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Foaming Behavior of Microsized Aluminum Foam Using Hot Rolling Precursor

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Abstract: Aluminum foam that is lightweight with high specific strength, high energy absorption and other characteristics can be used in aerospace, transportation, machinery manufacturing and other fields. The PCM method is usually used to prepare closed-cell aluminum foams. The microsized aluminum foams made by this process can solve the non-uniform pore structures caused by liquid drainage during the foaming process of large aluminum foams. The surface morphology and internal pore structure of microsized aluminum foams are affected by the quality of the precursor used for foaming. In this paper, foamable precursors were obtained via either hot rolling or hot extrusion and subsequently foamed. By analyzing the micromorphology and foaming process of the precursor, the influence of the technological method on the macroscopic pore structure of the final aluminum foam was studied. The results show that the aluminum powder particles in the precursor prepared with the hot rolling method had metallurgical bonding, and the outer surface was dense, with almost no porosity and holes in the interior. The microsized aluminum foam obtained after foaming was smooth in appearance, and the internal pore structure was round and uniform. The reason is that during the foaming process of microsize aluminum foam, the foaming agent was evenly distributed in the precursor of the hot rolling process because of its compact structure. During the foaming process, the decomposed gas of the foaming agent will not escape, and the evenly distributed foaming agent tends to nucleate in situ. In the process of rapid foaming, the pressure in the bubble is enough to resist the liquid drainage phenomenon caused by gravity, and the growth direction of the gas core is isotropic, which promotes the foam structure to be more rounded and uniform.



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Keywords: aluminum foam; precursor; pore structure; degree of circularity; diameter of equivalent

1. Introduction

Metal matrix composites have excellent mechanical and physical properties such as high specific strength, specific modulus, good stability, low coefficient of thermal expansion and good electrical and thermal conductivity, which show great potential for application in many fields. As the most widely used aluminum matrix composites, aluminum foam prepared with aluminum as the matrix has both metallic properties and porous material structure characteristics, and it is a new functional material with low density and high porosity [1], which has received widespread attention because of its light weight and high strength, good force and thermal and electromagnetic properties [2]. It has also shown great potential for applications in aerospace, transportation and machinery manufacturing [3–9].

Closed-cell aluminum foam preparation methods include direct melt foaming, gas injection foaming, Powder Compact Melting (PCM for short), etc. [10,11]. The specific method of preparing aluminum foam via powder metallurgy is to mix metallic aluminum powder and foaming agent powder in a certain ratio; after compaction, the precursor is made, and then the precursor is processed in the next step, which involves processes such as rolling and hot extrusion to obtain the foamable precursor. The precursor is placed in a mold designed in advance and heated to a temperature near the melting point of the mixed alloy powder. After the decomposition of the foaming agent to produce gas, the

precursor gradually expands due to the molten precursor base metal material limiting the gas overflow, thereby producing aluminum foam. Compared with other methods, the PCM method is a simple process and easy to operate, but the phenomenon of liquid discharge exists in the preparation process, and the larger the size, the more serious the phenomenon of liquid discharge [12–19]. It is easy for this process to lead to bubble rupture or merging, extra-large pores and the phenomenon of an upper bubble layer and a lower solid layer appearing, making the overall pore non-uniform and resulting in poor pore structure or even deterioration. It was found that this problem can be effectively solved by improving the PCM method to prepare small-volume foam structures with advanced pore structures (Advanced Pore Morphology (APM)) by separating the foaming process from the fabrication process. By heating the preform particles in a continuous foaming furnace to obtain miniature aluminum foam spheres with a maximum diameter of 15 mm and a minimum diameter of 5 mm (APM), the resulting specimens have a complete surface and a uniform internal pore structure. In this process, due to the direct contact of heat in the heating furnace with the preform, the foaming time is very short, and the pore structure of the resulting aluminum foam spheres is very uniform. Moreover, because of the simple geometry of the preform and the resulting aluminum foam spheres, the foaming process is easier to control, which provides the idea and process basis for the preparation of an aluminum foam composite structure. It can also effectively solve the phenomenon of uneven pore structure caused by the phenomenon of liquid discharge in large-size aluminum foams generated using the PCM method [20,21].

