Microstructure and Compressive Properties of Aluminum Foams Made by 6063 Aluminum Alloy and Pure Aluminum

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Aluminum foams are new kind of structural-functional composite materials which comprised of aluminum matrix and gas pores. In this paper, aluminum foams with homogeneous pore structure made by 6063 aluminum alloy were fabricated by melt foaming method. As comparison, the aluminum foams were also fabricated by pure aluminum. Studies on process parameter, microstructure and mechanical properties have been carried out. Process optimization for aluminum foams made by 6063 alloys has been studied according to the orthogonal experimental design method. The cell wall of aluminum foam is comprised of Al matrix, Ca-thickening phase and Ti-containing phase. The difference between foams made by 6063 aluminum alloy and pure aluminum is that there is element Mg and element Si dissolved in the matrix in the 6063 aluminum foam, which are positive to the foam strength accordingly. For different base materials, the compressive strength of foams made by 6063 aluminum alloy is greater than that made by pure aluminum.

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Keywords: microstructure, compressive property, 6063 aluminum foam, orthogonal experimental design

1. Introduction

Metal foams are a new kind of materials originated from nature, like wood and bones, which composed of continuous metal phase and separated gas phase. For their unique structures, metal foams are becoming promising structural-functional composite materials. Aluminum foam, the most commonly used metal foam, is light-weight, and has advantages in energy absorption, noise reduction, electromagnetic shielding, heat insulation, etc.1–5) The bright applications in aviation, aerospace, building industry and automobile industry arouse widespread attention from researchers.6–8)

Melt foaming method is one of the most popular manufacturing techniques.1,2) The fabricating process is complicated and controlled by many factors. So single-factor experiments for aluminum foams are not enough to figure out all the influences. Orthogonal experimental design, also named Taguchi method, is a kind of experimental method to study multi-factor and multi-level experiments, which can be used to improve manufacturing process, optimize or improve efficiency.9,10) Surace et al.11) applied Taguchi method to optimize the gas injection manufacturing parameters for aluminum foams. Surace et al.12) and Solórzano et al.13) used Taguchi method to find the optimal process parameters for aluminum foam manufactured by powder metallurgy route. In order to investigate the influences of experimental parameters on aluminum foams, orthogonal experimental design is an excellent choice for reducing the experiment workload and improving the efficiency correspondingly.

As structural-functional integrative material, the pore structure and mechanical properties of aluminum foams are widely concerned. However, reports on the microstructure of cell wall are few. The manufacturing process of melt foaming method brings in various compounds which created into sophisticated phases after reaction at high temperatures. Thus, the sophisticated cell wall microstructure results in the sophisticated mechanical behaviour. When the pore structure is the same, the different cell wall microstructure affects the micro deformation mechanism significantly.14) There was evidence indicating that some kind of phase can induce property failure, such as Al3Ti15) and Al13Fe.16) V.K. Jeenager et al.17) developed different microstructures through solutionizing and quenching followed by thermal ageing treatment, and the uniaxial compression tests showed that the solutionized sample had the best energy absorption capacity (29.3 MPa). Yuan et al.18) prepared aluminum foams by gas injection method and found that the cell wall property was impaired by the defects in cell walls and the oxide films on the cell wall surface. Taking these into consideration, the relationship between cell wall microstructure and compressive property is of vital importance.

Commercial 6063 alloy are widely used in construction fields for the applications of doors and windows, and large amount of scraps were produced. Preparing foams by aluminum 6063 scraps is environmental friendly for recycling and can reduce production cost greatly. Meanwhile, the 6063 aluminum alloy is suitable for foaming due to the small amount of element Mg existing in 6063 alloy is just appropriate to reduce the surface tension between pores and melt.19)

In this study, aluminum foams based on 6063 aluminum alloy were fabricated by melt foaming method. As a comparison, aluminum foams based on commercial pure aluminum ingot were also produced. Four manufacturing parameters were performed in the orthogonal experimental design: Ca adding temperature, TiH2 adding temperature, amount of TiH2 and holding time after TiH2 stirring. What is more, the microstructure and compressive property of foams made by 6063 aluminum alloy and pure aluminum are compared.

