International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
Vol. 48 No. 1 December 2024, pp. 20-31

The Potential of Additive Manufacturing Technology in Customizing Bone Implants to Fit Human Anatomy

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Abstract — Additive Manufacturing (AM) technology has revolutionized the healthcare industry, particularly in implant applications, by enabling the production of bone implants that are specifically customized to human anatomy. Unlike conventional methods that cannot be tailored individually, this technology allows for the rapid and precise creation of implants based on each person's anatomy, derived from CT scans and MRIs. Various additive manufacturing methods, including Material Extrusion, Powder Bed Fusion (PBF), Material Jetting, Directed Energy Deposition (DED), Binder Jetting, VAT Photopolymerization, and Sheet Lamination, offer the capability to produce complex structures with mechanical properties similar to natural bone and porous implant surfaces that enhance osteointegration. This technology supports the development of implants that improve osteointegration and accelerate patient recovery. Although additive manufacturing has tremendous potential for producing bone implants, challenges such as material selection, biocompatibility, and regulatory standards still need to be addressed. Research and development are crucial to advancing the role of additive manufacturing technology in biomedical applications, promising a future with personalized, efficient, and effective bone implant solutions. Some studies demonstrate that additive manufacturing technology offers design flexibility, increased production efficiency, and personalized implants. However, challenges in material selection and process standardization still need further development. The potential of additive manufacturing to produce personalized implants offers a significant opportunity to revolutionize bone injury treatment and support faster healing processes

Keywords — Additive Manufacturing;Bone Implant; Customize; Techonolgy; Osteointegration.

I. INTRODUCTION

Technological advancements in healthcare have progressed remarkably over the past few decades, particularly in developing methods that enhance the effectiveness of patient treatment and recovery[1]. One technological innovation that continues to evolve is the use of Additive Manufacturing (AM) technology, commonly known as 3D printing[2][3]. Additive manufacturing offers a revolutionary innovation in bone implant fabrication, allowing for more specific, personalized implant production with faster production times compared to conventional methods like casting[4][5][6]. Bone implants are devices used to replace or repair damaged bone tissue within the human body[7]. The need for implants that can be customized to fit each individual's anatomy is crucial, especially in cases of severe trauma or bone damage, where successful healing relies heavily on the compatibility of the implant with the patient's bone structure[8][9]. Traditional implant manufacturing methods, which have been used for years, often face challenges in precisely adapting the implant to the patient's bone morphology, ultimately affecting the level of osteointegration, or the bonding between bone and implant[10].

Osteointegration is a biological process in which the bone connects with the implant surface without any adverse reactions, which is critical for ensuring the implant's long term viability and its ability to support bodily functions[11]. With additive manufacturing, implants can be created with higher precision, based specifically on CT or MRI scans of the patient's anatomy, allowing for personalized implants that improve osteointegration properties[12]. Additive manufacturing technology enables the design of complex implant structures that promote bone cell growth on the implant[13]. Studies indicate that the porosity of implants produced through additive manufacturing enhances nutrient flow and accelerates osteointegration, resulting in faster patient recovery compared to conventional technology[14]. However, implementing additive manufacturing for bone implant production requires careful material selection, as the material must possess good biocompatibility and be able to withstand mechanical loads within the body. Stainless steel 316L is a leading choice due to its strong mechanical properties, corrosion resistance, cost effectiveness, and good biocompatibility[15]. Using additive manufacturing, SS 316L can be produced in more complex shapes and designs, enabling structural designs that mimic natural bone structures[16].

Therefore, further research and development are essential to explore the potential of additive manufacturing technology in creating bone implants that are more responsive to human anatomy. Innovations in additive manufacturing not only have the potential to enhance patient recovery but also provide valuable insights and knowledge in the field of biomedical technology. This article aims to examine the potential of additive manufacturing technology in producing bone implants tailored to human anatomy, with the goal of accelerating patient recovery times.

