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REVIEW OF MECHANICAL PROPERTIES, MANUFACTURING, AND APPLICATIONS OF METAL FOAMS

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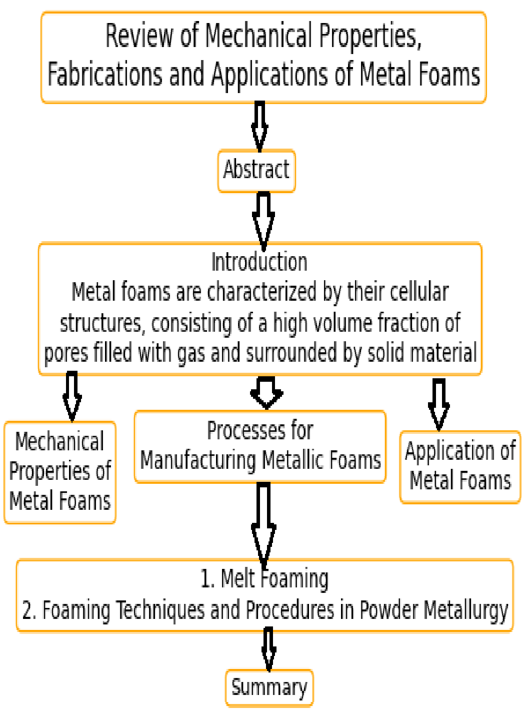
Graphical abstract



Abstract

This review offers a comprehensive overview of the mechanical properties of metal foams and their various applications. It provides a detailed examination of the production techniques used in the manufacturing of metal foams and assesses the challenges encountered in the fabrication process. Metal foams, with their low weight, rigidity, exceptional compressive strength, and energy absorption capabilities, have found applications in a wide range of engineering fields. The manufacturing techniques for metal foams vary, including liquid state, solid state, and ion or vapor processing, each presenting distinct advantages and limitations that influence the properties of the final foam product. A thorough understanding of these processes and their effects on the mechanical characteristics of the foams is crucial for optimizing their application across various industries. The review also addresses the challenges associated with metal foam fabrication, such as the control of pore size and distribution and the high costs of production. Advanced techniques like 3D printing are proposed. The paper emphasizes the importance of interdisciplinary collaboration to overcome existing challenges and unlock new possibilities in metal foam technology across various industries as potential solutions to enhance precision and reduce waste. The paper emphasizes the critical need for interdisciplinary collaboration bringing together expertise from materials science, manufacturing technologies, and computational modeling to effectively overcome current challenges and unlock new possibilities in metal foam technology across various industries.

Keywords: Metal foam, lightweight material, composite, mechanical properties

1.0 INTRODUCTION

Mineral foams are characterized by their cellular structures, consisting of a high volume fraction of pores filled with gas and surrounded by solid material. The distinct mechanical and physical properties of mineral foams are a result of their cellular structure. Their exceptional properties make them well-suited for various of engineering uses, including sound and vibration dampening, sandwich panel construction, thermal insulation, fire resistance, and explosion-proof components [1, 2].

As a result, there has been a growing interest in these materials over the past few years. One of the remarkable aspects of foams is their ability to vary properties such as geometry, pore size, density, and material choice. When utilized for energy absorption, these foams can endure substantial deformations under prolonged pressure and strain [3].

In addition, metal foams are easily recyclable, with no disposal problems [4]. Metalfoams exhibit outstanding properties , including being lightweight, possessing high compressive strength, having a lower specific weight, being highly stiff, and showing excellent energy absorption capabilities [5]. They have unique advantages like electrical conductivity and mechanical properties, making them suitable for various applications in fields such as wearable electronics, automotive, aerospace, and acoustic and electromagnetic shielding [6].

Metal foams combine the properties of metallic materials with the properties of porous materials. These properties render them highly suitable for aerospace applications, where multifunctional lightweight materials are essential [7].

Metal foams can be produced through various manufacturing processes, including liquid state, solid state, and ion or vapor processing, each with its advantages and limitations [8]. Metal foams can also be used as enhanced surfaces in heat exchangers, providing significant benefits in terms of heat transfer performance and compactness [9].

Overall, the advantages of metal foams lie in their unique properties and their potential for diverse applications in different industries. These materials enhance fuel efficiency and are able to resist the forces exerted by collisions because of their high energy absorption capacity, which is important for achieving superior performance and providing effective protection [10, 11]. Mineral foams are suitable for structurally and functionally diverse realms due to their good mechanical , acoustic, thermal, electrical, and chemical properties. Through a combination of these properties, mineral foams are an excellent choice for many uses in different fields, including engineering, manufacturing, construction, aviation, aerospace, energy, and more. These properties allow it to play a vital role in achieving the required performance and meeting the diverse needs of different industrial and technical applications [11, 12]. Mineral foams are typically produced by incorporating foaming agents or space carriers into the mineral matrix. Various methods are employed to create these foams, such as introducing a foaming agent during the dissolution of the liquid phase, compacting metal powder with a blowing agent, and injecting gas to induce foaming [13, 14, 15]. These foams consist of porous structures made of metals like aluminum, nickel, magnesium, copper, zinc, and steel. They can be produced using methods such as melt foam, gas injection foam, and porous molding. Mineral foams are used in diverse applications.Their properties can be enhanced by adding small ceramic parts to improve hardness and flexibility while maintaining lightness [13, 16–23].

Metal foams are developed mainly by adding foaming agents or space carriers into the metal matrix. Methods include adding foaming agents as the liquid material dissolves, compressing the metal powder with blowing agents, and blowing the gas into the mixture[24–25].

This review focuses on the manufacturing methods, mechanical properties, and applications of metal foams. The evaluation of these characteristics (properties) through various techniques is crucial for determining optimal approaches to production and understanding the results of various parameters on mechanical properties and strength. This review was divided into three sections:

- Mechanical Properties: This section discusses the mechanical properties of metal foams, emphasizing elasticity, strength, and durability. Special attention is paid to how these properties vary based on the manufacturing technique employed.
- Manufacturing Methods: The second section highlights key manufacturing methods for metal foams and how these methods influence the foam's properties . Techniques such as powder metallurgy, liquid infiltration, and precursor-based methods are explored in detail.
- Applications: The final section explores the diverse applications of metal foams across different industries. Examples include their use in automotive crash structures, aerospace components, and thermal insulation.

