

Research Paper

A Review of Powder Metallurgy Techniques for the Production of Aluminium Foams

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Abstract

Lightweight cellular materials with low density and appealing mechanical, thermal, acoustic, and energy-absorption qualities are known as aluminium foams. The presence of regulated pores in an aluminium or aluminium-alloy matrix gives them their distinctive qualities. Because it offers significant control over porosity, pore size, pore morphology, composition, and overall cellular architecture, powder metallurgy has become a significant technique among the various manufacturing methods. The two main methods used in powder metallurgy are space-holder techniques for creating open-cell structures and precursor foaming utilizing blowing agents. Aluminium powder and a gas-releasing agent—typically titanium hydride (TiH_2)—are combined, compressed into a dense precursor, then heated to create controlled expansion in precursor foaming. In space-holder processing, a porous metallic skeleton is created by blending aluminium powder with transient particles that are eliminated following compression and sintering. With a focus on precursor foaming, space-holder processing, sintering-dissolution techniques, processing parameters, pore formation, mechanical properties, benefits, drawbacks, and possible applications; this review explores the fundamentals of powder-metallurgy processing of aluminium foams. Foam structure and performance are examined in relation to powder properties, compaction pressure, sintering conditions, blowing-agent concentration, and space-holder features. Although issues with oxidation, pore homogeneity, processing cost, scalability, and reproducibility still exist, the review shows that powder metallurgy offers an efficient method for creating application-specific aluminium foams. Sustainable processing, functionally graded structures, enhanced characterisation, computational optimization, and scalable production should be the main areas of future development.

Keywords: Aluminium foam; powder metallurgy; space-holder technique; precursor foaming; titanium hydride; porous aluminium; cellular materials; energy absorption.

1. Introduction

Metallic cellular materials have attracted a lot of attention due to the growing need for lightweight and multipurpose engineering materials. Because they combine the useful qualities produced by a cellular structure with the low density and corrosion resistance of

aluminium, aluminium foams are very appealing. Aluminium foams can offer high specific stiffness, energy absorption, vibration damping, acoustic absorption, thermal management, and fluid permeability, depending on their pore architecture. These qualities make them promising materials for technical applications in the automobile, aircraft, railroad, construction, defense, and thermal management industries.

The metallic matrix's relative density, pore size, shape, distribution, cell-wall thickness, and connection all affect aluminium foam's performance in addition to its chemical makeup. As a result, manufacturing technology is crucial in establishing the material's final characteristics. Liquid-metal, solid-state, powder-metallurgy, infiltration, casting, and additive manufacturing processes can all be used to create aluminium foams. Among these, powder metallurgy has drawn a lot of interest since it allows for the integration of alloying elements, reinforcements, and temporary pore-forming materials and provides rather good control over the cellular structure.

Powder mixing, compaction, thermal treatment, and, depending on the method used, foaming or removal of a transitory phase are all common steps in powder metallurgy. For the manufacture of aluminium foam, two key strategies are especially crucial. The first is precursor foaming, which involves compacting aluminium powder into a dense precursor, mixing it with a blowing agent like titanium hydride, and heating it until expansion is caused by gas evolution. The second is the space-holder method, which involves combining aluminium powder with a substance that can be removed. An open-cell aluminium foam is created by removing the space holder following consolidation and the proper heat treatment.

This review's goal is to provide a succinct evaluation of the main powder-metallurgy methods used to make aluminium foams, together with information on their processing principles, regulating factors, characteristics, benefits, drawbacks, and potential future research areas.

2. Powder Metallurgy Routes for Aluminium Foam Production

2.1 Precursor Foaming Technique

One of the most well-known powder-metallurgy processes for producing aluminium foams is precursor foaming. This method involves combining powdered aluminium or aluminium-alloy with a tiny amount of a blowing agent, most frequently titanium hydride (TiH_2). Pressing, extrusion, or similar high-density method is used to consolidate the mixture to create a relatively dense precursor. TiH_2 breaks down and releases hydrogen when heated further. The gas expands and creates pores when the aluminium matrix is sufficiently pliable. Eventually, a cellular structure emerges from the growing precursor. The blowing agent's quantity and distribution, precursor density, heating rate, foaming temperature, matrix viscosity, and chilling conditions all affect the final pore morphology.