II. Research Method

This study uses a literature review approach to examine the potential of additive manufacturing technology in creating bone implants customized to the human anatomy. This approach is based on various relevant scientific journals, focusing on the technology, materials, and implant design produced through the additive manufacturing process. This section will discuss the different types of additive manufacturing technologies that hold potential in bone implant fabrication. Each additive manufacturing technology has unique characteristics, which can influence the printing process and the types of materials used. A comprehensive understanding of these additive manufacturing technologies is essential to determine which is most effective for implant production. Additive manufacturing is the process of creating three dimensional objects by adding material layer by layer, based on a 3D design or scanned data. This technology encompasses various methods that differ in their operating principles and the materials used. Below are some of the main types of additive manufacturing technologies:

A. Material Extrusion

Material extrusion is one of the most common additive manufacturing methods, primarily recognized through Fused Deposition Modeling (FDM) technology. In this process, thermoplastic filament is heated until it melts and is then extruded through a nozzle, layer by layer, onto a platform to form a 3D object. This process is well suited for prototyping and producing functional objects at a relatively low cost. Material extrusion is popular due to its simplicity and the wide availability of materials such as ABS, PLA, and TPU, though its production resolution and detail are lower than other methods like SLA or SLS[17].

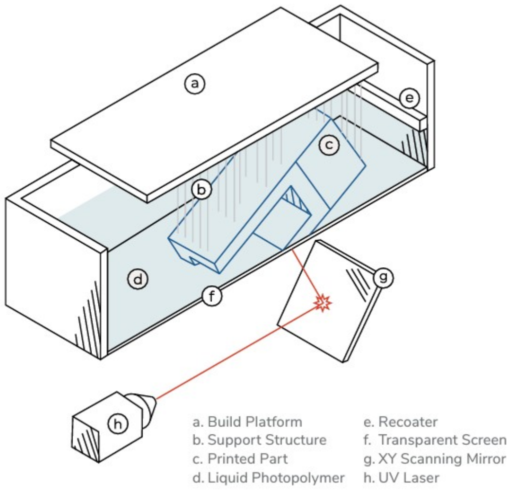

Figure 1. Material extrusion additive manufacturing system

B. Material Jetting

Material jetting is an additive manufacturing process that uses a printhead to jet droplets of liquid material, such as photopolymer or wax, which harden upon exposure to UV light or rapid cooling. This process operates similarly to an inkjet printer, but the material droplets are layered to form a 3D object. Material jetting technology allows for multi material and multi color object production in a single process and produces smooth surface details with high resolution. This technology is commonly used in the medical, dental, and industries where high detail objects are required[18].

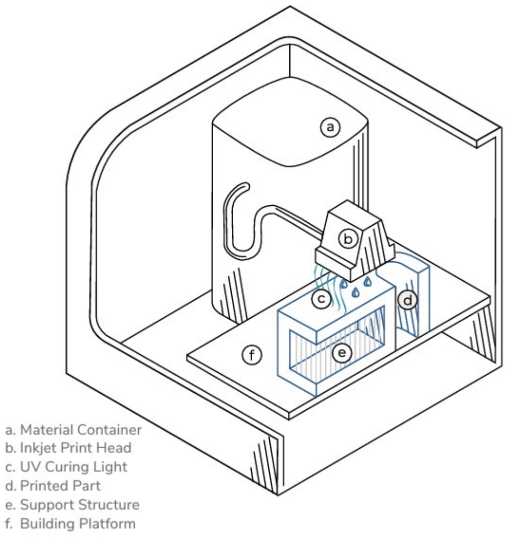

Figure 2. Material jetting additive manufacturing system

C. VAT Photopolymerization

VAT photopolymerization is an additive manufacturing technology that uses photosensitive liquid resin, selectively hardened by an ultraviolet (UV) light source. This process involves a tank filled with liquid resin, which is exposed to light to harden the

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ISSN: 2509-0119.

https://ijpsat.org/
Vol. 48 No. 1 December 2024, pp. 20-31

resin in the desired areas until the object is fully formed. The two main methods used are Stereolithography (SLA) and Digital Light Processing (DLP). SLA uses a laser to trace patterns on the resin's surface, while DLP projects an entire layer image at once. This technology offers high precision and fine detail, making it ideal for producing dental prototypes and other high detail products[19].