The objective of this review is to systematically examine the manufacturing methods, mechanical properties, and various applications of metal foams. Emphasis is placed on understanding how different production techniques influence the structural and functional characteristics of metal foams, with the aim of identifying the most effective approaches for their use in engineering applications. Additionally, the review seeks to address the challenges associated with metal foam production and explore potential advancements in the field

2.0 MECHANICAL PROPERTIES OF METAL FOAMS

Mineral foams have unique mechanical features such as low density, high stiffness, and excellent energy absorption capabilities. Their cytoskeleton is crucial in determining their mechanical behavior, as parameters such as cell size and shape greatly influence their properties. In general, metal foams are versatile materials and possess a diverse array of mechanical properties that permit their use in a wide range of engineering applications [26–29]. The compressive strength and energy absorption characteristics of metal foams are influenced by their cellular architecture, porosity, and relative density. According to Table 1 and Figure 1 (a) shows the stress-strain relationship for metal foams with different porosity levels (50%, 60%, 70%). It is clear that the plateau stress is highest at the porosity level of 50%, and decreases as the porosity increases to 60% and 70%. it can be noted too in Ffigure 1 (b) that mineral foams with low porosity (50%) tend to be more effective in absorbing energy than foams with higher porosity. This is due to the denser structure and fewer voids, which allows for greater energy absorption under compression. This indicates that the choice of porosity depends on the required application; if the ability to absorb energy is important, then low porosity will be the best choice. However, if the goal is to reduce weight, then higher porosity may be more suitable, although it comes at the expense of lower energy absorption [27, 28, 30–32]. The porosity ratio of metallic materials has a significant impact on their mechanical behavior and properties.

Table 1 Describing the mechanical characteristics of metal foams at different levels of porosity and under strain rate 0.01/s

Foam type	Porosity	Energy Absorption (Mj/m^3)	Plateau Stress (Mpa)	Ref
Al foam	50	20.9	29.5	[30]
	60	13.5	18.8	
	70	6.6	9.9	
Ti foam	68	120	100	[32]
	57	160	180	
	46	220	260	
Ti foam	80	--	12.55	[28]
	78	--	15.42	
	76	--	15.84	
	74	--	21.61	
	72.4	--	25.43	
	70	--	27.97	
	66.6	**--**	**30.76**	

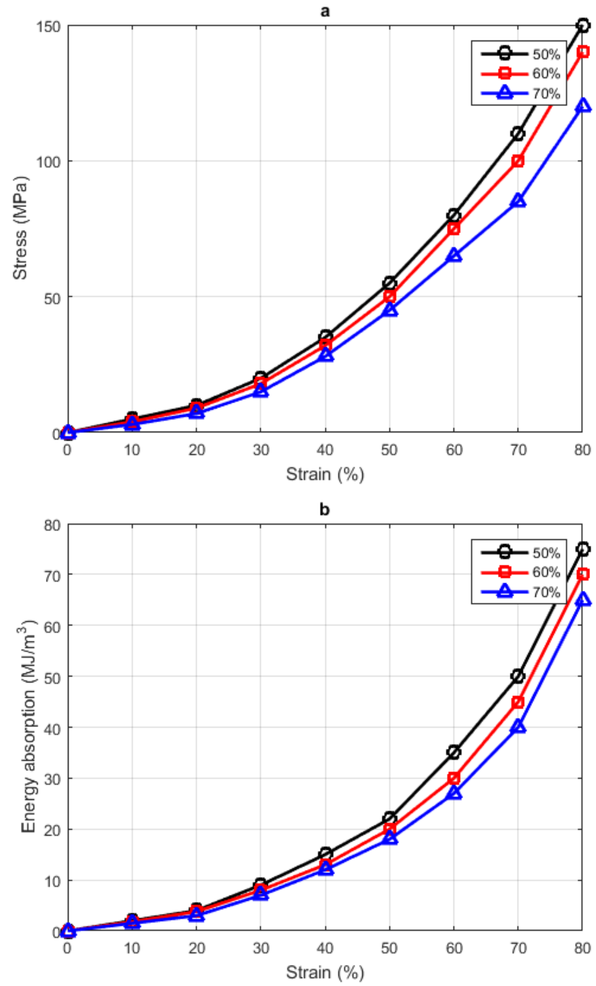


Figure 1 (a) Stress-strain diagrams for aluminum foams; (b) Energy absorption curves for aluminum foams at different porosity levels [30]

Previous studies indicate that compressive strength is significantly affected by the properties of mineral foams, particularly pore size. Research has also demonstrated that adding TiB2 particles to lead-based foams significantly enhances the overall strength of the foams while also increasing their energy absorption capacity [33–35].

Research suggests that high porosity values may reduce the ability of foams to absorb energy. For example, a study found that increasing the porosity in an AlCu5Mn alloy from 45.8% to 91.2% reduces the ability of foams to absorb energy, falling from 72.22 MJ to 2.70 MJ. In addition, studies indicate that increased porosity in TiNi foams causes an ongoing decrease in the elastic properties and compressive strength of the Foam [32]. The Research investigated how porosity impacts the compressive strength of TiNi foams, finding that higher porosity results in a consistent reduction in both the compressive strength and elastic modulus of the foams. Another investigation noted a decline in densification strain as foam density increased, alongside uniform deformation, stress, and strain hardening. The compressive strength of powdery foams was found to correlate with both the volume fraction of fibers glass and the fraction of porosity. Composite foams were found to have higher compressive strength than pure foams, with stress-strain curves in the densification phase showing dependence on strain rate at high-pressure levels. [36–38]

Studies suggest that reinforcements and well-defined pore structures are closely associated with an increase in compressive strength. For instance, closed-cell aluminum alloy foams with enhanced compressive strength were developed using additives such as TiB_2 [39]. Additionally, Mg–Al–Zn alloy foams were prepared via a gas-fired technique using the powder metallurgy method, which resulted in improved compressive properties [40]. Similarly, Mg–X foams produced via the gas-fired technique exhibit an improved cellular structure, contributing to enhanced mechanical properties [41]. In another study, the addition of scandium to aluminum foams was found to positively affect mechanical properties [42]. Al-3.7% Si-0.18% Mg foam was also reinforced with Aluminum Nitride (AlN) particles, leading to an increase in compressive strength [44]. Another study indicated that reinforcing Al-Cu-Fe foams with semi-crystalline particles improved both mechanical and microstructural properties [45]. Moreover, Zn–Mg foams produced via gas release technology showed significant improvements in compressive properties [47]. Finally, research suggests that zinc content plays a crucial role in determining the properties of closed-cell aluminum foams [48].

