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3D PRINTING IN BIOMEDICAL ENGINEERING

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Abstract: *In this post, we will present a complete and up-to-date overview of 3D printing as well as its utilization in biomedicine. We show and discuss 3D printing technology, materials, cells, and their applications related to biomedical engineering. We provide our research and perspectives on the problems of 3D printing in biomedical engineering, as well as potential future advances. It is clear that 3D printing is becoming increasingly essential in biomedical engineering, with the potential to produce an extensive variety of high-value biomedical items.*

This comprehensive study can assist in understanding the present state and identifying future prospects for 3D printing in biomedical engineering, and also advancing 3D printing toward the production of newer and better biomedical goods.

Keywords: *3D printing, materials, technology, biocompatible, biomedical engineering, biomedical, bioengineering.*

1. INTRODUCTION

Over the last two decades, 3D printing [1] is being used in biomedical engineering to create customized products for various clinical uses. Advances in materials science, engineering, biology, and medicine have contributed to this growth. 3D printing can create patient-specific anatomical models, allowing surgeons to prepare ahead of time with 3D views and details [1-3]. It has the potential to create tailored implants and prostheses that align with host tissue abnormalities and anatomy [3-5]. 3D printing is increasingly being used in pharmaceutics to create biomimetic structures for drug screening and customized drug delivery systems with sophisticated release mechanisms [6].

3D printing has dramatically increased our capacity to create artificial tissues and organs with precise structural and biological qualities [7]. The first phase involves collecting pictures for a patient using advanced medical imaging technologies such as MRI and CT. Medical imaging data is processed using CAD software to create a 3D virtual model of the patient. This model is then exported as a digital file, usually in stereolithography format.

The STL file data is sliced using the 3D printing machine's software to create 2D layers, each matching an area of the digital model. The 3D printing machine uses 2D-sliced data to accurately arrange materials, biomolecules, and living cells layer-by-layer to create 3D biological products. 3D printed items might need post-printing processing to eliminate support materials or enhance structural qualities. [7].

In conclusion, 3D printing has the ability to create patient-specific and exact structures for many healthcare purposes.

2. TECHNOLOGIES AND MATERIALS

3D printing methods fall into five categories based on the materials used to create the objects:

- liquid-based 3D printing, including stereolithography apparatus (SLA), digital light projection (DLP), inkjet printing, and Polyjet;
- filament- or paste-based 3D printing, including fused deposition modeling (FDM), 3D dispensing, robocasting, and laminated object manufacturing (LOM);
- powder-based 3D printing, including selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM),

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3D powder binding (3DPB), and laser engineered net shaping (LENS);
- 3D bioprinting;
- "Smart materials"-based 3D printing, i.e., 4D printing (including 4D bioprinting).

Table 1:
Technology, materials and pros/cons for each one of those

3D Printing Technique	Typical Materials	Pros.	Cons.
Liquid-based 3D printing: Stereolithography (SLA) [9]	Photo-curable polymer resins	High resolution, smooth surface of fabricated structure	Over-curing, which can cause overhanging parts, oxygen inhibition
Digital light projection (DLP) [10]	Photo-curable polymer resins	High printing speed, less affected by oxygen inhibition	Requiring low viscosity resins,
Inkjet printing [11]	Polymers, hydrogels	Relatively high printing speed (up to 10 000 drops/s),	Limited materials in a narrow range of viscosity (3.5–12 mPa.s),
Polyjet [12]	Photo-curable polymer resins with very low viscosity and high surface tension	High resolution, good surface quality of printed structures,	Very limited materials choices, expensive
Fused deposition modeling (FDM) [13]	Polymers and their composites in the filament form	Robust, low cost, ability to process a variety of materials	Slow printing speed, requiring high temperature
3D dispensing [14]	Polymers, hydrogels, ceramics, and their composites	Ability to process in a wide range of viscosity (6–30_107 mPa·s), capable of printing bioinks containing living cells	Printing nozzle clogging, rough surface of products, relatively low printing resolution
Robocasting [15,16]	Dense ceramics and their composites	Allowing processing of very high dense ceramics pastes	Crude objects, difficulty in building complex structures
Laminated object manufacturing (LOM) [17,18]	Thermoplastic sheets, metal sheets	Low cost, high build speed	Limited materials, low precision, waste of residual materials,
Powder-based 3D printing: Selective laser sintering (SLS) [19]	Polymer powders, ceramic powders, and composite powers	Relatively wide range of powder materials, fabrication of complex structures	Requiring high temperature, low reusability of un-sintered powders
Selective laser melting (SLM)[20]	Polymer powders, ceramic powders, metal powders, and composite powders	Ability to process metallic materials, near net-shape fabrication	Difficult to control printing, balling, high residual stress, deformation issues for printed parts
Electron beam melting (EBM) [21]	Metal powders	High-power electron energy source	Lower resolution and rougher surface as compared to SLM
3D powder binding (3DPB) [22,23]	Polymer powders, ceramic powders and their composite powers	Fast, low cost, allowing fabrication of multicolor objects	Rough surface, and limited mechanical strength of products
Laser engineered net shaping (LENS) [24–29]	Metal powders	Free of powder bed, allowing fabrication of large-size objects	Low accuracy, rough surface of products
3D bioprinting: 3D dispensing, inkjet printing, laser-assisted printing, SLA, DLP, etc. [30–34]	Hydrogels, biomolecules, living cells	Ability to create 3D structures with living substances	Expensive, complex operation, requiring sterile environment for printing
4D printing and 4D bioprinting: 3D dispensing, SLA, DLP, FDM, etc. [35]	Shape memory polymers and hydrogels	Fabrication of dynamic structures that can change their shape	Still in infancy, limited choices for stimulus-responsive materials