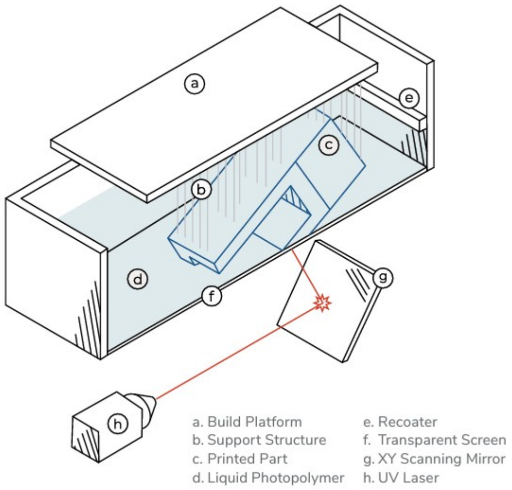

Figure 3. VAT photopolymerization additive manufacturing system

D. Powder Bed Fusion (PBF)

Powder Bed Fusion (PBF) is an additive manufacturing process in which powdered material as metal, plastic, or ceramic is spread over a build platform and then selectively fused with a laser or electron beam, which melts and binds the powder together in specific areas. This process is repeated layer by layer until the object is fully formed. Examples of PBF technologies include Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). PBF is known for its ability to produce parts with strong mechanical properties, making it suitable for functional prototypes and mass production in various industries, including aerospace, automotive, and medical[20].

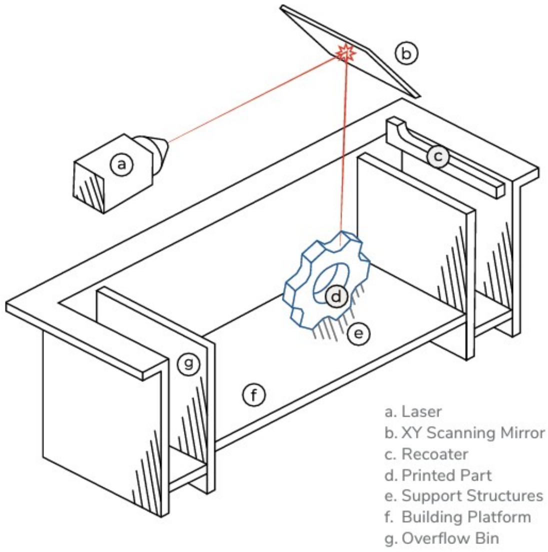

Figure 4. Powder bed fusion additive manufacturing system

E. Binder Jetting

Binder jetting is an additive manufacturing technology in which powdered materials, such as metal, sand, or ceramics, are spread in thin layers on a platform. A printhead then selectively sprays a liquid binder onto specific areas to bond the powder in that layer. This process is repeated layer by layer until the entire 3D object is formed. After printing, the product typically undergoes a post processing sintering step to improve strength and stability. Binder jetting is commonly used in industries for prototyping, mold casting production, and small scale manufacturing, offering a cost effective alternative compared to other processes like PBF[20].

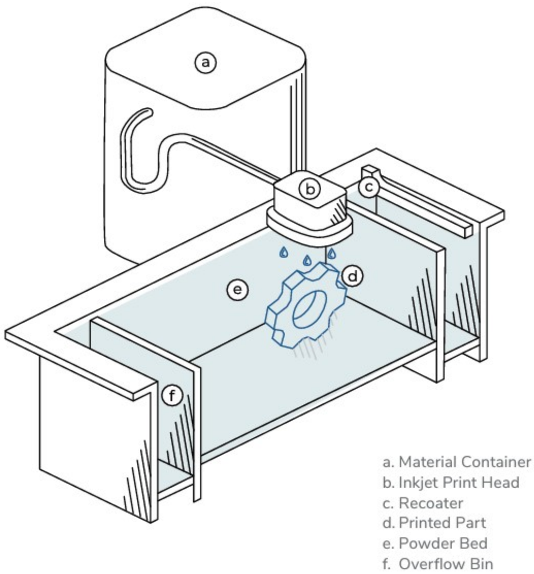

Figure 5. Binder jetting additive manufacturing system

F. Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is an additive manufacturing technology primarily used for metals, where wire or powder material is directly melted by energy sources such as lasers, electron beams, or plasma. This process allows for the creation or repair of parts directly on existing components, making it valuable for applications in repair, welding, or functional enhancement of large components. DED provides flexibility to add material only in specific areas, making it popular in industries for part repairs or manufacturing of large scale components[17].

