

Recent Advances in Additive Manufacture of Orthopaedic Implants: Materials, Processes, and Clinical Applications

ABSTRACT

Aim: This study reviews recent advancements in the additive manufacturing (AM) of orthopaedic implants, with particular focus on Ti-based alloys, bioresorbable metals, porous structures, implant integration, and clinical case studies.

Study Design: A comprehensive literature review of developments in materials and processes utilized in additive manufacturing for orthopaedic applications, covering literature published between 2020 and 2025.

Methodology: The review employed a systematic literature search using databases including Google Scholar, Scopus, PubMed, and Web of Science. Studies focused on additive manufacturing of orthopaedic implants, especially those investigating titanium-based alloys, magnesium and zinc-based bioresorbable metals, and their mechanical and biological performance in clinical applications.

Results: Findings suggest that additive manufacturing significantly enhances the precision and functionality of orthopaedic implants, with Ti-6Al-4V emerging as the most studied alloy. Bioresorbable materials like Mg and Zn alloys show potential in temporary implant applications, particularly in paediatric and trauma cases. Porous structures optimized through AM methods like selective laser melting (SLM) and electron beam melting (EBM) facilitate osseointegration and bone ingrowth. Case studies report promising clinical outcomes in hip, knee, and spinal implants.

Conclusions: Additive manufacturing is revolutionizing orthopaedic implant production through tailored material design, improved patient-specific structures, and better clinical integration. Despite these advances, more in vivo trials and long-term data are necessary to standardize these innovations in routine orthopaedic practice.

Keywords: Additive manufacturing, orthopaedic implants, Ti-based alloys, bioresorbable metals, implant integration, porous structures..

1. INTRODUCTION

Orthopaedic implants are now important tools in modern medicine for the management of bone fractures, joint degeneration, spinal injury, and congenital defects [1]. Hip and knee prostheses, spinal cages, bone plates, and screws are a few of the medical devices utilized for replacing or augmenting damaged skeletal structures so that patients can once again move

about freely and improve their lifestyle [1, 2]. Traditionally, orthopaedic implants have been made using subtractive manufacturing methods such as machining, forging, and casting that used to impose design limitations, reduce the efficiency of material use, and limit customization [3, 4]. Because of growing patient-specific implant needs and rapid prototyping demands, the healthcare industry has turned more towards additive manufacturing (AM), a groundbreaking technology where digital models are used to create complex geometries layer by layer [5].

Additive manufacturing, or 3D printing, has opened a new horizon for the design and production of orthopaedic implants. AM processes such as Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Binder Jetting allow for precise control of microstructures, porosity, and mechanical properties. Unlike traditional manufacturing processes, AM can create intricate lattice structures that mimic the trabecular bone structure with great precision, giving rise to better mechanical compatibility and better osseointegration [6]. Besides, AM can also be utilized to create personalized implants that are custom-made to fit the anatomy of a specific patient based on computed tomography (CT) or magnetic resonance imaging (MRI) data—radically increasing surgical accuracy and patient recovery [7, 8].

Material selection is a significant component of orthopaedic implant design, and new advances have been driven by the use of Ti-based alloys, bioresorbable metals, and porous metallic scaffolds. Titanium and its alloys, especially Ti-6Al-4V, have long been the material of choice in orthopaedics due to their favorable characteristics of possessing high corrosion resistance, low weight, good biocompatibility, and mechanical properties close to those of cortical bone [9]. AM enables Ti-6Al-4V to be structurally sound and processable, and therefore appropriate for the manufacture of load-bearing implants. Moreover, lattice optimization and surface finishing can ensure such implants promote biological fixation and reduce the likelihood of loosening of the implant with time [10].

Studies on bioresorbable metals such as magnesium (Mg) and zinc (Zn), and their alloys, have gained momentum since they are able to degrade innocuously within the body once they have served their structural role. These materials have unique applications in provisional use, such as fixation hardware for fractures and paediatric orthopaedics, where long-lasting implants might need revision surgery. The biodegradable nature of Mg and Zn alloys also initiates bone regeneration, offering twofold advantages of mechanical fixation and biological reconstruction [11]. However, their rate of degradation must be well managed to correspond with the timescale for healing of tissue—a feature in which AM is able to make a particular

contribution through the ability to customize microstructure at the design stage [12].