Because the stability of aluminum foam represents its ability to maintain the pore structure, the strength of aluminum foam is the key to ensuring its mechanical properties. The pore structure of the stable aluminum foam is characterized by slight differences in pore size at high porosity, uniform wall thickness, and the absence of huge pores and cracks [22,23]. In the literature [24,25], precursors were prepared by using the cold pressing, hot pressing and investigated hot extrusion methods in preparing aluminum foam using the PCM methods, and the foaming effects of the precursors were obtained via different pressing methods. The results showed that the precursors prepared with other methods had different foaming effects, among which the precursors made with the cold pressing method could not be foamed. In the precursors prepared with the hot extrusion method, the pore structure of aluminum foam obtained after foaming was better than that made with the hot pressing method, indicating that the quality of precursors significantly influences the quality of aluminum foam. In preparing microsized aluminum foams using the PCM method, higher stability aluminum foam spheres can be obtained if high-quality precursors can be produced [26–28].

In previous studies on powder metallurgy foaming of aluminum foams, it was found that the density of the matrix power is the most important factor affecting the foaming effect, and a high power density can make the foam structure uniform after foaming and reduce the chance of no-bubble layers and large through-holes. If the powder density is not high, through-holes and excessive oxidation of the powder can easily occur, resulting in poor foam structures after foaming [29]. Based on this, a technique consisting of hot extrusion and the rolling of precursors under the premise of powder metallurgy treatment was investigated in this paper based on previous research results and systematic experiments. This technique compares the foaming effect of aluminum foam under different methods with two different methods of treating the precursor with hot extrusion and rolling on the basis of mixing power in a ball mill and cold pressing into a block. The main purpose of rolling the preform is to obtain a significantly higher density of the matrix than that of the hot extrusion process to create favorable conditions for the foaming process. In this study, we performed hot rolling and hot extrusion to prepare precursors, study their effects on the foaming process of microsized aluminum foams and analyze their foaming mechanisms. The study focused on the role of the process of preparing precursors by rolling to improve the density of the matrix, and the effect of the density of the matrix on the foaming effect was analyzed.

In this study, the precursors were prepared via hot rolling and hot extrusion. The densities of the composites prepared via powder metallurgy are mainly related to the plasticity of the reinforcement itself, the volume fraction and the plastic flow of the matrix. The densification behavior of powder hot extrusion molding is mainly two processes of volume shrinkage and plastic deformation, but it cannot make the composite achieve complete densification, and hot rolling can make the holes in the material close to achieve better metallurgical bonding. In the process of hot extrusion, the extrusion temperature mainly affects the combination between the powders, the degree of densification and the plastic deformation of the material. A reasonable hot extrusion process can make the powder particles fully deform, and completely break the oxide film to achieve metallurgical bonding between the particles. The reasons for the increased strength of aluminum matrix composites under rolling process conditions can be summarized as follows: grain refinement, weave strengthening, improved dispersion and orientation of the reinforcement, promotion of better interfacial metallurgical bonding and increased densification. After hot rolling, the powder is further compressed, and the number of secondary microcracks is reduced accordingly [30]. This article investigates the effect of two different methods on the foaming process of micro-sized aluminum foams and analyzes the foaming mechanism. The focus is on the role of rolling preparation precursor process on improving the matrix densities, and the effect of matrix densities on the foaming effect is analyzed.

2. Materials and Methods

The materials used in this experiment were aluminum powder, silicon powder and TiH₂ powder, where the mass fraction of Si was 12% and the mass fraction of TiH₂ powder was 0.5%. Figure 1 shows the flow chart of two different methods of preparing aluminum foam spheres. The powder was mixed in a ball mill, and the mixed powder was cold-pressed into a block under a certain pressure. After hot extrusion and hot rolling, the cold pressing blocks formed sheet and strip precursors, respectively. The cut precursor was used for foaming. The furnace temperature for foaming was set at 700 °C, and the precursor foams were in a Φ10 mm hemispherical copper mold. After foaming, the micro-sized spherical aluminum foam was cooled and solidified.

