $0.001 s^{-1}$ to the order of 10^3 s^{-1}. In our case, the stress value at 5% total deformation is taken as the plastic collapse strength of aluminum foam.

Table 2 Compression strengths of aluminum foams under quasi-static and dynamic loading

ρ^*/ρ_s	$\overline{d}$ /mm	$\dot{\varepsilon}$ /s^{-1}	$\sigma_{0.05}$/MPa	$\sigma_{0.1}$/MPa	$\sigma_{0.2}$/MPa
0.361	0.75	0.001	4.58	5.74	8.05
0.360	1.50	0.001	4.54	5.95	8.67
0.362	2.50	0.001	3.90	4.93	7.00
0.357	0.75	1 185	7.24	9.72	14.89
0.361	1.50	1 171	9.63	12.18	18.26
0.361	2.50	1 190	6.27	8.28	12.14
0.411	0.75	0.001	7.06	8.66	11.97
0.412	1.50	0.001	7.10	9.30	13.38
0.410	2.50	0.001	5.46	7.21	11.49
0.408	0.75	1 310	9.92	12.09	18.07
0.414	1.50	1 361	11.73	13.93	19.18
0.408	2.50	1 317	6.82	12.09	17.65

$\sigma_{0.05}$, $\sigma_{0.1}$ and $\sigma_{0.2}$ are the compressive strengths when compressive strain is 5%, 10% and 20%, respectively.

It is obvious that the compressive strength is influenced by cell size. According to the model presented by ONCK et al[7], suppose a foam sample with cell size d and specimen width $W=\alpha d$, α is the ratio of the specimen width to the cell size, then

$$\frac{\sigma_{pl}}{\sigma_{bulk}}=\frac{(\alpha-1/2)^2}{\alpha^2} \quad (1)$$

where σ_{bulk} is the stress value when $W\rightarrow\infty$. i.e. σ_{pl} will tend towards σ_{bulk} with the increase of α. The reduced strength of small specimens is caused by the presence of a layer of cell walls at the free edge that does not carry load. The smaller α is, the higher the fraction of free edge is, and the smaller σ_{pl} will be. For the same specimen diameter, the smaller the cell size is, the larger α is, and then the larger σ_{pl} will be. This means that the plastic collapse strength of foam with small cell size should be higher than that of foam with large cell size, but our experiment result is not in agreement with this theoretical analysis.

The yield of foam materials may be caused by the failure of foam cells. For an open cell foam, slender foam struts (cell walls) can be treated as beams of length l with two ends hinged, the critical failure stress is

$$P_{cr} = \frac{\pi^2 EJ}{l^2} \tag{2}$$

where E is the elastic modulus and J is the moment of inertia. For foam materials with the same cross-section and equal density, cell size and arrangement determine both solid distribution in section and the moment of inertia. The larger the cell size is, the larger the moment of inertia J is, so if the elastic modulus is constant, the higher the P_{cr} will be, and so the σ_{pl}. The result from beam theory is opposite to that from the model of ONCK, and meantime the elastic modulus is not constant from the result in 3.1. So to explain the effect of cell size on the strength of foams should take all these factors(α, J, E etc) into consideration.

Table 3 lists the strength increase when the strain rate increases from 0.001 s^{-1} to an order of 10^3 s^{-1} of foams with different cell sizes. It can be obviously seen that the aluminum foams used in our study are very sensitive to strain rate, and the foams with middle cell size and lower density in our study show more significant strain rate sensitivity, the strength increase is larger than 110 %.

Table 3 Strain-rate sensitivity of aluminum foams

Relative density	Average cell size/mm	Strength increase/%		
		$\sigma_{0.05}$	$\sigma_{0.1}$	$\sigma_{0.2}$
0.36	0.75	58.08	69.34	84.97
0.36	1.50	112.11	104.71	110.61
0.36	2.50	60.77	67.95	73.43
0.41	0.75	40.51	39.61	50.96
0.41	1.50	65.21	49.78	43.35
0.41	2.50	24.91	67.68	53.61

GIBSON and ASHBY[1] pointed out that there are three factors, which influence the crushing stress of foam materials: localization of deformation, micro-inertia and densification. And we think that the cell size influences the strain rate sensitivity of foam materials through the procedure: Localization of deformation results in the thin layer near loading surface be compacted quickly under dynamic loading, the strain rate in this local area is far larger than the apparent one, then makes the inertia effect of cell wall torsion and bending be significant when cell walls buckling. Densification process is accompanied by the collision between cell walls when the cells collapse. The higher the strain rate is, the higher the collision velocity will be and the larger the collision force will be.

3.3 Energy absorption

When a metallic foam is compressed, the work is done by the force to it, or in other words, the compressive energy is absorbed. The energy absorption capacity W and the energy absorption efficiency I are two parameters to characterize energy absorption in foam, and they are defined as

$$W = \int_0^{\varepsilon_m} \sigma(\varepsilon)\, d\varepsilon \tag{3}$$

$$I = \frac{1}{\sigma_m \varepsilon_m} \int_0^{\varepsilon_m} \sigma\, d\varepsilon \tag{4}$$

where ε_m is the given strain, σ_m is the corresponding compressive stress, and σ is the compressive stress as the function of strain ε.

In Table 4 the maximum I during whole compression process and energy absorbed at certain strain are listed. The results show that the effects of cell size on energy absorption efficiency and energy absorption capacity of a foam are not as significant as those on modulus and strength. Foams with middle cell size show the largest energy absorption capacity among the three cell sizes in our study.