Mathematical models developed by Gibson and Ashby was used to forecast the mechanical characteristics of metal foam [49]. These models establish correlations between relative stress and relative density and ascertain crucial parameters such as elastic modulus (E_f/E_s) and plateau stress (at yield point) of the metal foam [50–51].

$$\sigma_{pl} = \sigma_{ys} C \rho_{rel}^{3/2} \text{ (open cell)} \quad (1)$$

$$\frac{E_f}{E_s} = \rho_{rel}^2 \text{ (open cell)} \quad (2)$$

$$\sigma_{pl} = \sigma_{ys} C \rho_{rel}^2 \text{ (closed cell)} \quad (3)$$

Where σ_{pl} (Plateau stress), σ_{ys} (Yield stress of the solid material), C (constant related to the material's structure), ρ_{rel} (Relative density = density of the foam divided by the density of the solid material) ,E_f (Elastic modulus of the foam), E_s (Elastic modulus of the solid material)

Jain *et al.* [52] conducted a study on foam made of austenitic stainless steel, examining its compressive behavior across different relative densities and varying compressive strain rates. Their analysis identified three distinct regions on the stress-strain curves: elastic, plateau, and dense. They compared the elastic modulus and compressive yield stress obtained from their experiments with predictions made by the Gibson-Ashby model, finding a strong agreement between the two. Notably, they observed that the shape factor for yield stress varied with strain rate, becoming more significant as shown in Figure 2, the strain rate increased. Similarly, the shape factor for the elastic modulus showed a clear relationship with the strain rate, demonstrating the model's ability to predict these trends accurately.

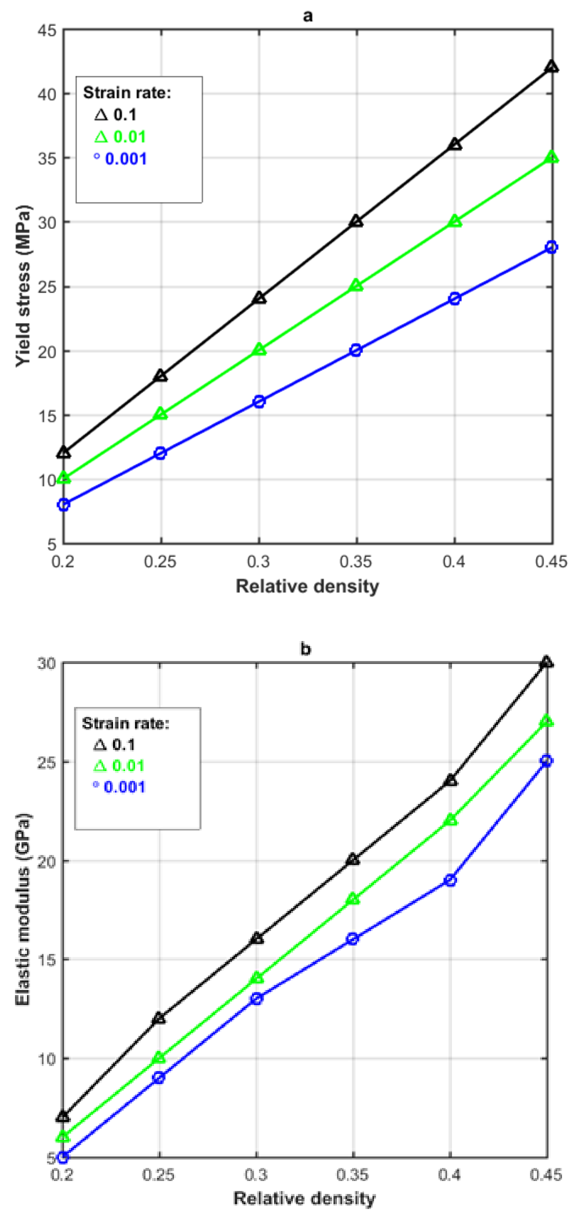


Figure 2 (a) Stress at the yield point and (b) modulus of elasticity as functions of relative density at different strain levels [52]

Yield strength and plateau stress are significantly influenced by relative density [52]. Oktay and Bekoz [54] investigated steel foam manufacturing using various carbamide particle shapes. They compared the compressive strengths (yield strengths) of these steel foams with modulus predictions from the Gibson-Ashby model, as shown in Figure 8c. Their study revealed that at lower relative densities, the compressive yield stress was lower than the model's predictions. They found that the proportion of total stiffness and strength attributable to cell face stretching increased linearly with relative density, while cell edge bending contributed in a nonlinear manner. Additionally, Ally's study [55], also depicted in Figure 3, showed that the compressive stress (at the yield point) is impacted by the relative density. Foams with pores (spherical shape) demonstrated superior performance due to their smoother cell wall surfaces, whereas the presence of sharp edges in irregular pores caused stress concentrations, and as a result, strength was diminished.

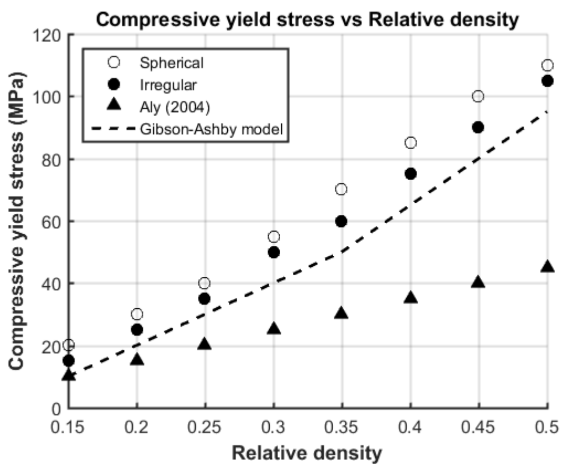


Figure 3 Comparison of the density and compressive yield stress of Fe–1.5% Mo steel foams [55]

As per the model proposed by Gibson-Ashby, the post-collapse behavior and plateau stress vary depending on whether the foam has a closed cell or open structure. Moreover, Mo, Oktay, and Bekoz [56] learned that the compressive strengths (stress at yield point) of Ni-Cu-Mo steel foams were lower than what the Gibson-Ashby models had predicted, especially at low relative densities, as shown in Figure 4.