Orthopaedic device porosity serves a number of functions: it reduces the mismatch in elastic modulus between implant and native bone (and thus reduces stress shielding), facilitates transportation of nutrients, and permits bone tissue in-growth. Using AM, porosity within the implants can be created as graded porosity, wherein the external surface imitates cortical bone to support load, and the interior imitates cancellous bone to encourage biological integration [8].

Clinical applications of AM-fabricated implants are no longer confined to experimental models and lab studies. Several successful case reports have been observed in the field of spinal reconstruction, the repair of pelvic fractures, mandibular reconstruction, and joint replacement. Custom implants have been used in the treatment of complex anatomical deformities, where off-the-shelf devices failed to provide a solution. For instance, in spinal surgeries, 3D-printed intervertebral cages have improved implant-host interface integration, reduced surgery time, and reduced infection risk [13]. In maxillofacial surgery, patient-specific titanium implants restored facial symmetry and function in post-trauma reconstruction, proving the clinical efficacy of AM in personalized medicine [6].

Despite these positive advances, wide-ranging acceptance of AM in orthopaedics is stymied by several challenges. Among them are the need for strong regulatory frameworks, prolonged clinical correlations, and consistent protocols for design, testing, and post-processing. Material heterogeneity, residual stress, and cytotoxicity potential from unprocessed powders or alloying elements remain ongoing concerns [9]. Cost-effectiveness and scalability are also key considerations towards orthopaedic mainstreaming of AM technologies, especially in low-resource environments. Yet, the potential of additive manufacturing to revolutionize the orthopaedic implant industry cannot be overlooked. Merging material science, computational modeling, and clinical acumen, AM provides a platform for continuous innovation with the aim to enhance patient outcomes [10]. Research are now focused on multi-material printing, smart implants that can monitor healing, and bioactive coatings that release therapeutic pharmaceuticals heralding an era of bio-integrative and functional implants.

While numerous studies have investigated the individual components of AM for orthopedic applications, few have comprehensively synthesized these parameters with long-term clinical outcomes. Clinical trials tend to be small in nature or provide only case-specific results without comparative analysis for different materials and patient populations. Besides, the employment of

bioresorbable materials in AM is new, and there is scarce in vivo information on the degradation of such materials and their biological impact. There is insufficient research connecting porous structure design to precise healing factors or patient groups. It is with such resolution that the current review attempts to set the interdisciplinary equilibrium involving the most recent advances in material synthesis, manufacturing processes, and clinical assessment of orthopaedic implants manufactured via AM.

2. METHODOLOGY

The strategy in this review was based on a systematic and structured literature search to obtain the most relevant, up-to-date studies on additive manufacturing (AM) applications in orthopaedic implants. The objective was to identify high-quality, peer-reviewed articles exploring the designing and clinical relevance of Ti-based alloys, bioresorbable metals, porous structures, and implant integration, particularly in orthopaedic usage. The search strategy was for articles between the years 2020 and 2025 since the timeframe is the most recent advancements in AM technologies and clinical applications.

The literature search was conducted among four established scholarly databases: Google Scholar, Scopus, PubMed, and Web of Science. Specific search terms were combinations of the following keywords: "additive manufacturing," "orthopaedic implants," "3D printing," "Ti-6Al-4V," "bioresorbable metals," "porous structures," "implant osseointegration," and "clinical applications." Boolean operators and database-specific filters were applied to refine the results so that only English-language studies that were directly relevant to the subject matter of orthopaedics were included. This initial search yielded a total of 98 records: 35 in Google Scholar, 25 in Scopus, 22 in PubMed, and 16 in Web of Science.

