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Additive Manufacturing of Porous Titanium Scaffolds for Enhanced Osseointegration

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ABSTRACT

Background: Solid titanium implants are far stiffer than cortical bone, promoting stress shielding, while additive manufacturing (AM) now enables porous titanium scaffolds with tunable pore architecture. Objective: This narrative review synthesizes published evidence on selective laser melting and electron beam melting of porous Ti-6Al-4V scaffolds for enhanced osseointegration. Methods: Peer-reviewed studies and reviews addressing AM process characteristics, pore design, mechanical trade-offs, and preclinical/clinical osseointegration outcomes were synthesized. Findings: Compressive modulus and strength fall approximately exponentially with porosity, and pore sizes of roughly 300-700 micrometers with 50-80% porosity are widely reported as a practical compromise between bone ingrowth and mechanical competence; triply periodic minimal surface and graded lattice designs further improve stress distribution and fatigue resistance. Animal studies confirm superior bone ingrowth and bonding for engineered porous scaffolds over solid or roughened surfaces, and porous titanium is now used clinically in acetabular and maxillofacial reconstruction, though outcomes vary by application. Conclusions: AM porous titanium is a validated but still-maturing strategy for improving osseointegration, requiring continued co-optimization of architecture, manufacturing quality control, and clinical follow-up.

Keywords: *additive manufacturing; porous titanium scaffolds; osseointegration; selective laser melting; stress shielding*

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Introduction

Titanium and its alloys, principally Ti-6Al-4V, have been the workhorse biomaterials of load-bearing orthopedic and dental implants for decades because they combine high strength, corrosion resistance, and favorable biocompatibility [1,2]. Wrought and cast titanium components are, however, fully dense, and their bulk elastic modulus (roughly 110-114 GPa) greatly exceeds that of cortical bone (10-30 GPa), a mismatch that concentrates load in the stiffer implant and shields adjacent bone from physiological strain [3,1]. This stress-shielding phenomenon promotes peri-implant bone resorption, aseptic loosening, and, ultimately, revision surgery. Powder-bed fusion additive manufacturing (AM) technologies-chiefly selective laser melting (SLM, also called laser powder-bed fusion) and electron beam melting (EBM)-have reframed this problem by making it possible to fabricate implants with fully interconnected, geometrically controlled porosity directly from a patient-specific or generic computer-aided design file, layer by layer, without the tooling constraints of casting or subtractive machining [4,2,5]. Because pore size, strut thickness, and unit-cell topology can be prescribed independently of external implant shape, AM offers simultaneous control over two previously conflicting requirements: an effective modulus low enough to reduce stress shielding and a pore network open enough to support vascularized bone ingrowth, or osseointegration [1,6].

This narrative review synthesizes the published literature on AM of porous titanium scaffolds for enhanced osseointegration, organized around three themes: the dominant fabrication techniques and how their process physics shapes achievable porosity; the resulting trade-offs among pore architecture, mechanical performance, and stress shielding; and the preclinical and clinical evidence that AM porous titanium actually improves bone-implant integration relative to solid or conventionally roughened surfaces. Recent design work extending beyond simple strut lattices to triply periodic minimal surface (TPMS) architectures, functionally graded porosity, and surface bioactivation is also considered, since these strategies increasingly define the state of the art [7,8,9].

Additive Manufacturing Techniques for Porous Titanium Scaffolds

SLM and EBM are the two powder-bed fusion processes most widely used to produce porous Ti-6Al-4V scaffolds [4,10]. In SLM, a high-power fiber laser selectively melts thin layers (20-60 micrometers) of pre-alloyed powder under an inert atmosphere, enabling fine features, smooth strut surfaces, and pore sizes down to roughly 300-500 micrometers with high geometric fidelity [2,11]. EBM instead uses a focused electron beam in a vacuum chamber and preheats the powder bed to 650-750 degrees Celsius, which reduces residual thermal stress and produces an in-situ annealed, more ductile microstructure, but at the cost of coarser resolution and a characteristically rougher, partially sintered strut surface from adhered semi-melted powder particles [12,11,4]. Both processes can reproducibly manufacture strut-based lattices (cubic, diamond, rhombic dodecahedron) as well as TPMS unit cells such as gyroid, primitive, and Fischer-Koch S surfaces; TPMS designs are increasingly favored because their smoothly curved, self-supporting surfaces avoid the stress concentrations found at sharp strut junctions and can be tuned to a target porosity through a single controlling parameter in the level-set equation [7,8].