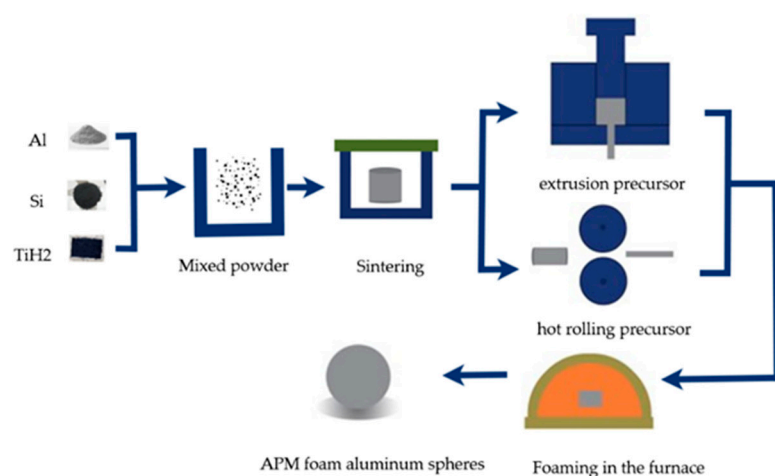


Figure 1. Different ways to prepare aluminum foam spheres.

3. Results and Analysis

According to the principle of powder weight conservation before and after the rolling of metal powder [31], Equation (1) was derived:

$$\rho_2 = \rho_1 k_1 k_2 \left(\frac{k_3}{h} + 1 \right) \quad (1)$$

where ρ_1 is initial density; ρ_2 is density of the powder after rolling; $k_1 \cdot k_2$ are the rolling parameters; k_3 is also a rolling mill parameter. From Equation (1), it can be seen that the density of the powder after rolling is related to the initial density ρ_1 , and $k_1 \cdot k_2$ are determined by the rolling parameters to ensure that the other parameters of the mill remain unchanged, that is, when k_3 remains unchanged, the change of $k_1 \cdot k_2$ can be measured by the depression rate. The volume of the substrate material in the experiment was certain, and the initial density before rolling can be indirectly measured by the amount of loaded powder, that is, from the above theoretical derivation, it can be seen that the density of the substrate after rolling depends on the initial density of the powder and the rate of compression. The initial density of the hot-rolled and hot-extruded powder is the same; thus, the pressing rate determines the density of the substrate.

Hot rolling process parameters: rolling force is 30 t, roll diameter $\Phi 320$ mm, roll length 350 mm, rolling speed 3.00 mm/s. After three passes of rolling to get 3 mm thickness of the prefabricated sheet body, line cutting of the prefabricated body is performed to get the required size of the prefabricated body.

Hot extrusion process parameters: cold pressing pressure 300 Mpa, extrusion pressure 250–300 Mpa, holding temperature 450–550 °C. Comparing the parameters of the hot rolling and hot extrusion process, the pressing rate of hot rolling was higher than that of the hot pressing method, and the density of the precursor after rolling was significantly higher than that of the existing hot pressing process, which is very beneficial to the subsequent foaming process.

3.1. Microstructure of Cold-Pressed Block

The density of the precursor is one of the key factors that affect whether it can be foamed properly, and the pore structure of the resulting spheres differs from the density of the matrix. Figure 2 shows the metallographic structure of the cold-pressed block, and it is evident that Si powder was evenly distributed among the aluminum powder particles. The powder particles were pressed together, but there was no metallurgical bonding between the aluminum powder particles. There were still tiny pores, which will make the gas generated by the decomposition of the foaming agent overflow from the pores during the foaming process, resulting in foaming failure. Therefore, the next process step was needed to increase the densities of the foamed precursors.

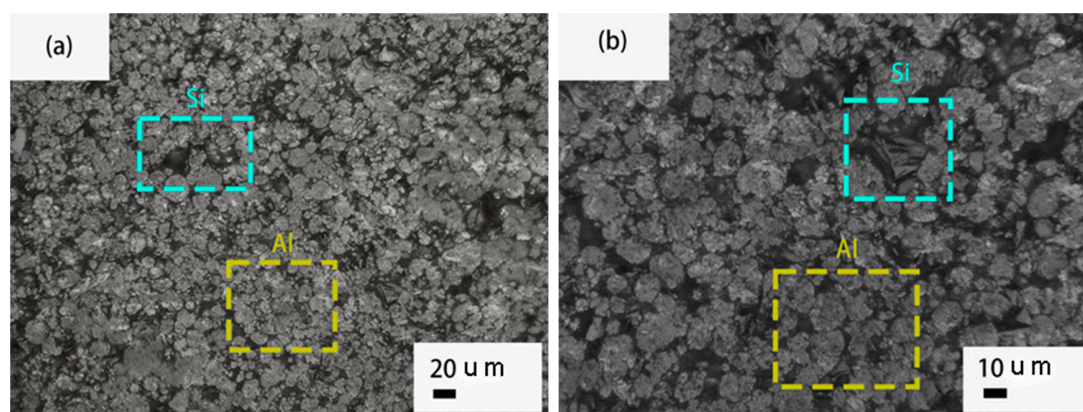


Figure 2. The metallographic structure of the cold-pressed block. (a) $\times 500$; (b) $\times 1000$ magnification.