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2. Experimental Procedure

The base materials used were 6063 aluminum alloy (matrix material, Al, Mg: 0.45–0.9 wt.%, Si: 0.2–0.6 wt.%), commercial pure aluminum ingot (matrix material, purity 99.7%), calcium granules (thickening agent, average size 3–4 mm, purity 99.7%), titanium hydride powder (foaming agent, TiH2 < 48 µm, purity 99.4%). TiH2 powder was pre-treated at 500°C for 120 minutes in air to delay its decomposition in foaming process.

Aluminum foams were prepared by melt foaming route. (1) Melting: the base materials were melted in an electrical resistance furnace at the temperature of 700°C; (2) Thickening: put 2 wt.% calcium granules into the melt at the temperature from 660°C to 700°C and stirred the mixture mechanically for about 10 minutes; (3) Stirring: put TiH2 into the melt and stirred the melt for about 6 minutes; (4) Foaming: the melt was preserved heat in the furnace for foaming; (5) Cooling: aluminum foam was taken out in the air.

Orthogonal experimental design was applied. Four factors and three levels were selected to set up a L₉³⁴ orthogonal experiments. The factors and levels were shown in Table 1. The primary and secondary of the factors and the best combination of them are obtained according to range analysis. The range value is derived from the difference between the maximum value and the minimum value of every level. The high range value demonstrates the factor influences the measurable variable greatly. Porosity, pore size and uniformity were the measurable variables to characterise the pore structure of aluminum foams. Porosity is a function of foams were calculated by eq. (1), where ρk is the relative density, ρk is the density of corresponding dense material, which is the density of pure aluminum, 2.7 g·cm⁻³, M is the foam weight, and V is the foam volume. Pore size was calculated by Image-Pro Plus 6.0.¹⁹) The uniformity of pore size was represented by the slope value of the pore diameter accumulative fraction curves. The specific method is as follows: select the scatters ranged from 5% to 95% of the pore diameter accumulative fraction and make a linear fitting, then the slope value of the fitting line is that of the accumulative fraction curves. The range from 5% to 95% is the estimation interval of the population parameter consisted of pore size value, which indicates that the probability of the true value of this parameter to fall around the measurement results is 95%. As a result, a high slope value means a good pore size uniformity.

\[ \theta = (1 - \mu_k) = \left(1 - \frac{\rho_k}{\rho_d}\right) = \left(1 - \frac{M}{V\rho_d}\right) \]  

Microstructure was investigated on a scanning electron microscope (SEM, Zeiss MERLIN-VP-COMPACT, accelerating voltage = 15 kV) with the energy dispersive spectrometer (EDS, Oxford INCA). The quasi-static compressive tests were carried on a WDW computer-controlled electronic universal testing machine (Sinotest Equipment Co., Ltd., Model: WDW-50) with the loading rate of 5 mm/min.

3. Results and Discussions

3.1 Orthogonal experimental design analysis

Table 2 shows the L₉³⁴ orthogonal array and the measurable variables of the foams accordingly. Figure 1 shows the longitudinal sections of the foams. The pore size distribution and its accumulative fraction are shown in Fig. 2, which indicates that foam 9 has the smallest pore size and the best uniformity.