The capacity of precursor foaming to create lightweight closed-cell structures with comparatively high expansion ratios is its main benefit. However, proper synchronization between matrix softening and gas development is necessary for successful processing. While excessive gas evolution can lead to non-uniform pores and cell-wall rupture, premature gas release can result in gas loss. The concentration of titanium hydride is especially crucial. The amount of gas accessible for expansion usually increases as its concentration rises, although high concentrations can cause foam collapse, wide holes, pore coalescence, and surface

flaws. As a result, the blowing-agent content needs to be tailored to the specific alloy and processing circumstances.

2.2 Space-Holder Technique

The space-holder method works especially well for making aluminium foams with open cells. Particles of a transitory substance known as a space holder are combined with aluminium powder. The volume that will eventually form the pore network is occupied by the space holder. The transient particles are eliminated by dissolving, evaporation, or thermal degradation following compaction and sintering. The capacity to directly alter pore size and porosity is this method's most significant advantage. The volume percentage of the space holder regulates the total porosity, while the size of the space-holder particles generally dictates the pore size. Additionally, the space-holder particles' morphology is transferred to the pores. Sodium chloride, carbamide, ammonium bicarbonate, sucrose, starch-based compounds, and polymeric particles are frequently studied space-holder materials. The inexpensive cost and great water solubility of sodium chloride make it appealing. Because carbamide can be broken down into pretty regular particles and then dissolved, it has also drawn a lot of study.

2.3 Sintering-Dissolution Processing

One type of space-holder processing that has been extensively researched is sintering-dissolution. After mixing and compacting aluminium powder with a soluble space holder, the aluminium phase is sintered. The space holder is then dissolved, usually with water when a water-soluble substance like carbamide or sodium chloride is used. The technique offers significant control over the form and amount of pores. However, before removing the space-holder, there must be enough bonding between the aluminium particles. While too much sintering can lead to unwanted densification or partial pore closure, insufficient sintering can result in brittle cell walls. It is also crucial to remove the space holder completely. Mechanical dependability may be negatively impacted by residual salt or other impurities that lower corrosion resistance. Washing, drying, and post-treatment are therefore crucial steps in the procedure.

Table 1. Major Powder-Metallurgy Techniques for Aluminium Foams

Technique	Main principle	Typical structure	Major advantage	Major limitation
Precursor foaming	Gas release from TiH_2 during heating	Mainly closed-cell	High expansion and lightweight structures	Difficult control of pore uniformity
Space-holder method	Removal of temporary particles	Open-cell	Direct pore-size control	Space-holder removal required
Sintering-dissolution	Sintering followed by dissolution	Open-cell	High porosity and controlled pores	Time-consuming post-processing

Technique	Main principle	Typical structure	Major advantage	Major limitation
Dissolution-sintering	Space-holder removal before final sintering	Open-cell	Flexible processing sequence	Green skeleton may be fragile
Hybrid powder metallurgy	Combination of foaming, spacers and reinforcement	Tailored	Potential multifunctional performance	Greater processing complexity

3. Important Processing Parameters

The parameters utilized during powder preparation, compaction, thermal treatment, and pore formation have a significant impact on the ultimate properties of aluminium foams.

3.1 Aluminium Powder Characteristics

Powder packing, compaction, sintering, and final foam strength are all influenced by particle size, morphology, purity, oxide concentration, and particle-size distribution. Although they can facilitate sintering and offer more surface area, fine powders are more prone to oxidation. Although they may result in less homogenous structures, coarser particles may lessen oxidation effects. Because a stable oxide layer covers every particle, aluminium powder is very difficult. During sintering, this oxide layer may prevent interparticle bonding. Although total removal is challenging, mechanical compaction may fracture some of the oxide layer and enhance metallic contact. As a result, the manufacturing environment and powder properties need to be carefully regulated.

3.2 Compaction Pressure

The precursor or space-holder compact's strength and green density are regulated by compaction pressure. In general, higher pressure decreases unwanted residual porosity and enhances particle interaction. On the other hand, too much pressure might change the intended pore structure by fracturing or deforming space-holder particles. The ideal compaction pressure for space-holder processing is determined by the required porosity, particle size, space-holder type, and powder shape. As a result, stated experimental values ought to be regarded as material-specific rather than general.