3.2. Microstructure of Precursor

The metallographic structure of the precursor obtained after hot extrusion and hot pressing of the cold-pressed block is shown in Figure 3. In the figure, the dark gray strips are Si powder particles, and the black dots are TiH_2 powder particles.

In contrast to the cold-pressed block, the aluminum powder particles were bonded metallurgically in the precursor after hot rolling and hot extrusion. However, the aluminum powder particles in the extrusion precursor showed the original morphology (Figure 3a),

whereas the aluminum powder particles in the hot rolling precursor basically disappeared with no noticeable gap in the structure (Figure 3b). The results show that the hot rolling method basically eliminated the pores in the precursor, and it had a denser surface and internal structure. Moreover, the TiH_2 powder particles in the precursors obtained by the extrusion method were aggregated, and the TiH_2 powder particles in the precursors obtained by hot rolling were significantly smaller. The results show that the distribution of TiH_2 powder in the hot-rolled precursor was more uniform.

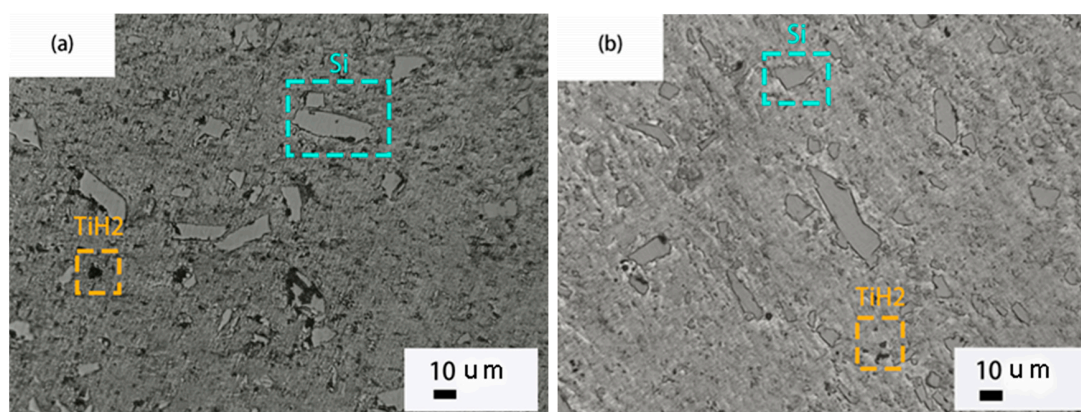


Figure 3. The metallographic structure morphology of foaming precursors. (a) The extrusion precursor. (b) The hot rolling precursor.

In the process of foaming, when the temperature reached the decomposition temperature of the foaming agent, TiH_2 powder released H_2 to form a gas nucleus first. In the process of growing a hydrogen nucleus, if the surrounding force was uniform, then the gas nucleus was more likely to grow into a spherical hole with the same orientation, and the pore size also tended to be more uniform. If the force was not uniform, the pores grew in different directions, and the pores with anisotropic growth were more likely to make contact and then merge, which affected the uniformity of the pore structure.

Therefore, the size of the density of the matrix and the uniform distribution of the foaming agent in the matrix affected the subsequent foaming effect. The higher the density of the matrix, the more uniform the force on the gas nucleus formed by the decomposition of the foaming agent, which reinforced the consistent orientation of the pores after they grow. The same contact conditions between the pores after they grow made the pore morphology highly similar. On the contrary, there were large pores merged with small pores into larger pores, and the unmerged small pores were distinguished from the oversized pores, making the distribution of pores uneven.

3.3. Aluminum Foam Ball Structure

The precursors obtained by different methods were foamed to obtain aluminum foam pellets with a diameter of 10 mm. The appearance morphology, profile morphology and binarization morphology are shown in Figure 4.

