



Review Paper

Advancements in Orthopedic Implants: A Comprehensive Review of Selective Laser Melting Technology in Manufacturing Human Prosthetics

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ABSTRACT

The advancement of Additive Manufacturing (AM) technologies, particularly Selective Laser Melting (SLM), has significantly influenced the development of orthopedic, dental, and spinal implants. This paper provides a comprehensive review of the role of SLM in enhancing the properties of implants, including biocompatibility, wear, fatigue and corrosion resistance. SLM offers significant advantages such as customization, design flexibility, and the ability to produce intricate geometries with precise porosity, which plays a critical role in osseointegration and bone regeneration. This paper examines various materials used in implant manufacturing, such as titanium alloys and Co-Cr-Mo alloys, and discusses their mechanical and tribological properties, emphasizing their suitability for use in load-bearing implants. Furthermore, the impact of surface texture, roughness, and porosity on the performance and longevity of implants is explored, highlighting how these factors influence mechanical properties, cell attachment, and overall integration with human tissue. In summary, SLM has emerged as a powerful method for producing orthopedic and dental implants with tailored mechanical properties, improved bioactivity, and enhanced biocompatibility, making it a promising tool for the future of implantable medical devices. In this study, 2D drawings and suggestions for further research have been provided to future researchers in various sections.

Keywords: *Selective Laser Melting, Additive Manufacturing, Dental Implants, Orthopedic*

I. INTRODUCTION

A. Selective Laser Melting & Additive Manufacturing, A Brief Overview

The advancement of 3D printing technologies has resulted in the enhancement of different techniques. Stereolithography (SLA) is recognized for its high accuracy in manufacturing and the utilization of photopolymer resins. Fused Deposition Modeling (FDM) is more economical because it employs thermoplastic materials. Selective Laser Sintering (SLS) improves the strength of parts by leveraging lasers to fuse polymeric or metallic powders. Selective Laser Melting (SLM) creates components with considerable

density and durability by completely melting metal powder. Binder Jetting allows for the fabrication of intricate parts with specific internal designs through the use of adhesive substances. Electron Beam Melting (EBM) generates precise and robust metal components utilizing electron beams.

All these techniques are classified under Additive Manufacturing (AM). In AM, the complete object is formed by layering materials, in contrast to conventional techniques where material is removed from a larger block. Each technique such as SLA, FDM, SLS, SLM, Binder Jetting, and EBM incorporates a layer-by-layer addition to create a final 3D object. The primary benefit of AM is its capability to produce geometrically intricate objects with high precision and minimal material waste, a characteristic that all these techniques possess.

Traditional methods for dental prosthetics encompass casting and Computer-Aided Design and Manufacturing (CAD/CAM), which utilize CNC machines to carve materials in a subtractive fashion. Nonetheless, Selective Laser Melting (SLM), an AM technique that constructs parts layer by layer, is progressively being adopted in body implants (Leordean et al., 2015a). SLM, an advanced developing additive manufacturing technology, offers an excellent platform for fabricating titanium components (Zhang & Attar, 2016). Additive manufacturing of implants presents advantages such as customization, adaptability, design flexibility, and the capability to alter chemical and physical parameters. The limitations include achieving surface quality and dimensional precision, as well as the expense of equipment and materials (Revilla-León et al., 2021). Implants made through AM feature attributes like controlled porosity and micro- and nanoscale surface roughness, facilitating new bone growth and improving the osseointegration process (Pen et al., 2016; Hyzy et al., 2016).

V4Al6Ti alloy can be generated using additive manufacturing techniques and shows similar mechanical and tribological properties to those produced through traditional methods. Even when the properties between SLM-fabricated samples and conventional techniques are alike, SLM may be the preferred option due to its design flexibility and production adaptability, particularly for intricate designs, enhanced quality control requirements, or low to medium production runs (Vilhena et al., 2020). Among the many techniques available, Selective Laser Melting (SLM) is an appropriate choice because of its compatibility with titanium and its capacity to maintain configurations with dimensional accuracy within a few hundred micrometers (Fukuda et al., 2011). However, products made using SLM often display non-equilibrium microstructures and slight surface imperfections due to sharp thermal gradients and rapid cooling rates during the laser melting process. An optimal surface exhibiting a hydrophilic, rougher, and more uniform texture has been created through annealing to improve the biocompatibility and osseointegration of SLM-derived substrates. This straightforward, economical, and effective technique typically resolves the surface flaws (Wang et al., 2016).

The creation of a femoral head implant using the selective laser melting technique from porous titanium alloys is examined. The findings indicated that the innovative multi-structural orthopedic endoprosthesis introduced in this study satisfied the biocompatibility standards because of its material (titanium alloy Ti6Al7Nb), design, and structures featuring spatial porosity (Leordean et al., 2015b).

The EBM and SLM methods have been shown to be effective additive manufacturing technologies using metal or alloy powders: particularly Ti-6Al-4V atomized powders. The findings demonstrated that biomedical implants created by SLM and EBM methods can possess simple geometries along with a microstructure that may improve mechanical performance to a level similar to or surpassing that of wrought or cast Ti-6Al-4V items (Murr et al., 2009).

Cu5-V4Al6Ti alloys show promise for biomedical uses due to their favorable antibacterial characteristics. The generation of Cu2Ti can bolster the strength of the material and enhance the microhardness of the titanium-copper alloy. The Cu5-V4Al6Ti alloy has shown adequate wear resistance in a variety of wear conditions and displayed suitable resistance to corrosion. Incorporating copper contributed to reducing the melting point of the alloy and improved its strength and overall properties (Zong et al., 2020). Another significant attribute is the blend of low density, low Young's modulus, solid mechanical properties, high corrosion resistance, and remarkable biocompatibility, rendering titanium alloys among the most sought-after materials for biomedical implant applications (Zhang & Attar, 2016). The combination of low density, low Young's modulus, good mechanical properties, high corrosion

resistance, and excellent biocompatibility renders titanium alloys among the most sought-after materials for biomedical implant applications (Han et al., 2022).

II. PROSTHESES MADE USING THE SLM METHOD

In this section, the materials, instruments, and devices used should be presented clearly and in detail. Experimental setups, preparation steps, and analysis methods should be described in a way that ensures the reproducibility of the study. The specifications of the devices, equipment, or software used should be stated whenever possible. Standard solutions can be briefly summarized if appropriate sources are cited; however, new components that have been modified or adapted should be described in detail. Furthermore, sustainable analyses and data evaluation approaches should be described, including the benefits of the results and the presentation of the results.

