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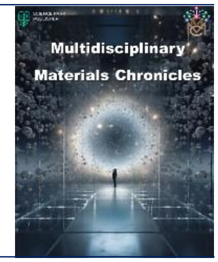

Multidisciplinary Materials Chronicles

Porous Titanium for Medical Implants

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Abstract

Porous titanium and its alloys have shown immense promise as orthopedic and dental implant materials owing to their outstanding properties, namely tailorable porosity, the ability of blood vessels and bone ingrowth, the transport of nutrients and/or biofluids, and vascularization. The previously mentioned properties facilitate osseointegration, a crucial device integration and stability factor. The presented review investigates the influence of pore characteristics of porous titanium and its alloys (e.g., size, shape, interconnectivity, and gradients) on biological response, mechanical properties, and key considerations in scaffold design. Recent literature showed that the progress of porous titanium and its alloys is summarized in biomaterials, specifically the processing techniques utilized in fabricating porous. Accordingly, recent advances in the previously stated processing techniques are powder metallurgy, additive manufacturing, plasma spraying, etc., which are applied in constructing optimized porous architectures. Overall, porous titanium structures with controlled porosity and tailored pore networks can promote bone ingrowth and long-term stability, thereby overcoming the limitations of traditional dense titanium (Ti) implants.

Keywords: Porous titanium, Titanium alloys, Biomedical implants, Additive manufacturing, Elastic modulus

1. Introduction

The organs and tissues in the human body have precise and complex functions. Our lives always depend on the performance of these organs versus their proper functioning. However, these organs and tissues are sometimes damaged and can fail due to diseases or accidents. There are many medical treatments available that can help treat damaged organs, but many of these treatments still lack the ability to repair the organ until it regains its full function. The field of regenerative medicine seeks to provide new tools that repair or replace damaged organs and tissues [1]. Regenerative medicine uses tissue engineering to develop new strategies for repairing damaged organs and tissues. Tissue engineering involves biology, chemistry, and engineering to make new biomaterials compatible with the human body and can be used to repair or replace damaged organs and tissues [2]. Biomaterials have improved significantly since their first development and are still changing as scientists try to better understand diseases and how these materials interact with the body. Biomaterials can take many forms and are produced from many different materials. Ideally, biomaterials should have a porous structure with small holes that allow air, fluids, and even cells to pass through, like the organs and tissues they are intended to treat [3]. Cells aiding in the healing process are

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loaded into these tiny holes that permeate the biomaterial [2]. In this way, a porous biomaterial can be used to transfer cells to damaged tissue. The biomaterial helps maintain new cells in tissues and, at the same time, is necessary to promote the healing process. Moreover, the porous structure of the biomaterial closely resembles the "exocellular matrix," which resembles the hooks by which cells in the body are "grabbed" [2, 4].

Titanium and its alloys are extensively used in biomedical implants because they offer a combination of high strength, lightness, resistance to corrosion, and compatibility with biological tissues. Currently, materials used in these applications include 316L stainless steel, cobalt-chromium (Co-Cr) alloys, and Ti-based alloys (specifically Ti-6Al-4V) [5, 6]. However, these materials sometimes fail after prolonged due to their stiffness relative to bone, inadequate wear and corrosion resistance, and insufficient compatibility with biological tissue. Achieving a critical stiffness matching between orthopedic implants and adjacent bone is crucial in avoiding stress shielding, bone resorption, and implant failure. Despite advances in biomaterials and tissue engineering, ongoing research focuses on developing durable metallic implants due to concerns about the long-term performance of current metallic biomaterials.

Porous titanium structures have demonstrated immense potential to transform orthopedic and dental implant performance via tailorable interconnected pore networks facilitating bone infiltration and vascularization. It is reported that the elastic modulus of these porous titanium structures is significantly lower, ranging from 91% to 96%, compared to dense Ti alloys [7]. Moreover, porous titanium and its alloys have emerged as promising candidate materials for orthopedic and dental implants owing to their outstanding biocompatibility, corrosion resistance, and mechanical properties closer to natural bone [8-10]. Incorporating of controllable porosity in titanium implants facilitates bone ingrowth, transport of nutrients and/or biofluids, and vascularization, promoting osseointegration for device integration and stability. Subsequently, it can significantly enhance post-implantation healing outcomes and long-term implant lifespan performance. Accordingly, extensive research has focused on engineering Ti implant surfaces and bulk structures with optimized porous architectures. It includes the fabrication of porous coatings on conventionally dense implants as well as the printing of fully porous titanium components using additive manufacturing. Additionally, processing innovations, pore topography, interconnectivity, and gradients influence biological responses [11, 12].

