Rare Metal Materials and Engineering
Volume 52, Issue 1, January 2023
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Wang Zhaoming, Liu Yuan, Xu Fating, et al. Pore Structure and Compressive Properties of Open-Cell Aluminum Foams Prepared by Infiltration Casting Based on NaCl Space-Holder[J]. Rare Metal Materials and Engineering, 2023, 52(01): 119-124.

ARTICLE

Pore Structure and Compressive Properties of Open-Cell Aluminum Foams Prepared by Infiltration Casting Based on NaCl Space-Holder

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Abstract: Nearly spherical NaCl particles prepared by a disc granulator were used to produce open-cell aluminum foams via infiltration casting. The average compressive strength of the salt balls is 3.9 MPa, and they can be completely collapsed within 5 min in the ultrasonic cleaner. By controlling the hot-pressure sintering duration as 0.5–2 h and the hot-pressing temperature at 700 °C, the preforms with bulk density of 0.66−0.83 g/cm^3 can be prepared. Prolonging the duration of hot-pressure sintering can increase the pore size of the open-cell aluminum foams from 0.48 mm to 1.16 mm, and also increase the porosity from 64% to 82%. Compression test results show that the macroscopic deformation characteristics of the foams with different pore structures are basically the same, and they all exhibit the deformation characteristic of layer-by-layer collapse. In addition, the densification strain value, elastic modulus, plateau yield stress, and energy absorption capacity of open-cell aluminum foams are al decreased with increasing the porosity. The energy absorption capacity is the largest (15.0 MJ·m^{-3}) when the porosity is 64%.

Key words: NaCl beads; open-cell aluminum foams; hot-pressure sintering; compressive properties

Porous materials have been widely applied into the engineering fields and play an important role in the engineering structural materials[1]. Open-cell metal foam (reticular metal foam) is one of the important porous materials. In engineering application, the metal foams present good controllability in mechanical and physical properties, including the electrical conductivity, tensile strength, elongation, elastic modulus, biaxial tension, multiaxial tension/compression, fatigue performance, specific surface area, bending property, torsion property, and shearing property[2–3]. The open-cell aluminum foam is a lightweight material with unique structure and function integration, which has metal elasticity, high temperature resistance, superb corrosion resistance, low density, high specific surface area, and excellent damping due to its foam structure. Because of its excellent performance in energy absorption, sound absorption, electromagnetic shielding, and heat insulation/dissipation, the open-cell aluminum foam can be used in lightweight manufacture, energy absorption, shock absorption, buffering, electromagnetic shielding, and other multifunctional integration[4–8]. Therefore, the open-cell aluminum foam has a broad application prospect in aerospace, automobile manufacture, petrochemical, and other fields[9–10].

Infiltration casting method is a common method to prepare open-cell aluminum foam. High-temperature-resistant water-soluble salts, such as NaCl, $MgSO_4$, and $CaCl_2$, are usually used as the pore-forming materials. These salts are cheap and easy to obtain with stable high temperature performance and good collapsibility. However, the low porosity and difficulty in elimination of salt particles of open-cell aluminum foams severely restrict their application. Since the performance of open-cell aluminum foam is affected by the matrix properties and the cell structure, and the pore structure of the open-cell aluminum foam prepared by the infiltration casting method is

Received date: April 28, 2022
Foundation item: National Natural Science Foundation of China (51771101)
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heavily dependent on the filler structure, it is of great significance to optimize the infiltration casting method to prepare open-cell aluminum foam with high porosity.

The open-cell aluminum foams with porosity of 90% can be fabricated by the soft ceramic balls which are easily compressed. The ceramic balls contain alumina particles, polyvinyl alcohol, water, a small amount of bentonite, and carboxymethyl/hydroxypropyl-methyl cellulose. However, the granulation process is complicated and these insoluble ceramic granules are difficult to remove[11]. Wang et al[12] prepared the mixed salt powder and flour to produce weakly corrosive porous spherical particles with a pan-type pelletizer, which were then used as the space-holder particles for the preparation of magnesium foams. These porous particles are easy to remove, but they may be infiltrated by the melt, resulting in the fact that they can only be used in the powder metallurgy process. Wan et al[13] prepared $CaCl_2$ preform particles via the hot-pressure deformation and obtained open-cell aluminum foams with high porosity, which provided a reference for the preparation of high-bulk-density preforms.