Process parameters strongly influence whether a designed lattice is faithfully realized. Laser or beam power, scan speed, hatch spacing, and layer thickness govern melt-pool geometry and therefore strut diameter, surface roughness, and the incidence of unintended micro-porosity from incomplete fusion or gas entrapment [11,13]. Because the same nominal unit cell can print with a thicker or thinner effective strut depending on these settings, designed and as-built porosity routinely diverge, and process qualification against micro-computed tomography or gravimetric density measurement is now considered a prerequisite for translating a computational lattice design into a scaffold with predictable mechanical and biological behavior [13,11]. Reused powder feedstock, a practical concern for cost-effective production, has been shown to alter powder morphology and flowability enough to change scaffold density and mechanical response, underscoring the need for powder-batch qualification in EBM and SLM workflows [11]. Post-processing steps-stress-relief heat treatment, hot isostatic pressing, and chemical or electrochemical polishing to remove loosely adhered partially melted particles-are commonly required before porous titanium components can be considered clinically ready, since residual powder can shed as debris in vivo [13,5]. Direct energy deposition and non-AM alternatives such as space-holder sintering and foaming were used historically to create porous titanium, but they generally cannot match the reproducibility of pore interconnectivity and independent control of pore size and porosity that powder-bed AM provides [5,2].

Pore Architecture, Mechanical Properties, and Stress Shielding

The central design tension in porous titanium scaffolds is that increasing porosity to favor bone ingrowth simultaneously lowers strength and stiffness. Across the AM literature, compressive elastic modulus falls approximately exponentially with porosity, moving from near-bulk values around 100-110 GPa for fully dense Ti-6Al-4V toward the 0.5-20 GPa range of cortical and trabecular bone once porosity reaches roughly 60-80% [1,6]. Compressive yield and ultimate strengths decline in parallel, from several hundred megapascals in dense material to tens of megapascals at high porosity, which constrains how much porosity can be used in load-bearing regions before the scaffold falls below physiologically required strength [1,9]. Because bone ingrowth generally improves with larger, more open pores while mechanical competence favors smaller pores and thicker struts, most reviews converge on an effective pore-size window of roughly 300-700 micrometers and porosities of 50-80% as the practical compromise for trabecular-mimicking scaffolds, though the optimum depends on anatomical site and loading regime [9,14,1].

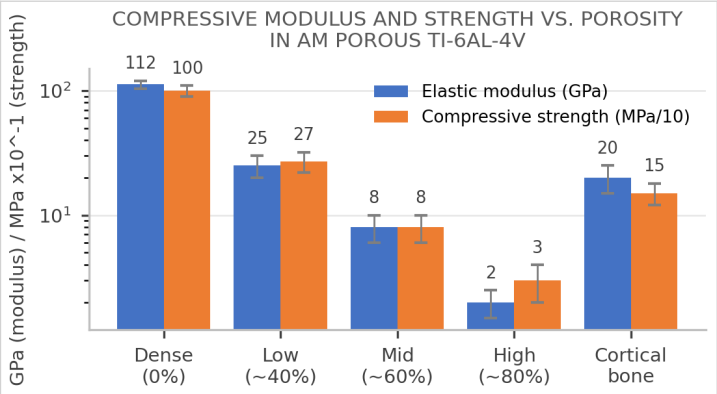
Comparison of the two dominant powder-bed fusion additive manufacturing techniques used to produce porous titanium scaffolds.