A prime determinant of in-vivo device integration is the effective pore volume fraction. Studies showed that ≥ 50% porosity enables sufficient bone ingrowth [13]. Wang et al. [14] found that in the context of early-stage osteonecrosis of the femoral head (ONFH) after core decompression, a biogenic trabecular porous Ti rod that is manufactured through the selective laser melting technique exhibited notable quantitative advantages over core decompression alone. The rod group demonstrated significantly higher ratios of bone volume to total volume (BV/TV) at both 3 months (890.0% increase) and 6 months (438.1% increase) compared to the core decompression (CD) group. The histological analysis supported these findings, showing substantial improvements in BV/TV in the rod group, with increases of 881.0% at 3 months and 413.3% at 6 months. Woodard et al. [15] found that hydroxyapatite (HA) scaffolds with multi-scale porosity, specifically microporous (MP) scaffolds with both microporosity (250 - 350 μm), and microporosity (2 - 8 μm), demonstrated superior osteoconductivity, drug-carrying efficacy, and mechanical properties compared to non-microporous (NMP) scaffolds. Thus, it is showcases the importance of scaffold microporosity for bone ingrowth and mechanical behavior in HA implant materials. The profound influence of porous titanium surface topographies on modulating osteoblast cell morphology, adhesion, differentiation, and mineralization also underlines the role of multiple hierarchical porosity.

The presented study provides a short review of the current advances in porous titanium-based biomaterials for medical implants. The review explores the impact of pore characteristics

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18
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on biological and mechanical aspects and summarizes recent progress in processing techniques for constructing optimized porous architecture.

2. Titanium Properties

The widespread use of Ti in medical implants is grounded in its exceptional biocompatibility, with attributes inertness, a stable oxide layer, and the potential for osseointegration. Its strength-to-weight ratio and flexibility, resembling human bone's elastic modulus, result in robust yet lightweight implants, essential for load-bearing applications such as joint replacements. The adsorption of proteins onto Ti surfaces plays a crucial role in osseointegration, influencing cellular responses and promoting implant integration [16]. Beyond its neutral interaction with the body, Ti actively fuses with bone, ensuring the stability and durability of implants, particularly in dental and orthopedic applications. With minimal ion release, Ti exhibits corrosion resistance inside the human body, avoiding potential harm or allergic reactions. Its non-magnetic nature makes it ideal for patients requiring MRI scans, ensuring safety and compatibility.

The innate oxide layer grants passive corrosion protection while permitting biofunctionalization that is essential for integration. However, elastic moduli still exceed natural bone, leading to stress-shielding long-term failures. Figure 1 shows the failure causes of implants leading to revision surgery.

Thus, ongoing research scrutinizes the absolute biocompatibility of Ti alloys, leading to the development of new beta Ti (β-Ti) alloys with non-toxic elements (e.g., Tantalum (Ta), Niobium (Nb), and Zirconium (Zr)). These alloys show promise in improved biocompatibility, strength, and wear resistance, addressing concerns associated with traditional Ti alloys such as Ti-6Al-4V. The quest for materials devoid of cytotoxic elements and with a low elastic modulus continues, fueled by the need for enhanced biomaterials in medical applications. Hence, porous titanium structures better emulate the cellular architecture of bone through an interconnected, open-cell network with adjustable porosity and pore sizes while harnessing the advantages of dense titanium/alloy compositions.

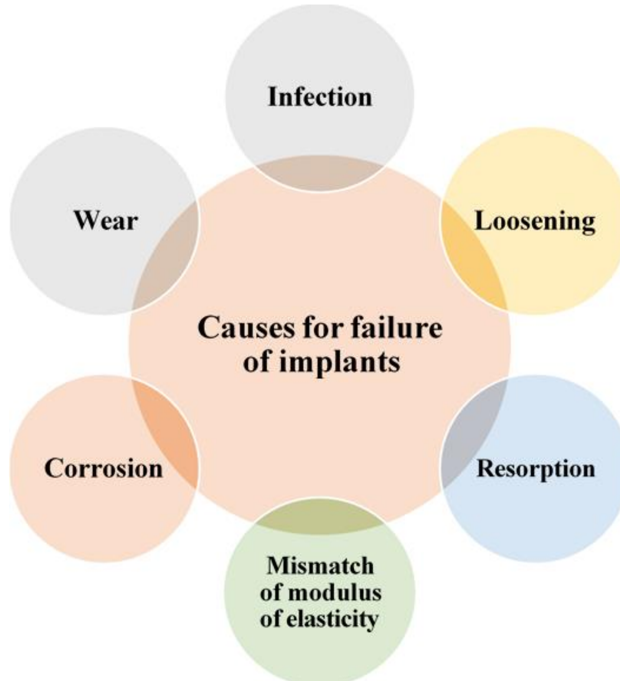

Figure 1. The causes for failure of implants leading to revision surgery.

3. Types of Titanium-Based Alloys

The biocompatibility and mechanical properties of titanium and its alloys, vital for medical implants, stem from their crystalline structure, transitioning between hexagonal close-packed (hcp) α-and body-centered cubic (bcc) β-phases at an allotropic phase transformation temperature [17-19].