In this research, the nearly spherical space-holder particles were prepared by a disk granulator and then used to manufacture the open-cell aluminum foams with uniform structure and good three-dimensional connectivity. The space-holder particles consisted of NaCl powder, kaolin, bentonite, and binder. These particles were then sprayed with water in the disc granulator for granulation, producing salt balls with size of 1 – 5 mm. Preforms with different densities were prepared by controlling the hot-pressure sintering duration. The open-cell aluminum foams with controllable structure were prepared by the infiltration casting method, and their structure and compressive properties were studied.

1 Experiment

The preparation process of open-cell aluminum foams by infiltration casting method based on NaCl space-holder is shown in Fig.1. Step 1: 70wt% NaCl powder (size of 75 μm), 20wt% kaolin (size of 45 μm), 10wt% bentonite (size of 45 μm), and binder were mixed together. Step 2: the mixture was granulated into salt balls with size of 3 – 3.5 mm by water spraying in the disc granulator, and then air-dried or dried at low temperature. Step 3: the salt balls were then placed into a hot-pressure sintering mold for compaction at 9 – 10 kPa for different sintering durations. Step 4: the sintered salt ball preform and the ZL102 aluminum were placed in a heat-resistant stainless steel crucible for infiltration casting at 700 °C and 202.3 kPa for 2 h. The aluminum salt ball composite was produced in this process. Step 5: the top surface of the composite was removed by lathe, and the composite was placed in water for soaking and washing. Step 6: the open-cell aluminum foams were obtained after the salt particles were completely dissolved and removed.

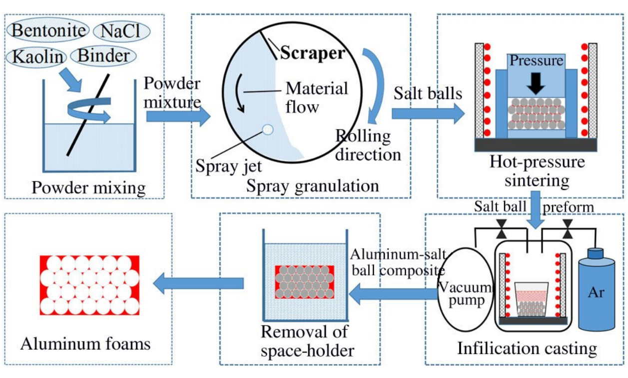

Fig.1 Schematic diagram of preparation process of open-cell aluminum foams by infiltration casting method based on NaCl space-holder

An electronic AGX-V 50KN universal material testing machine was used to analyze the compressive strength of the salt balls and the quasi-static compression performance of the open-cell aluminum foams. The crushing force of one salt ball with diameter of 5 mm was determined by twenty times and the average compressive strength of the salt ball was calculated. The porosity of the open-cell aluminum foams was determined by measuring the foam volume and mass. Image-Pro software was used to analyze the images obtained by optical microscope (OM) of the open-cell macrostructures and interconnected holes. The specimens of 20 mm×20 mm×21 mm for compressive tests were cut by a wire-cut electric discharge machine, and the compression rate was 2 mm/min.

