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Multifunctionality of Aluminum Alloy Foams: A Critical Review of Processing, Mechanical Behavior, and Applications

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Abstract

This research examines aluminum alloy foams in detail, highlighting current advancements in their manufacturing processes, mechanical and thermal characteristics, structural capabilities, and diverse range of uses. This study emphasizes the relationship between foam architecture and processing characteristics, such as porosity, cell structure, and compositional alteration, based on 40 previous investigations. Alongside hybrid reinforcements made of ceramics, graphene, and industrial waste, advanced manufacturing techniques like stir casting, powder metallurgy, template replication, and additive manufacturing are covered. Analysis is done on crashworthiness, energy absorption, electromagnetic shielding, and mechanical behavior under static and dynamic loads. Furthermore, insights into upcoming research trends are provided to address present issues including cost, stability, and recyclability.

Keywords: Aluminum Alloy Foams, Multifunctionality, Processing Techniques, Mechanical Properties, Energy Absorption, Corrosion Resistance, Biomedical and Aerospace Applications.

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1- Introduction

Metal foams are made of metals with a lot of pores. Metal has great strength, durability and the pore structure makes the material lighter. Because of their pores, metal foams have special mechanical and physical characteristics. High gas permeability, excellent thermal conductivity, a large specific strength to weight ratio, and excellent energy and sound absorption qualities are examples of special qualities [1].

One family of cutting-edge materials that combines superior mechanical and thermal capabilities with minimal density is metallic foam. Of these, alloys of aluminum foams (AAFs) have garnered a lot of research interest because of their exceptional multifunctionality, corrosion resistance, specific strength, and energy absorption capacity [2,3].

AAF structures are made up of many gas-filled pores in a metal matrix. The physical and mechanical characteristics of these pores can vary greatly depending on whether they are isolated (closed-cell) or connected (open-cell) [4,5,6]. The automotive and aerospace sectors use metal foams because of their unique combination of mechanical and physical qualities, such as their highly specific stiffness, high strength to weight ratios, lightweight nature, and significantly enhanced energy-absorbing capacity. It has also been demonstrated to exhibit fatigue degradation in both compression and tension [7].

AAFs can be processed using a variety of methods, including: Melt foaming using chemical blowing agents like calcium-based compounds or titanium hydride (TiH_2) [8]. Powder metallurgy using urea and NaCl as space holders, then sintering [9]. Infiltration casting, in which molten aluminum is poured into a porous template [10]. Additive manufacturing, which gives architects and microstructure control [11].

Additionally, numerous researchers have added reinforcements to the matrix to get around mechanical constraints like brittleness. Among these are ceramic particles for increased strength (SiC, AlO_3, $MgAlO_4$) [12]. Recycled industrial waste to lower costs and environmental effect, such as fly ashes, lithium slag, or powdered eggshells [13].

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2- Classification of Aluminum Alloy Foams

Aluminum alloy foams (AAFs) can be categorized according to a number of factors, such as architectural configuration, matrix composition, manufacturing process, and pore morphology. These categories dictate the foam's end-use applications, mechanical behavior, and thermal performance. The main categories that have been validated by the results of recent research are included in this section.

2.1. By Pore Structure: Comparing Closed-Cell and Open-Cell

Open-cell foams are distinguished by their interconnecting pores. These foams are appropriate for use as sound absorbers, filters, and heat exchangers because they allow for the permeability of gases and fluids. In order to absorb electromagnetic waves, [3] created reticulated open-cell aluminum foams strengthened with reduced graphene oxide. These foams have a high open porosity (>90%) and a lightweight construction.

Closed-cell foams, comprise separate gas-filled pores surrounded by solid walls, in contrast. Compared to open-cell structures, they offer superior thermal insulation and stronger compressive strength. The behavior of these foams under compression has been thoroughly investigated, and they are frequently utilized in crash energy-absorbing systems [14].

2.2. By Manufacturing Method

Melt foaming generally leads to formations with closed cells. For example, using TiH_2 as an agent for foaming in melt-foamed AAFs results in spherical pores, but unless fixed by oxides such as $MgAl_2O_4$, it may have erratic distribution [12].

Powder metallurgy with space-holders allows for exact control over connection and pore size. [4] produced open-cell foams with adjustable porosity for thermal and structural uses using binders derived from industrial waste and NaCl.

Infiltration casting produces either open-cell or structured foams when deposited into a detachable porous template (such as a salt bed or polymer sponge). Using this method, ZnAl22 syntactic foams were effectively synthesized, producing high damping and specific strength [10].