Titanium alloys are classified into α-, near-α, (α+β), and β-types based on their microstructure and alloying elements [20]. The α-type includes commercially pure titanium (CP-Ti) and Ti alloys, known for exceptional corrosion resistance but limited mechanical strength at room temperature [21, 22]. Near-α Ti alloys, featuring minor β phases, share similar characteristics with α-type alloys but have not been extensively utilized in biomedical applications. (α+β)-type Ti alloys, exemplified by Ti-6Al-4V, dominate biomedical applications due to their superior strength, corrosion resistance, and osteointegration capabilities [20, 23]. Despite their prevalence, concerns about

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18

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toxic elements such as vanadium have led to the development of alternatives, for instance, Ti-6Al-7Nb and Ti-5Al-2.5Fe [24–26]. However, high moduli in (α+β)-type alloys may pose challenges (see Table. 1), prompting the exploration of β-type Ti alloys with non-toxic β-stabilizers such as molybdenum (Mo), tantalum (Ta), and Zr for improved biocompatibility and suitable elastic modulus [27, 28]. Figure 2 compares the elasticity modulus of different biomedical Ti alloys with human bone, stainless steel, and Co alloys. When comparing (α+β)- and β-Ti alloys to 316L stainless steels and Co alloys, their ultimate strength values are comparable with those of 316L stainless steels but lower than those of Co alloys. However, their yield strengths are also comparable with those of 316L stainless steels but closer to the lower side of the range for Co alloys, as shown in Table. 1.

However, dense forms of these Ti biomaterials with a misfit Young's modulus can induce stress-shielding, which in turn causes instability at the bone-implant interface. Thus, it results in fibrous tissue ingrowth, disruption of osseointegration, implant mobility, and an inflammatory response necessitating revision surgery. Porous materials have been developed to overcome these issues associated with bulk materials such as Ti. These materials aim to decrease Young's modulus, approaching values similar to bone, thereby improving stress distribution patterns and creating favorable conditions for bone remodeling.

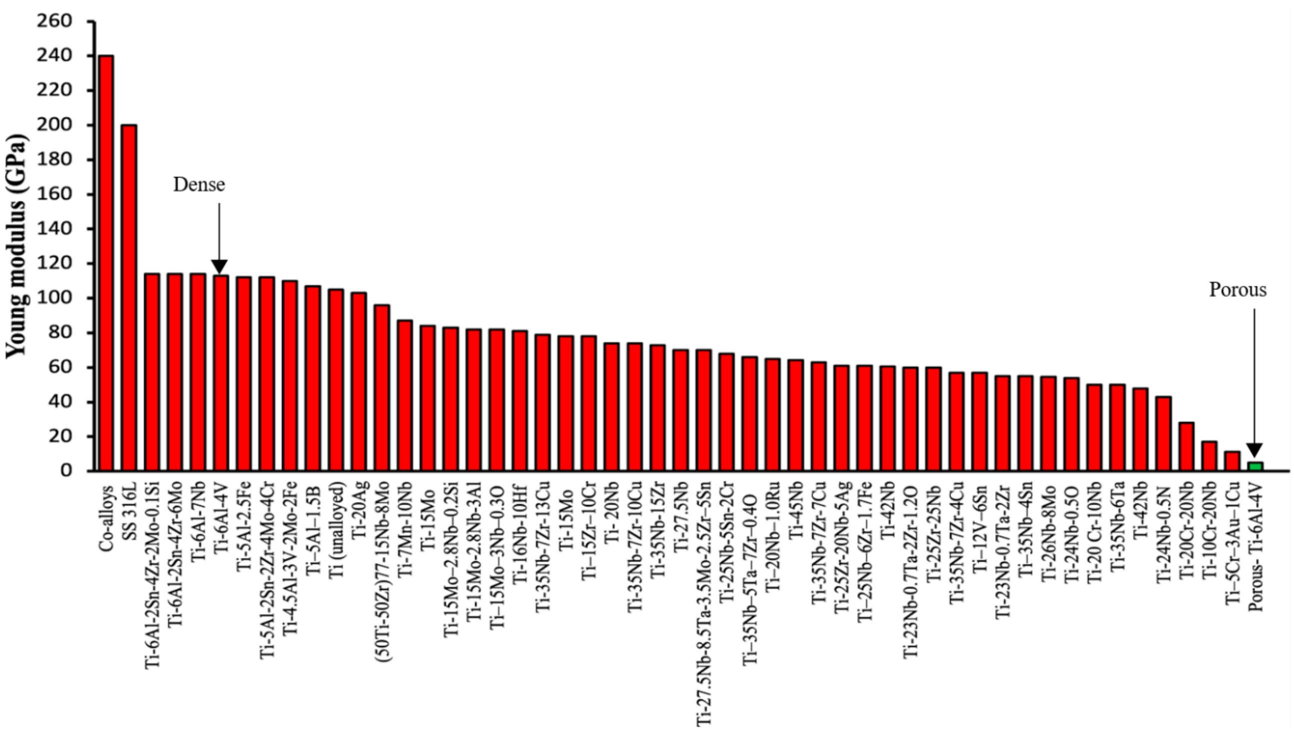

Figure 2. Elasticity modulus of various dense Ti alloys with a comparison of porous Ti-6Al-4V.

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18

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Table 1. A comparison of mechanical properties of metallic implants titanium alloys for biomedical applications with human bone, stainless steels, and Co-alloys.