2 Results and Discussion

2.1 Nearly spherical salt balls

The preparation process of nearly spherical particles is shown in Fig. 2. The powder is sufficiently mixed with the liquid in the granulator, forming discontinuous concave liquid bridges around the contact points between the powder particles and resulting in loose aggregates. During the mixture, the aggregates are compressed, which reduces the gap between the particles. Because the liquid is sprayed onto the local area, the particles are in contact with each other. Under the capillary effect of liquid and the mechanical force, a large aggregate easily forms, namely cue ball, which indicates the nucleation stage. In the nucleus (cue ball), the liquid between the aggregates is evenly distributed in the gaps, and the formed aggregates are still plastic. Because the excess liquid film exists on the aggregate surface, the

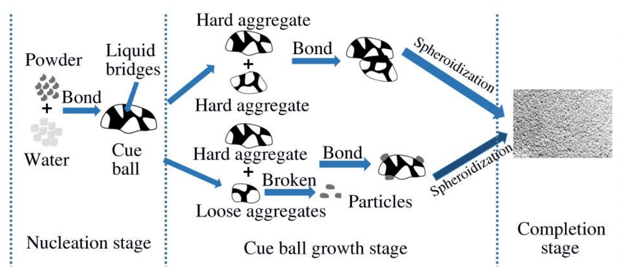

Fig.2 Schematic diagram of preparation process of nearly spherical particles

aggregate deforms when it collides with other small particles. Some aggregates with weak bonding may break into small pieces and then fill in the surface of other aggregates. The nearly spherical particles are obtained by reciprocating rotation. When the aggregates collide with other aggregates of similar size and bonding strength, they are gradually compressed and densified because of the mutual surface friction, therefore forming the high-strength particles. The particle growth ends as the liquid supply stops, and the content of liquid between particles reaches about 90% theoretical saturation content. The excess liquid diffuses from the granular surface to the interior of particles, which increases the surface capillary force and enhances the internal bonding force of the granules. The liquid volume is reduced owing to the volatilization during rotation. By this time, the particles do not deform or adhere to other particles when they collide with other particles. Therefore, the particle stops growing and the particle formation is completed.

The strength and collapsibility of the salt ball are the key factors for its application as space-holder, which are influenced by the amount of added liquid, binder, granulation process, and the physical and chemical properties of raw materials. The optimum addition of water is crucial for granulation. If the addition amount of liquid is too low, the speed of particle formation is slow, and the particles are small and fragile. If the addition amount of liquid is too high, the particles may easily bond with each other, forming excessively large particles. The bottom and surrounding areas of the plate may easily stick to the material, which is difficult to form cue balls. For some materials that are difficult to pelletize or have low strength after particle formation, the binder can be added during the preparation. The binder can increase the capillary cohesive force and the molecular force of the particles, stabilize the bridge between the particles, and thereby increase the particle formation rate and low-temperature strength. After the particles are formed, they further roll in the granulator at a faster speed, which improves the particle strength due to the action of mechanical force, extrusion, and rubbing between particles. The optimal process parameters are as follows: the added water is 25wt% of the powder, the granulator speed is 50 r/min, and the granulation duration is 5 min. Thus, the average compressive strength of the obtained salt balls is 15 N, which sufficiently satisfies the requirement of particle strength. Therefore, the nearly spherical salt balls with size of 1−5 mm can be prepared, and their average compressive strength is 3.9 MPa. The bulk density of preforms is 0.66–0.83 g/cm^3.

Particle collapsibility is related to the physical and chemical properties of the raw materials and the collapse agent. The salt balls contain 70wt% NaCl and therefore they are highly soluble in water. The dissolution rate of NaCl particles with size of 3 mm and salt balls in water was characterized by the immersion tests. Results show that the dissolution time of the granular NaCl particle is more than 20 min, whereas the salt balls can completely collapse within 5 min in an ultrasonic cleaner. Thus, the collapsibility of the salt balls is better than that of granular NaCl particles.

2.2 Pore structure of open-cell aluminum foams

Fig. 3 shows macrostructures of open-cell aluminum foams obtained by NaCl space-holder after hot-pressure sintering at 700 °C for 30, 60, 90, and 120 min. It is found that there is no clear difference between the salt ball preforms after hot-pressure sintering for 2 and 12 h. Thus, the longest sintering duration was set as 120 min for simplification. It can be seen that the interconnected cells are at the touch zones formed by hot-pressure sintering between particles, and the cell size directly determines the difficulty of salt ball removal. The larger the size of interconnected cells, the easier the salt ball removal from the open-cell aluminum foams.