The range analysis value is shown in Table 3. Porosity range value ranks as R₀ > R₄ > R₆ > R₇ which demonstrates that porosity is affected by TiH2 adding temperature most, and the followings are Ca adding temperature, holding time after TiH2 stirring, amount of TiH2. The optimal combination of parameters to get the highest porosity is A₂B₃C₁D₂, which is adding calcium at 680°C, adding 0.6 wt.% TiH2 at 650°C, and cooling after keeping foaming for 5 min. Pore size range value ranks as R₉ > R₆ > R₄, which demonstrates that pore size is affected by TiH2 adding temperature most, and followed by the amount of TiH2, Ca adding temperature, holding time after TiH2 stirring. The optimal combination of parameters to get the smallest pore size is A₂B₃C₁D₂, which is adding calcium at 660°C, adding 0.4 wt.% TiH2 at 670°C, and cooling after keeping foaming for 7 min. Uniformity range values as R₃ > R₄ > R₂ > R₇, which demonstrates that uniformity is affected by TiH2 adding temperature most, and the followings are Ca adding temperature, holding time after TiH2 stirring, amount of TiH2. The optimal combination of parameters to get the best uniformity is A₁B₃C₂D₃, which is adding calcium at 660°C, adding 0.5 wt.% TiH2 at 670°C, and cooling after keeping foaming for 7 min.

As illustrated in Fig. 3, the relationship between each factor and the measurable variable is obviously presented. Shown in Fig. 3(a), with the increasing of Ca adding temperature, the porosity and the pore size increase first and then decrease, and the uniformity of the foams goes the opposite. When adding Ca at 660°C the reaction in the melt is not much severe than adding Ca at 680°C and 700°C. Thus, the thickening phase is less and the melt viscosity is low, which makes the foaming agent easier to escape out of the melt.

<table>
<thead>
<tr>
<th>Table 1 Factor-level table of orthogonal experimental design.</th>
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<tr>
<td>Factor</td>
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<tr>
<td>Ca adding temperature/°C</td>
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<tr>
<td>TiH2 adding temperature/°C</td>
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<tr>
<td>Amount of TiH2/%</td>
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<td>Holding time after TiH2 stirring/min</td>
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<table>
<thead>
<tr>
<th>Table 2 L₉³⁴ orthogonal array.</th>
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<td>Factor Level</td>
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Table 3  Range analysis value.

<table>
<thead>
<tr>
<th>Porosity $\theta/%$</th>
<th>$\bar{K}_1$ (Mean value of level 1)</th>
<th>$\bar{A}_1 = 74$</th>
<th>$\bar{B}_1 = 85$</th>
<th>$\bar{C}_1 = 78$</th>
<th>$\bar{D}_1 = 76$</th>
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<td>$\bar{K}_2$ (Mean value of level 2)</td>
<td>$\bar{A}_2 = 83$</td>
<td>$\bar{B}_2 = 79$</td>
<td>$\bar{C}_2 = 76$</td>
<td>$\bar{D}_2 = 82$</td>
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<td>$\bar{K}_3$ (Mean value of level 3)</td>
<td>$\bar{A}_3 = 76$</td>
<td>$\bar{B}_3 = 69$</td>
<td>$\bar{C}_3 = 80$</td>
<td>$\bar{D}_3 = 75$</td>
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<td>Range value: $R = \max(\bar{K}_i) - \min(\bar{K}_i)$</td>
<td>$R_A = 9$</td>
<td>$R_B = 16$</td>
<td>$R_C = 4$</td>
<td>$R_D = 7$</td>
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<th>Pore size $d/mm$</th>
<th>$\bar{K}_1$ (Mean value of level 1)</th>
<th>$\bar{A}_1 = 2.7$</th>
<th>$\bar{B}_1 = 4.5$</th>
<th>$\bar{C}_1 = 2.8$</th>
<th>$\bar{D}_1 = 3.0$</th>
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<td>$\bar{K}_2$ (Mean value of level 2)</td>
<td>$\bar{A}_2 = 3.6$</td>
<td>$\bar{B}_2 = 3.0$</td>
<td>$\bar{C}_2 = 3.0$</td>
<td>$\bar{D}_2 = 3.7$</td>
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<td>$\bar{K}_3$ (Mean value of level 3)</td>
<td>$\bar{A}_3 = 3.3$</td>
<td>$\bar{B}_3 = 2.2$</td>
<td>$\bar{C}_3 = 3.9$</td>
<td>$\bar{D}_3 = 3.0$</td>
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<td>Range value: $R = \max(\bar{K}_i) - \min(\bar{K}_i)$</td>
<td>$R_A = 0.9$</td>
<td>$R_B = 2.3$</td>
<td>$R_C = 1.1$</td>
<td>$R_D = 0.7$</td>
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<th>Uniformity $U$</th>
<th>$\bar{K}_1$ (Mean value of level 1)</th>
<th>$\bar{A}_1 = 41$</th>
<th>$\bar{B}_1 = 21$</th>
<th>$\bar{C}_1 = 37$</th>
<th>$\bar{D}_1 = 36$</th>
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<tr>
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<td>$\bar{K}_2$ (Mean value of level 2)</td>
<td>$\bar{A}_2 = 27$</td>
<td>$\bar{B}_2 = 35$</td>
<td>$\bar{C}_2 = 38$</td>
<td>$\bar{D}_2 = 30$</td>
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<tr>
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<td>$\bar{A}_3 = 37$</td>
<td>$\bar{B}_3 = 49$</td>
<td>$\bar{C}_3 = 30$</td>
<td>$\bar{D}_3 = 39$</td>
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<tr>
<td></td>
<td>Range value: $R = \max(\bar{K}_i) - \min(\bar{K}_i)$</td>
<td>$R_A = 14$</td>
<td>$R_B = 28$</td>
<td>$R_C = 8$</td>
<td>$R_D = 9$</td>
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melt. Then the porosity and the pore size of the foam are smaller. When adding Ca at 700°C, the thorough mixing of Calcium and the melt helps produce more thickening agent, which makes the melt move hard and lets the foaming agent get together to burn out. Thus, there is less TiH₂ left and the foam porosity and the pore size are small. When adding Ca at 680°C, the temperature is appropriate for thickening, which makes a high foam porosity and a large pore size. Generally speaking, if the pore size is large, the pore uniformity is bad. It is illustrated in the variation tendency of uniformity in Fig. 3(a).