Alloy	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Engineering strain (%)	Ref.
Cortical bone	5 − 23	30 − 70	194 − 195	-	[29]
SS 316L	200	200–700	500–1350	10–40	[30]
Co-alloys	240	500–1500	900–1800	10–50	[30]
Ti (unalloyed)	105	692	785	-	[31]
Ti-20Ag	~103	-	-	-	[32]
Ti-6Al-2Sn-4Zr-2Mo-0.1Si	114	990	1010	-	[33]
Ti-6Al-4V	113	999	1173	6	[34]
Porous- Ti-6Al-4V	5.1	-	171.86	-	[35]
Ti-6Al-7Nb	114	880-950	900-1050	8-15	[36]
Ti-5Al-2.5Fe	112	895	1020	15	[36]
Ti-6Al-2Sn-4Zr-6Mo	114	1000-1100	1100-1200	-	[33]
Ti-5Al-2Sn-2Zr-4Mo-4Cr	112	1050	1100-1250	-	[33]
Ti–5Al–1.5B	107	820–930	925–1080	15–17	[37]
Ti-10Cr-20Nb	17	1180	1580	-	[38]
Ti-20 Cr-10Nb	50	980	1590	-	[38]
Ti-20Cr-20Nb	28	1015	1700	-	[38]
Ti–12V–6Sn	57	897	1024	10	[39]
Ti-4.5Al-3V-2Mo-2Fe	110	900	960	-	[33]
Ti-35Nb-7Zr-4Cu	57	1062	1374	-	[40]
Ti-35Nb-7Zr-7Cu	63	1205	1602	-	[40]
Ti-35Nb-7Zr-10Cu	74	1469	1856	-	[40]
Ti-35Nb-7Zr-13Cu	79	1216	1571	-	[40]
Ti- 20Nb	74	-	-	-	[41]
Ti-45Nb	64.3	438	527	-	[42]
Ti-42Nb	60.5	674	683	11.7	[43]
Ti-42Nb	47.9	715	718	17.8	[44]
Ti-27.5Nb	70	800	820	10	[45]
Ti-15Mo	84	745	921	25	[34]
Ti-15Mo	78	544	874	21	[37]
Ti-35Nb-6Ta	50	-	820	~10-12	[46]
Ti-35Nb-15Zr	72.82	1185.18	1199.39	6.7	[47]
Ti–15Zr–10Cr	78	1038	-	-	[48]
Ti-7Mn-10Nb	87	842	1842	~34	[49]
Ti-16Nb-10Hf	81	730–740	740–850	10	[30]
Ti-25Zr-25Nb	60	1025	1588	32.9	[50]

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18
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Ti-24Nb-0.5O	54	665	810	-	[51]
Ti-24Nb-0.5N	43	665	665	-	[51]
Ti–35Nb–4Sn	55	-	~470	-	[52]
Ti-26Nb-8Mo	54.5	663	-	-	[53]
Ti–20Nb–1.0Ru	65	920	960	~22	[54]
Ti-15Mo–2.8Nb–0.2Si	83	945–987	979–999	16–18	[37]
Ti-15Mo-2.8Nb-3Al	82	771	812	-	[55]
Ti–15Mo–3Nb–0.3O	82	1020	1020	-	[55]
Ti-23Nb-0.7Ta-2Zr	55	280	400	-	[51]
Ti-25Zr-20Nb-5Ag	61	1544	2184	22.4	[50]
(50Ti-50Zr)77-15Nb-8Mo	96	545	-	-	[56]
Ti-25Nb-5Sn-2Cr	68	314	-	-	[57]
Ti–5Cr–3Au–1Cu	~ 11.2	~520	~670	31	[58]
Ti–25Nb–6Zr–1.7Fe	61	598	1256	15.7	[59]
Ti–35Nb–5Ta–7Zr–0.4O	66	976	1010	-	[55]
Ti-23Nb-0.7Ta-2Zr-1.2O	60	830	880		[51]
Ti-27.5Nb-8.5Ta-3.5Mo-2.5Zr–5Sn	70	826	846	-	[60]

4. Importance of Porosity in Medical Implants

Porosity is a critical property of biomaterials used for medical implants that enables tissue integration, vascularization, and diffusion of nutrients and waste products [11, 61-63]. Implants made from metals, ceramics, or polymers often aim to mimic the porous architecture of natural bone through engineered surface modifications that create microscopic pores and channels. The size, density, interconnectivity, and orientation of pores within an implanted biomaterial dramatically impact its performance and determine outcomes in osseointegration, infection resistance, and long-term viability.

For bone implants such as joint replacement prosthetics, dental implants, and fracture fixation devices, porosity facilitates bone ingrowth during osseointegration. Pore sizes between 100-400 microns allow osteoblasts and mesenchymal stem cells to penetrate the implant surface, differentiate, and begin secreting new bone matrix [64-66]. Moreover, it has been noted that for an implant to effectively encourage the growth of bone, having an optimal porosity level ranging from 20% to 50% is essential [67]. Highly porous surfaces with three-dimensional (3D) interconnected networks of pores enable more rapid bone integration across the entire implant rather than isolated regions. The degree of porosity can be tuned during manufacturing through extrusion, injection molding, or 3D printing of the bulk biomaterial. Beyond osseointegration, porosity imparts critical advantages in infection prevention and antibiotic delivery for orthopedic implants. Studies found that porous surfaces help protect bones from competing bacterial colonization while allowing the migration of macrophages, lymphocytes, and nutrients to fight infection [68, 69]. Local antibiotic elution is also enhanced by porous channels and reservoirs that increase drug loading capacity [69]. For hip and knee arthroplasties, the built-in porosity serves as a safeguard, where chronic infection can necessitate implant removal.