Feature	Selective Laser Melting (SLM)	Electron Beam Melting (EBM)
Energy source	High-power fiber laser	Focused electron beam
Build atmosphere	Inert gas (argon/nitrogen)	Vacuum
Typical layer thickness	20-60 micrometers	50-100 micrometers
Powder bed preheat	Minimal (room temperature to ~200 C)	High (650-750 C)
Residual thermal stress	Comparatively higher	Lower (in-situ annealing effect)
Achievable minimum pore/strut resolution	Finer (pores ~300-500 micrometers)	Coarser, rougher strut surface
Representative reference	[11], [4]	[12], [11]

Representative pore size, porosity, and mechanical property ranges reported for additively manufactured porous Ti-6Al-4V scaffolds relative to human bone.

Material/structure	Porosity (%)	Pore size (micrometers)	Elastic modulus (GPa)	Compressive strength (MPa)
Dense Ti-6Al-4V (wrought)	0	-	~110-114	~900-1100
AM porous Ti-6Al-4V (low porosity)	~30-50	300-500	~10-40	~150-400
AM porous Ti-6Al-4V (high porosity)	~60-80	500-700	~1-10	~20-100
Human cortical bone	-	-	10-30	~100-200
Human trabecular bone	50-90	-	0.5-3	2-20
Representative reference	[1]	[9], [14]	[1], [3]	[1]

Representative decline in compressive elastic modulus and compressive strength of additively manufactured porous Ti-6Al-4V with increasing porosity, illustrating the approach toward the stiffness range of cortical and trabecular bone at high porosity (values compiled from ranges reported in [1] and [3]).



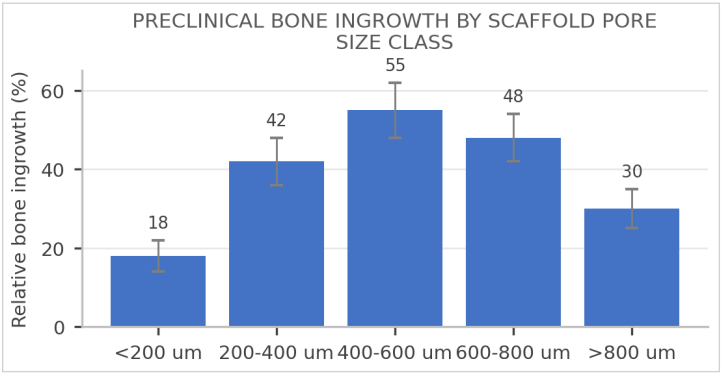
Unit-cell topology modulates this trade-off independently of porosity alone. TPMS gyroid structures distribute stress more uniformly than strut-based cubic or diamond lattices of equivalent porosity, reducing local stress concentrations that would otherwise seed fatigue cracks, and comparative studies report improved cytocompatibility and mechanical stability for gyroid over Fischer-Koch S geometries at matched porosity [7]. Anisotropic or axially graded TPMS designs, in which strut or wall thickness varies through the scaffold thickness or along the loading axis, can further tailor longitudinal and transverse mechanical response to approximate the anisotropy of native bone [8]. Functionally graded porosity-dense at the bone-implant interface, more open toward the scaffold core-has been proposed specifically to balance immediate mechanical stability against long-term ingrowth and to redistribute strain more favorably across the implant-bone construct, and finite-element and fatigue analyses indicate that scaffolds allowing partial bone ingrowth experience markedly reduced predicted stress compared with fully porous, non-integrated lattices, highlighting that fatigue safety is not fixed at the time of implantation but evolves as bone forms within the pores [15]. Because cyclic, physiological loading rather than monotonic compression ultimately governs implant survival, fatigue behavior of porous Ti-6Al-4V remains comparatively understudied relative to static mechanical characterization, and reviews note that fatigue strength can fall disproportionately with porosity relative to static strength, making conservative, ingrowth-aware design essential for permanent load-bearing applications [15,1].