Due to the low density of the precursor prepared with the hot extrusion method, there were large voids between the powder particles; thus, at foaming temperature, a large part of the H_2 released by TiH_2 decomposition circulated and escaped along the pores between the powders, resulting in insufficient foaming driving force and, finally, the formation of a bubble-free layer. In addition, some large-sized connecting holes appeared after foaming the hot-extruded precursors, which is mainly due to the existence of certain voids and other defects within the hot extruded matrix, and the bubble holes in these parts grew abnormally during foaming, forming broken holes and connecting holes. There were many tiny pores at the edges, leading to the uneven structure of the overall small spherical pores, as seen in Figure 4b. The precursor powder prepared with the hot-rolling method achieved high densities, thereby effectively overcoming the shortcomings of the hot extrusion process, as

seen in Figure 3e. The ideal core layer foam structure was obtained after the foaming of the rolled precursors: the bubble-free layer was significantly reduced, the hole size did not differ much, there were no obvious broken holes and connecting holes in the core layer and the hole structure of the whole cross-section was uniform.

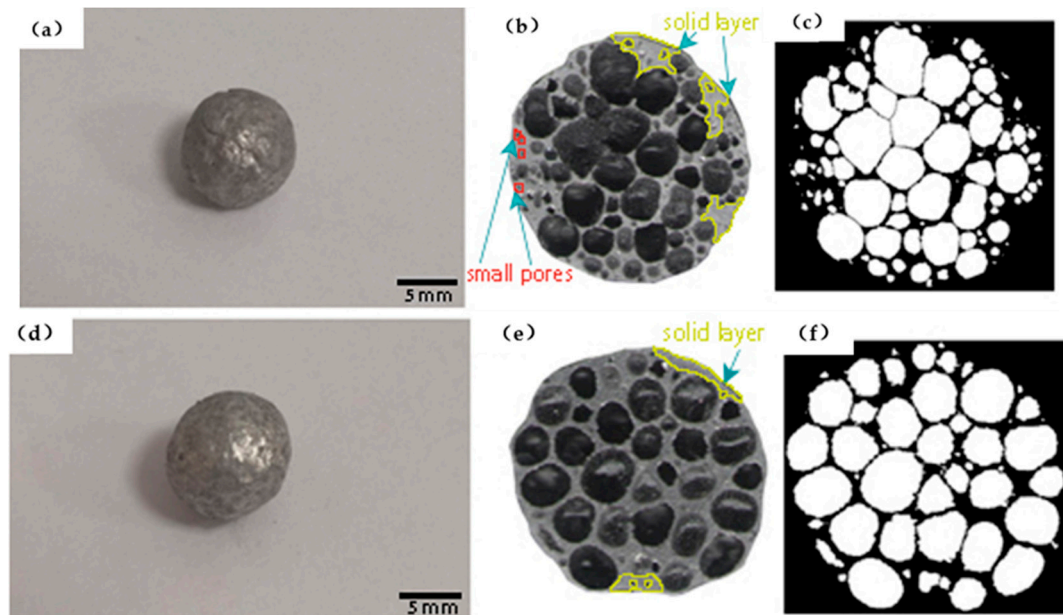


Figure 4. Aluminum foam spheres prepared with the hot extrusion (a–c) and hot rolling (d–f) methods and their cross-sectional pore structures.

The pore structure of aluminum foam was characterized by equivalent circular diameter D_i and circular degree C_i .

Equivalent circle diameter D_i refers to the corresponding diameter of a circle equal to the area A_i of the hole. The calculation formula is:

$$D_i = \sqrt{\frac{A_i}{\pi}} \times 2 \quad (2)$$

Figure 5 shows the comparison of the equivalent circle diameters of the holes of aluminum foam spheres prepared with different processes. The results show that the number of cross-sections of aluminum foam pellets prepared by the hot rolling method is concentrated in the cross-section of pores corresponding to a pore diameter of about 1.75, reflecting a smaller difference between the pore diameters of the hot rolling method, i.e., the pore structures of the pellets prepared with the hot rolling method were more uniform.