The porous architecture that assists short-term bone ingrowth can also determine the long-term stability of an implant by

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allowing continued diffusion of nutrients and waste transport. Densely calcified, avascular interfaces between bone and implants often lead to fibrous encapsulation, isolating the implant over time. Such starvation causes cell death, loosening, and a potential fracture around the affected region. Implant designs and surfaces that facilitate highly vascular integration through interconnected porosity help prevent this scenario.

5. Titanium Scaffolds Design

Porous titanium scaffolds for bone implants and tissue engineering applications require careful design considerations across multiple vital parameters. The pore geometry, including overall topology (e.g., spherical, cubical, etc.) and pore size distributions, needs optimization based on mechanical requirements and intended bone and vascular ingrowth behavior. According to Van Bael et al. [70], Ti-6Al-4V scaffolds featuring hexagonal pores exhibited the most significant cell growth, which decreased in scaffolds with rectangular pores and further diminished in those with triangular pores, as illustrated in Figure 3. Hence, such discrepancy is attributed to the higher number of corners and the shorter distance between the two arches in the corners, especially noticeable in hexagonal pores. Consequently, cell bridging occurs more rapidly in hexagonal pores than in rectangular and triangular pores, where the struts are more widely spaced. Despite this, it was observed that the regulation of osteogenic differentiation in the cells was independent of their proliferation, and alkaline phosphatase (ALP) activity increased in triangular pores [70].

Manufacturing technique constraints, including solid-state foaming, powder sintering, electrodeposition, or additive manufacturing, inform achievable pore geometries [71]. For a given production method, fine-tuning processing factors specifically applied stresses, sintering profiles, laser scanning patterns, and post-treatments enable tailoring final porous structure metrics such as density, surface-area-to-volume ratios, interconnectivity, and anisotropy based on application needs. Robust characterization using scanning electron microscopy (SEM), micro-computed tomography, and related image analysis quantifies the resulting pore morphology down to the micron scale. Then, it feeds back into subsequent design revisions and process parameter improvements for the Ti scaffold architecture. Following these steps in scaffold design, optimized application-specific porous titanium implants can be constructed to promote bone ingrowth.

6. Effect of Pores on Mechanical Properties

The pore structure and distribution in a material significantly impact its mechanical properties and performance. Porosity, referring to the volume of pores within a material, influences strength, stiffness, durability, etc. For example, higher porosity tends to decrease the density of a material and reduce its strength and stiffness, which is due to pores representing discontinuities in the material structure that can serve as stress concentrators. However, some levels of controlled porosity can also benefit properties such as impact and energy absorption through mechanisms like crack deflection. An interconnected pore network could also influence fluid transport properties, particularly permeability and wicking action. The specific pore size distribution further influences the mechanical response. Zaharin et al. [72] produced titanium porous alloy implants with 57.48 % to 79.36 % porosity using laser powder bed fusion (LPBF). They observed that at around 70 % porosity, the mechanical properties resemble those of natural bone. Zhao et al. [73] produced octahedral porous scaffolds with two different porosities using LPBF. The findings indicate that scaffolds with a 500 μm pore size exhibit superior compression and fatigue properties, while those with a 1000 μm pore size and 77 % porosity are more suitable for cell adhesion. Yan et al. [73] manufactured Ti-6Al-4V ELI porous implants with an octahedral lattice structure using LPBF, and the results indicate that implants with 60 % porosity closely align with the mechanical properties of human bone. Zhang et al. [7] utilized electron beam powder bed fusion (EBPBF) to produce porous titanium structures with porosity ranging from 61.4 % to 79.7 %. Their findings reveal that the elastic modulus of these porous titanium structures is significantly lower, ranging from 91% to

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18

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96 %, compared to dense Ti alloys. Figure 4 provides concise summaries considering the impact of pore size and porosity on mechanical properties. Figure 4 (a) illustrates the correlation between pore size and yield strength, while Figure 4 (b) depicts the relationship between porosity and elastic modulus.