As shown in Fig. 3(b), with the increasing of TiH₂ adding temperature, the porosity value and the pore size value increase, and the uniformity value goes the opposite. When
adding TiH₂ at a temperature higher than the melting point, the decomposition rate goes up with the adding temperature. Then the undecomposed TiH₂ left in the melt becomes less, which makes the porosity and pore size smaller. So the uniformity of the foams goes better correspondingly.

It can be seen from Fig. 3(c), with the increase of amount of TiH₂, the pore size value increases. Less TiH₂ makes the pore size smaller and the cell wall thicker. Too much TiH₂ prompts pores crack and combine together to form big-sized pores and thin cell walls. With the increase of TiH₂ amount, pore porosity goes down just a little, which indicates that the change in amount of TiH₂ at a thousandth level has little influence on porosity. The uniformity of the foams has a peak value with the increase of amount of TiH₂, which indicates that there is a best stirring condition for different amount of foaming agent in the melt.

As everyone can be seen from Fig. 3(d), with the increasing of holding time after TiH₂ stirring, the porosity value and the pore size value increase first and then decrease, and the uniformity value goes the opposite. During the process of foaming, the foam experiences rapid expansion stage, slow expansion stage, stabilisation stage, and shrinking stage in turn. The most appropriate holding time is stopping heat preservation just before the foam expands to the highest level. When the holding time is from 5 min to 6 min, the hydrogen released from the TiH₂ spreads out fully, and the pores can have a long time to grow up. This situation brings about high-porosity foam with homogeneous pores. Prolonging the holding time after TiH₂ stirring continuously, the pores will crack and incur defects as local macro pores, collapse, and crispy cell walls.

### 3.2 Microstructure

SEM microstructure and EDS energy spectra of 6063 alloy, re-melting 6063 alloy, re-melting 6063 alloy with 2 wt.% calcium are shown in Fig. 4.