Osseointegration Outcomes: Preclinical and Clinical Evidence

Preclinical animal studies provide the strongest direct evidence that AM-controlled porosity enhances osseointegration relative to solid or surface-only roughened titanium. In a rabbit femoral defect model, SLM-fabricated porous titanium scaffolds supported new bone formation and direct bone-implant contact within the pore network over several weeks of healing, consistent with pores functioning as conduits for vascular and osteogenic cell infiltration [16]. A systematic in vivo comparison of additively manufactured implants with varying pore sizes found that intermediate pore diameters (roughly in the several-hundred-micrometer range) maximized bone ingrowth compared with both smaller, ingrowth-limiting pores and larger, mechanically compromised pores, reinforcing the pore-size window identified from mechanical and topological analyses [17].

In a rabbit model of dental implant anchorage, SLM-produced multi-rooted porous implants achieved substantially higher bone volume density and bone-implant bonding strength than implants treated only with resorbable blasting media, directly demonstrating that engineered internal porosity outperforms surface roughening alone for this outcome [18]. EBM-fabricated three-dimensional mesh titanium scaffolds used for mandibular reconstruction similarly promoted osseointegration and vascularized tissue ingrowth through their open-cell architecture in animal testing [12].

Reported bone ingrowth/bone-implant bonding outcomes as a function of scaffold pore size class in preclinical additive manufacturing studies, showing reduced ingrowth at very small and very large pore sizes and a favorable window at intermediate pore diameters (compiled from findings in [17] and [9]).



Beyond hip reconstruction, three-dimensional-printed titanium mesh scaffolds and dental implant systems incorporating porous surfaces have moved into prospective multicenter follow-up, reflecting growing surgeon confidence that AM porosity can be manufactured with sufficient consistency for regulatory approval and routine clinical use [19,2]. Clinical translation is most mature in joint reconstruction and increasingly visible in maxillofacial and dental applications. Porous, fully three-dimensional-printed titanium acetabular components and augments are now used clinically for complex acetabular bone loss in revision hip arthroplasty, where their high-porosity, high-friction surfaces are intended to promote biological fixation in compromised host bone, and intermediate-term follow-up series report favorable functional and radiographic integration outcomes [20]. AM titanium has also been adopted for custom cranial and maxillofacial reconstruction and for surgical planning devices, exploiting both patient-specific geometry and porous surface design to encourage soft- and hard-tissue integration [19]. Clinical performance is not uniformly favorable, however: a six-year follow-up of custom three-dimensional-printed subperiosteal titanium implants found that only about one-quarter of cases avoided complications such as frame exposure or device mobility, indicating that porous AM titanium alone does not guarantee successful long-term integration in all anatomical or loading contexts and that patient selection, surgical technique, and design refinement remain critical [21]. Taken together, the preclinical and clinical record supports engineered porosity as a genuine enabler of osseointegration when pore architecture, mechanical loading, and surface characteristics are co-optimized, while cautioning against treating porosity as a universal solution independent of application-specific biomechanics [21,5].

Conclusion

Additive manufacturing has converted porous titanium from a laboratory curiosity into a clinically deployed strategy for

reducing stress shielding and promoting osseointegration in orthopedic and dental implants. SLM and EBM each offer distinct combinations of resolution, surface texture, and residual stress that influence scaffold fidelity and biological performance, while advances in TPMS and functionally graded lattice design continue to refine the balance between mechanical competence and pore-driven bone ingrowth [4,7,15]. The convergent evidence across in vivo models and early clinical series indicates that pore sizes in the range of roughly 300-700 micrometers and porosities of 50-80% represent a practical design envelope, though fatigue behavior under physiological cyclic loading and long-term clinical durability remain comparatively less well characterized than static mechanical and short-term ingrowth outcomes [1,9]. Future work integrating patient-specific graded architectures, verified powder and post-processing quality control, and longer clinical follow-up will be needed to fully realize the promise of additively manufactured porous titanium scaffolds for durable osseointegration [13,6].

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Kask K conceived the review, conducted the literature search, and drafted the manuscript. Gallagher S contributed to the literature screening and technical framing and critically revised the manuscript for important intellectual content. Nicolae D contributed additional context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

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