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RUNGTA
International Journal of Mechanical and Automobile Engineering

REVIEW ARTICLE

Titanium Foam: Redefining Biomedical Engineering and Performance-Driven Technologies

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ABSTRACT:

Titanium foam, a lightweight and porous metallic material, is valued for its biocompatibility, robust mechanical properties, and resistance to corrosion, enabling its use across diverse industries. This review explores its critical applications in biomedical, aerospace, defence, and energy sectors, with a primary emphasis on biomedical innovations. Its porous architecture, typically with pore sizes ranging from 100 to 600 µm, supports osseointegration and tissue growth, making it ideal for orthopaedic implants, dental structures, regenerative scaffolds, and targeted drug delivery systems. Surface enhancements, such as hydroxyapatite coatings, further improve its bioactivity. In aerospace and defence, titanium foam's exceptional strength-to-weight ratio enhances airframe designs, turbine parts, military aircraft frameworks, and lightweight vehicle armour, boosting performance and longevity. In the energy sector, it functions as an electrode substrate in batteries, supercapacitors, and fuel cells, improving electrochemical efficiency for sustainable energy solutions. Nevertheless, challenges like achieving consistent porosity and high production costs hinder large-scale adoption.

KEYWORDS: Titanium foam; Lightweight materials; Porous materials; Biocompatibility; Osseointegration.

1. INTRODUCTION

Titanium and its alloys have long been valued in engineering and medicine for their high strength-to-weight ratio, excellent corrosion resistance, and superior biocompatibility relative to stainless steel and cobalt-chromium alloys [1,2]. Introducing controlled porosity into titanium to form titanium foam extends these advantages further: the resulting cellular architecture combines low density and high specific strength with a tunable elastic modulus that can be brought closer to that of human bone, directly addressing the stress-shielding effect that limits the long-term performance of solid, fully dense titanium implants [1,3].

Because titanium has a high melting point (1670°C) and a strong chemical affinity for oxygen, nitrogen, carbon, and hydrogen at elevated temperature, liquid-state foaming techniques that are effective for aluminium are difficult to apply to titanium; solid-state powder-metallurgy processes are therefore the dominant fabrication route for titanium foam, offering more

Received on 19.02.2026 Revised on 31.03.2026
Accepted on 03.04.2026 Published on 08.04.2026
Rungta International Journal of Mechanical and Automobile Technology. 2026; 3(1), 6.
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precise control of pore size, shape, and distribution than melt-based alternatives [2,4].

This review examines titanium foam's critical applications across the biomedical, aerospace, defence, and energy sectors, with primary emphasis on biomedical innovation given the depth of literature in this area. It further surveys the principal fabrication routes that govern the resulting porosity, pore architecture, and mechanical properties of titanium foam, and identifies the reproducibility and cost challenges that continue to constrain broader industrial adoption.

2. FABRICATION ROUTES

2.1. Space-Holder Powder Metallurgy

The space-holder technique is the most widely employed method for producing titanium foam, in which a sacrificial particulate space-holder — sodium chloride, calcium chloride, magnesium powder, urea, or acrowax — is blended with titanium powder, compacted, and subsequently removed by dissolution, evaporation, or thermal decomposition prior to sintering, leaving a network of pores whose size, shape, and connectivity are governed by the space-holder characteristics [4,5]. This route allows fabrication of foams across a wide porosity range, from approximately 35% to 89%, with reported studies using calcium chloride [5], acicular urea particles [6], magnesium powder of varying particle size [7], and evaporative acrowax or ammonium bicarbonate space holders [8] each yielding distinct cell-size and cell-wall-thickness characteristics.

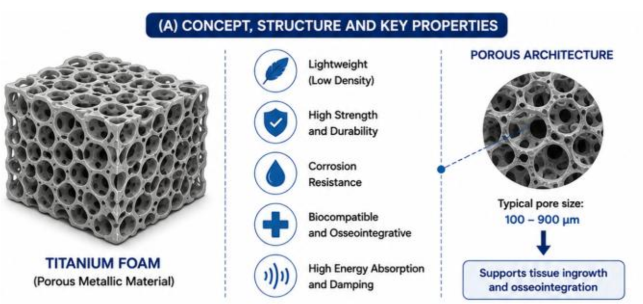

Figure 1. Schematic overview of Titanium foam. (A) Concept, structure, and key properties.

2.2. Replica Impregnation and Slurry-Based Methods

Replica impregnation methods, in which a titanium slurry is used to coat a sacrificial polymeric sponge template that is subsequently burned out and the remaining titanium structure sintered, offer an alternative route to high-porosity open-cell titanium foam; optimised titanium slurry compositions (75 wt.% titanium powder, with polyvinyl alcohol binder and Dolapix dispersant) have been used to produce foam with porosity as high as 84% and limited processing contamination [9].