A. Hip Joint

Using titanium alloys as a substance for creating orthopedic implants like Hip and femoral implants is common in the medical field. Figure 1 shows an example of a Hip joint that can be fabricated using SLM. The creation of complex-shaped custom implants from titanium alloys featuring high biocompatibility, mechanical attributes, and improved osseointegration through surface texturing can be accomplished by additive manufacturing (AM), particularly selective laser melting (SLM). In this document, the possibility of producing a customized hip implant from Ti-6Al-4V powder is showcased. The findings indicated that the fabrication of a tailored hip implant was achieved through an additive manufacturing technique, resulting in decreased operation time and reduced risk of infection (Popovich et al., 2016a).

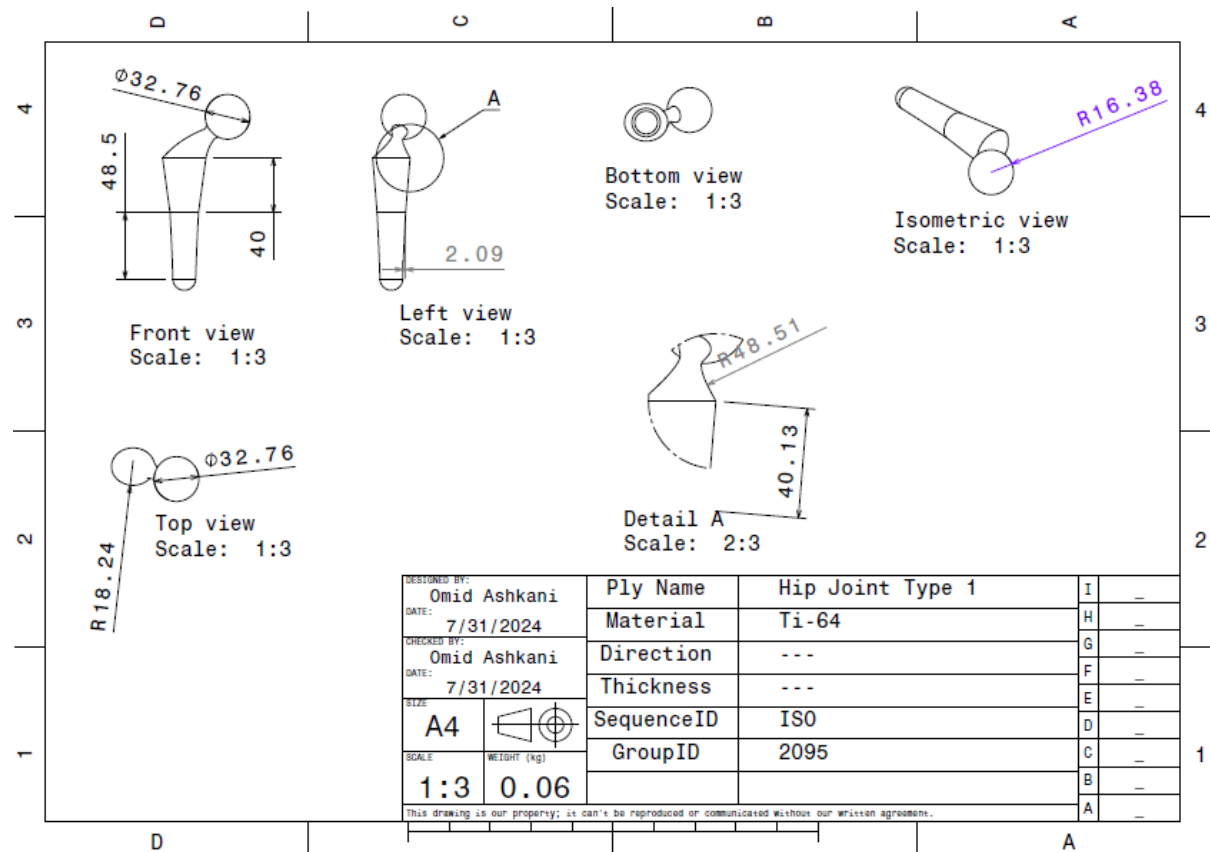


Figure 1. 2D design of Hip joint that can be fabricated Using SLM Technology (designed by Authors of this article)

In a research by Popovich, A., et al, SLM manufacturing process was utilized to create a Hip implant from Ti-6Al-4V powder. The findings indicated that employing additive manufacturing was a favorable approach

for producing the customized hip implant as the processing time was greatly decreased (Popovich et al., 2016b).

Structures featuring a Ti6Al4V inner region and a NiTi outer region have been produced using selective laser melting (SLM). The primary goal of this study was to showcase a design and manufacturing process for hip implants that can integrate NiTi and Ti6Al4V biomaterials into a single component through the SLM method (Bartolomeu et al., 2020a).

The primary aim of this research was to create an innovative method of grafting the surface of selective laser melted (SLM) (Ti-6Al-4V) with poly (2-methacryloyloxyethyl phosphorylcholine) (PMPC), in order to improve the surface properties and biocompatibility of the Hip implant. The findings demonstrated that the mechanical strength of the surface was improved by the PMPC graft, which safeguarded the underlying implant substrate from damage under heavy loads (Ghosh et al., 2018).

The excessive weight of Co-based knee femoral components poses a significant risk for patients which should be mitigated by decreasing the weight of implant components without sacrificing the outstanding mechanical properties. In this study, femoral components of the knee made from Ti6Al4V alloy (86 g) or Co-Cr alloy (192 g) were produced using selective laser melting (SLM). The findings demonstrated that the hardness, anti-wear performance, and corrosion resistance of SLM-Ti6Al4V have been significantly improved by applying thin TiN and TiCrN coatings, making them comparable to SLM CoCr. The TiN and TiCrN coated SLM Ti6Al4V also showed moderate antibacterial properties and excellent biocompatibility in comparison to SLM Ti6Al4V and SLM CoCr (Ni et al., 2021). It is worth noting that among the research conducted, less attention has been paid to the wear and tribological behavior of alloys in simulated body fluid (SBF) such as Ringer's, and it is suggested that researchers pay attention to investigating the abrasion behavior in body-simulating solutions in the future.

B. Knee Joints

Co-Cr alloy is the second most commonly utilized material in the orthopedics sector. In a study, the microstructure, aspect ratio (i. e. the ratio of deposition width to height), results of tensile and compression tests along with their fractography, and abrasion resistance of the improved depositions of novel materials for knee implants is analyzed. The new deposition material was created by incorporating 2, 4, and 6 wt% of Ti into Co-Cr-Mo alloy using a μ -plasma based additive manufacturing approach. Additionally, a finite element analysis of the tibial tray made from optimized alloys was conducted. The findings indicated that Co-Cr-Mo-4Ti alloy can be regarded as a superior material for knee implants due to its consistent porosity without thermal cracks, finer grain size, elevated yield tensile and compressive strength, greater ductility, and better abrasion resistance (Kumar et al., 2022).