The curve of the spheres prepared by the hot extrusion method shows a humped curve with a sharp change in the short distance of concavity and convexity, and the number of holes in the cross-section of the spheres was similar, but the pore diameters varied widely, with most pore diameters distributed between 0.75 and 1.75, which led to an extremely uneven distribution of the overall pore cross-sections of the spheres.

Circularity C_i refers to the ratio between the circumference of the equivalent circle corresponding to each hole and the circumference of the actual hole L_i , calculated with the formula:

$$C_i = \frac{4\pi A_i}{L_i^2} \quad (3)$$

Through the ball cross-section to observe the pore diameter and hole roundness, aluminum foam internal pores are not spherical but close to an irregular polyhedral configuration, but for convenience in the calculation, it is still regarded as a certain diameter D

sphere. The closer the roundness of the hole was to 1, the closer the pores were to sphere roundness. Figure 6 shows a comparison of aluminum foam sphere pore roundness as prepared with different processes. The results show that the roundness curves of aluminum foam pores with the hot extrusion method were distributed between 0.45–0.85 and concentrated around 0.65. The curves of roundness of aluminum foam pores in balls prepared using the hot-rolling method were distributed between 0.55–0.85 and concentrated around 0.75. According to both curves, it is obvious that the roundness of aluminum foam prepared with the hot rolling method is better than that of the hot extrusion method, and the holes in the aluminum foam spheres prepared with the hot rolling method are closer to roundness.

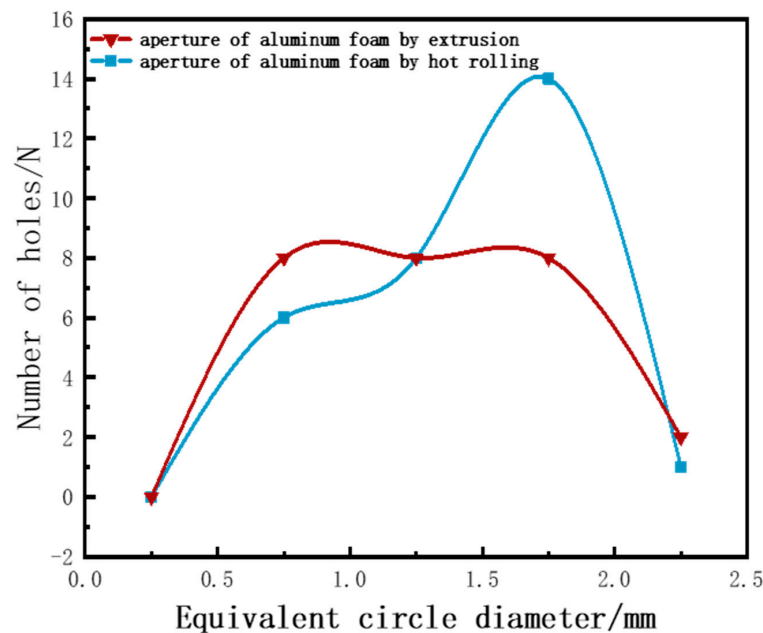


Figure 5. Aluminum foam pellet apertures prepared by different processes.

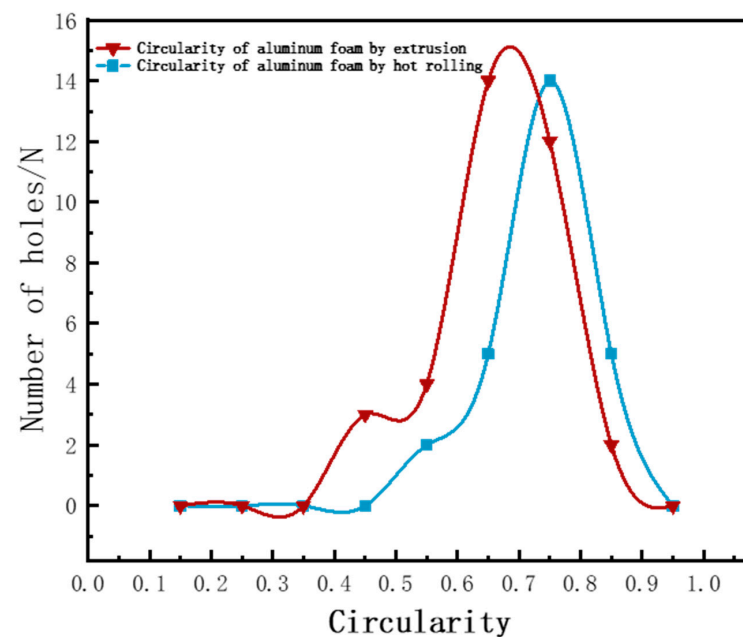


Figure 6. The roundness of aluminum foam ball holes prepared by different processes.