Duplicates were eliminated, and 72 unique records remained. The abstracts and titles of these records were stringently screened for applicability. Studies that focused on dental implants, cardiovascular applications, or cosmetic reconstruction were excluded since they were not the main theme of orthopaedic additive manufacturing. In addition, articles published before 2020 or those that included no original research—editorials, comments, or purely theoretical articles—were excluded. Screening resulted in the exclusion of 52 articles. The final 20 full-text papers were then filtered for eligibility based on more specific inclusion criteria: explicit focus on the use of AM methods to produce orthopaedic implants, exploration of either Ti-based alloys or biodegradable metals, exploration of porous structural design, and/or clinical evaluation of implant function.

Of these, 12 articles were selected for qualitative analysis. These were valuable sources of information on novel AM materials, manufacturing processes, mechanical performance, and use in clinical orthopaedic practice. Some of them included case studies demonstrating the practical application of AM implants to spine, hip, and limb procedures. Others showed comparative analysis between AM-manufactured and conventional implants, detailing improvements in patient-specific customization, osseointegration, and recovery.

Despite the systematic approach taken, there are certain shortcomings to this review. First, the selection was restricted to English-language articles, and thus, some good-quality work based on other languages may have been left out. Second, due to the nature of the topic and the continuous technological progress, some very recent studies—especially those still in peer review or available as preprints—were not captured. Third, efforts were made to cover a variety of AM technologies and material breakthroughs but the field is broad and dynamic, and some suitable areas may not have been fully covered. Lastly, the qualitative nature of this review implies that the results are based on thematic synthesis rather than quantitative meta-analysis, so the potential to generalize findings in large populations or in clinical trials is limited. Yet, the methodological rigor that is adopted in literature search and selection ensures that the review is comprehensive, current, and indicative of the significant progress achieved in additive manufacturing of orthopaedic implants in recent years.

3. RESULTS AND DISCUSSION

This section combines findings from the shortlisted studies concerning new advancements of additive manufacturing (AM) of orthopaedic implants, and four significant topics are chosen as focus areas: material innovations, structural design, manufacturing processes, and clinical translation. Using thematic analysis on these 12 shortlisted articles, future trends, practical implications, and current limitations were identified.

3.1 Material Innovations in Additive Manufactured Orthopaedic Implants

Material innovation lies at the core of AM-based orthopaedic implants, and it directly affects biomechanical compatibility, osseointegration, corrosion resistance, and implant longevity. Within metallic systems, titanium and titanium alloys are most studied due to their favorable properties. Classic Ti-6Al-4V was the standard reference, yet recent advances indicate a new generation of titanium alloys. Ti-Zr-Nb alloys manufactured by AM have mechanical properties closer to those of natural bone, reducing stress shielding—a factor for long-term implant stability. Sergienko et al. [14],

reported that these alloys have improved mechanical strength and corrosion resistance, which are critical for load-bearing implants in the joint and long bones. Additionally, their reduced elastic modulus reduces risk of periprosthetic fracture by creating a more similar biomechanical response of host tissue.

Silicon-modified Ti–Nb–Zr–Si alloys have also proved to be suitable potential alternatives. Bordbar-Khiabani and Gasik [15], proved silicon additions for promoting stable passive film formation and osteoblast adhesion, proving to have an excellent potential for biointegration. Furthermore, the alloys exhibit improved fatigue resistance, which is a consideration of importance for dynamic skeletal devices like spinal and hip implants.

Additionally, bioresorbable metals such as magnesium and zinc have opened up avenues for temporary implants. However, Mg–Ca alloys offer the advantage of progressive degradation along with acceptable mechanical strength during the initial-stage bone regeneration (See Figure 1).



Figure 1: The Spot for Temporary Bone Implants

Touret et al. [16] highlighted good degradation kinetics and higher cellular response and therefore are suitable for trauma or pediatrics where permanent implants can cause long-term complications. Zinc-based alloys, particularly Zn–Mg composites, possess antibacterial properties and lower corrosion rates, which are useful in preventing implant-related infection and prolonging support for the period of bone healing. Shaikh et al. [4], and Ye et al. [17] demonstrated that the alloys enhance pre-osteoblast proliferation and ensure stable mechanical properties for extended periods, which can ultimately minimize the need for secondary surgeries.