Also, the Co-Cr-Mo alloy is widely used for knee replacements because of its excellent corrosion and wear resistance. In this regard, a research article introduces a comparison between traditional knee replacements created through conventional casting and material produced by 3D printing, specifically selective laser melting (SLM). The outcomes indicated that the Co-28Cr-6Mo alloy showed a similar response in hardness measurements to annealing at various temperatures, even though there was a notable difference in the primary microstructural state. Regarding the enhancement of wear resistance, if the CCM alloy is utilized for knee or hip implants, optimizing the hcp-Co phase proved to be promising only for the 3D-printed material (Roudnicka et al., 2021). It is worth noting that researchers are advised to pay more attention to the biocompatibility of knee joints manufactured using the SLM method in the future. In this regard, Figure 2 presents a 3D model of a knee joint that can be manufactured using the SLM method.

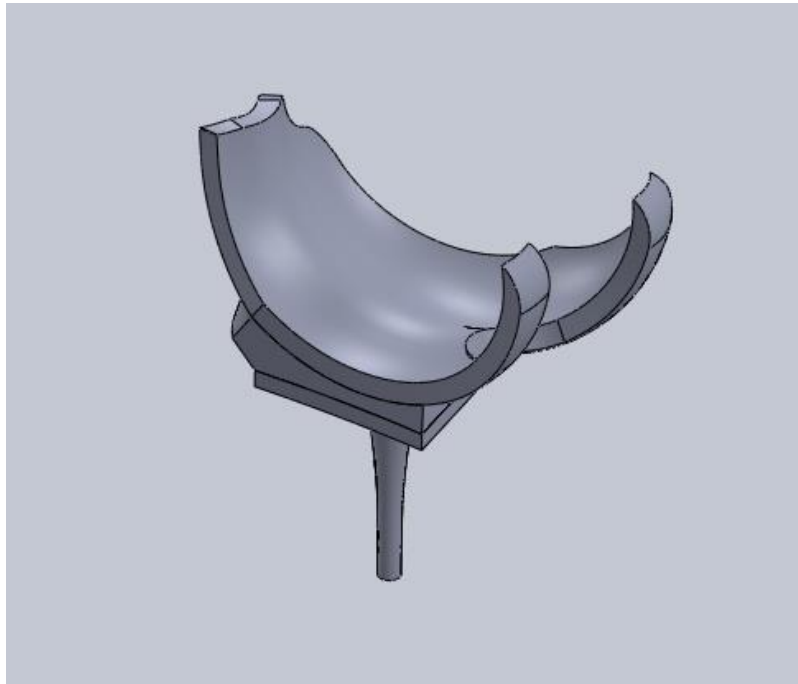


Figure 2. A 3D model of a Knee joint can be fabricated using SLM Technology (designed by the Authors of this article).

C. Craniomaxillofacial

Reconstruction of cranial defects is a challenging endeavor for Craniomaxillofacial surgeons. Effective reconstruction of cranial defects can be accomplished using 3D printing techniques such as selective laser melting (SLM). Titanium patient-specific implants (PSIs) produced through additive manufacturing or three-dimensional (3D) printing have become common in the area of cranioplasty, which results in improved clinical outcomes for complex surgical procedures. In a paper, the feasibility of producing a lightweight Titanium cranial prosthesis through selective laser melting (SLM) has been examined. The findings indicated that creating a cranial implant utilizing SLM was feasible (Sharma et al., 2021).

The primary aim of article was to evaluate the surgical precision and postoperative stability of patient-specific titanium implants (PSTIs) produced using the selective laser melting (SLM) technique and utilized for mandibular contour reconstruction. Surgical precision was characterized as an average Haus Dorff distance (Yang & Oh, 2022). This research sought to create a design approach to produce a titanium alloy porous condylar prosthesis that is made using selective laser melting (SLM) with suitable functional and aesthetic characteristics for mandibular reconstruction. The findings indicated that a patient-specific porous condylar prosthesis with fixation can be produced along with a fixation plate. Additionally, the weight of the 3D printed Ti-6Al-4V porous condylar prosthesis has been lessened, and the effective modulus of elasticity is similar to that of cortical bone (Cheng et al., 2022). Of course, it is suggested that corrosion resistance characteristics be discussed further.

In this regards, another research by Mommaerts et, al shows a novel design for a cranial implant made from titanium grade 23 and calcium phosphate paste (CeTi) is suggested, which is produced using the selective laser melting (SLM) method. Based on the results, it can be inferred that ceramic 3D-printed Titanium cranioplasty has shown its usefulness in particular instances of inlay cranioplasty (claimed sensitivity to plastics, infected secondary PMMA and PEEK cranioplasties) and significant only operations (Mommaerts et al., 2020).

Also, the viability of using ZrO₂ implants as an innovative application of this material for craniofacial bone defect reconstruction is examined. The clinical outcomes over 6 months and 6 to 8 years were robust and uniform; from these results, it can be inferred that the subsequent option for skeletal reconstruction can include Osseo integrated, radio-opaque, customized implants made of ZrO₂ material (Kozakiewicz et al., 2021).

D. Dental implants

Dental implants are generally made from materials that are biocompatible, such as metals or ceramics. The metals that are most frequently utilized for dental implants consist of stainless steel 316L, Co-Cr alloy steel, and titanium alloys (Zhou & Fun, 2017).

One of the first materials employed in this medical sector is stainless steel 316L. Utilizing 316L powder can greatly improve mechanical characteristics. SLM settings can enhance tensile strength, reaching a 20% increase in recent studies, and a relative density exceeding 99% can be achieved. The acquired yield strength can create new possibilities for biomedical researchers to decrease the mass of implants, prostheses, or cell grafts constructed from 316L, while preserving the same safety factor (Revilla-León et al., 2021).

Advancements in this field involve the total removal of stainless steel, replacing it with chromium alloys. At first, nickel-chromium alloys gained significant popularity in the medical and implant sectors, but subsequently, cobalt-chromium emerged as a more appropriate option in recent years due to the resolution of shortcomings. This transition was influenced by the increasing costs of precious metals and the significant allergenic risk associated with nickel-chromium alloys, resulting in the widespread use of dental cobalt-chromium alloys (Cr-Co). Nonetheless, Cr-Co alloys feature the highest melting ranges among casting alloys, presenting difficulties in handling them within dental laboratories (Revilla-León et al., 2021).