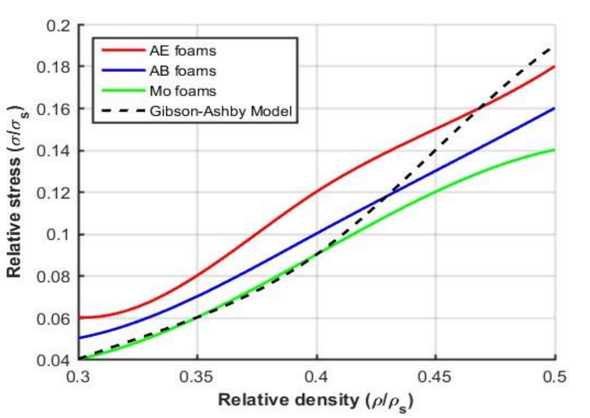


Figure 4 Relationship between relative density and relative stress of the foams (steel) [57]

3.0 PROCESSES FOR MANUFACTURING METALLIC FOAMS

Metal foam synthesis can vary depending on the desired characteristics of the foam. Below are some of the methods commonly employed for preparing metal foams:

3.1 Melt Foaming

A number of factors, one of which is the foam's composition, affect its quality, the degree of temperature during the forming process, cooling conditions, the duration of holding, distribution, as well as the size and volume fraction of reinforced foam-stabilizing particles like Al_2O_3 or SiC [58–60]. A graphite crucible is typically used in the foaming process to melt a composite powder mixture in an electric resistance furnace. This process can be categorized into:

3.1.1 Melt Gas Injection Method

Kirkevag and Ruch initially patented the concept of gas injection in 1991 [61], which was subsequently further patented and refined by Jin *et al.* in 1992 [62]. In this process, aluminum and other reinforcing particles such as alumina, SiC, zirconia, titanium diboride, and magnesium oxide are melted together. By injecting gas (air, nitrogen, or argon) directly into the melt using rotating impellers, fine bubbles are generated and move through the molten material. These reinforcing particles make up 10 to 20% of the volume, with particle sizes ranging from 5 to 20 µm [63].

According to Kenny *et al.* [64, 65], there is an inverse relationship between the average cell wall thickness and the average cell size. The control of foam density can be achieved by adjusting various parameters and regulating the gas flow rate at the nozzle. This method is illustrated in Figure 5.

Over the years, various methods have been developed to produce closed-cell aluminum foams. These methods include techniques such as inducing foaming in a melt (liquid) through the use of foaming agents [66].

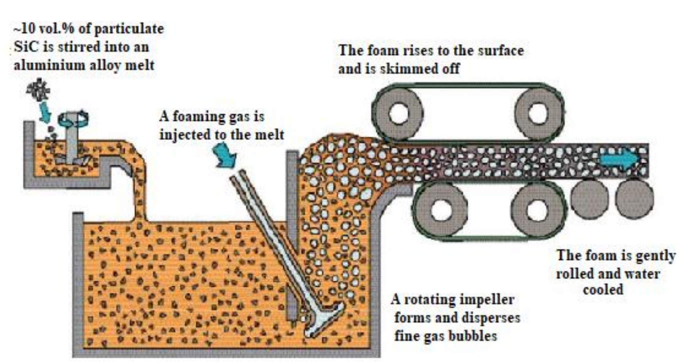


Figure 5 Melt gas injection method [67]

3.1.2 Foaming by Adding Substance (Blowing Agents)

This method, as shown in Figure 6, involves increasing the viscosity of the melt by adding 1-2% calcium as a thickening agent. Additionally, a foaming agent, usually hydrides such as CaH_2 or TiH_2 in fine powder form, is added at 1–2% to initiate foaming [68, 69]. These hydride particles decompose at the foaming temperature, releasing hydrogen gas, which causes the melt to bubble.

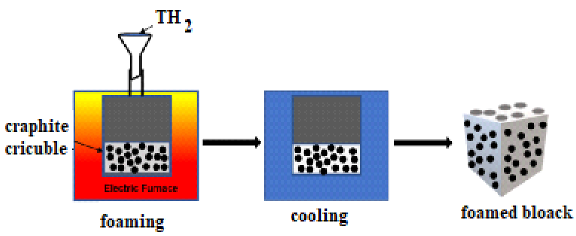


Figure 6 Foaming by adding blowing agents [60]

Common foaming agents and injection gases include TiH_2 [70–74], $CaCO_3$ [75, 76], zirconium hydride [77, 78], and dolomite ($CaMg(CO_3)_2$) [49, 50]. Stabilizing particles such as CaO, Ca, Al_2O_3, and ZrB_2 are added to the melt to ensure uniformity [79]. The melt is continuously stirred to evenly distribute both the stabilizing particles and the foaming agent. The crucible remains inside the furnace to maintain the required temperature for the decomposition of TiH_2, which releases gas and forms bubbles. After foaming, the melt is removed from the furnace and allowed to cool in the surrounding air. This method has been used to produce A356/20SiC composite foams with varying porosities and cell sizes, using TiH_2 as the blowing agent [60]

The quality of ALPORAS foams depends on several factors, such as viscosity, melt temperature, cooling rate, and the uniformity of powder mixing. To achieve higher foam quality, more uniform mixing and increased nucleation sites through high-speed stirring are necessary. The viscosity of the melt can be increased by adding thickening agents like calcium, alumina, SiC, or fly ash. Aluminum foam produced using this method typically has closed-cell pores, with relative densities ranging from 0.2 to 0.9 [80,69].

In another similar work, fabrication of AlSi9Mg/SiC composite foams was done by direct melt foaming. SiC served as stabilizer of foams, while the blowing agent was $CaCO_3$. It was found that higher volume fractions of SiC showed higher yield and collapse plateau stresses in composite foams [81]. Magnesium alloy foams were also fabricated using melt processing techniques with the use of powders such as $CaCO_3$, TiH_2 or MgH_2 as foaming agents. The decomposition of these agents releases gas gradually to foam the magnesium alloy melt [83-84]. In this process, magnesium alloy foams were subjected to microstructural analysis by a technique called Foaming by Adding Blowing Agents [85]. A higher elastic limit thereby improved strain hardening properties of SiC-reinforced AlSi9Mg composite foams obtained by using this method were observed [86]. AlSiCu cellular foams containing per se TiH_2 were fabricated in order to study the influence of the thermal decomposition of TiH_2 on the foaming process of the Al alloy. The efficiency of the melt foaming of the Al alloy has been determined to be strongly connected with characteristics of the decomposition of the TiH_2 [87]. Different additives such as carbon, SiC, and calcium particles have been added to the melt for improved viscosity enhancement.

The melt foaming technique has been widely used in the development of various metallic foams. $CaCO_3$ and TiH_2 are commonly used as foaming agents for the creation of foam structures, as outlined in Table 2.

Table 2 Metal closed foams developed by melt foaming

Reference		Foaming Agents
[89]	Al	TiH_2
[90]	Al/SiC	
[91]	Al/Ca	
[92]	Al 6061/Cu	
[93]	Al alloy (ALPORAS)	
[94]	Al (ALPORAS)	
[95]	ZA22/SiC	$CaCO_3$
[96]	Zn/22Al/SiC	
[97]	Al/Si/Mg	

3.1.3 Gas-reinforced Foaming

Porous structures are created by leveraging a eutectic reaction in hydrogen-supersaturated melts. As the melt cools to the eutectic point, both gaseous and solid phases form simultaneously from the liquid. Directional solidification is driven by heat extraction, which raises the H_2 content near the solidification front, resulting in the formation of a gas bubble [98]. In Figure 7, the patent enumerates the following base materials: aluminum, copper, nickel, iron, chromium, magnesium, and Al_2O_3-MgO [99].