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Additive manufacturing (AM) permits the creation of architected foams with periodic lattices and personalized porosity gradients. [15] used laser powder bed fusion (LPBF) to create AlSi10Mg cellular materials with both stochastic and non-stochastic geometries.

2.3. By Matrix Alloy Composition

Pure aluminum foams are not very strong, but they are ductile and resistant to corrosion.

Aluminum-silicon alloys Studies on 3D-printed foam have demonstrated that materials with higher hardness and heat resistance (such as AlSi10Mg) [16].

High-strength alloys such as ZnAl22 or AA7075 enable high-performance foams with enhanced mechanical responsiveness [17].

Composite matrices, incorporating reinforcements that enhance load transmission and thermal resistance, such as SiC, graphene, or ceramic cenospheres. showed significant mechanical improvement with these additions [19, 18]

3. Techniques for Processing Foams of Aluminum Alloy

An important factor in determining the composition, characteristics, and functionality of aluminum alloy foams (AAFs) is the fabrication process. Different techniques produce different mechanical behavior, porosity, and functionality depending on the application. Here, we classify and assess the main techniques for creating AAFs, emphasizing advancements from more recent research.

3.1. Melt Foaming Technique

One of the oldest techniques for creating closed-cell AAFs is melt foaming. It entails utilizing a blowing agent, like TiH_2 or $CaCO_3$, to introduce a gas into molten aluminum.

Working principle: Heat causes the blowing agent to break down, releasing carbon dioxide or hydrogen gas and forming pores in the molten metal. To stop pore collapse, stabilizers such AlO_3 particles are introduced [20].

Advantages: High production rates make crash-absorbing foams viable for mass production.

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Limitations: Pore homogeneity is difficult to regulate; cautious temperature management is necessary to prevent premature or delayed foaming.

3.2. Powder Metallurgy (PM) with Space Holders

In powder metallurgy, metal powder is mixed with a space-holding agent (such as urea or NaCl), compacted, and then sintered. Later, the space holder is eliminated through thermal breakdown or dissolution.

Control: Ideal for attaining consistent, customized porosity (50–90%) and capable of incorporating fly ash, Zr, or Ti reinforcements [4].

Sintering: usually carried out for Al-based systems between 580 and 620 °C to guarantee bonding while maintaining pore structure.

Sustainability: provides the option to utilize materials obtained from waste, like coal gangue or eggshell powder [4].

3.3. Infiltration Casting

This method entails pushing molten aluminum into a porous template that has already been created and is then taken out, like compacted salt grains or ceramic foams.

Replica process: The final foam replicates the original template's architecture.

Application: ideal for creating periodic or syntactic foams that are employed in crash energy absorption and thermal control [10].

Control: provides precise control over the connection, alignment, and geometry of pores.

3.4. Additive Manufacturing (AM)

Architected metallic foams with regulated geometry and porosity can be created using additive manufacturing, particularly Laser Powder Bed Fusion (LPBF).

Benefits of Additive Manufacturing (AM) Tailored lattice structure design, Graded and anisotropic porosity and The capacity to create hollow nodes and thin-wall characteristics. Alloys used in AM like AlSi10Mg, AA7075, and Al-Mg-Zr systems.

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And Post-processing is frequently consists of surface polishing and stress-relieving annealing [21].

3.5. Green and Sustainable Methods

Recent studies have concentrated on sustainable manufacture because of material costs and environmental concerns:

Binder-free systems: Reduce emissions from sintering and get rid of organic additives [22].

Industrial waste use: Eggshells, fly ash, and lithium slag can be used in place of synthetic fillers, greatly reducing expenses and carbon emissions [4].

Hybrid techniques: Infiltration combined with AM or powder metallurgy for enhanced functionality [23].

4. Aluminum Alloy Foams' Mechanical and Functional Characteristics

Numerous parameters, such as relative density, pore size and shape, cell wall thickness, alloy content, and reinforcing presence, affect the mechanical and functional characteristics of aluminum alloy foams (AAFs). The efficiency of the foam in structural, damping, thermal insulation, and energy absorption applications is determined by these characteristics. The main conclusions drawn from 50 recent studies are outlined in this section.

4.1. Deformation Behavior and Compressive Strength

The most basic characteristic of AAFs that has been researched is compressive behavior. Usually, the compressive stress–strain curve displays:

An **elastic region** (first linear increase).

A **plateau region** (gradual cell breakdown under almost continuous stress).

A **densification region** (As pores constrict, tension increases quickly).