Owing to the limitations of nickel-chromium alloys, researchers were forced to explore alternative alloys. Titanium and its alloys are predominantly utilized for dental and orthopedic implants because of their remarkable mechanical strength, durability against corrosion, and superior biocompatibility (Xiong et al., 2019).

Ti-6Al-4V alloy is among the most commonly utilized titanium materials for implant applications due to its biocompatible characteristics. This alloy possesses low density, excellent mechanical properties, high corrosion resistance, and a relatively low Young's modulus approximating 110 GPa. Furthermore, it demonstrates appropriate strength, hardness, corrosion behavior, and processing precision for medical uses. This alloy ranks as one of the most frequently employed materials in the medical and dental fields because of its outstanding biocompatibility, corrosion resistance, and specific strength (Yan et al., 2015; Elsayed et al., 2019; Wally et al., 2019)

In the development of dental implants using SLM technology, Ashkani and colleagues (Liu et al., 2020) demonstrated that it is possible to manufacture various types of dental implants using this method. Their research results showed that dental implants manufactured using SLM had sufficient strength and their surface had cavities suitable for bone formation. It is worth noting that it is suggested that in the future, researchers should focus more on manufacturing regular-type implants such as those shown in the 2D drawing in Figure 3.

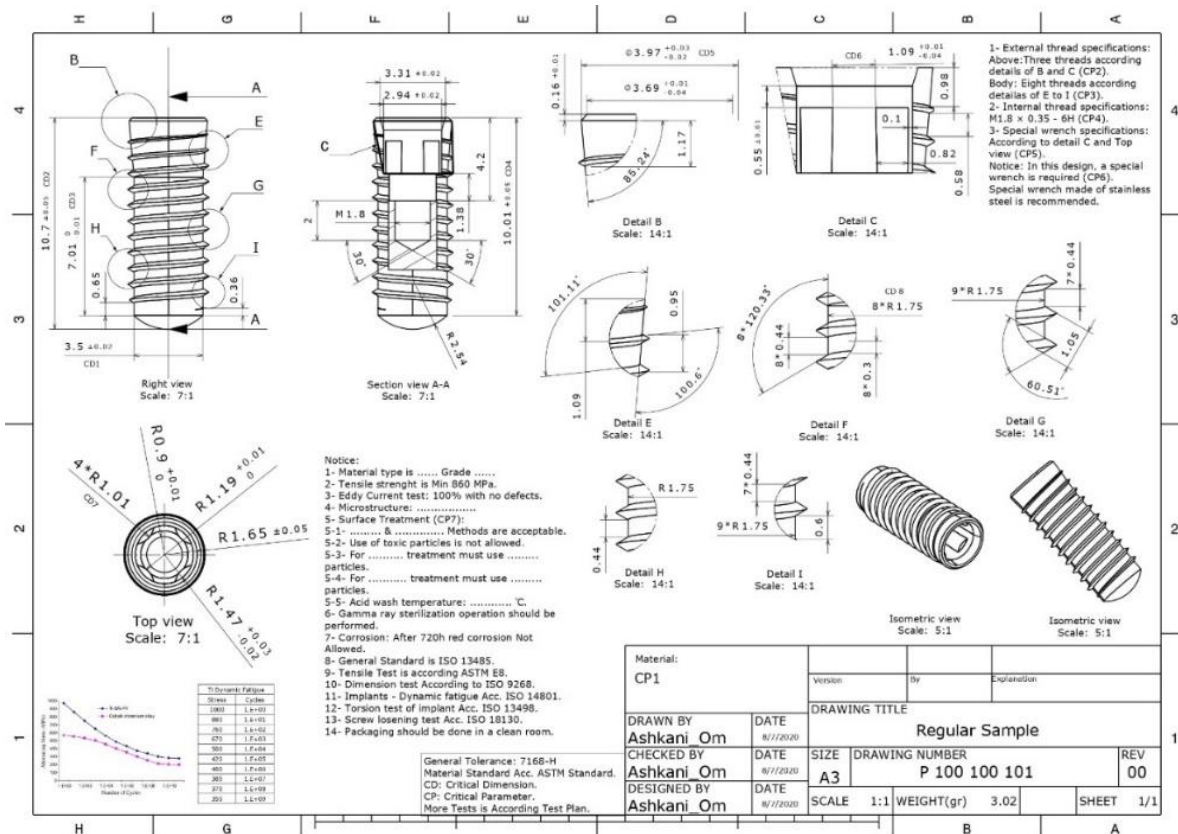


Figure 3. 2D drawing of regular-type dental implant (Designed by Omid Ashkani, dimensions may differ from the actual sample).

E. Spinal

As mentioned before, the use of Ti-6Al-4V is widely applicable in medical fields, specifically for the Manufacturing of Orthopedic implants. From the manufacturing standpoint, research revealed that the vertebral Implants made by Ti64 and fabricated by selective laser melting have shown great precision (Rezayat et al., 2024). This paper compared Ti64 alloy and PEEK; in short, Ti64 exhibited better osteoconductivity and a lower tendency for substances, which lead to improved bone-implant interface, but it has higher stiffness (Przekora et al., 2022). In terms of its application in imaging techniques, orthopedic implants fabricated by SLM had better performance because it didn't show any artifactual distortion (Lin et al., 2007). Furthermore, the influence of additive angles, which is inevitable in SLM Manufacturing technique has been discussed with regard to surface properties and bio compatibility the result showed that the surface roughness and hydrophobicity increased as angle increased (Chen et al., 2019). Moreover, the Ti64 implants fabricated by SLM showed lower stiffness which result in a reduced stress-shielding effect (Murchio, 2023). Ti64 caged with Porosity in the range of 65% and 85% and 600 micrometer pore size was better for Application in Lumbar Inter body Fusion (Luo et al., 2023).

III. CHARACTERISTICS OF PARTS MADE USING THE SLM METHOD

A. Porosity

Porosity plays a crucial role in the functionality and performance of medical implants, influencing their mechanical properties, biological integration, and long-term success. It affects stress distribution, mechanical strength, and wear resistance while enhancing Osseo integration and bone regeneration. Figure 4 shows a sample of a dental implant fabricated using the SLM method and a scanning electron microscope (SEM) image of the surface. This implant was made by the researchers of this study. A Ti-6Al-4V alloy powder was used to make it. The laser system was fiber laser 400 watts and the layer thickness was 25 microns. Also, the manufacturing was done in an inert argon gas environment, and the purpose of making this sample in this study was to demonstrate the ability and surface porosities. As is clear, with the correct

selection of parameters, the probability of cavities and porosity is almost zero, which is an advantage of this manufacturing method.