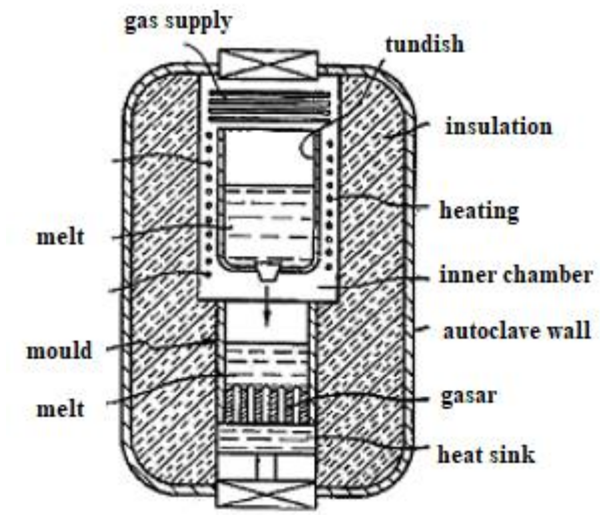


Figure 7 Apparatus for Gasar [100]

Based on the information provided in the reference [100–107]. it can compare the three types of melt foam manufacturing methods, as summarized in the paragraph below.

3.1.4 Comparison of Methods for Manufacturing Metal Foam by Melting

Melt Gas Injection Method

The melt gas injection method is particularly advantageous due to its suitability for continuous processing, which facilitates the bulk production of metal foams. This method is economically attractive, simple, and straightforward, making it an efficient option for large-scale operations. It is especially effective when implemented with aluminum alloys, as these materials have low density and minimal oxidation when exposed to air or oxygen-containing gases. However, this method has several disadvantages, including the production of non-uniform pore sizes, which can lead to poor foam quality. Additionally, it is challenging to produce complex shapes, with the process typically limited to slabs. These slabs often exhibit gradients in pore size and density due to drainage issues. Controlling gas dispersion within the foam is also a significant challenge, further complicating the process.

Foaming by Adding Blowing Agents

This method is notable for its ease in synthesizing aluminum foams, which generally results in more consistent pore formation. Additionally, this method offers simpler melt stabilization, providing better control over process parameters compared to other methods such as the Alcan route. However, the disadvantages of this approach include high production costs due to the expensive metal hydrides used as blowing agents. The method is also limited in its ability to create complex structures and shapes. Moreover, rapid cooling and removal of the mold from the furnace can induce thermal stresses and cracks in the cell walls, further complicating the process. Controlling porosity and cell size remains a challenging aspect of this method.

Reinforcing Foam with Gas

The method of reinforcing foam with gas is versatile, as it can be applied to a wide range of materials, including steel, cobalt, and molybdenum. This technique allows for the creation of various pore morphologies, with void content ranging between 5% and 75%. Notably, it does not require the use of costly hydrides, making it a more economical option for some applications. However, the disadvantages of this method include the need for complex equipment, which can make the process uneconomical for large-scale manufacturing. Additionally, the relatively slow growth rates observed with this method make it unsuitable for high-volume production processes, limiting its industrial applicability.

3.2 Foaming Techniques and Procedures in Powder Metallurgy

In this method, the metallic powder is combined with a specific mass fraction of a foaming agent, such as space holders or TiH_2 powder, in a powder mixer. The resulting mixture is cold-compacted using uniaxial compaction, which involves compressing a material in one direction, typically using a lubricated tool and applying pressures required to achieve steel die precursor green densities. These precursor samples are then moved to a furnace for the foaming process at high temperatures if they contain foaming agents. Samples with space holders are processed to create porosity through a leaching process, followed by sintering [100]. Foamed metals can be manufactured using a powder metallurgical process, which has been invented and patented [102, 103]. as shown in Figure 8.

The powder route of foam production, while not as commonly utilized, proves effective when prioritizing high foam quality. Despite the commercial dominance of the melt route, some companies employ the powder metallurgy route due to its ability to offer better control over process parameters, resulting in foams with improved structural, mechanical, and physical properties. This method allows for the production of complex shapes, sizes, and sandwich panels. However, it is worth noting that processing foam via the powder route is not economical [104]. The powder route of manufacturing metal foam involves

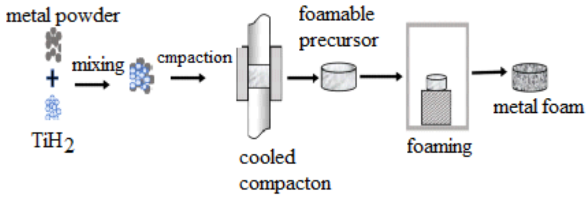


Figure 8 Diagrammatic representation of the metallic foam process using powder metallurgy [105]

3.2.1 *Space-Holder Technique*

The space-holder method allows for the production of metal foams with precise control over pore structure [108]. Initially, the space holders, which can be made of polymeric materials or salts like NaCl particles, are mixed with the metal powders [109–114]. Carbamide particles [31, 115], k_2CO_3 [38], polymethyl methacrylate (PMMA), etc. [116]. Carbohydrate particles, etc [117]. About 1 to 2% binders are included to enhance the strength of the final product. The mixture is then subjected to compression or injection molding, followed by sintering. During the sintering process, the space holders are eliminated through heating, solvent debinding before sintering, or dissolution after sintering [118, 119]. It can show this process in Figure 9.

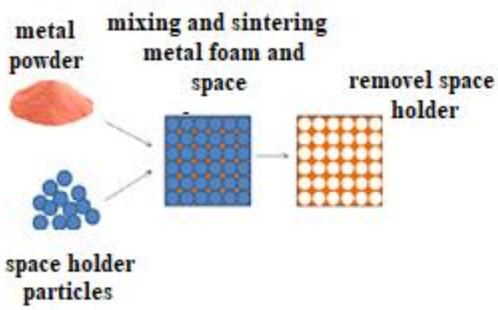


Figure 9 The space-holder method for processing metal foams [120]

The removal of space-holder materials results in interconnected pores, which can be either closed or open. The green sample is then sintered to improve its structural integrity. Overall, the space-holder method is regarded as a relatively simple technique for manufacturing metal foams [121].

Iron-based foams are commonly produced using this method because they enable the production of nearly pure materials, largely devoid of impurities [122, 123]. Metal foams produced using spherical space holders typically exhibit increased compressive strength compared to other fabrication methods [124 ,125].