According to Fig. 3, with prolonging the hot-pressing sintering duration, the contact area between the particles is gradually increased, the connected pores also become larger, and the opening degree of the open-cell aluminum foam is also increased. When the opening degree increases, the pore edges and pore walls become thinner, the porosity is increased, and the three-dimensional connectivity is improved. The porosity of open-cell aluminum foams prepared by NaCl space-holder after hot-pressure sintering for 30, 60, 90, and 120 min is 64%, 69%, 76%, and 82%, respectively.

Fig.4 shows the distributions of interconnected pore sizes in different open-cell aluminum foams. When the hot-pressure sintering duration was 30 min, the diameter of nearly 80% interconnected pores is less than 0.6 mm, and their average diameter is only 0.48 mm. When the sintering duration is 120 min, the size of the interconnected pores is increased and the average pore size is 1.16 mm. Hence, the interconnected pore sizes and the cell structure of the open-cell aluminum foams can be controlled by the hot-pressure sintering duration. In a certain range, the longer the hot-pressure sintering duration, the greater the porosity of the open-cell aluminum foam. When the hot-pressure sintering reaches a certain time, the salt ball preform barely deforms, and thus the porosity of open-cell aluminum foam hardly changes.

In Fig. 5, the compressive stress-strain curves of aluminum

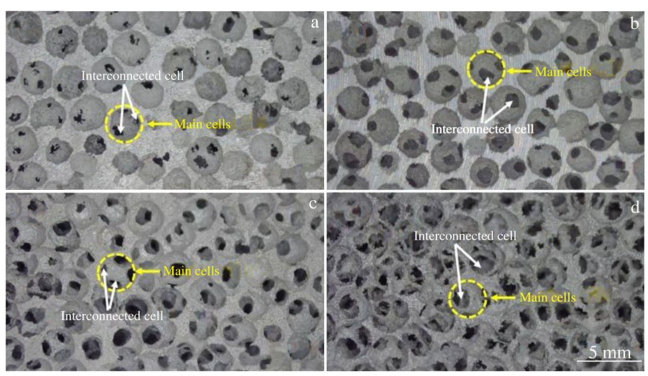

Fig.3 Macrostructures of open-cell aluminum foams prepared by NaCl space-holder after hot-pressure sintering for 30 min (a), 60 min (b), 90 min (c), and 120 min (d)