Morphology of as-received 6063 alloy in Fig. 4(a) reveals that the grains are fine, granular and homogeneous distributed without segregation which goes against subsequent process. EDS analysis (Fig. 4(b)) indicates the bright white acicular structure at Point 1 is AlFeSi phase ($\beta$-Al₈Fe₂Si), and the dark gray is the matrix phase. The solution of Fe in liquid Al is relatively high (700°C, 2.5 wt.%; 800°C, 5 wt.%), so Fe is inevitable in aluminum alloys. However, the solution of Fe in solid Al is low (655°C, 0.03 wt.%), so Fe precipitates out to forming the bright white acicular structure.

After re-melting, 6063 alloy has been fully homogenized, and the bright write structure (Point 2 in Fig. 4(c)) gathered at the crystal boundary which is in the form of network. The microstructure of re-melting 6063 alloy is similar to that of 6063 alloy. The difference is that there is less bright write structure in the re-melting alloy. That is because the AlFeSi phase ($\beta$-Al₈Fe₂Si) is dissolved in the melt gradually after re-melting, which leads to a decrease in amount. In analysis, there is no big bulk Mg₂Si gathered in, and the Mg element in solid solution is homogeneous distributed. In addition, the Si element is partially distributed in solid solution of the matrix and partially exists in AlFeSi phase. The Fe element is mainly in AlFeSi phase.

The microstructure of the re-melting 6063 alloy with 2 wt.% calcium is illustrated in Fig. 4(e). The compound of Ca (Point 3), which is the thickening phase, precipitates along the dendritic network boundary of eutectic Si in the $\alpha$-Al matrix. Besides, there exists some write pot discontinuously in the dendritic network, which is proved to be the Fe impurity phase according to the EDS in Fig. 4(g), which phenomenon indicates that some hard brittle
plate-like $\beta$-Al$_8$Fe$_2$Si transformed into Chinese-script $\alpha$-Al$_5$FeSi. When the calcium granules were added into the melt, they will have a fully reaction with the melt and release heat during the stirring, which makes the melt temperature go up to about 900°C. Literature 14 reported that the superheat for the melt helps promote forming Chinese-script $\alpha$-Al$_5$FeSi. The plastic processing property of monoclinic $\beta$-Al$_8$Fe$_2$Si is better than that of bcc-structured $\alpha$-Al$_5$FeSi. The EDS analysis of the matrix (Point 5) is shown in Fig. 4(h) with a small quantity of Si element and Mg element, which are dissolved in the Al matrix.

Figure 5 is the microstructure of the cell wall of foams made by 6063 aluminum alloy. The bright write acicular structure (Point 6) is iron-riched phase with the EDS spectrum of Al-Fe-Si. The morphology of iron-riched phase is shown in Fig. 5(b). Due to the foaming crucible is made of carbon steel, some Fe element is dissolved into Al melt to increase the Fe content in the foam cell wall to some extent after rapid stirring in high temperature. Another phase in the cell wall is the Ca-containing phase with a gray network structure (Point 7). The morphology of the gray phase is Al-Ca-Mg-Si compound which is indicated by the EDS spectrum is shown in Fig. 5(d). There also exists some write polygonal phase (Point 8) which shown in Fig. 5(f) in the Al matrix regarded as a kind of oxide Al-O-Ca-Mg according to the EDS analysis. In addition, for the blowing agent is added into the melt to react and release hydrogen, so the Ti element is left behind to form Al-Ca-Ti compound (Point 9). Such compound is Al-Mg-Ti-Ca bearing phase, which tends to gather together near the pores in the form of bulk shape shown in Fig. 5(h) by the EDS spectrum indicated.

SEM microstructure and EDS energy spectra of commercial pure aluminum ingot, re-melting pure aluminum, re-melting pure aluminum with 2 wt.% calcium are shown in Fig. 6. The gains are homogenously distributed in commercial pure aluminum ingot. The EDS spectrum in Fig. 6(b) shows the bright write acicular structure is an iron-riched phase. Microstructure of re-melting pure aluminum and its EDS spectrum are shown in Fig. 6(c), (d). After adding the thickening agent, Ca phase is precipitated along the eutectic Si network boundary.