2.3. Process-Property Relationships

Across fabrication routes, foam porosity, pore size, and space-holder type collectively determine the resulting Young's modulus, yield strength, and energy-absorption capacity; reported titanium foams span a wide property envelope, with Young's modulus and yield strength values ranging from approximately 22 to 126 MPa and 0.06 to 1.18 GPa respectively depending on space-holder particle size and resulting porosity [7], and compressive plateau stress and densification behaviour similarly varying with pore architecture [9]. Because titanium's high reactivity necessitates vacuum or inert-gas sintering to avoid oxygen and nitrogen contamination, process atmosphere control is an additional significant lever governing final foam quality and mechanical consistency [2,8].

3. BIOMEDICAL APPLICATIONS

3.1. Osseointegration and Orthopaedic Implants

Titanium foam's interconnected porosity, with pore sizes broadly comparable to those of human cancellous bone (approximately 100–600 µm, extending up to approximately 900 µm in some foam architectures), supports bone-cell ingrowth and vascularisation through the implant's interior, promoting mechanical interlocking (osseointegration) that is difficult to achieve with a solid-surface implant [9,10]. In vivo evaluation of a novel titanium foam implant in the distal femur of a rabbit demonstrated promising histological evidence of bone ingrowth, with a compressive modulus considered clinically adequate despite being lower than that of conventional sintered-bead porous coatings [11]. Comparative in vivo work on porous titanium with and without a cenosphere space-holder additive has further correlated surface roughness and porosity characteristics with bone-tissue interface performance [12].

3.2. Dental Implants

Numerical finite-element investigation of titanium foam dental implants across a range of porosities (50–80%) found that a porosity of 62.5% offered the closest match between titanium foam's elastic modulus (13.82 GPa) and that of cortical bone (14.5 GPa), minimising the stress-level discrepancy between implant and surrounding bone relative to solid titanium and other tested porosities [13]. This finding illustrates that an intermediate, rather than maximal, porosity is often optimal for load-bearing dental and orthopaedic applications where bone-matching stiffness, rather than porosity alone, governs clinical performance.

3.3. Surface Bioactivation and Hydroxyapatite Coatings

Because titanium is intrinsically bioinert, surface bioactivation is widely used to accelerate osseointegration and improve clinical outcomes. Comparative evaluation of inorganic thermo-chemical treatment versus organic peptide-adsorption coating on porous titanium implants found both strategies improved osseointegration relative to untreated foam, with successful bone colonisation observed through the interconnected pore network [14]. Hydroxyapatite (HA) coating remains the most widely used bioactivation strategy: hydroxyapatite-coated porous titanium scaffolds functionalised with adipose-stem-cell-derived exosomes have demonstrated improved bone regeneration and integration relative to uncoated titanium implants [15], while multilayered, porosity-graded HA coatings on Ti6Al4V have additionally been engineered to combine strong substrate adhesion with functional drug-loading capacity [16].

Figure 2. Schematic overview of Titanium foam. (B) Fabrication and application.

3.4. Drug Delivery Applications

The porous architecture of hydroxyapatite-coated titanium implants has increasingly been exploited for local, sustained drug delivery: drug-loaded chitosan polymer impregnated into porous HA coatings on Ti6Al4V has demonstrated sustained drug release over 180 hours alongside improved fracture toughness and antibacterial activity against Staphylococcus aureus [16], while nanotubular titanium implants loaded with alendronate and gentamicin have shown sustained release profiles (92% and 94% respectively) alongside enhanced cell adhesion and antibacterial efficacy, illustrating the dual structural and pharmaceutical functionality achievable with porous titanium-based implant systems [17].

4. AEROSPACE AND DEFENCE APPLICATIONS

Titanium foam's high strength-to-weight ratio, high specific strength and modulus, and excellent corrosion resistance have long been recognised as attractive for aerospace and naval structural applications, including potential use in airframe components, turbine parts, catalyst substrates, and heat exchangers operating in demanding thermal and mechanical environments [6,7,9]. Because titanium foam additionally exhibits good energy-absorption characteristics through progressive cellular buckling, similar in principle to the load-bearing and impact-absorbing behaviour established for aluminium and other metal foams, it has also been explored for lightweight protective and defence-oriented structures where blast or impact mitigation is required alongside weight reduction [5]. Despite this established research interest, most aerospace and defence applications of titanium foam remain at the research or early-adoption stage relative to its considerably more mature biomedical use, reflecting the greater processing cost and qualification burden associated with aerospace-grade structural materials [9].

5. ENERGY SECTOR APPLICATIONS

Titanium foam's high surface area, open interconnected porosity, and strong corrosion resistance to aggressive electrolytes make it an attractive substrate for electrochemical energy-storage and conversion devices. Polypyrrole-modified titanium foam electrodes, in which a conductive polymer is grown directly on the titanium foam substrate via a redox reaction, have demonstrated high specific capacitance and excellent cycling stability for supercapacitor applications [18]. Relative to copper and nickel foam substrates more commonly used in battery and supercapacitor research, titanium foam offers superior corrosion resistance to electrolytes, and its porous structure is well suited to in-situ growth of hierarchical electrode materials, supporting improved charge/discharge rates and accommodating the volume changes associated with high-capacity anode materials during battery cycling [19]. Porous metal-foam electrode architectures more broadly have been shown to increase active-material loading several-fold relative to conventional planar electrodes while reducing internal resistance, benefits directly transferable to titanium-foam-based battery and fuel-cell electrode design [20].