The study by Razali *et al.* examined how the shape and content of spaceholder particles affect the fabrication process. Spherical pores resulted in more uniform cell walls due to enhanced particle contact during sintering. The compressive strength of aluminum foams decreased with larger space holder particle sizes but showed increased energy absorption capacity, except for compacted samples [126]. Magnesium alloy foams were created using carbamide particles as space holders, while water-soluble polymers like polymethyl methacrylate PMMA particles show potential for foam development. Both aluminum and magnesium foams were produced via powder metallurgy, using PMMA particles as space holders. This method allows for precise control over porosities and densities by adjusting the PMMA content. During sintering, PMMA particles decompose, leaving minimal residue [127–129]. Additionally, Table 3 outlines these methods' benefits and drawbacks.

Table 3 Advantages and Disadvantages of Powder Metallurgy and Melt Foaming Methods

Method	Powder metallurgy	Melt Foaming	
advantages	Produces complex parts close to final shape	Readily stabilizes the melt	
	High-quality foams without additional	High-quality foams without additional machining	- Suitable
	Suitable for various metals and alloys (e.g., brass, lead, zinc)	Economically attractive for metal foam production	
	Adjustable size and quantity of space holders	Adjustable size and quantity of space holders	- Easily in
		Simple process, resistant to oxidation	
		Readily stabilizes the melt	
Disadvant-ages	Costly method	Limited in creating intricate shapes	
	Laborious and time-consuming manufacturing process	Expensive due to metal hydrides	
		Challenges in controlling cell size and porosity	
		Thermal stresses and cracks may develop during cooling	

Various methods are employed in the fabrication of metal foams, which have a major role in choosing the final properties; these include compressive strength and energy absorption capacity. A synthesis of the manufacturing processes for Al foams is given in Table 4. It also tabulates the type of foam, whether open or closed cells; the used processing technique; and the BA or SH agents used for each technique. That information is tabulated effectively, whereby an easier understanding of the basic factors relating to each of the methods in terms of the materials involved and the advantages that accrue from their adoption is made. Such tabulation removes the necessity for verbose textual descriptions comparing and bringing out more easily essential scientific and technical issues associated with the technology of production of metal foams.

Table 4 Details of the manufacturing processes (open and closed cell) space holder (SH) and blowing agent (BA)

Type cell of Foam	Processing Technique	Material	(SH) (Carbamide) / (BA)	ref
Open cell	SH technique	Al/Al_2O_3	SH	[130]
Closd cell		Al-CNT	SH	[131]
		Al	SH	[132]
	Powder metallurgy (foaming agent)	Al	BA (Dolomite)	[13]
		AA7075/SiC	Foaming agent ($CaCo_3$)	[133]
	Melt Foaming	Al/MnCu	BA(TiH_2)	[55]

3.2.2 *Gas Entrapment*

This fabrication process is time-consuming, and it is not widely employed for producing metal foam due to its complexity. This process entails compacting metal powders to generate a precursor material and concurrently entrapping gas within the arrangement of metal components during compression. When heated, the trapped gas causes the metal to expand, resulting in foam formation. This technique mainly applied to produce porous titanium structures, entails filling a can with a titanium powder, evacuating it, refilling it with argon gas, dandifying it through hot isotactic pressing, working it, and finally foaming it via heat treatment. The resulting porous body typically exhibits 40–20% unconnected porosity with pore diameters ranging between 100 and 6 µm [134, 135]. as shown in Figure 10.

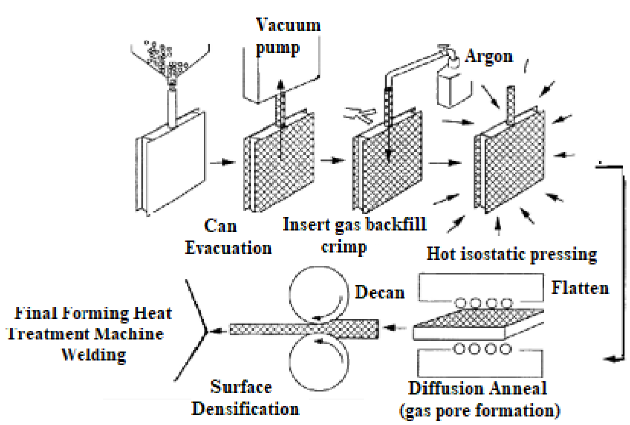


Figure 10 Gas entrapment method [104]

The manufacturing method of metal foams affects pore distribution and mechanical properties. Table 5 shows how the fabrication method affects metal foam's mechanical properties and behavior. This table compares molten foam and powder metallurgy production methods and how they affect metal foam compressive strength, pore structure, and energy absorption.

Table 5 Comparison of molten foam and powder metallurgy production methods and their effect on mechanical characteristics

Ref	Foam Type	Agent	Method of Fab_rication	Foam Material Mechanical Characteristics
[40]	Al /alloy	TiH_2	Melt Foaming	Increased compressive strength
[43]	Al/ scandium			Adding scandium improved the compressive strength
[45]	Al/(3.7%) Si/(0.18%) Mg			Increasing the foaming temperature reduced porosity and resulted in more homogeneous pore distribution. Notably, oxide particles or metal calcium granules were not required to stabilize the foam at elevated temperatures. This improvement in pore structure led to increased energy absorption per unit mass. Furthermore, the uniformity of the cell walls and the consistent pore morphology contributed to a smooth plateau stress region.
[35]	Al/TiB_2			TiB_2 particles increased foam expansion without reducing stabilization. Thus, composite foams absorbed more energy and had higher proof stresses.
[44]	Zn (Foam)			Zinc oxide was used to stabilize the foams. Both the maximum expansion and the expansion rate of the foams increased as the oxide Powder metallurgy content did as well.
[47]	Al/ Al_2O_3			The inclusion of Al2O3 led to enhancements in both compaction and hardness characteristics.
[49]	Al/Zn foams	$CaCO_3$	Melt Foaming	When oxide phases form in molten material, cell wall thickness and melt viscosity both increases.

Ref	Foam Type	Agent	Method of Fab_rication	Foam Material Mechanical Characteristics
				Foams containing four wt% Zn displayed a consistent cell structure, leading to an extended plateau stage and increased yield strength. Foam density and energy absorption per unit volume both increased as Zn content increased.
[42]	Mg-(Al), Mg-(Zn) and Mg–Cu foams			Facilitated efficient foaming by generating intermetallic compounds with low melting temperatures during the sintering process.
[48]	Zn-(Mg) alloy foam			The Foam demonstrated commendable mechanical strength but showed a compressed curve of stress-strain with serrations in the plateau area, which is explained by intermetallic.
[41]	Mg / Al /Zn foams			Increased compressive strength

4.0 APPLICATION OF METAL FOAM

This review paper examines sandwich engineering structures designed for various applications to meet the current engineering demand for lightweight structures [135].