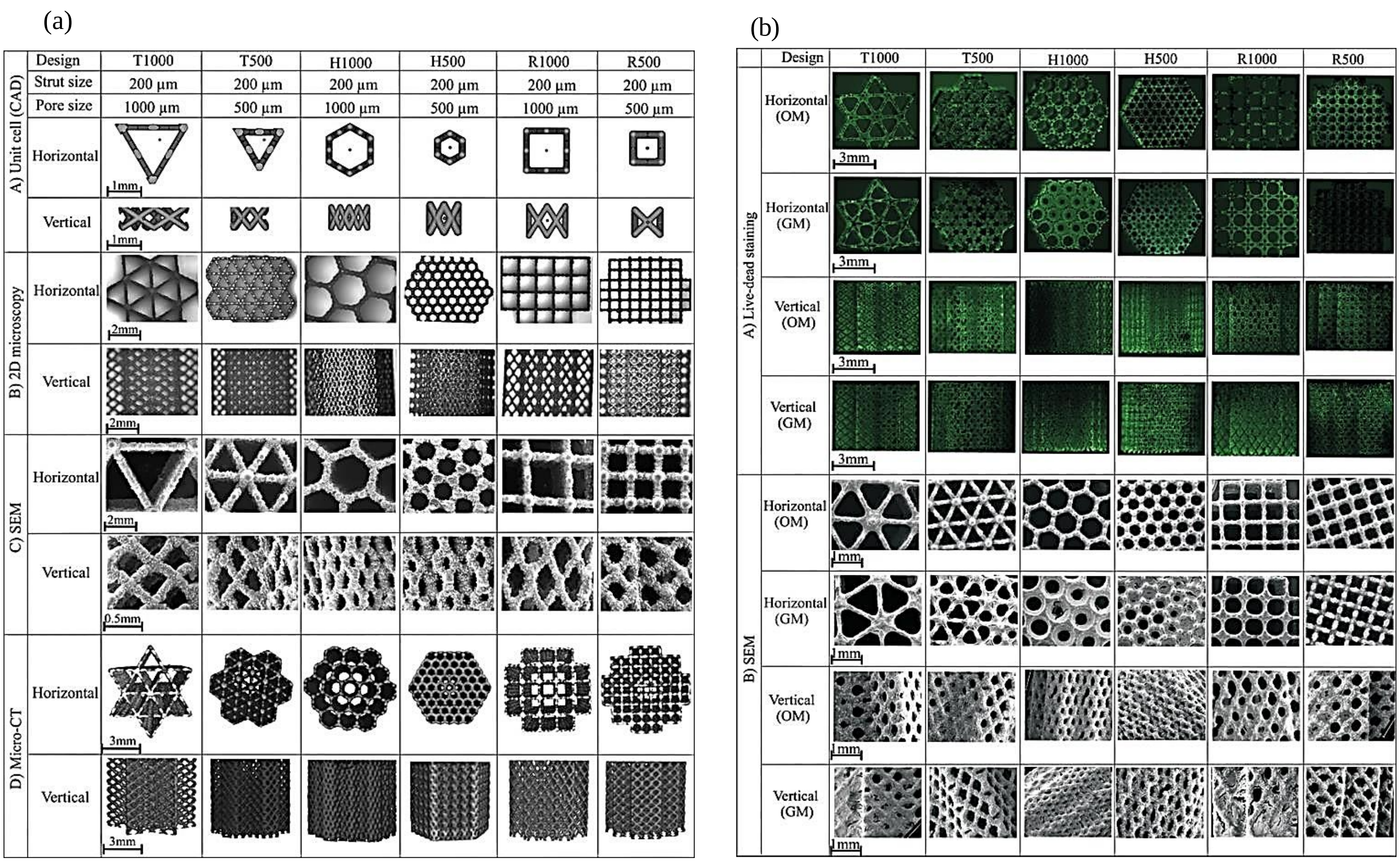

Figure 3. (a) Differently designed Ti-6Al-4V scaffolds and (b) representative live and/or dead staining images with green fluorescence for living cells as well as SEM images of osteoprogenitor cells on six Ti-6Al-4V scaffold designs for 14 days, indicating differences in pore occlusion among designs (T: triangular, H: hexagonal, R: rectangular) and culture media (OM: osteogenic medium, GM: growth medium) [70].

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18

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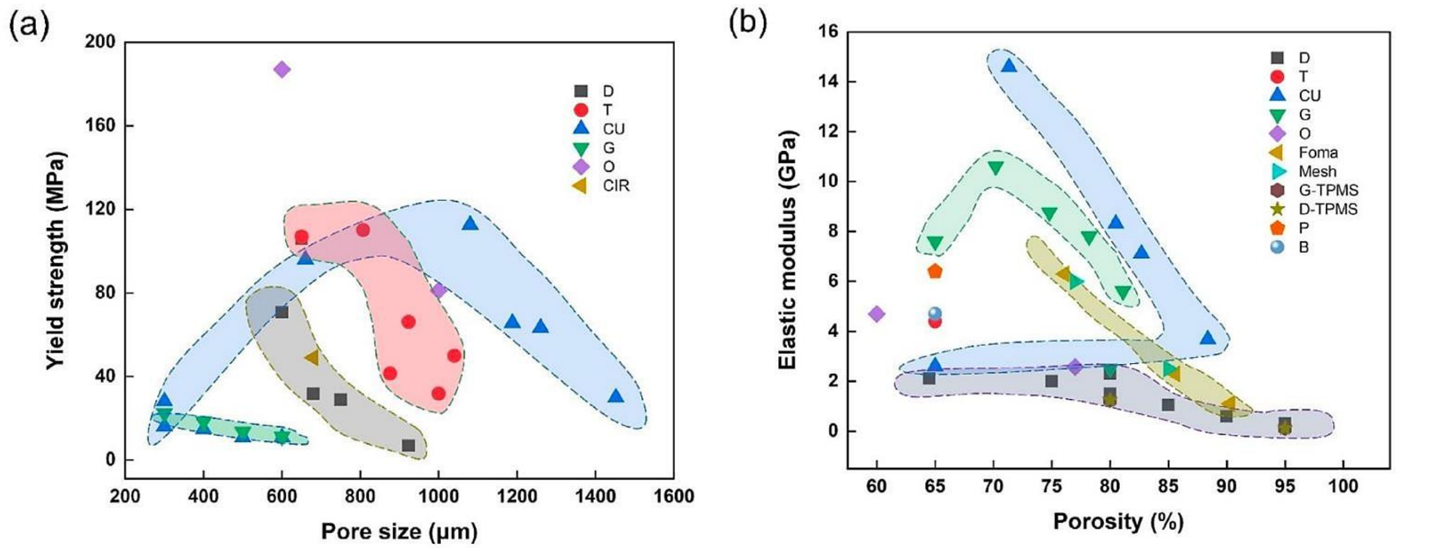