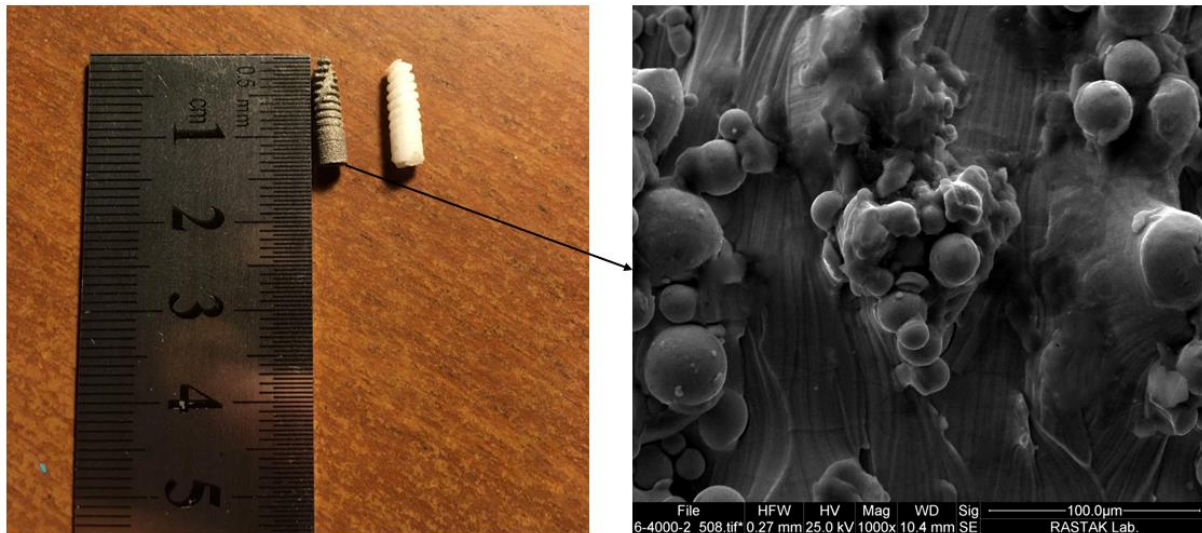


Figure 4: An implant sample made with SLM and its surface image, sample fabrication carried out by researchers.

The introduction of porosity into implant designs has been widely studied, particularly in orthopedic and dental implants, with findings supporting the use of controlled porosity to optimize implant performance (Taniguchi et al., 2016; Abate et al., 2021; Mondal et al., 2022; Lerebours et al., 2020; Zaharin et al., 2018; Shaoki et al., 2016; Cosma et al., 2014; Yoo, 2013; Wu et al., 2014; Götz et al., 2004; Bram et al., 2006; Sikavitsas et al., 2001). The relationship between porosity and mechanical performance is critical, as excessive porosity may weaken the implant, while insufficient porosity limits osseointegration. Studies have shown that porous scaffolds with an elastic modulus close to natural bone can reduce stress shielding and improve implant longevity. Various titanium scaffolds with 60-70% porosity, produced using selective laser melting (SLM), were found to have an elastic modulus similar to that of human bone, with mechanical properties decreasing as porosity increased (Mondal et al., 2022). The Young's modulus of porous structures declines as pore size increases, with optimal performance observed in cube porous structures with pore sizes of 0.3–0.5 mm, while gyroid structures across all tested sizes remain suitable for orthopedic implants (Zaharin et al., 2018). Additionally, porous titanium structures adjust their stiffness to align with cortical bone (~5-10% porosity) or trabecular bone (~50-90% porosity), ensuring compatibility with the mechanical behavior of natural bone (Wu et al., 2014). Research on V4Al6Ti components has demonstrated that introducing porosity significantly reduces stiffness, making the implant's elastic modulus more similar to cortical bone and mitigating stress shielding (Shaoki et al., 2016). The size and proportion of pores directly influence bone cell migration and tissue ingrowth. A study on titanium implants in rabbits revealed that implants with a 600 µm pore size and 65% porosity exhibited the most favorable bone ingrowth (Taniguchi et al., 2016). Similarly, cellular hip implants with 56% and 58% porosity showed promising results for osseointegration (Abate et al., 2021). Porous scaffolds designed with pore sizes between 300 and 600 µm exhibited enhanced porosity, improving their mechanical compatibility with natural bone. While the yield strength of porous scaffolds decreases with increasing pore size, structures with 0.3 mm pores demonstrated properties closest to natural bone, making them highly suitable for implant fabrication (Zaharin et al., 2018).

In dental applications, research suggests that an optimal pore size range of 100–600 µm facilitates the best performance, with pores exceeding 300 µm being particularly beneficial for capillary and jaw tissue integration. Among different sizes, a 500 µm pore size yielded the most significant impact on bone cell growth, making it a desirable choice for porous implants (Fukuda et al., 2011; Cosma et al., 2014; Yoo, 2013). Additionally, a porosity ranges of 48% to 84% was found to be advantageous for bone regeneration, as confirmed by biological testing (Ji et al., 2018). Furthermore, studies indicate that a minimum pore size of 100 µm is essential for osseointegration, as it allows for adequate bone cell migration and transport. However, pore sizes ≤300 µm are recommended to enhance new bone and capillary formation (Götz et al., 2004). Porosity categorization further shows that cortical bone is relatively dense and robust (5-10%

porosity), while trabecular bone is weaker and more porous (50-90% porosity) (Sikavitsas et al., 2001). In artificial joints, porosity plays a key role in wear performance. A study on AM-produced CoCrMo discs with varying surface porosity (0.4% to 19.7%) revealed a strong correlation between the wear rate of UHMWPE and the total porous area. Reducing porosity significantly improved wear resistance, highlighting the importance of optimizing porosity in weight-bearing implants (Lerebours et al., 2020).

The geometric configuration of porous implants influences stress distribution and bone integration. A study evaluating different unit cell designs found that a diamond-shaped porosity structure facilitated bone infiltration and reduced stiffness (Peng et al., 2016). Another investigation designed implants to mimic a diamond crystal structure with a 109°28' angle between square columns (0.2 mm side length, 0.5 mm height), leading to favorable mechanical and biological outcomes (Xiong et al., 2019). Additionally, porous scaffolds with a three-dimensional architecture significantly enhance cell seeding, vascularization, nutrient transfer, and metabolite exchange (Yoo, 2013). These factors contribute to faster and more effective tissue integration.