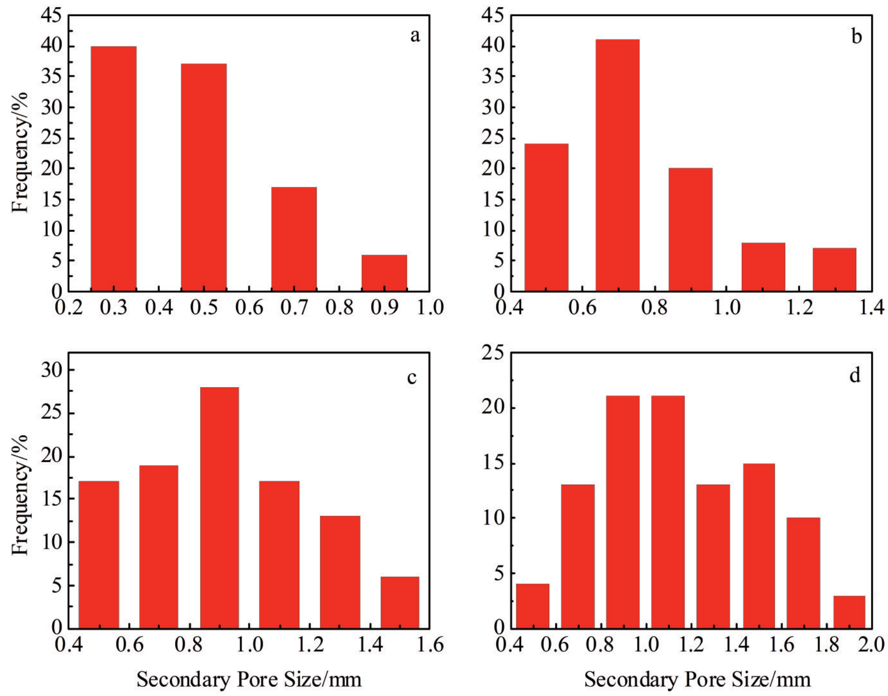

Fig.4 Secondary pore size distributions in open-cell aluminum foams prepared by NaCl space-holder after hot-pressure sintering for 30 min (a), 60 min (b), 90 min (c), and 120 min (d)

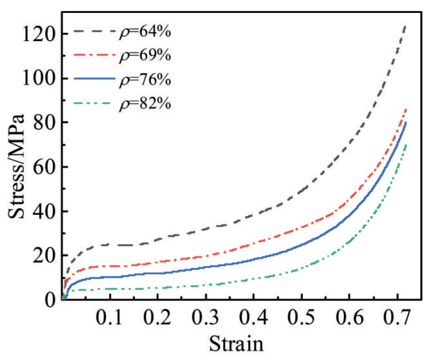

Fig.5 Quasi-static compressive stress-strain curves of different open-cell aluminum foams

foams with different porosities (ρ =64%, 69%, 76%, 82%) exhibit three typical metal-foam stages: elasticity, plateau, and densification. The yield stress and plateau region of open-cell aluminum foams are decreased with increasing the porosity. In the aluminum foams with low porosity, the voids become less and the foam becomes more. In the area perpendicular to the loading direction, the wall of bearing hole is thicker, thereby withstanding greater stress. Thus, a higher yield stress and a higher plateau region are obtained for the open-cell aluminum foams with low porosity. In the open-cell aluminum foams with high porosity, the voids are more and the foam is less. Thus, in the area perpendicular to the loading direction, the wall of bearing hole is thinner, and less stress can be withstood. Hence, a lower stress yield and a lower plateau region are obtained for the open-cell aluminum foams with high porosity.

As shown in Fig.6, the deformation characteristics of open-cell aluminum foams with different porosities are basically the same during quasi-static compression, and they all exhibit the layer-by-layer collapse[14–17]. After a rapid elastic deformation, the cell begins to plastically deform. When the strain exceeds the plastic strain limit of cell wall, the cell begins to collapse. The plastic deformation of the cells usually starts in the weakest area and forms a localized deformation zone. The cell collapse occurs only in the deformation zone, and the area outside the deformation zone does not deform. With increasing the compressive strain, the deformation zone expands outward, and new deformation zones are continually formed. The formation of deformation zones and layer-by-layer collapse and the compaction of cells are the main deformation characteristics during the plastic platform stage of compression. The appearance of the stress plateau during compression is closely related to the deformation mode of the layer-by-layer cell collapse. Finally, when the deformation zone extends all over the cell, the cell collapses and is compacted, i. e., the compression process enters into the densification stage. Then the compression further deforms the base metal and the stress rises sharply with increasing the strain.

The energy absorbed by the open-cell aluminum foam during compression can be obtained by integrating the stress-strain curve, as follows:

$$W\left(\varepsilon_0\right)=\int_0^{\varepsilon_0}\sigma\left(\varepsilon\right)\mathrm{d}\varepsilon \tag{1}$$

where ε represents the instantaneous strain; σ represents the stress (MPa); ε_0 represents the given strain value; W is the