Table 4 presents the contents of 6063 aluminum alloy and commercial pure aluminum. The major elements are Al, Si, Mg and Al, respectively. Compared with 6063 aluminum alloy, there are less Si, Mg and Fe in pure aluminum than 6063 alloy. Thus, there is less acicular iron-riched phase in pure aluminum. The network of eutectic Si in pure aluminum is intermittent because of the low Si content.

Figure 7 is the microstructure of the cell wall of pure aluminum foam. The bright write phase is iron-riched...
compound (Point 6), the gray network compound is Ca-containing phase (Point 7), and the dark gray structure is the matrix phase (Point 9). After foaming, the remanets of the blowing agent TiH2 are observed in Al matrix (Point 8), which is shown in Fig. 7(b).

The difference between foams made by 6063 aluminum alloy and pure aluminum is that there is element Mg and element Si dissolved in the matrix in the 6063 aluminum foam, which are positive to the foam strength accordingly.

3.3 Compression behavior

Both pore structure and matrix property affect the compressive behaviour of aluminum foams greatly. Pore structure is determined by the relative density, while the matrix property is determined by the matrix material. According to the eq. (2) that is given by Gibson and Ashby, the relationship between the plateau stress of aluminum foam and the relative density is presented as follows:24)

\[
\frac{\sigma_{pl}}{\sigma_{ys}} = C \left(\frac{\rho^*}{\rho_y}\right)^n
\]

where \(\sigma_{pl}\) and \(\sigma_{ys}\) are the foam’s plateau stress and foam’s density, \(\sigma_{ys}\) and \(\rho_y\) are the strength and density of base material, \(C\) and \(n\) are coefficients which are related to base material. Generally speaking, the range of coefficient \(n\) is from 1.5 to 2.25. With the increase of the relative density and the decrease of porosity, the plateau stress of aluminum foam increases.

The plateau stress \(\sigma_{pl}^*\) is calculated by the following equation:26)

\[
\sigma_{pl}^* = \frac{\int_0^{\varepsilon_{cd}} \sigma(\varepsilon)\,d\varepsilon}{\varepsilon_{cd} - \varepsilon_y}
\]

where \(\varepsilon_y\) is the strain of the upper yield stress, \(\varepsilon_{cd}\) is the strain of the maximum energy absorption efficiency, which can be calculated by the following two equations:27)

\[
\eta(\varepsilon) = \int_0^\varepsilon \frac{\sigma(\varepsilon)}{\sigma^*} d\varepsilon
\]

\[
\frac{d\eta(\varepsilon)}{d\varepsilon} = 0
\]

where the solution \(\varepsilon\) from the equations above is \(\varepsilon_{cd}\).

In this paper, \(\sigma_{ys}\) refers to the compressive strength of the solid base material combined with the thickening agent. The adding amount of blowing agent is not too much, so its influence can be ignored comparing with the solid base material. The compressive strain-stress curves of the solid base materials with 2 wt.% Ca are shown in Fig. 8, which implies that the compressive strengths of the 6063 alloy with 2 wt.% calcium and pure aluminum with 2 wt.% calcium are 111 MPa and 100 MPa, respectively. Due to the hole-defect comes from the casting process, the real compressive strength should be a mixture interaction of initial test value (Fig. 8) and the porosity of the solid material. After correction, the real compressive strengths of the 6063 alloy with 2 wt.% calcium and pure aluminum with 2 wt.% calcium are about 148 MPa and 127 MPa, with the porosity of about 25% and 21%.