The incorporation of porosity in medical implants provides multiple advantages, including:

Enhanced Tissue Integration: Porosity enables bodily tissues to penetrate the implant's structure, establishing a strong interface with surrounding tissues and improving clinical outcomes (Zhou & Fun, 2017).

Improved Mechanical Properties: The ability to tailor porosity allows for mechanical properties that match those of natural bone, reducing stress shielding and improving implant longevity (Yan et al., 2015; Ji et al., 2018).

Optimized Load Distribution: Porosity decreases implant weight while optimizing stress transfer, reducing the risk of mechanical failure. **Increased Biocompatibility:** Surface micro-porosity supports the infiltration of bioactive agents (e.g., HA, β -TCP, enzymes, and growth factors), further promoting osseointegration (Cosmo et al., 2014).

Potential for Customization via Additive Manufacturing: Porous structures created through additive manufacturing provide the flexibility to design patient-specific implants with tailored porosity and mechanical properties (Revilla-León et al., 2021). The overall porosity (P) of an implant is determined using the formula:

$$p = \left(1 - \frac{\rho}{\rho_0}\right) * 100$$

Where ρ represents the density of the sample, estimated by the weight-to-volume ratio derived from the geometric data of the test sample, and ρ_0 denotes the standard apparent density of the material. The overall porosity of implants is determined based on the relationship between the measured densities. Research indicates that scaffolds featuring a porous structure and three-dimensional architecture may be advantageous for cell seeding, vascularization, nutrient transfer, and metabolite exchanges (Yoo, 2013).

Porosity is a fundamental feature of modern implant designs, significantly improving their mechanical stability, tissue integration, and overall clinical success. Research indicates that orthopedic implants with porosity levels between 50-70% closely match natural bone properties, making them highly effective for long-term applications. Meanwhile, dental implants benefit from controlled porosity with a preferred range of 100-600 μ m for optimal Osseo integration.

Advancements in additive manufacturing have enabled the precise control of porosity, allowing implants to be tailored for various medical applications. A well-designed porous structure can modify an implant's elastic modulus, reducing stress shielding and promoting bone regeneration (Revilla-León et al., 2021; Yan et al., 2015; Yoo, 2013). Ultimately, porosity in implants enhances mechanical compatibility, accelerates tissue integration, and improves patient outcomes, making it a standard practice in modern medical implant manufacturing.

B. Spinal

In an article, the comparison with conventional implants and intervertebral fusion cage has been explored. The result revealed that about better clinical outcomes of patients, bionic cage had significant performance (Chen et al., 2019). The Analysis of in vivo tests showed that the cylindrical Ti6Al4V porous fusion cage was promising for better spinal fusion surgery (Levy et al., 2023). The spinal interbody mechanics vascularization osteoblast attachment and ingrowth potential have been fostered dramatically by intrinsic Porosity. Furthermore, the Titanium mesh Porosity fabricated by additive

Manufacturing exhibited that the Osseointegration and, eventually, bone-implant interface could be enhanced (Levy et al., 2023). In another paper, the gradient porosity has been discussed. It can be concluded from the result that the risk of incidence could be decreased by utilizing the gradient Porosity devices made with a selective laser melting process (SLM) (Pan et al., 2017). In this work, the comparison between an optimized frame-reinforced porous cage and a fully porous cage has been done. The results showed that the fully porous fusion cage increased compressive strength and stiffness. In addition, the anisotropic biomimetic trabecular in the 70% frame-reinforced Ti-6AL-6V cage showed promise for lumbar interbody fusion (Rezayat et al., 2024).

C. Corrosion Resistance

Corrosion resistance is crucial in orthopedic implants as corrosion can lead to surface roughness, complicating restoration, and can result in the release of elements from metals or alloys. The excessive weight of Co-based knee femoral components has become a significant concern for patients, thus making it essential to reduce their weight while maintaining excellent mechanical properties. In a study, the femoral component of the knee is produced using Ti6Al4V alloy (86 g) or Co–Cr alloy (192 g) and is fabricated through selective laser melting (SLM). The findings indicated that the hardness, anti-wear characteristics, and corrosion resistance of SLM Ti6Al4V were significantly improved after applying thin TiN and TiCrN coatings, making them comparable to SLM Co-Cr. Also, regarding antibacterial properties, the TiN and TiCrN coated SLM Ti6Al4V demonstrated superior biocompatibility in comparison to both SLM Ti6Al4V and SLM CoCr (Ni et al., 2021). The primary aim of this study is to assess the corrosion resistance of the Ti-6Al-4V alloy produced through electron beam melting (EBM) and selective laser melting (SLM). The findings indicated that the corrosion resistance of the specimen produced by SLM was outstanding. Overall, the scaffolds created using both EBM and SLM demonstrated encouraging outcomes concerning corrosion resistance (Zhao et al., 2017). Another research assessed the impact of heat treatment on the corrosion resistance adhesion of *Streptococcus mutans* and the mechanical characteristics of CoCrMo alloys produced through selective laser melting (SLM). Regarding corrosion resistance, the findings showed the adhesion of *Streptococcus mutans* and the mechanical properties of CoCrMo alloys created via selective laser melting (SLM) (Zhang et al., 2018).

Biocompatibility and corrosion resistance of implants hold critical importance for Ti6Al4V parts produced by selective laser melting (SLM). In another study, the effect of SLM processing parameters on the corrosion resistance and biocompatibility of Ti6Al4V components is examined by changing the scanning speeds and laser powers. From the findings, it can be inferred that the corrosion resistance and biocompatibility of Ti6Al4V components can be modified by altering the scanning speed and laser power due to the constituent phase and the number and size of defect holes in Ti6Al4V parts. In comparison to the laser power, the scanning speed has a more significant impact on the performance of the part, allowing for “coarse tuning” based on the performance requirements. At a scanning speed of 1100 mm/s and a laser power of 280 W, Ti6Al4V parts with improved corrosion resistance can be obtained. Ti6Al4V parts with enhanced biocompatibility are produced at a scanning speed of 1200 mm/s and a laser power of 200 W (Xiang et al., 2022).

D. Wear Resistance

Wear resistance in orthopedic materials is crucial for the longevity and functionality of implants, as excessive wear can lead to complications such as pain, loosening, and inflammation. The materials used for implants must therefore demonstrate high wear resistance to ensure their durability under the mechanical stresses experienced in the human body. Several alloys, such as Co28Cr6Mo, Ti6Al4V, Cu5–V4Al6Ti, and

commercially pure titanium (CpTi), are commonly utilized for their wear resistance and other mechanical properties.