3. EXPERIMENTAL AND TEXT DATA

3D printing technologies have become increasingly significant in biomedical engineering, offering potential solutions for the fabrication of medical devices, implants, and anatomical models. Among the various techniques available, Fused Deposition Modeling (FDM), Stereolithography (SLA), and metal 3D printing are widely studied for their distinct material capabilities and fabrication processes. However, their suitability for medical applications depends on meeting specific requirements, such as mechanical strength, biocompatibility, precision, and surface characteristics. This section aims to evaluate the strengths and weaknesses of FDM, SLA, and metal 3D printing by examining test samples produced by each method. The assessment will include optical microscopy and Scanning Electron Microscopy (SEM) for FDM and SLA samples to analyze surface morphology, structural integrity, and layer adhesion. For metal 3D printing, additional spectroscopy-based chemical analysis and optical microscopy will be conducted to assess material composition and surface properties.

Through these tests, we aim to provide a comprehensive comparison of these 3D printing methods, highlighting their potential and limitations in medical settings. The results will inform the selection of appropriate 3D printing technologies for various biomedical applications, considering their performance under controlled experimental conditions.

The experimental setup involved the use of three distinct 3D printers to fabricate test samples: the Markforged X7 for FDM (Figure 1), the Formlabs Form 3 for SLA, and the InssTek MX-Mini for metal 3D printing. Each printer was selected based on its relevance to biomedical applications, offering different material compatibilities and print technologies.

The Markforged X7 is an industrial-grade FDM printer known for its ability to print high-strength parts using continuous fiber reinforcement. It supports a range of thermoplastic filaments, including materials suitable for functional prototypes and end-use parts.

Fig. 1. The Markforged X7 3D printer.

Key features include precise layer-by-layer deposition, a dual-nozzle system, and the capability to print with engineering-grade materials, which are important for assessing mechanical performance in a biomedical context.

SLA Printer Formlabs Form 3 (Figure 2) utilizes low-force stereolithography (LFS) technology, which allows for high-resolution printing with a variety of resins.

Fig. 2. The Formlabs Form 3 3D printer

Its precision optics system and adaptive layer thickness make it ideal for producing complex, detailed structures with smooth surface finishes. This printer is particularly suited for creating accurate models and devices that demand fine detail, such as surgical guides or dental models.

The InssTek MX-Mini (Figure 3) employs Direct Energy Deposition (DED) technology, which uses a laser to melt metal powder and deposit it layer by layer. This method is advantageous for creating dense, strong metallic components suitable for biomedical applications such as implants and orthopedic devices. The printer supports a range of metal alloys, providing versatility in material selection and optimization for specific medical uses.