3.3 Sintering Temperature and Time

Sintering determines the strength of the aluminium skeleton. Insufficient sintering results in weak interparticle bonding, while excessive temperature or holding time can promote excessive densification, dimensional distortion, or pore closure. The optimum thermal cycle must therefore provide adequate metallurgical bonding without significantly changing the desired cellular architecture. Furnace atmosphere and heating rate can also influence oxide behavior and pore evolution.

3.4 Space-Holder Characteristics

Pore morphology is directly impacted by the space holder's size, shape, volume percentage, and distribution. While larger pores are typically produced by increasing particle size, porosity is increased by increasing space-holder content. While irregular particles form more angular and complicated structures, spherical space holders typically produce more regular pores. The thickness and mechanical stability of the metallic skeleton might be considerably diminished by extremely high porosity. Space-holder composition must therefore be optimized in accordance with the necessary blend of mechanical strength and lightweight qualities.

3.5 Foaming Temperature and Blowing-Agent Content

Temperature must be carefully chosen for precursor foaming such that gas production takes place while the aluminium matrix has enough deformability. Gas may escape from the precursor if it is released before the matrix can expand. Cell walls may become fragile and collapse if the matrix becomes excessively fluid. Pore formation and gas development are influenced by the quantity and size of TiH_2 particles. For consistent foaming, the blowing agent must be evenly distributed throughout the aluminium powder.

4. Structure and Properties of Aluminium Foams

The cellular structure of aluminium foam strongly determines its properties. Relative density is one of the most important parameters and is expressed as:

$$[\bar{\rho} = \frac{\rho_f}{\rho_s}]$$

where (ρ_f) is the density of the foam and (ρ_s) is the density of the fully dense aluminium matrix.

Porosity can be expressed as:

$$[P = \left(1 - \frac{\rho_f}{\rho_s}\right) \times 100]$$

The amount of load-bearing aluminium reduces as porosity rises. As a result, stiffness and compressive strength typically decline. Higher porosity, however, results in more mass reduction and can enhance the material's capacity to absorb specific energy. Aluminium foams typically exhibit three distinct stages under compression: a densification zone, a reasonably stable collapse or plateau region, and an early elastic region. Because significant deformation can occur without a correspondingly big increase in stress, the plateau region is very crucial for impact and crash-energy absorption. Pore morphology is equally significant. In general, very irregular holes with sharp corners or narrow struts are less effective in distributing stress than uniform and moderately spherical pores. Premature failure may result from large flaws and uneven pore distributions. As a result, average porosity is not enough to assess the quality of foam.

5. Applications of Powder-Metallurgy Aluminium Foams

Aluminium foams now have prospects in a number of engineering fields due to their low density and multipurpose qualities. Aluminium foams can be used in the automotive sector for sandwich panels, impact-resistant parts, crash absorbers, and lightweight structural components. They can disperse impact energy while retaining low structural mass thanks to their energy-absorption capacity. Because reduced structural mass can lead to increased energy efficiency, weight reduction is especially beneficial in railroad and aeronautical applications. Additionally, aluminium foam cores can offer helpful stiffness-to-weight ratios. Because their interconnected pores offer a large surface area for fluid-solid heat transfer, open-cell aluminium foams have additional uses in heat exchangers and thermal management systems. They are also helpful for filtering and fluid-flow applications due to their permeability.

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6. Advantages and Limitations

Compared to traditional aluminium-foam manufacturing techniques, powder metallurgy has a number of advantages. Alloying and reinforcing phases can be included, porosity and pore shape can be controlled reasonably precisely, and intricate cellular structures can be created. When creating open-cell materials with predefined pore properties, the space-holder technique is especially beneficial. Aluminium powders' vulnerability to oxidation, insufficient interparticle bonding, processing expenses, comparatively complicated post-processing, and challenges in attaining consistent porosity over large components are the main drawbacks. It may take a long time and thermal or water treatment to remove the transitory phase in space-holder processing. Controlling gas release and foam stability in precursor foaming is still difficult. Reproducibility is a significant additional constraint. Significant variations in the final structure and mechanical performance can result from variations in powder particle size, space-holder distribution, compaction pressure, heating rate, and sintering conditions. Standardized characterisation and dependable process control are consequently crucial for industrial use.