Metal foams, especially aluminum foams, are advantageous in various industrial applications. In the automotive, aerospace, military applications, and aviation industries, they are utilized for structural components because of their lightweight characteristics and multifunctional attributes. In machine tools, they mitigate vibrations, enhancing performance. Aluminum foams are incorporated into recuperates in micro gas turbines to enhance thermal efficiency. . Metallic foam-like materials like iron, magnesium, and zinc alloys coated with biocompatible substances may be used in orthopedics and bone tissue engineering [136-140]. Common metal foam sandwich uses are listed below.

4.1 Automotive and Aerospace Industries

Metal foams, like aluminum foams, are extensively used in the automotive and aerospace industries because of their lightweight properties, high strength, and ability to absorb energy. In the automotive sector, they're employed in impact energy absorbers, sound absorbers, honeycomb panels, and automobile bumpers [140]. Likewise, the aerospace industry favors metal foams for their multifunctional properties, which combine strength with lightweight characteristics, making them ideal for use in aircraft and spacecraft structures [136]. These materials are manufactured using various methods, such as liquid metallurgy and powder metallurgy routes, with techniques like melt foaming, gas injection foaming, and the space holder technique. The distinctive properties of metal foams make them valuable for improving safety and performance in automotive and aerospace applications [141–142]. In automotive engineering, sandwich structures are increasingly used in public transportation. For example, a multiscale approach has been developed for the roofs of railway vehicles. This approach optimizes the design process by combining experimental, numerical, and analytical methods [143]. The study concentrated on glass fiber composite-foam sandwich structures for the front structure of a high-speed train. It concluded that the structural behavior of sandwich panels is primarily dependent on the strength properties of the foam core material [144]. An electric multiple unit (EMU) car body employed a glass fiber reinforcement fiber /al honeycomb sandwich structure for both the under-frame and roof structure, demonstrating the successful application of lightweight design principles to urban transit car bodies [145].

The Thermhex Waben company proposed A lightweight sandwich semi-finished product was manufactured. Boasting weight savings exceeding 80% compared to monolithic designs. These a lightweight sandwich structures find applicability across various automotive components such as door modules, inner bonnets, battery housings, and back-end modules. Sandwich structures are utilized in aviation applications. These lightweight materials are incorporated into essential aircraft components, including wings, floor panels, and trailing edge panels, to improve structural efficiency [146–148]. Sandwich structures are utilized in aviation applications. These lightweight materials are incorporated into essential components of the Flying-V aircraft, including wings, floor panels, and trailing edge panels, to improve structural efficiency. Sandwich structures are utilized in vital components such as pylons, nacelles, spoilers, ailerons, and nose landing gear doors, facilitating weight reduction and enhancing mechanical performance, which is crucial for the aircraft's aerodynamic and operational efficiency as illustrated in Figure 11 [149-150].

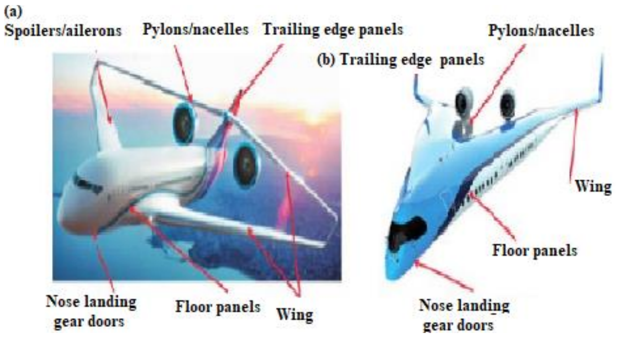


Figure 11 A sandwich structure is being explored for potential use in an aircraft concept (a) proposed blueprint for a box-shaped plane [149] (b) the V24 Flying-Star (News has granted permission for this reproduction) [150]

4.2 Marine Applications of Sandwich Structures

The marine industry extensively utilizes sandwich panels for various boat and ship components, offering significant advantages. Sandwich structures are prevalent in vessel categories like pleasure and race boats. This discussion focuses on recent and innovative marine applications across these categories to underscore advanced uses and encourage further adoption in the marine sector [151]. As outlined in Figure 12, this boat adopted a groundbreaking lightweight design.

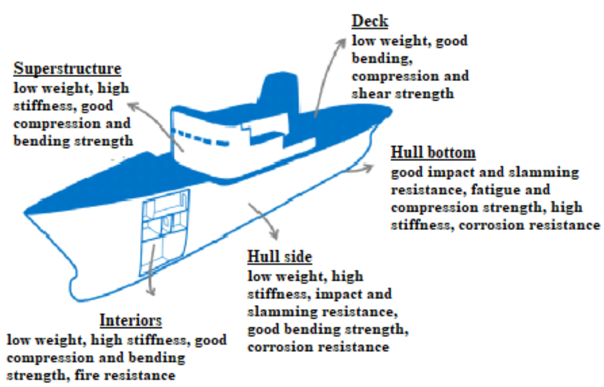


Figure 12 the metal foam used in marine applications [152]

4.3 Metal Foams for Energy Absorption Applications

Metal foam demonstrates exceptional energy absorption capabilities, making it ideal for various applications. Furthermore, the morphology, pore topology, and relative density of metal foams are key characteristics that contribute to their energy absorption potential [153]. Studies have shown that aluminum foam-filled energy absorption connectors significantly enhance energy absorption performance, making them valuable for blast-resistant structural designs [154]. In summary, the energy absorption abilities of metal foam make it a versatile material suitable for a wide range of engineering applications. Metal foams are becoming more highly regarded for their capacity to attenuate vibrations, rendering them valuable in diverse applications [155]. These materials possess benefits such as a favorable weight-to-stiffness ratio, a high capacity for dissipating energy, and exceptional properties for reducing vibrations. These advantages are essential for improving structural performance in industries such as aerospace, automotive, and machinery [115, 156].

Metal foams are utilized across various fields due to their exceptional properties [19, 157], including structural, biomedical, and chemical applications. Specific materials like aluminum, steel, iron, cobalt-chromium, titanium, copper, nickel, and others are chosen based on the specific application [158]. The structural integrity of metal foams is critical for their effectiveness and depends on factors such as pore morphology, density, mechanical properties, and microstructure [104, 141]. Research indicates that as the density of metal foams increases, so does their compressive strength, flexural strength, and hardness, making them ideal for structural applications due to their high strength-to-weight ratio and excellent vibration-damping characteristics. These properties make metal foams highly attractive for a wide range of engineering applications, highlighting the importance of understanding their properties for practical use.