Table 4 Energy absorption of aluminum foams under quasi-static and dynamic loading

ρ^*/ρ_s	$\bar{d}$ /mm	$\dot{\varepsilon}$ /s^{-1}	I_{max}/%	W/(MJ·m^{-3})
0.361	0.75	0.001	74	2.07
0.360	1.50	0.001	72	2.19
0.362	2.50	0.001	74	1.80
0.357	0.75	1 185	71	3.81
0.361	1.50	1 171	73	4.73
0.361	2.50	1 190	70	3.10
0.411	0.75	0.001	74	3.08
0.412	1.50	0.001	71	3.39
0.410	2.50	0.001	70	2.65
0.408	0.75	1 310	71	4.53
0.414	1.50	1 361	75	4.97
0.408	2.50	1 317	63	4.23

I_{max} and W are energy absorption efficiency and energy absorbed during compression at strain of 30 % respectively.

It is shown that the strain rate does not have significant effect on the I_{max}, because the plateau region is reduced much under dynamic loading compared with that under quasi-static loading. But the energy absorption capacity of foams has a strong dependency on the strain rate, at which the foam is compressed, the energy absorbed under dynamic loading is 1.47−2.16 times that under quasi-static loading at the same strain. A number of mechanisms contribute to energy absorption in cellular solids. For open-cell aluminum alloy foams, the energy is absorbed largely through the bending and collapse of the walls in the foam, which occurs mainly in the long stress plateau. Low I_{max} value of about 75% may be due to the un-ideal structure of foams and short stress plateau.

4 Conclusions

1) The quasi-static and dynamic compressive stress-strain curves for various relative density aluminum foams of different average cell sizes have been studied using MTS810 material test system and SHPB. The elastic modulus and compressive strength of foams not only depend on relative density but also depend on cell size, and the foams of cell size about 1.50 mm have larger modulus and higher strength under both quasi-static and dynamic compression. The effects of cell size on the modulus and strength of aluminum foam are becoming significant when the strain rate is increased from 0.001 s^{-1} to the order of 10^3 s^{-1}.

2) The aluminum foams investigated have strong strain rate sensitivity. The foams with middle cell size and lower density show more significant strain rate sensitivity, the strength increase is even larger than 110 %.

3) Cell size effects on the energy absorption efficiency and the energy absorption capacity are not as significant as those on the modulus and strength of foams.

References

[1] GIBSON L J, ASHBY M F. Cellular Solid: Structure and Properties[M]. 2nd ed. Cambridge: Cambridge University Press, 1997.

[2] BAUMEISTER J, BANHART J, WEBER M. Aluminum foams for transport industry[J]. Materials & Design, 1997, 18(4/6): 217−220.

[3] BANHART J. Manufacture, characterization and application of cellular metals and metal foams[J]. Progress in Materials Science, 2001, 46: 559−632.

[4] CHEN He-fa, HUANG Xiao-mei, XU Ling. Effects of matrix properties on compressive behavior and energy absorption of foamed Al alloys[J]. Nonferrous Metals, 2003, 55(3): 10−12.(in Chinese)

[5] NIEH T G. Effects of cell morphology on the compressive properties of open-cell aluminum foams[J]. Mater Sci & Eng, 2000, A283: 105−110.

[6] LI J R, CHEN H F, YU J L, HAN F S. Effect of dual-size cell mix on the stiffness and strength of open-cell aluminum foams[J]. Mater Sci & Eng, 2003, A362: 240−248.

[7] ONCK P R, ANDREWS E W, GIBSON L J. Size effects in ductile cellular solids(Part I): modeling[J]. International Journal of Mechanical Sciences, 2001, 43: 681−699.

[8] ANDREWS E W, GIOUX G, ONCK P, GIBSON L J. Size effects in ductile cellular solids(Part II): experimental results[J]. International Journal of Mechanical Sciences, 2001, 43: 701−713.

[9] ZHOU J, SHROTRIYA P, SOBOYEJO W O. Mechanism and mechanics of compressive deformation in open-cell Al foams[J]. Mechanics of Materials, 2004, 36: 781−797.

[10] MARKAKI A E, CLYNE I W. The effect of cell wall microstructure on the deformation and fracture of aluminium-based foams[J]. Acta Mater, 2001, 49: 1677−1686.

[11] PAN Yi, HU Si-sheng, FENG Yi, et al. Cell-size effect on mechanical property of open-cell aluminum alloy foam[J]. Engineering Mechanics, 2003, 20: 171−175.(in Chinese)

[12] LEHMHUS D, BANHART J. Properties of heat-treated aluminium foams[J]. Mater Sci & Engn, 2003, A349: 98−110.

[13] ZHOU J, GAO Z, CUITINO A M, SOBOYEJO W O. Effects of heat treatment on the compressive deformation behavior of open cell aluminum foams[J]. Mater Sci & Eng, 2004, A386: 118−128.

[14] CHEN He-fa. Effect of cellular microstructure on the mechanical properties of open-cell aluminum foams[J]. Hot Working Technology, 2003(3): 1−2.(in Chinese)

[15] WANG Xi, YU Ji-lin. Uniaxial mechanical behavior of aluminum foam[J]. Experimental Mechanics, 2001, 16(4): 438−443.(in Chinese)

[16] BANHART J, BAUMEISTER J. Deformation characteristics of metal foams[J]. J Mater Sci, 1998, 33: 1431-1440.

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