Figure 9 shows the plateau stress of 6063 aluminum foam and pure aluminum foam, and their fitting curves. When the relative density is the same, the plateau stress of foams made by 6063 aluminum alloy is bigger than that by pure aluminum, which indicates that the compressive strength of foams made by 6063 aluminum alloy is better than that by pure aluminum. The equations of the fitting curves are shown in Table 5.
Actually, there are some differences between the fitting curves in Fig. 9 and traditional Gibson-Ashby model ($n = 1.5$): The plateau stress by the traditional model is higher in the low-relative density region, and lower in the high-relative density region than the practical fitting curves. The differences are caused by the pore geometrical characteristic and deformation mechanism. In the traditional model, a single pore is regarded as polygon under ideal conditions, which is shown in Fig. 10(a). However, defects like cracks and holes in the cell wall of the foam with a low relative density reduce the strength greatly. The pore tends to be in spherical shape when the relative density of foam aluminum is high (Fig. 1(r)), so that the deformation mechanism of the foam in the traditional model is no longer applicable. The cell walls of the foams are short and squat that they yield axially before they bend. Model with small pore size is more applicable (Fig. 10(b)) for the aluminum foam are thought of as the solid materials with holes in them. Then the plateau stress-relative density curves should be segment fitted to present the characteristics of foams with different density in Fig. 11. The equations of the fitting curves are shown in Table 6. When the relative density is lower than 0.2, the coefficient $C$ in the fitting curve is lower than 1, and the coefficient $n$ is approximate to 1.5. When the relative density is higher than 0.2, the coefficient $C$ in the fitting curve is higher than 1, and the coefficient $n$ is approximate to 2. According to the literature, the variation of the coefficients $C$ and $n$ can be derived from two mainly aspects: the geometry of the foams, which means the geometry differs in different densities; or the value of $\sigma_{ps}$ is rarely known with precision, which varies from the contents change brought about by the foaming agent, the cell wall oxidation, and other unknown factors.

According to Lu et al., the plateau stress is governed by one of three different possible failure mechanisms of the foam cells: buckling, collapse or fracture. The power of the equations of the fitting curves is between 1.5 and 2 for the relative density of the foams lower than 0.2 reflecting the combined effect of buckling and collapse of the cell walls. While for aluminum foams with relatively thick cell walls, which means that the relative density of the foams is higher than 0.2, collapse of these walls will be the mechanism governing the plateau stress, so the power of the equations of the fitting curves is greater than 2.

### 4. Conclusion

(1) The optimized fabrication process has been studied according to the orthogonal experimental design method. For the maximum porosity and the maximum pore size, the optimized process is adding Ca at 680°C, adding TiH$_2$ 0.6 wt.% at 650°C, foaming in the crucible for 6 min, and cooling in the air. For the minimum porosity and the best uniformity, the optimized process is adding Ca at 660°C, adding TiH$_2$ 0.5 wt.% at 670°C, foaming in the crucible for 7 min, and cooling in the air. For the minimum pore size, the optimized process is...
adding Ca at 660°C, adding TiH₂ 0.4 wt.% at 670°C, foaming in the crucible for 7 min, and cooling in the air.

(2) According to the range value analysis, porosity, pore size, and uniformity are affected by TiH₂ adding temperature most for the four factors of TiH₂ adding temperature, Ca adding temperature, holding time after TiH₂ stirring, and amount of TiH₂.

(3) The cell wall of aluminum foam made by 6063 aluminum alloy is comprised of Al matrix, Ca-thickening phase, Ti-containing phase, and some iron-riched phase. The difference between the two kinds of foams is that there is element Mg and element Si existed in most of the cell wall phases. The cell wall of aluminum foam made by pure aluminum is comprised of Al matrix, Ca-thickening phase, Ti-containing phase, and some iron-riched phase. The difference between the two kinds of foams is that there is element Mg and element Si dissolved in the matrix in the 6063 aluminum foam, which are positive to the foam strength accordingly.

(4) Quasi-static compressive tests results shown that the relationship between the plateau stress and the relative density follows the relationship between the plateau stress and the relative density is lower than 0.2, the coefficient C is approximate to 1.5. When the relative density is higher than 0.2, the coefficient C in the fitting curve is lower than 1, and the coefficient n is approximate to 2. For different base materials, the compressive strength of foams made by 6063 aluminum alloy is better than that made by pure aluminum.

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