Figure 4. Correlation between pore size and mechanical properties: (a) Relationship between pore size and yield strength and (b) Influence of porosity on elastic modulus. The symbols denote the lattice structure shapes, such as Diamond (D), Gyroid (G), Primitive (P), and Cube (C). TPMS stands for triply periodic minimal surface [74].

7. Fabrication Techniques for Porous Titanium

Fabrication techniques for porous titanium play a pivotal role in tailoring the structure and properties of implants to meet specific biomedical requirements. Various methods are employed to create porous structures, including powder metallurgy, selective laser melting (SLM), electron beam melting (EBM), 3D printing, etc. These techniques allow precise control over pore size, distribution, and overall architecture, influencing mechanical strength, permeability, and biological integration. The selection of a fabrication method depends on the desired application and the balance between structural integrity and biological functionality in porous titanium implants for medical use. As depicted in Figure 5, fabrication techniques for porous titanium alloys include:

7.1. Powder Metallurgy (MP)

The powder metallurgy technique provides the advantages of precise control over porosity, the ability to create complex geometries, and improved mechanical properties due to eliminating some traditional manufacturing steps. For porous titanium alloys, PM utilizes powder particles of Ti alloys to create porous structures. The process involves powder blending, compaction, and sintering to form a porous scaffold [75, 76].

7.2. Selective Laser Sintering/Melting

A laser is selectively applied to Ti alloy powder layers, melting and solidifying them layer by layer. The additive manufacturing technique allows for precise control over porosity and structure. Figure 5 shows a schematic depiction elucidating the operational principles of selective laser sintering/melting (SLS/SLM) processes [77, 78].

7.3. Electrochemical Machining

Electrochemical machining (ECM) is a modern machining process that relies on removing workpiece atoms by electrochemical dissolution (ECD) based on the principles of Faraday.

7.4. Foam Replication Technique

A sacrificial template, often made of polymer foam, is infiltrated with a Ti alloy slurry. After solidification, the template is removed, leaving behind a porous titanium structure [79, 80].

7.5. Metal Injection Molding

Titanium alloy powder is combined with a binder material to

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18

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create a feedstock. Afterward, the feedstock is injected into a mold, forming a porous green part, which is then sintered to achieve the final porous structure [81, 82].

7.6. Plasma Spraying

Titanium alloy particles are melted in a plasma flame and deposited onto a substrate, creating a porous coating. Such a technique is often used for surface modification to enhance osseointegration [83].

7.7. 3D Printing

Various 3D printing techniques, like binder jetting or EBM, are employed to build porous titanium structures layer by layer, offering design flexibility and precision [84].

7.8. Solvent Casting Particulate Leaching

Solvent casting particulate leaching is an effective method for creating porous titanium structures. In this process, Ti metal powder is mixed into a polymer solution consisting of a solvent such as chloroform and a soluble polymer such as sodium chloride or polyethylene glycol (PEG). The mixture is cast into a desired mold shape and then dried so that the polymer forms a matrix composite with embedded Ti particles. The composite is then immersed in water, which dissolves and leaches out the salt or PEG particulates. The leaching of polymer particles leaves pores of controlled sizes and distributions within the Ti matrix. Properties like porosity percentages and pore interconnectivity can be tailored by adjusting the polymer-to-titanium particle ratio. After leaching, the porous titanium scaffold maintains the shape of the original mold. Thus, the solvent-casting particulate leaching approach provides a simple and inexpensive way of fabricating porous titanium with open and interconnected pores suitable for bone ingrowth needed in biological implants and tissue engineering scaffolds [85, 86].

7.9. Hydrothermal Synthesis

It involves a reaction between Ti precursors in an aqueous solution at elevated temperatures and pressures, forming porous titanium structures.

7.10. Fused Filament Fabrication

Fused filament fabrication (FFF) utilizes a continuous filament of Ti alloy, which is melted and extruded layer-by-layer to create a porous structure. The FFF technique is commonly used in desktop 3D printing [88, 89].

8. Challenges and Considerations in Using Porous Titanium

Utilizing porous titanium in various applications presents both promising opportunities and distinct challenges. The unique properties of porous titanium, namely its lightweight nature, excellent strength-to-weight ratio, and biocompatibility, make it an attractive choice for medical implants, aerospace components, and other engineering applications. However, several challenges need careful consideration. Achieving a balance between porosity and structural integrity is crucial, as excessive porosity may compromise mechanical strength. In addition, the fabrication techniques for porous titanium demand precision and control to ensure consistent pore size, distribution, and interconnectivity. Furthermore, issues related to long-term stability, corrosion resistance, and biological interactions need thorough examination, especially in the context of medical implants. Addressing these challenges will be pivotal in harnessing the full potential of porous titanium across diverse fields.

Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 1-18

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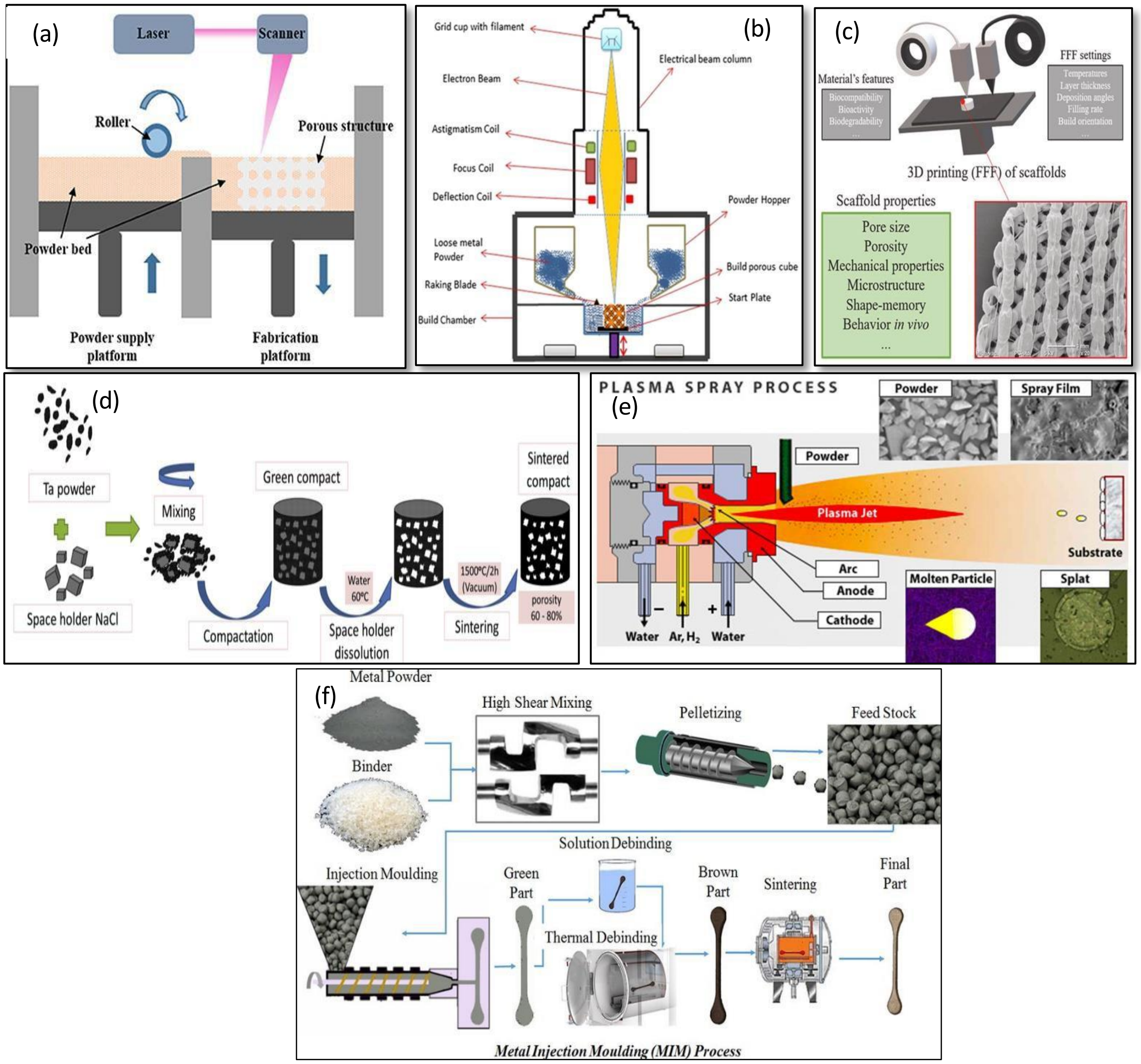

Figure 5. Illustration depicting the principals of: (a) selective laser sintering and selective laser melting [90], (b) electron beam melting [91], (c) fused filament fabrication (FFF) [92], (d) powder metallurgy [93], (e) plasma spraying [94], and (f) metal injection molding (MIM) [95].

9. Conclusions and Future Trends

The presented review has provided a perspective on the progress and future trends in porous titanium alloys for medical implants. Key findings and insights include:

- Porous titanium is promising for orthopedic and dental applications due to its adjustable porosity and pore structure that facilitates bone ingrowth, vascularization, and stable long-term osseointegration.

- Pore characteristics, including size, shape, interconnectivity, and gradients, significantly impact biological response, mechanical properties, and overall scaffold performance.

- Various advanced fabrication methods allow for the construction of porous titanium structures with controlled porosity and optimized pore networks tailored for specific bone regeneration requirements.

- Further optimization of pore architecture, surface engineering, alloy development, and manufacturing processes can enhance the integration and stability of porous titanium implants.

- Interdisciplinary efforts integrating biological factors with materials functionality and manufacturing innovations will be pivotal in unlocking the full potential of porous titanium biomaterials.

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Conflicts of Interest

The authors declare no conflict of interest.

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