Density effect: Although they have a higher compressive strength, foams with a higher density absorb less energy per unit weight [24].

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Influence of reinforcement: The addition of graphene or SiC strengthens cell walls and prevents pore collapse [25].

Strain-rate sensitivity: Due to inertia effects, foams exhibit enhanced strength under dynamic loading [26].

4.2. Energy Absorption Capacity

An essential characteristic of applications in the automotive, aerospace, and military industries is energy absorption.

Specific Energy Absorption (SEA) Depending on cell structure and density, values can range from 5 to 50 kJ/kg [27].

Multilayer Structures: Transmitted force is decreased by the incremental absorption of impact energy by foam layers of varying densities [28].

4.3. Thermal and Acoustic Performance

Depending on density and pore isolation, closed-cell AAFs have a thermal conductivity of 0.1 to 0.3 W/m·K. These are appropriate for insulation and passive cooling in buildings and airplanes [29].

Sound absorption: Viscosity losses in the pores of open-cell structures cause them to absorb mid-to-high frequency sound [30].

4.4. Damping and Vibrational Behavior

Aluminum foams show significant damping ratios as a result of localized plastic deformation and frictional energy dissipation [31].

Dynamic mechanical analysis (DMA) demonstrates improved damping when reinforced with ceramic or polymeric materials[32].

4.5. Surface Stability and Corrosion Resistance

Coatings (such as Zn, Ni, or oxide coatings) greatly increase foams' ability to withstand corrosion in salty or acidic conditions [33].

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Self-repairing oxide layers, As demonstrated, prolong the lifespan of foams utilized in biomedical or maritime applications [34].

Composite walls enhance chemical durability and lessen moisture intrusion by using fly ash or glass [35].

5. Applications of Aluminum Alloy Foams

Aluminum alloy foams (AAFs) are extremely beneficial in a variety of industries due to their special mix of qualities, which include energy absorption, damping, corrosion resistance, lightweight structure, and thermal insulation.

5.1. Automotive and Transportation

Automotive applications of AAFs are among the most well-known, particularly in the areas of crashworthiness, reducing weight, and vibration and noise damping (NVH).

Crash absorbers: Because of their high specific energy absorption, closed-cell aluminum foams are utilized in door reinforcements, bumpers, and crash boxes [36].

Lightweight sandwich panels: While retaining strength, foam cores sandwiched between aluminum sheets greatly reduce vehicle bulk [37].

5.2. Aerospace and Aviation

AAFs provide advantages in the aerospace industry in terms of fuel efficiency, vibration dampening, and impact resistance

Lightweight structures: utilized to minimize weight while maintaining structural integrity in satellite frames, wing edges, and aircraft flooring [38].

Thermal protection systems (TPS): To safeguard spacecraft during re-entry, TPS layers employ closed-cell foams [39].

Noise insulation: Noise from engines and cabins is absorbed by open-cell foams [40].

5. 3. Biomedical Applications

Aluminum alloy foams have gained emerging interest in biomedical engineering, particularly for use in orthopedic implants, bone scaffolds, and biomedical cushioning structures due to their high porosity, low density, and biocompatibility when appropriately treated. Open-cell aluminum foams mimic the architecture of cancellous bone, allowing for cell infiltration, nutrient transport, and vascularization, which are essential for bone ingrowth and osseointegration[41]. Additionally, their mechanical properties can be tailored to match the modulus of bone, thus minimizing stress shielding effects [42]. Surface modifications, such as oxide coatings or bioactive layers, further enhance corrosion resistance and biocompatibility, making these foams suitable for use in orthopedic fixation systems and dental implants [43].

6. Conclusion

Aluminum alloy foams (AAFs) are a type of cutting-edge materials that combine outstanding functional qualities, such as thermal insulation, crash energy absorption, and multifunctional flexibility, with low density. The improvements in their broad-spectrum applications, mechanical behavior, processing techniques, and classification have been emphasized in this review. Even if conventional methods like melt foaming and powder metallurgy are still widely used, newer strategies like manufacturing with additives and sustainable fabrication from industrial waste are opening the door to foams that are both ecologically benign and perform better.

The main obstacles still exist, though: regulating pore homogeneity, boosting corrosion resistance, increasing toughness, and guaranteeing scalability. Future studies will probably concentrate on hybrid reinforcement (graphene, ceramics), green production, and smart foam integrations (sensorized, responsive materials). AAFs will be able to explore new possibilities in aircraft constructions, biomedical implants, and future protective systems if these problems are resolved.

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