4.4 Metal Foam Applications in Different Industries

Due to their unique properties, metal foams are used in many industries. In structural and aerospace applications, aluminum, steel, and iron foams absorb impact energy and provide structural support [141, 159]. Biomedical implants and tissue engineering generally use cobalt-chromium, steel, titanium, and copper foams [160]. Chemical companies use copper- and nickel-based foams [161]. Metal foams are ideal for aircraft and spacecraft structures due to their lightweight and energy absorption. Their applications are diverse and growing, with many engineering applications yet to be discovered [7]. Metal foams are used in structural, biomedical, and chemical applications due to their exceptional properties [19, 157]. Based on the application, aluminum, steel, iron, cobalt-chromium, titanium, copper, nickel, and others are used [160, 162]. Pore morphology, density, mechanical properties, and microstructure determine metal foam structural integrity, which affects their effectiveness. [104, 141]. Research shows that steel foam density increases compressive, flexural, and stiffness. Steel foams are ideal for construction due to their high strength-to-weight ratio and vibration-dampening properties, making them desirable for a variety of industrial applications. It is not only used in improving mechanical applications but also used in civil applications. as illustrated in Table 6 and Figure 13.

Table 6 Some examples of structural applications and advantages of metal foams include

ref	Importance to engineering application	Prototype/In-production applications:	What improve
[157]	This proof-of-concept showcases the production feasibility of steel foam rods, bars, sandwich plates, and foam-filled tubes. It implies that nearly all aluminum foam applications could potentially be expanded to encompass steel foam.	Steel foam bars, rods, sandwich plates	Improved Weight(w) stiff.(k) Energy(EN)
[161]	Metal foam panels exhibit remarkable load-bearing capabilities, even under localized stress, rendering them ideal for utilization in floor slabs. This includes high-traffic zones such as parking garages, where loads redistribute effectively across the structure.	Balcony platform, parking floor slab	Improved stiff.(K) Energy(EN)
[163]	The feasibility of mass-producing metal foam panels has been established, facilitating a diverse array of bending stiffness-to-weight ratios.	Wall/floor foam sandwich panels	Improved stiff.(K) Energy(EN)
[163]	Metal foams excel in dissipating kinetic energy, a key advantage stemming from their ability to absorb energy. The transfer of load to the support is constrained by the Foam's yield strength. The slower deceleration resulting from the energy absorption capacity of metal foams mitigates dynamic effects, consequently enhancing driver safety.	Race car crash absorber	Improved Energy(EN)
[164]	Metal foam beams capable of supporting high or typical structural loads can be manufactured fatigue is not a singular concern with crane arms fabricated using metal foam have been subjected to fatigue testing am.	Crane lifting arm and support.	Improved Stiff (K) Energy (EN)

Figure 13 also shows some examples and applications of the metal foam.

Figure 13 Some examples and applications of the metal foam

5.0 SUMMARY

In summary, metal foams exhibit distinct mechanical properties like low density, excellent energy absorption, and high stiffness, rendering them ideal for different engineering applications. Metal foams, specifically aluminum foams, are extensively used in several different industries, such as automotive, aerospace, marine application, civil engineering, biomedical, and chemical sectors, due to their unique properties.

Their mechanical behavior is notably influenced by cellular architecture, relative density, and porosity, with higher porosity. In general, using metal foam instead of metal caused increased energy absorption but reduced compressive strength and elastic modulus. The incorporation of additives such as TiB_2 and distinct fabrication methods, comprising melt foaming and powder metallurgy, can improve energy absorption and strength. Theoretical models, like those created by Gibson and Ashby, precisely predict these properties, focusing on the relationships between density and relative stress. Experimental studies verify these models, displaying that the energy absorption characteristics and compressive strength of metal foams vary with shape, cell size, and processing techniques.

In automotive applications, they function as impact energy absorbers and lightweight structural elements, whereas in aerospace, they improve safety and performance in aircraft and spacecraft structures. Marine applications encompass lightweight sandwich panels for vessels, enhancing structural integrity. In civil engineering, metal foams are utilized in floor slabs, balcony platforms, and crash absorbers because of their superior stiffness-to-weight ratio and energy absorption properties. The chemical and biomedical sectors utilize particular metal foams, including copper for implants and cobalt-chromium for chemical processing. Despite advancements, manufacturing challenges such as achieving controlled cell size and uniform pore distribution persist, necessitating continued research to improve techniques and investigate new applications and materials to expand the potential of metal foam technology.

Metal foam synthesis encompasses a variation of techniques, each with its unique benefits and challenges, to achieve unique foam characteristics. Among these, melt foaming techniques, such as the use of blowing agents and melt gas injection, are common because of their simplicity and efficiency in producing foams with uniform pores and variable densities. Factors like foam temperature composition, cooling circumstances, and the inclusion of stabilizing particles like SiC or Al_2O_3 notably impact foam quality. Gas injection techniques, first patented early in the 1990s, make fine bubbles in the molten material, even though adding substances such as TiH_2 or CaH_2 as blowing agents improves foam stability by raising melt viscosity. An additional technique, gas-reinforced foaming, utilizes hydrogen-supersaturated melts to take shape porous structures throughout cooling.

Powder metallurgy, although less typical, involves mixing metallic powder with space holders or foaming agents, compacting it, and then heating it to generate foaming. This mechanism produces high-quality foams and permits the creation of complex sizes and shapes, although it is more labor-difficult and costly. Each method affects the mechanical properties of the resulting metal foams in different ways, influencing energy absorption, compressive strength, and overall structural integrity.

Metal foams possess exceptional characteristics that render them highly suitable for various engineering applications, including automotive and aerospace industries, owing to their exceptional energy absorption capabilities and low mass. Nevertheless, the manufacturing process of these products encounters notable obstacles such as the management of pore size and distribution, elevated production expenses, technical intricacy, and concerns regarding sustainability and durability in demanding conditions.

In order to tackle these difficulties, the study suggests employing sophisticated manufacturing methods, such as 3D printing to enhance manufacturing precision and minimize waste. Exploring novel materials or metal compounds has the potential to improve the characteristics of foams and bolster their sustainability. Enhancing recycling processes is a crucial measure in order to enhance the efficiency and cost-effectiveness of manufacturing.

Therefore, in order to fully utilize the capabilities of metal foams, it is necessary to foster cooperation among disciplines such as materials science, manufacturing technologies, and computational modeling. This collaboration will facilitate the development of novel solutions and enhance the use of metal foams in diverse industries.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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