6. COMPARATIVE SUMMARY

Table 1 summarises representative titanium foam fabrication routes, porosity ranges, and principal application domains compiled from the literature surveyed in Sections 2–5. The compiled evidence indicates that space-holder powder metallurgy remains the dominant and most versatile fabrication route across all four application sectors, that biomedical applications benefit from an intermediate, bone-matched porosity rather than maximal porosity, and that aerospace, defence, and energy-sector applications generally favour higher-strength, lower-porosity or surface-functionalised foam architectures.

Table 1: Representative titanium foam fabrication routes, porosity ranges, and principal application domains.

Fabrication Route / System	Reported Porosity	Principal Application	Ref.
Space-holder ($CaCl_2$)	Variable, high	Orthopaedic implants / energy absorption	5
Space-holder (acicular urea)	Wide range	Aerospace / naval structural	6
Space-holder (Mg powder)	35–65%	Biomaterial / aerospace	7
Space-holder (acrowax / NH_4HCO_3)	55–89%	Structural / energy absorption	8
Replica impregnation (slurry)	Up to 84%	Bone-mimicking scaffolds	9
HA-coated porous Ti (dental)	62.5% (optimal)	Dental implants	13
HA-coated porous Ti + drug loading	Graded porosity	Drug delivery + osseointegration	16
PPy-modified Ti foam electrode	High surface area	Supercapacitor electrodes	18

7. CHALLENGES AND LIMITATIONS

7.1. Porosity Consistency and Reproducibility

Achieving consistent, reproducible porosity, pore size, and pore-wall thickness across production batches remains a significant challenge for titanium foam manufacturing, since final foam architecture is sensitive to space-holder particle size and distribution, compaction pressure, and sintering temperature and time, and even modest process variation can shift mechanical properties substantially [7,8].

7.2. Processing Cost and Contamination Control

Titanium's high reactivity with atmospheric gases necessitates vacuum or inert-gas processing throughout fabrication and sintering, adding cost and process complexity relative to less reactive metals such as aluminium; oxidation of several percent of the titanium content during sintering has been reported even under controlled atmospheres, illustrating the persistent difficulty of fully eliminating contamination during processing [2,8].

7.3. Property-Application Matching

Because biomedical, aerospace, and energy-sector applications each demand different combinations of porosity, pore connectivity, and mechanical strength, no single titanium foam architecture is optimal across all application domains; the finding that an intermediate 62.5% porosity best matches cortical bone stiffness for dental implants, for example, does not directly generalise to the higher-porosity, high-surface-area architectures favoured for energy-storage electrode applications, requiring application-specific process optimisation rather than a universal titanium foam specification [13,19].

8. FUTURE DIRECTIONS

Based on the compiled evidence, three directions appear most promising for the continued development of titanium foam. First, continued refinement of space-holder selection and process-parameter control, building on the demonstrated influence of space-holder particle size and type on resulting mechanical properties, should help improve batch-to-batch reproducibility and reduce the property scatter currently observed across independently reported studies [7,8]. Second, further integration of multifunctional surface coatings — combining hydroxyapatite bioactivation with drug-delivery and antimicrobial functionality — represents a rapidly advancing direction for next-generation orthopaedic and dental implants [16,17]. Third, continued exploration of titanium foam as an electrode substrate for batteries, supercapacitors, and fuel cells, leveraging its superior electrolyte corrosion resistance relative to copper and nickel foam alternatives, is likely to expand titanium foam's role in sustainable energy-storage technologies beyond its currently dominant biomedical application base [18,19].

9. CONCLUSION

The principal conclusions of this compiled review are as follows:

• Titanium foam combines low density, biocompatibility, mechanical strength, and corrosion resistance with a tunable, bone-matching elastic modulus, positioning it as a leading material for biomedical, aerospace, defence, and energy-sector applications.

• Space-holder powder metallurgy is the dominant fabrication route, owing to titanium's high melting point and reactivity, with foam porosity and mechanical properties governed jointly by space-holder type, particle size, and processing parameters.

• In biomedical applications, an intermediate rather than maximal porosity (approximately 62.5% for dental implants) best matches native bone stiffness, mitigating stress shielding while supporting osseointegration through interconnected porosity of approximately 100–900 µm.

• Hydroxyapatite surface coatings, increasingly combined with drug-loading and antimicrobial functionality, represent the most mature bioactivation strategy and a rapidly advancing direction for next-generation implants.

• In aerospace, defence, and energy applications, titanium foam's strength-to-weight ratio and electrolyte corrosion resistance support emerging use as lightweight structural material and as a battery/supercapacitor electrode substrate, though porosity-consistency and production-cost challenges continue to constrain large-scale industrial adoption across all four sectors.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ACKNOWLEDGEMENT

The authors would like to acknowledge the RCET, Bhilai for providing the collaborative environment and resources necessary for conducting this literature review.

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