Fig. 3. The InssTek MX-Mini 3D printer

For sample evaluation, the following equipment was utilized. Optical Microscope Nikon P-DSL32 (Figure 4) was used to perform optical microscopy on FDM and SLA samples. This microscope allowed for the detailed examination of surface features, layer adhesion, and overall structural integrity. Optical microscopy was critical in assessing the quality of printed samples and identifying surface defects that may affect performance in medical applications.

Fig. 4. The Nikon P-DSL32 Microscope

SEM Microscope (TESCAN VEGA LMU): The TESCAN VEGA LMU (Figure 5) was employed for Scanning Electron Microscopy (SEM) to provide high-resolution imaging of the FDM and SLA samples. SEM analysis enabled the observation of microstructural details, such as interlayer bonding and surface roughness, providing a deeper understanding of how each printing method impacts sample quality.

Fig. 5. The TESCAN VEGA LMU SEM Microscope

Spectroscopy Analysis for Metal Printing (Hitachi High-Tech OE720): For the metal 3D-printed samples, a Hitachi High-Tech OE720 metal analyzer was used to perform spectroscopy-based chemical analysis. This equipment allowed for the precise determination of the elemental composition of the metal samples, identifying impurities or variations in the alloy structure that could impact the material's suitability for medical use. Optical microscopy was also employed to further assess surface quality and microstructural features.

Fig. 6. The Hitachi High-Tech OE720 Metal chemical analysis.

The machines used in this study were procured under the project INFRATECH, entitled “Infrastructure for Excellence Research in Welding.”

3.1 Results

1. FDM 3D Printing Results - Markforged X7 (Onyx Filament with Carbon Fiber)

Optical Microscopy Analysis: The FDM part printed using Onyx filament with continuous carbon fiber reinforcement displayed a distinct surface texture characterized by visible layer lines and fiber distribution.

The optical microscopy revealed a smooth but slightly uneven surface due to the fused deposition process.

Carbon fiber reinforcement was observed as continuous internal strands, providing structural integrity.

Micrographs showed minimal warping and excellent layer adhesion, suggesting the Markforged X7's precision in maintaining part dimensionality.

Fig. 7. Picture of the FDM part showing the layer lines

Fig. 8. Image showing the internal continuous carbon fiber reinforcement.

Key Observations:

- Layer resolution: Well-defined but visible layers.
- Fiber distribution: Continuous, evenly spread within the matrix.
- Surface finish: Smooth but shows FDM-specific texture.

2. SLA 3D Printing Results – Formlabs Form 3 (White V4 Resin)

Optical Microscopy Analysis: The SLA part printed with White V4 resin exhibited a highly smooth surface with no visible layer lines, highlighting the superior surface finish achievable with stereolithography.

Fig. 9. Image showing the layer lines of the SLA 3D printed part

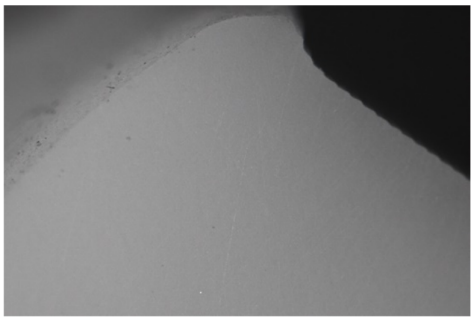

Fig. 10. Image showing irregularities at the interface between the supports and the 3D part.

SEM Microscopy Analysis: SEM images provided a deeper look into the part's surface morphology, revealing highly detailed structures and small, uniform polymer chains. There were occasional voids detected near the edges, which could be attributed to resin pooling during the printing process. The microstructure was otherwise dense and homogeneous, indicating excellent curing and resin polymerization.

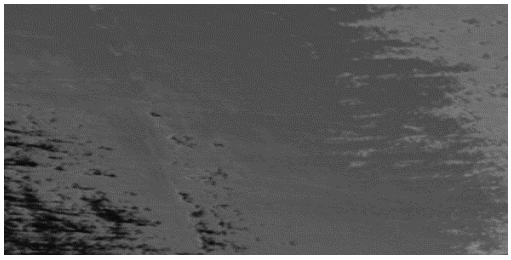

Fig. 11. The SLA 3d printed part viewed using SEM microscopy.

Key Observations:

- Surface finish: Highly smooth, minimal defects.
- Microstructure: Dense with few irregularities.
- SEM details: Occasional micro-cracks and voids, uniform resin polymer structure.