3.2 Optimization of Porous and Lattice Structures

The ability to customize internal geometries with AM has led to a paradigm shift in the design of orthopaedic implants. The lattice and porous structures, besides enhancing osseointegration, also offer modulated mechanical properties that reduce stress shielding to a minimum. Traditional manufacturing methods cannot replicate such complex structures with the same degree of precision. Zhai et al. [18], performed a meta-analysis of porous titanium cages for ACDF procedures and established higher fusion rates, reduced implant subsidence, and improved preservation of spinal alignment compared to conventional PEEK devices. These outcomes were largely attributed to the microarchitecture of AM designs, which enable improved load transfer as well as cell migration.

Wang et al. [19], validated these findings in multilevel cervical fusion procedures. Their study showed that 3D-printed titanium cages provided earlier radiographic fusion and improved postoperative stability. The implants also shortened recovery time through increased osseointegration. Finite element modeling plays a central role in the design of such porous constructs. Fatemi et al. [20] demonstrated how gradient porosity reduces the focal point of stress concentrations and improves the distribution of loading. This biomimicry reduces stress shielding occurrence and improves implant survival. In addition to this, pore size optimization (300–600 μm) and optimal porosity content (>50%) have been determined to improve vascularization and diffusion of nutrients needed for successful bone in-growth [21]. Real-time adjustment of porosity and structural parameters to personal anatomical requirements by employing advanced software tools and patient imaging data guarantees enhanced accuracy for personalized implants.

3.3 Advances in AM Processes and Techniques

The stability and quality of orthopaedic implants fabricated by AM highly depend on the procedure followed during manufacturing. The best current techniques for metal additive manufacturing are Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Both of the processes have advantages in various perspectives; including resolution, build rate, and thermal management (See Figure 2).

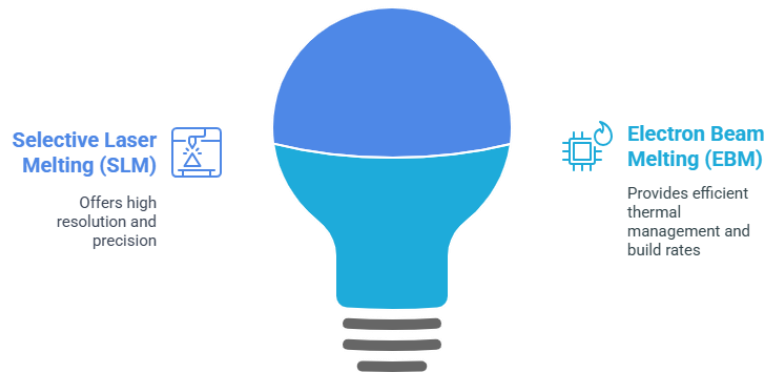


Figure 2: Metal Additive Manufacturing Techniques

Tshephe et al. [22] addressed the relative performance of SLM and EBM for β -Ti–Nb alloys. SLM boasts high-resolution control and can be used to create intricate structures like trabecular lattices but is prone to generate more residual stress. EBM creates components with lower residual stress and better fatigue properties due to the high-temperature build environment, and therefore it is most appropriate for bulkier load-carrying components. Binder jetting has also drawn interest as an inexpensive, scalable technology for the production of porous implants. It was noted by Jia et al. [23], that although binder-jetted implants are surface-rougher than cast implants, sintering following treatment improves their mechanical integrity and allows interconnective porosity to facilitate the migration of cells. However, sintering processes require further optimization to maintain consistency in batches.