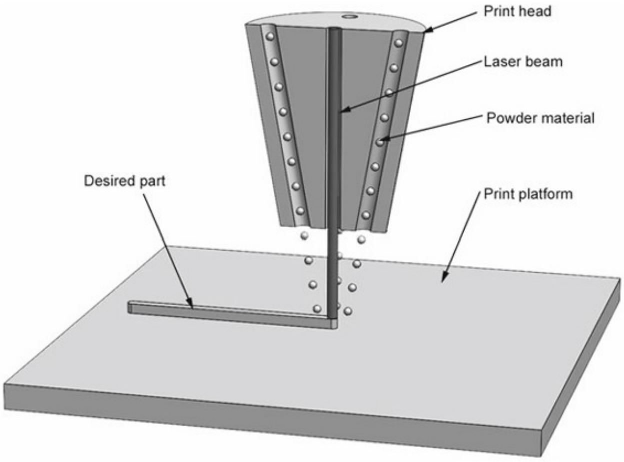

Figure 6. Directed energy deposition additive manufacturing system

G. Sheet Lamination

Sheet lamination is an additive manufacturing technique that involves bonding layers of sheet material using heat, pressure, or adhesive to create a 3D object. Each layer is cut to the desired shape based on a digital design, usually with a laser or blade, before being attached to the previous layer. Its two main variants are Laminated Object Manufacturing (LOM) and Ultrasonic Additive Manufacturing (UAM). LOM typically uses paper or plastic, while UAM works with metals and relies on ultrasonic welding. Sheet lamination is known for its fast printing speed and low material costs, although its geometric accuracy may be less precise compared to other additive processes[21].

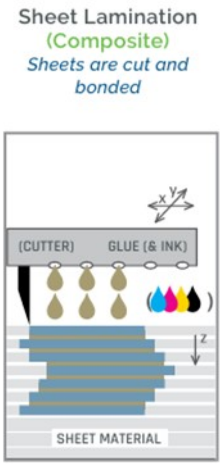

Figure 7. Sheet lamination additive manufacturing system

Table I. Relevant research on additive manufacturing technology in implant fabrication

No	Author	Title	Research objectives	Methodology	Research results
1.	Obinna Okolie, Iwona Stachurek, et al., (2020)	3D Printing for Hip Implant Applications: Review	The challenge of traditional hip implants that lack personalization and biocompatibility	Different 3D printing techniques used to fabricate hip implants, with a focus on improving their mechanical strength and integration with bone tissue	Advantages of 3D printing in creating custom implants with optimized porosity and surface structure
2.	Jianghui Dong, Hangxing Ding, Qin Wang and Liping Wang (2023)	A 3D Printed Scaffold for Repairing Bone Defects	traditional methods are slow and may not integrate well with the patient's tissue	involves using 3D printing to create scaffolds that mimic the natural structure of bone	showed that these scaffolds promote faster bone growth and better integration with the surrounding bone tissue
3.	Zhaolong Li 1, Qinghai Wang and Guangdong Liu (2022)	A Review of 3D Printed Bone Implants	limitations in traditional bone implants, such as poor fit, biocompatibility issues, and long healing times	involves reviewing existing research on 3D printed bone implants, focusing on materials, manufacturing techniques, and clinical applications	indicate that 3D printing can produce highly customized, biocompatible implants that promote faster recovery and better integration with bone
4.	Si He, Jiang Zhu, Yiwan Jing, et al., (2024)	Effect of 3D Printed Porous Titanium Alloy Pore Structure on Bone Regeneration: A Review	how to design porous structures that improve osseointegration and bone growth	involves reviewing studies on different pore sizes and structures in 3D printed titanium alloys.	that specific pore designs can enhance cell proliferation and nutrient flow, leading to better bone regeneration
5.	Meng Meng, Jinzuo Wang, Huagui Huang, et al., (2023)	3D printing metal implants in orthopedic surgery	limitations of conventional metal implants, which often cannot be customized to fit individual patients' anatomical needs,	clinical studies related to 3D printed metal implants in orthopedics. They analyzed various printing methods	3D printing allows for personalized implants that enhance biocompatibility, reduce stress