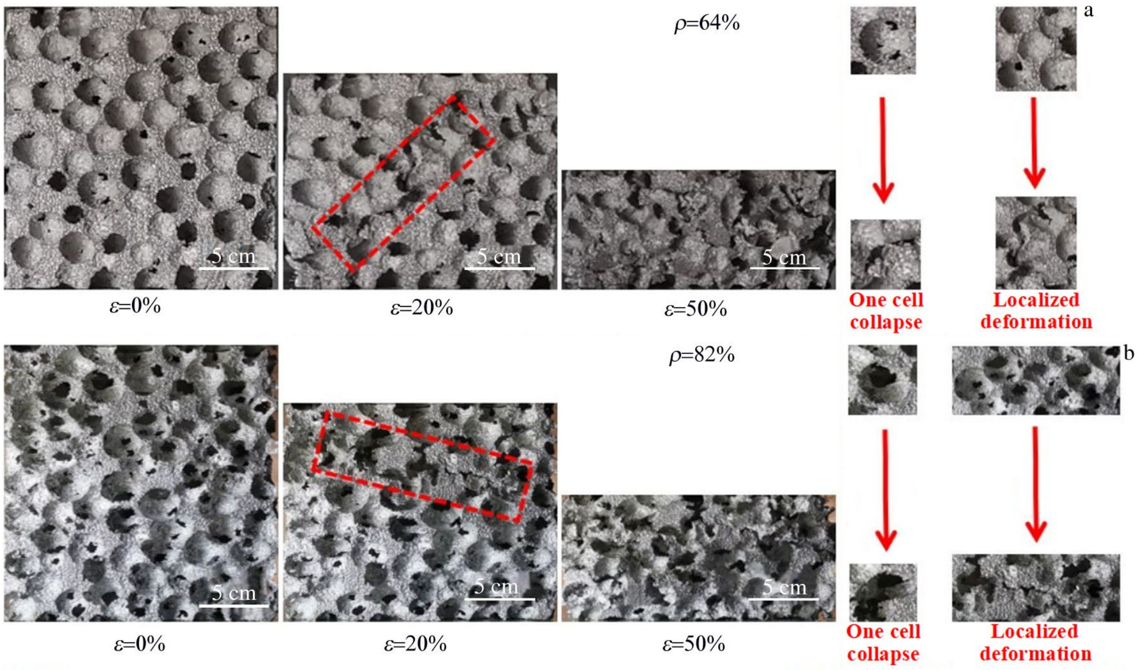

Fig.6 Deformation morphologies of different open-cell aluminum foams during compression: (a) ρ=64% and (b) ρ=82%

energy absorption ($MPa\cdot m^{-3}$).

The specific compression performance of open-cell aluminum foam is the plateau region: the stress changes a little in a long period, thereby increasing the energy absorption capacity. Generally, the energy absorption of open-cell aluminum foams is characterized by the strain energy of compaction, namely the energy absorbed before compaction. The energy absorption efficiency of open-cell aluminum foams during compression[18–19] can be expressed, as follows:

$$\eta(\varepsilon)=\frac{\int_0^{\varepsilon}\sigma(\varepsilon)\mathrm{d}\varepsilon}{\sigma(\varepsilon)} \tag{2}$$

where $\sigma(\varepsilon)$ and $\eta(\varepsilon)$ are the stress value and energy absorption efficiency when the strain is ε, respectively. The strain corresponding to the maximum value of the energy absorption efficiency curve is defined as the densification strain ε_d[18–19], as follows:

$$\frac{\mathrm{d}\eta(\varepsilon)}{\mathrm{d}\varepsilon}=\varepsilon_d=0 \tag{3}$$

Then, the energy absorption capacity $W(\varepsilon_d)$ can be calculated by Eq(4), as follows:

$$W(\varepsilon_d)=\int_0^{\varepsilon_d}\sigma(\varepsilon)\mathrm{d}\varepsilon \tag{4}$$

Furthermore, the plateau stress σ_p of the open-cell aluminum foams during compression can be calculated by Eq.(5)[18–19], as follows:

$$\sigma_p=\frac{\int_{\varepsilon_0}^{\varepsilon_d}\sigma(\varepsilon)\mathrm{d}\varepsilon}{\varepsilon_d-\varepsilon_0} \tag{5}$$