4. Foaming Process of Microsized Aluminum Foam

It was found that the formation process of the foamed aluminum balls can be divided into four stages: incubation period, foaming period, spherical retention period and deformation period. The four regions (a, b, c and d) are shown in Figure 7. The foaming process of the precursor is a process in which TiH_2 decomposes to form bubbles. Then, the bubbles grow and force the compacting precursor to expand. Whether the precursor can uniformly foam depends on the strength of the surrounding parent material, the hydrogen pressure generated by the decomposition of TiH_2 , and the additional pressure caused by the surface tension [32]. The pore size, porosity and distribution of the pores in aluminum foam are related to the properties of the precursor, that is, the preparation technology.

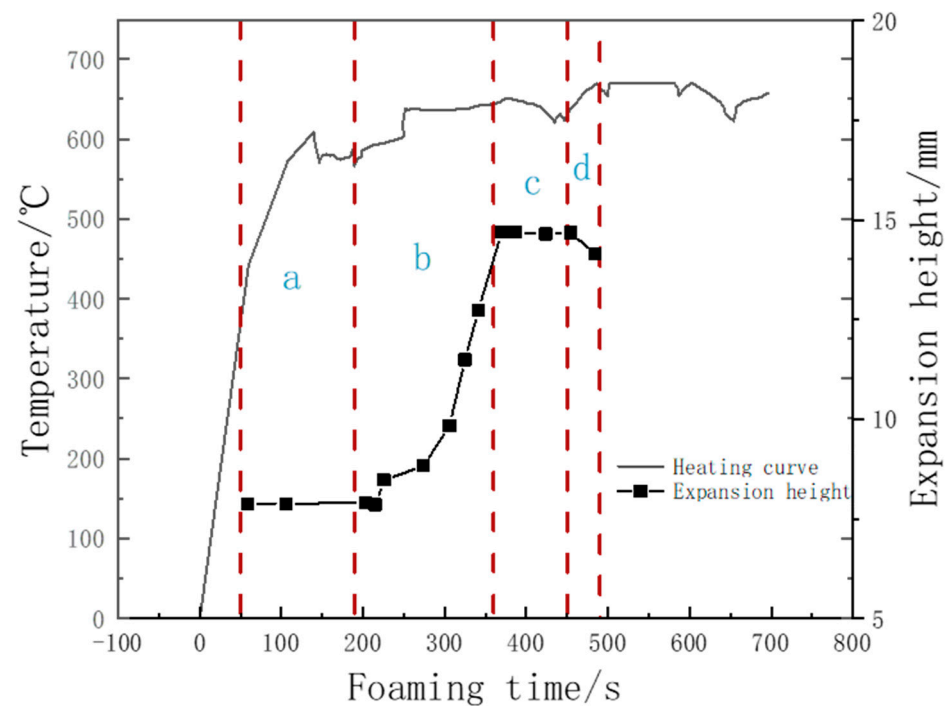


Figure 7. The expansion process of precursors.

4.1. Foaming Process of Microsized Aluminum Foam

Table 1 shows the macroscopic morphology of the hot-rolled precursors foamed for different periods at 700 °C furnace temperature and the evolution of the pore structure during foaming.

Table 1. The macroscopic morphologies and the evolution of pore structure of hot-rolled precursor foaming at 700 °C furnace temperature for different periods.






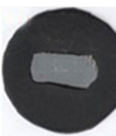




Foaming time	210 s	270 s	320 s	335 s	365 s
Foaming temperature	617.7 °C	662.2 °C	663.4 °C	666.3 °C	673.6 °C
Macroscopic morphologies					
Evolution of pore structure					

Table 1 shows that the precursor eventually formed a spherical aluminum foam after foaming in a semi-circular mold due to surface tension. At the initial heating stage, the strength of the aluminum alloy was still very high, the amount of foaming agent decomposition was small, and hydrogen is difficult to nucleate and grow; thus, the appearance of the prefabricated body did not expand significantly. With the increasing temperature of aluminum alloy, the hydrogen began to nucleate, and as time went by, hydrogen nucleation points increased and dispersed in the sample. With the extension of time, the viscosity of the aluminum melt decreased, the resistance of bubble growth decreased, a large amount of hydrogen was released, and the prefabricated body showed an obvious expansion process. Moreover, as the bubbles grew, the aluminum foam reached its maximum expansion point. If it is not cooled quickly, the bubbles cannot exist stably in the aluminum melt for a long time, and the bubble holes will burst and merge, resulting in the overall collapse of the aluminum foam.