7. Future Research Directions

Future studies should concentrate on creating powder-metallurgy processes that are more affordable, sustainable, and scalable. Closed-loop dissolving systems and recyclable space holders could lessen the impact on the environment. Process uniformity could be raised by automated compaction and better powder management. Another potential approach is the use of functionally graded aluminium foams. The pore structure could be altered in accordance with local mechanical or thermal requirements rather than keeping a component's porosity

constant throughout. High strength in load-bearing areas and high energy absorption in impact zones could be provided by such structures.

Three-dimensional data on pore shape, connectivity, and flaws can be obtained using sophisticated characterisation methods like X-ray computed tomography. Combining these observations with machine learning and finite-element modeling techniques may enhance foam behavior prediction and speed up process optimization. Mechanical performance may be further enhanced by hybrid powder-metallurgy processes that use ceramic particles, carbon-based reinforcements, alloying additives, and regulated pore topologies. The fabrication of intricately structured cellular architectures that are challenging to achieve by traditional particle packing may also be made possible by integration with additive manufacturing.

8. Conclusion

A very promising method for creating lightweight aluminium foams with regulated cellular architectures is powder metallurgy. Precursor foaming and space-holder processing are the main methods. While space-holder and sintering-dissolution techniques offer great possibilities for developing open-cell foams with regulated pore size and porosity, precursor foaming—especially with titanium hydride—is efficient for creating lightweight closed-cell structures. Aluminium powder properties, oxide-film behavior, compaction pressure, sintering circumstances, blowing-agent concentration, space-holder morphology, and thermal processing all have a significant impact on the final foam qualities. Powder metallurgy's main benefit is its capacity to modify cellular design in accordance with application needs. Low density, compressive strength, energy absorption, thermal performance, acoustic damping, and permeability can all be attractively combined in aluminium foams made using these methods. These characteristics make them promising for advanced applications in the automotive, aircraft, railroad, thermal-management, acoustic, and structural industries.

However, there are still many obstacles to overcome, especially in the areas of oxide-layer effects, pore homogeneity, residual space-holder contamination, manufacturing cost, scalability, and process reproducibility. Thus, sustainable processing, functionally graded structures, sophisticated three-dimensional characterisation, computational modeling, hybrid reinforcement techniques, and industrial-scale process management should be the focus of future study. Powder-metallurgy aluminium foams have a great deal of promise to grow into significant lightweight, multipurpose materials for next-generation engineering applications.

References

1. Ashby, M. F., Evans, A. G., Fleck, N. A., Gibson, L. J., Hutchinson, J. W., & Wadley, H. N. G. (2000). *Metal Foams: A Design Guide*. Butterworth-Heinemann, Oxford.
2. Banhart, J. (2000). Manufacturing routes for metallic foams. *JOM*, 52, 22–27.
3. Degischer, H. P., & Kriszt, B. (Eds.). (2002). *Handbook of Cellular Metals: Production, Processing, Applications*. Wiley-VCH.
4. Gutiérrez-Vázquez, J. A., & Oñoro, J. (2008). Aluminium foams: Manufacture, properties and applications. *Revista de Metalurgia*, 44.
5. Duarte, I., & Oliveira, M. (2009). Influence of processing parameters on aluminium foam produced by space holder technique. *Materials & Design*, 30, 1878–1885.

6. Duarte, I., & Oliveira, M. (2010). Production of aluminum foam by spherical carbamide space-holder technique—Processing parameters. *Materials & Design*, 31, 4122–4129.
7. Singh, S., & Bhatnagar, N. (2018). A survey of fabrication and application of metallic foams. *Journal of Porous Materials*, 25, 537–554.
8. Madgule, M., Sreenivasa, C. G., & Borgaonkar, A. V. (2023). Aluminium metal foam production methods, properties and applications—A review. *Materials Today: Proceedings*, 77, 673–679.
9. Basanth Kumar, K., Ingole, S. B., Saeedjassim, A., Gori, Y., Kaushik, A., Kumar, D., & Jain, A. (2023). Aluminum-foam by powder metallurgy: A review. *Materials Today: Proceedings*.
10. Nawaz, A., & Rani, S. (2023). Fabrication methods and property analysis of metal foams—A technical overview. *Materials Science and Technology*, 39, 1877–1902.