According to Fig.7, the energy absorption capacity of open-cell aluminum foams is increased with increasing the strain. Under the same compressive strain condition, the energy absorption capacity is decreased with increasing the porosity of aluminum foam. As listed in Table 1, the densification strain, elastic modulus, plateau stress, and energy absorption

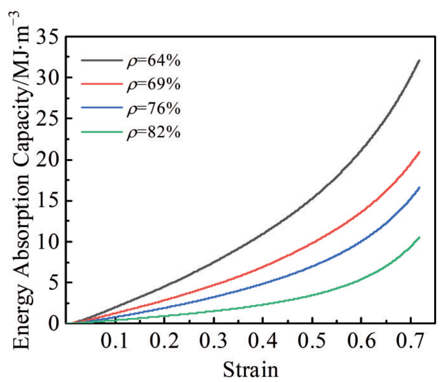

Fig.7 Energy absorption capacity-strain curves of different open-cell aluminum foams

Table 1 Compressive properties of different open-cell aluminum foams

Porosity, ρ/%	Relative density, ρ_{rel}	ε_d	Elastic modulus, E/MPa	Plateau stress, σ_p/MPa	Energy absorption capacity, $W(\varepsilon_d)$/$MJ\cdot m^{-3}$
64	0.36	0.49	449	30.6	15.0
69	0.31	0.48	284	21.4	12.0
76	0.24	0.47	187	13.4	6.3
82	0.18	0.45	92	6.2	2.8

capacity are all increased with decreasing the porosity, i.e., with increasing the relative density of aluminum foam. According to Fig.5 and Fig.7, the densification strain of open-cell aluminum foam is increased with increasing the relative density, because of the increase in the volume fraction of solid phase and the thickening of the pore edges and pore walls which increases the plateau stress. All these phenomena cause the late entry of densification stage during the compression process. It is found that the energy absorption capacity is maximum of 15.0 MJ·m^{-3} when the porosity is 64%.

3 Conclusions

1) The nearly spherical salt balls with size of 1–5 mm can be prepared, their average compressive strength is 3.9 N/mm^2, and they completely collapse within 5 min in an ultrasonic cleaner.

2) The porosity of the salt ball preforms can be adjusted by controlling the hot-pressure sintering duration, so the open-cell aluminum foams with porosity of 64%–82% can be prepared under the optimized process conditions.

3) The deformation characteristics of open-cell aluminum foams with different pore structures are basically the same, and they all show the layer-by-layer collapse. The densification strain value, elastic modulus, plateau stress, and energy absorption capacity are all increased with increasing the relative density. Under the same compressive strain condition, the energy absorption capacity is decreased with increasing the porosity. The energy absorption capacity is maximum of 15.0 MJ·m^{-3} when the porosity is 64%.

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盐球渗透铸造法制备开孔泡沫铝的孔结构及压缩性能

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摘　要：使用圆盘造粒机制备近球形的NaCl颗粒，并将其用于渗透铸造制备开孔泡沫铝。盐球的平均抗压缩强度为3.9 MPa，在超声波清洗机中可在5 min内完全塌陷。通过控制热压烧结时间为0.5~2 h，热压温度700 ℃，可制备堆积密度在0.66~0.83 g/cm^{3}的预制体。延长热压烧结时间会使开孔泡沫铝的孔径从0.48 mm增加到1.16 mm，孔隙率从64%增加到82%。压缩实验结果表明，不同孔隙结构下泡沫体的宏观变形特征基本相同，均表现出逐层塌陷的变形特征。此外，泡沫铝的致密化应变值、弹性模量、平台屈服应力和能量吸收能力均随着孔隙率的增加而降低。当孔隙率为64%时，能量吸收能力最大（15.0 MJ·m^{-3}）。

关键词：NaCl球；开孔泡沫铝；热压烧结；压缩性能

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