Hybrid AM processes potentially circumvent some of the shortcomings of single-step AM. Festas et al. [24] demonstrated that adding subtractive post-processing to AM created hip implants with improved surface smoothness, more dense dimensional tolerances, and improved patient-specific conformity. Such approaches also reduce time spent on manual post-processing, which is relevant to scalability and clinical acceptance. Post-processing remains a critical component of the AM process [4]. Processes such as hot isostatic pressing, surface polishing, anodizing, and bioactive coating are required to reduce surface imperfections, remove any residual powder, and ensure optimal implant-tissue interaction.

3.4 Clinical Translation and Case Studies

Additive manufacturing has successfully transitioned from the lab bench to the operating room. Increasingly, AM implants are appearing in actual clinical cases with promising outcomes. Singh et al. [25] evaluated the result of 25 SLM-produced patient-specific acetabular cups. Patients experienced significant improvement in mobility, pain reduction, and immobilization of the implant during the 18-month follow-up. Design flexibility to create implants tailored to complex bone defects ensures better anatomical adaptation and reduced intraoperative time.

Liu et al. [26], conducted a randomized clinical trial of 3D-printed titanium versus PEEK cages in lumbar interbody fusion. The titanium group had higher fusion success, better disc height restoration, and reduced implant migration rates. These benefits were primarily attributed to the porous structure that provided enhanced bone-implant interface stability. AM has enabled the development of implants used for mandibular and maxillofacial reconstruction within the craniofacial community. Long et al. [27], reported that individually crafted titanium implants restored not only structural function but also facial symmetry and masticatory function in trauma patients. Customization reduced intraoperative corrections and resulted in improved aesthetic outcomes. These clinical experiences demonstrate that AM is not just possible but also superior in a majority of complex cases when conventional implants fall short. Additional longitudinal studies are still needed to assess long-term implant performance, wear-pattern, and biological compatibility in a broad array of patient populations.

3.5 Challenges and Future Prospects

Aside from its possibility of revolutionizing orthopaedics, AM also faces a number of challenges. The regulatory approval processes remain geared towards considering the quirks of AM, including the variability of powder reusability, build consistency, and microstructural homogeneity. Choudhary et al. [28], pointed out the limitation that the lack of standardization among AM platforms hinders mass adoption in the clinic. Material purity and the cytotoxic potential of unprocessed powders or alloying elements remain concerns. Also, the cost of AM equipment, servicing, and post-processing is likely to exclude it from low-resource health care facilities.

To address these challenges, scientists are studying sophisticated monitoring systems incorporated into implants. Pannu et al. [29], emphasized the design of intelligent orthopaedic implants that have sensors providing real-time information regarding healing, loading, and infection markers. Data-backed implants can revolutionize post-operative care and personalize rehabilitation protocols. Another trend on the horizon is the use of bioactive and drug-eluting coatings. Antibiotic or osteogenic agent-infused coatings can minimize the risk

of infection and promote bone growth. Future workflows for AM could include incorporating coating procedures in the actual printing process, providing multifunctional implants that are therapeutic in nature.

In addition, advances in multi-material printing would enable composite implants with strength, degradability, and biological activity. Articulation with artificial intelligence for optimization of implant design and virtual planning of surgery is also becoming more common, potentially offering more precise and predictive outcomes.

4. CONCLUSION

Additive manufacturing (AM) has emerged as an ideal method in orthopaedic implant design, offering unprecedented potential for patient-specific design, structural optimisation, and material tailoring. Technological advances in titanium alloy and bioresorbable alloys have enhanced biomechanical compatibility and biological performance, and incorporation of porous and lattice architectures has enhanced osseointegration and reduced stress shielding. Process improvements in AM e.g., Selective Laser Melting, Electron Beam Melting, and hybrid fabrication have optimized implant accuracy, surface finish, and scalability. Clinical experience increasingly validates the clinical efficacy of AM-fabricated implants in orthopaedic and maxillofacial surgery, particularly for complicated or anatomically challenging cases. However, regulatory ambiguity, cost, material standardization, and long-term safety remain intrinsic barriers to widespread application. Continued investigation into smart implants, bioactive coatings, and integrated design platforms promises to expand the clinical applications of AM as a foundational component in the future of personalized and functional orthopaedics.

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