E. Co–Cr–Mo Alloys

The wear resistance of Co–Cr–Mo alloys, particularly those produced via Selective Laser Melting (SLM), has been a topic of investigation. Studies have shown that SLM Co28Cr6Mo alloys exhibit higher gravimetric wear and generate larger wear debris when compared to the forged Co28Cr6Mo alloys. This disparity is largely attributed to the differing structural properties of the two materials, such as grain size and material interaction at grain boundaries. This inferior tribological performance of SLM Co28Cr6Mo alloys suggests that SLM may not be the ideal method for producing implant prototypes intended for clinical applications, as it may affect their wear resistance negatively (Mróz et al., 2017).

F. Ti6Al4V Alloys

Ti6Al4V, a widely used titanium alloy, has also been evaluated for its wear resistance in biomedical applications. Various processing methods, including conventional casting, hot pressing, and SLM, have been compared. Among these, the Ti6Al4V alloy produced through SLM exhibited the highest hardness and wear resistance. These results suggest that SLM could be an advantageous manufacturing technique for creating implants that require both high hardness and excellent wear resistance (Mróz et al., 2017). Additionally, SLM treatment was found to enhance the biocompatibility and cell adhesion characteristics of the Ti6Al4V surface, further emphasizing its suitability for biomedical applications (Shaoki et al., 2016).

G. Cu5–V4Al6Ti Alloy

The Cu5–V4Al6Ti alloy, produced via SLM, is another material of interest due to its wear resistance and antibacterial properties. The alloy's enhanced wear resistance is attributed to the dispersion of fine Cu2Ti particles, which obstruct dislocation movement, thereby improving deformation resistance in simulated saliva and atmospheric conditions. This makes Cu5–V4Al6Ti a promising candidate for applications where wear resistance is critical (Zong et al., 2020).

H. Commercially Pure Titanium

Commercially pure titanium (CP-Ti) is frequently used in dental implants due to its excellent biocompatibility, adequate hardness, strength, corrosion resistance, and wear resistance. The formation of a stable oxide layer on pure titanium accounts for its biocompatibility and contributes to its corrosion resistance. Additionally, heat treatment processes that transform amorphous titania surface layers into crystalline TiO₂ rutile layers further enhance the wear resistance, biocompatibility, and corrosion resistance of CpTi implants (Wang et al., 2016; Liu et al., 2020). Of course, it is worth mentioning that it is usually necessary to apply a layer of surface coatings play a significant role in enhancing the wear resistance of titanium-based implants. Crystalline TiO₂ rutile layers, which can be developed during heat treatment, significantly improve the biocompatibility and corrosion resistance of titanium implants. The process is not only cost-effective but also improves the implant's performance by transforming amorphous titania into a more durable crystalline form (Wang et al., 2016). Wear resistance is a key factor in determining the effectiveness and longevity of orthopedic implants. Co–Cr–Mo alloys, Ti6Al4V, Cu5–V4Al6Ti, and commercially pure titanium all demonstrate varying degrees of wear resistance depending on their processing methods. SLM proves to be an effective method for enhancing the hardness and wear resistance of Ti6Al4V and Cu5–V4Al6Ti alloys, while Co28Cr6Mo alloys produced through SLM showed poorer tribological performance compared to forged counterparts. The use of surface coatings, such as TiO₂ rutile layers, further enhances the wear resistance and corrosion resistance of titanium-based implants, ensuring their suitability for long-term use in the human body.

I. Fatigue

Fatigue resistance is the ability of a material to withstand fracture or cracking under repeated loading conditions, which is crucial for orthopedic implants. Various materials, especially metallic alloys like Ti6Al4V, Co–Cr–Mo–W, and Ti64, are commonly used due to their excellent fatigue properties, making them viable candidates for applications such as spinal cages and hip implants. The incorporation of

advanced manufacturing techniques such as Selective Laser Melting (SLM) has led to the development of new porous structures that significantly influence the fatigue resistance of these implants.

Titanium and titanium alloys are frequently used in the biomedical sector due to their excellent fatigue resistance, low density compared to stainless steel and cobalt-chromium alloys, and effective corrosion resistance (Esen & Bor, 2007). The Ti6Al4V alloy, in particular, has been widely researched and found to exhibit improved fatigue resistance compared to commercially pure titanium, especially when subjected to processes like SLM (Zhou & Fun, 2017). Porous titanium structures, such as diamond unit cells, are produced using SLM and have been shown to have promising fatigue life, which can be further enhanced through post-manufacturing treatments. For instance, stress-relieving (SR) and hot isostatic pressing (HIP) treatments significantly improve fatigue properties, while a combination of HIP+CE (chemical etching) provides the most notable improvement, especially in high-cycle fatigue regions (Van Hooreweder et al., 2017). Figure 5 shows an example of a software simulation result for a Ti-10Cr alloy. This result shows that titanium alloys containing chromium can play an effective role in the development of fatigue-resistant alloys. It is worth noting that researchers need to conduct comprehensive research on the biocompatibility of titanium-chromium alloys in the future, because the graph shown only indicates the importance of mechanical properties, but biocompatibility is also of great importance. It is suggested that researchers use software simulation and its results as shown in Figure 5 in the future to develop titanium alloys with fatigue limits.

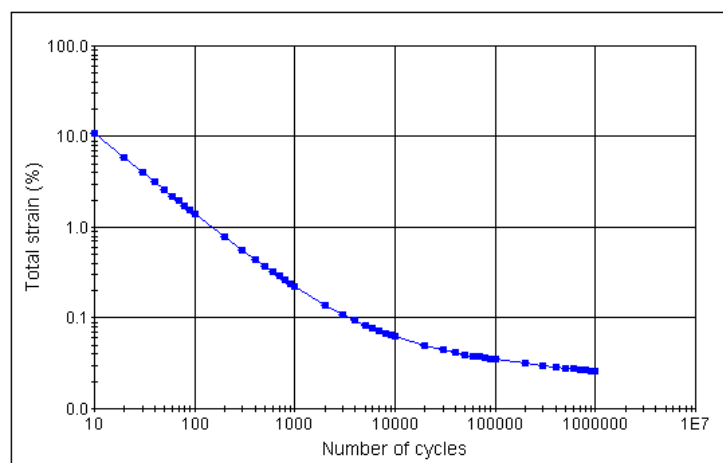


Figure 5. Simulation of the fatigue limit of a hypothetical Ti-Cr alloy sample to demonstrate the importance of simulation in alloy design (photo by Authors of this article).