			resulting in suboptimal surgical outcomes.	and materials	shielding, and promote bone growth
6.	G.J. Booysen1, A.F. van der Merwe & D.J. de Beer (2019)	Additive manufacturing for sustainable custom designed implants	The problem is that, unlike traditional subtractive manufacturing, AM lacks the same level of standardization and documentation required for medical implants	The study examines the entire process of designing and manufacturing implants, focusing on key areas such as risk management, design validation, and post processing	It emphasized that addressing these risks through structured guidelines and a certification framework helps improve the reliability and reproducibility of custom implants
7.	Siti Rohaida Mohamed, Saiful Anwar Che Ghani, Worapoong Sawangsri, Mohd Azwan Azizi (2021)	The Effect of Design Parameters on Mechanical Characteristics of Porous CoCrMo Scaffold Manufactured by Additive Manufacturing	Optimizing the balance between mechanical strength and biological compatibility in implants for bone regeneration.	Additive manufacturing Selective Laser Melting is used to fabricate the scaffolds with varying porosity, followed by mechanical testing.	The study finds that pore design significantly impacts mechanical characteristics like stiffness and strength
8.	Vysakh Venugopal, Omkar Ghalsasi, Matthew McConaha, et al., (2021)	Image processing based method for automatic design of patient specific. Cranial implant for additive manufacturing	The issue revolves around the need for precise, patient specific implants that fit perfectly and promote better healing	It uses 3D scanning and image processing techniques to generate a digital model of the patient's skull. This model is then used to design an implant through CAD software.	The process ensures high accuracy in the fit of the implant, reducing complications in surgery.
9.	Victor Verboeket, Siavash H. Khajavi, Harold Krikke, Mika Salmi, and Jan Holmström (2021)	Additive Manufacturing for Localized Medical Parts Production: A Case Study	supply chains are often disrupted due to long lead times and dependencies on global networks, which can lead to delays in critical medical parts	They created six different scenarios to compare localized and centralized supply chain configurations	cost gap could be narrowed by increasing production volumes, utilizing more advanced AM machines, and expanding the

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ISSN: 2509-0119.

https://ijpsat.org/
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Vol. 48 No. 1 December 2024, pp. 20-31

			production		distances between supply chain nodes
10.	Naresh Koju, Suyash Niraula, and Behzad Fotovvati (2022)	Additively Manufactured Porous Ti6Al4V for Bone Implants: A Review	Traditional solid metal implants, while strong, often cause a phenomenon known as "stress shielding" where the implant is much stiffer than the surrounding bone	The review compiles and analyzes existing literature on different additive manufacturing methods, such as Laser Powder Bed Fusion (LPBF) and Electron Beam Melting (EBM).	The study finds that gradient porous structures, which gradually change in porosity, closely mimic the mechanical properties and morphology of natural bone

III. Result and Discussion

Additive manufacturing technology has opened new opportunities in the healthcare industry, particularly in orthopedics. Unlike conventional methods, which often require significant time and cost to produce individually customized implants, additive manufacturing can quickly and accurately create implants based on each patient's imaging data. This data is obtained through processes like CT scans, MRIs, and other imaging techniques. This technology enables the production of highly precise, patient specific implants that can replicate the shape, size, and bone structure needed to enhance osteointegration.