4.2. Control of Pore Structure Homogenization

During the foaming process, the links that affect the shape and pore structure of aluminum foam include gas nucleation and gas diffusion, thinning and rupture of the liquid film and drainage caused by gravity.

When the gas core grows in liquid aluminum, it is affected by three forces: atmospheric pressure, static pressure and additional pressure caused by the surface tension of liquid aluminum. If the blowhole is to grow, the pressure inside the bubble needs to be greater than the external pressure. As in Equation (4).

$$P_B \geq P_{at} + P_{Al} + P_r = P_{at} + P_{Al}gh + 2\sigma_{LG}/r \quad (4)$$

Due to the small macroscopic size of micro-sized aluminum foam, the external forces' effect on pores of the same size at the bottom and top of the ball was small, so the pore structure was more uniform. As the temperature increased, the amount of hydrogen released by the decomposition of TiH_2 gradually increased, and the radius of the bubble also increased.

The decomposition of TiH_2 initially formed micron-scale spherical bubbles in the aluminum matrix. With the increase in temperature, many spherical bubbles gradually grew. The liquid phase between bubbles was expelled due to the action of gravity, and the liquid phase between bubbles became thinner. Finally, the bubbles increased, and only a thin liquid film was left between the bubbles. Due to the constraint of the liquid film, the bubbles could not move freely, and the spherical foam tended to be transformed into polyhedral foam. Because the precursor foams were in a spherical mold and the foaming time was very short, there was not enough time and space to minimize its surface energy. By controlling the content of the foaming agent in aluminum foam, the pores in aluminum foam could not maximally fill the space, and the spherical pore structure was finally obtained.

During the foaming process, the aluminum liquid flowed down and drained along the channel formed by the bubble wall and the Brad boundary under gravity. The drainage can be reduced in two ways: (1) reduce foaming time so that the drainage can occur too late or in a small amount; (2) inhibit the rupture of the pore wall and reduce the growth of bubbles.

Due to the small volume of its precursor and the fast expansion process, the stomatal expansion overcame the downward flow of liquid metal caused by gravity and reduced the liquid drainage phenomenon. The distribution of TiH_2 powder in the hot-rolled precursor was more uniform; thus, the hydrogen generated after decomposition was attached to the in situ Ti particles to form gas nuclei, resulting in the uniform distribution of gas nuclei. The precursor obtained by hot rolling was dense, and there was no crack on the surface during the foaming process, reducing the rate of hydrogen escape. At the same time, due to the high internal compactness, the pressure of pores in the growing process was uniform,

grew in situ and reduced the merging of pores. These factors led to a more uniform pore structure in micro-sized aluminum foams.

5. Conclusions

This paper focuses on the effects of hot extrusion and hot rolling processes on the organization and internal pore morphology of reinforced APM aluminum foam, and by observing the macroscopic and microscopic structures, the following conclusions were drawn:

1. It is known from foaming experiments that high-density precursors were obtained by using the hot rolling process, and micro-sized foamed aluminum with a more rounded and uniform pore structure was obtained after foaming in a spherical mold.
2. Closed-cell aluminum foam has a certain rolling capacity. Aluminum foam containing a 12% Si mass fraction was rolled with a rolling force of 30 t and a rolling speed of 3.00 mm/s. The rolled part completed three passes of rolling deformation to obtain a sheet preform of 3 mm thickness.
3. The density of precursors and the pore structure of foams differ with different preparation methods. There were micropores among the powder particles of the hot extrusion precursor, and the pores formed by foaming were not evenly distributed, with an obvious solid layer. The higher density of the hot rolling precursor caused metallurgical bonding between powder particles and the more uniform distribution of the foaming agent, resulting in the formation of a more uniform pore structure after foaming.

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