Co-Cr-Mo-W alloys, another critical class of biomaterials for implants, are also examined for their fatigue resistance. These alloys, produced via SLM, exhibit greater fatigue life, tensile strength, and ductility compared to their counterparts made via sand mold casting, which also share the same chemical composition (Dong et al., 2020). This highlights the potential of additive manufacturing in improving the fatigue properties of prosthetics and orthopedic components.

The manufacturing process plays a crucial role in the fatigue resistance of implants. In the case of SLM, the presence of un-melted particles and semi-adhered particles can increase the likelihood of fatigue failure, negatively affecting the mechanical properties of the alloys, including their fatigue and corrosion resistance (Revilla-León et al., 2021; de Souza Soares et al., 2022). Additionally, if sintering processes are not executed precisely, they may lead to brittleness and a reduction in fatigue resistance (Götz et al., 2004). On the other hand, a coarse layered microstructure has been shown to improve fracture toughness, which contributes to better fatigue crack resistance and creep resistance. The creation of protective titania layers further enhances surface hardness, fatigue resistance, and corrosion performance, making it an essential factor in the fatigue life of implants (Wang et al., 2016). Various post-manufacturing treatments are used to enhance the fatigue resistance of implants. One notable example is the use of HIP post-process treatment, particularly after SLM manufacturing. This treatment reduces porosity and crack initiation sites, improving fatigue life. Research also supports that fatigue resistance and ductility are significantly enhanced after HIP treatment (Murchio, 2023; Tsuang et al., 2023). These treatments can thus play a key role in ensuring the longevity and mechanical performance of implants in the human body. The fatigue resistance of orthopedic implants is heavily influenced by the material composition, manufacturing process, and post-manufacturing

treatments. Titanium alloys, particularly Ti6Al4V, and Co–Cr–Mo–W alloys, produced through advanced methods like SLM, have shown promising fatigue properties. With the right post-manufacturing treatments, such as HIP and chemical etching, the fatigue resistance can be significantly enhanced, making these materials viable candidates for use in load-bearing orthopedic implants. However, attention must be paid to the precision of manufacturing processes to avoid defects that could compromise fatigue life.

J. Cytotoxicity

Cytotoxicity refers to the property of being toxic and damaging to cells, making it crucial to avoid this occurrence. In a research, the SLM and EBM production techniques typically used in the fabrication of titanium orthopedic implants by examining the microstructure, mechanical properties, and cytotoxicity were compared. The findings indicated that cytotoxic effects were not observed in either method. Furthermore, materials produced by EBM could fulfill the ASTM F136 standard requirements for surgical implant applications when compared to SLM (Wysocki et al., 2017). A research article examines a collection of vital tools that might be utilized for improving the design of Ti6Al4V cellular structures created through selective laser melting (SLM). The findings of cell viability tests indicated that the structures produced by SLM did not emit any harmful or toxic substances into the medium (Bartolomeu et al., 2020b). The primary goal of another article was to investigate how Cu affects the microstructures, mechanical properties, corrosion behavior, and cytotoxicity. To accomplish this objective, CoCrWCu alloys with varying Cu contents (2, 3, 4 wt%) were produced through selective laser melting using a mixture of powders made of CoCrW and Cu, which were examined. Concerning cytotoxicity, it was reported that there was no cytotoxicity observed for Cu-containing CoCrW alloys toward MG-63 cells, and the cells were able to spread effectively on the surfaces of the alloys studied (Lu et al., 2018).

IV. SLM PARAMETERS AND EFFECT ON PROPERTIES

The impact of different SLM parameters on the creation of orthopedic implants, primarily emphasizing laser power, is examined. The incidence of hip revision has sharply risen due to the loss of fixation between the implant and bone, which ultimately leads to implant failure. In this article, a multi-material design and manufacturing approach was investigated to modify traditional manufacturing methods by integrating distinct biomaterials into a single component aimed at a multi-functional hip implant. This research concentrated on validating the SLM fabrication and processing parameters on a commercial SLM system. The findings indicated that high-quality NiTi-Ti6Al4V structures were achievable with 90 W of laser power, 600 mm/s of scan speed, 90 μm of scan spacing, and a layer thickness of 30 μm (Bartolomeu et al., 2020a).

In this study, a significant review concerning the SLM process parameters, defects, and various post-processing techniques is proposed by several researchers. When appropriate process parameters are selected along with suitable post-treatment, it can result in improvement in mechanical behavior compared to as-built SLMed Ti6Al4V components. The findings indicated that laser power within the range of 151–200 W is suggested for improved mechanical properties. Additionally, a considerable number of studies have advised lower laser power in the range of 51–100 W. Consequently, there is a necessity for more thorough investigations to determine the optimal laser power to guarantee the lowest cost of SLMed Ti6Al4V alloy (Singla et al., 2021)

V. CONCLUSION

Selective Laser Melting (SLM) has proven to be a transformative technology in the field of implant manufacturing, offering significant advantages in the production of orthopedic, dental, and spinal prosthetics. The ability of SLM to create customized implants with controlled porosity, microstructural properties, and intricate geometries allows for optimal integration with human tissues, enhancing osseointegration and reducing the risk of implant failure. Materials such as Ti-6Al-4V, Co-Cr-Mo alloys, and Cu5–V4Al6Ti, fabricated through SLM, exhibit exceptional mechanical properties, including wear and fatigue resistance, corrosion resistance, and biocompatibility, making them ideal candidates for load-bearing implants. The incorporation of surface texturing, porosity, and coatings further contributes to improving the performance of these implants, facilitating faster bone healing and better tissue interaction. Additionally, post-manufacturing treatments like hot isostatic pressing (HIP) and surface modifications such as sandblasting enhance the overall mechanical stability and biocompatibility of SLM-produced

implants. Despite the promising benefits, challenges remain regarding achieving surface precision and dimensional accuracy, particularly when compared to traditional manufacturing methods. However, ongoing research and development in SLM technologies continue to refine these aspects, paving the way for more reliable and efficient implant production. In addition to the above, the general results are:

- The development of this method can be considered as a suitable manufacturing method. It is suggested that in the future, researchers should focus more on manufacturing various types of prostheses using the SLM method.
- The results show that the development of this method can cause changes in the corrosion resistance and biocompatibility of the alloy, so in future research, researchers should focus more on investigating this issue.
- The results show that the use of the SLM method may lead to changes in the elastic modulus, so it should be investigated in future research.
- The SLM method is a suitable method for personalizing various types of implants, especially hip joint and dental implants.
- This method can be considered as a mass production method.

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