Additive manufacturing outputs show that the porous structures produced play an essential role in osteointegration. The porosity created during implant manufacturing with this technology promotes natural bone cell growth on the implant. Technologies such as SLM and SLS make it possible to create porous structures tailored to the patient's needs, especially with biocompatible metallic materials like Ti6Al4V, CoCrMo, and SS316L, which support bone growth effectively.

The ability of additive manufacturing to produce implants tailored to the specific anatomy of each patient is one of the greatest advantages of this technology. The table above indicates that bone implants can be designed based on scanned images from the patient's body, ensuring that the implant matches the shape of their bone, which optimally aids bone healing. Using scanning processes improves detailed accuracy, allowing for the creation of implants that conform to the patient's body structure and reduces the need for post production finishing, which is often required with conventional manufacturing methods.

Table 2. Additive manufacturing classified

Process type	Brief description	Related technologies	
Material Extrusion	Material is selectively dispensed through a nozzle or orifice	Fused deposition modeling (FDM) Fused Filament Fabrication (FFF)	Thermoplastic Filaments, Pellets and Metals
Material Jetting	Droplets of build material are selectively deposited	Multijet modeling (MJM) Smooth Curvatures Printing (SCP) Polyjet	Polymers, Waxes and Metals

VAT Photopolymerization	Liquid photopolymer in a vat is selectively cured by light activated or UV polymerization	Stereolithography (SLA) Digital light processing (DLP)	UV Curable Photopolymer Resins
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	Electron beam melting (EBM) Selective laser sintering (SLS) Selective laser melting (SLM) Selective heat sintering (SHS) Multi Jet Fusion (MJF) Direct metal laser sintering (DMLS)	Plastics, Metal and Ceramic Powders, and Sand
Binder Jetting	A liquid bonding agent is selectively deposited to join powder materials, and then product is baked in an oven for final curing.	Powder Bed and Inkjet Head (PBIH) Plaster based 3D printing (PP)	Powdered Plastic, Metal, Ceramics, Glass, and Sand.
Direct Energy Deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Laser metal deposition (LMD) Direct Metal Deposition (DMD) Laser Engineered Net Shaping (LENS) Direct Metal Deposition (DMD)	Metal Wire and Powder, with Ceramics
Sheet Lamination	Sheets of material are bonded to form an object	Laminatedo bject manufacturing (LOM) Ultrasonic consolidation (UC) Selective Deposition Lamination (SDL)	Paper, Plastic Sheets, and Metal Foils/Tapes

Despite the significant potential of additive manufacturing technology in bone implant production, several challenges must be addressed for broader application. For example, selecting the right materials for implant production is crucial, especially regarding biocompatibility, which remains a primary concern. Additionally, regulatory and safety standards for 3D printed implants need further development to ensure that the implants meet healthcare standards. The table above also highlights the importance of developing domestic supply chains for implant production using additive manufacturing technology, enabling faster production and distribution compared to conventional methods like casting.

IV. Conclusion

Based on several studies, additive manufacturing technology holds immense potential for producing bone implants that can be customized to fit the unique anatomy of each individual. This technology offers the advantage of flexibility in the production process, allowing for highly complex designs and the capability to produce personalized implants, enhancing osteointegration properties through the porous structures created by additive manufacturing. Various additive manufacturing technologies, such as Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Material Extrusion, have proven effective in producing implants with mechanical characteristics that can mimic those of natural bone. Metallic materials like Ti6Al4V, CoCrMo, and SS316L support bone growth, and studies indicate that using Additive Manufacturing technology can enhance osteointegration properties. Research also shows that the porous structures generated by additive manufacturing play a crucial role in supporting bone regeneration and implant integration within the human body.

Furthermore, additive manufacturing technology can produce implants accurately and precisely aligned with human morphology, using data from CT scans and MRIs. This leads to improved clinical effectiveness and reduces postoperative complications. Overall, additive manufacturing technology offers an innovative solution for producing more efficient, customizable, and effective bone implants. With further research, along with advances in technology and new materials, additive manufacturing could revolutionize healthcare, particularly in implant manufacturing. This development promises substantial benefits for people worldwide.

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