3. DED Metal 3D Printing Results - InssTek MX-Mini (AlTi Metal Powder)

Optical Microscopy Analysis: The optical microscopy of the DED printed metal part showed a rougher surface compared to polymer parts, inherent to the nature of Directed Energy Deposition. The surface contained visible layer formations and some un-melted powder particles. This roughness is typical for DED processes, indicating the need for post-processing like machining or polishing for smoothness.

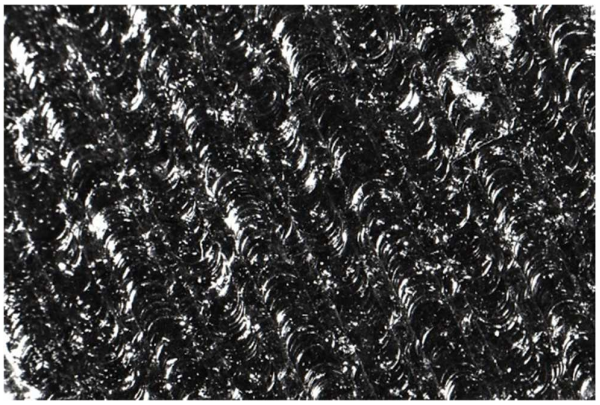

Fig. 12. This image shows the surface roughness of the 3d printed metal part.

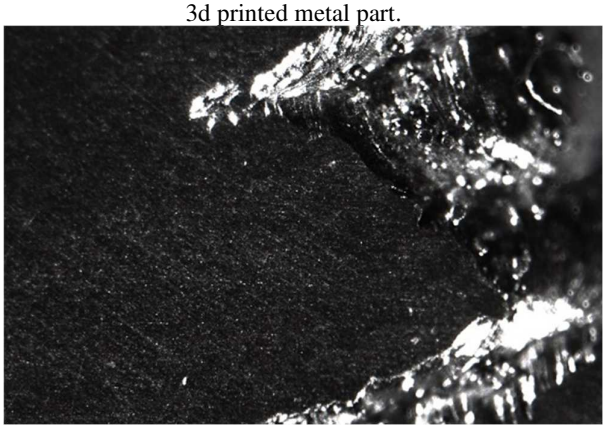

Fig. 13. Image of the polished surface showing no cavities in the part and on the part walls, minor un-melted particles.

Spectroscopy Analysis: The spectroscopy analysis of the AlTi printed component confirmed the chemical composition's adherence to the expected material properties, with an aluminum-titanium ratio indicating minimal contamination. The elemental distribution was consistent throughout, ensuring mechanical performance in line with biomedical application standards.

	Al [%]	Si [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Zn [%]
1	88.60	>2.000	0.3735	0.0136	0.0100	0.3400	0.1095
2	88.50	>2.000	0.4027	0.0148	0.0093	0.2866	0.1083
⇑							
↑							
Ø	**88.55**	**>2.000**	**0.3881**	**0.0142**	**0.0096**	**0.3133**	**0.1089**
↓							
⇓							
SD	0.074	0.0000	0.02070	0.00086	0.00051	0.03775	0.00089
RSD	0.08	0.00	5.33	6.03	5.30	12.05	0.82

	Cr [%]	Ni [%]	Ti [%]	Be [%]	Ca [%]	Li [%]	Pb [%]
1	>0.6000	>5.500	>0.5000	0.0002	<0.0001	0.0058	0.0604
2	>0.6000	>5.500	>0.5000	0.0002	<0.0001	0.0071	0.0615
⇑							
↑							
Ø	**>0.6000**	**>5.500**	**>0.5000**	**0.0002**	**<0.0001**	**0.0064**	**0.0609**
↓							
⇓							
SD	0.00000	0.0000	0.00000	0.00000	0.00000	0.00089	0.00077
RSD	0.00	0.00	0.00	0.36	0.00	13.83	1.27

	Sn [%]	Sr [%]	V [%]	Na [%]	Bi [%]	Zr [%]	B [%]
1	0.5277	0.0007	>0.1500	0.0023	0.3935	0.0081	0.0087
2	0.5484	0.0006	>0.1500	0.0026	0.4824	0.0079	0.0132
⇑							
↑							
Ø	**0.5380**	**0.0006**	**>0.1500**	**0.0025**	**0.4380**	**0.0080**	**0.0109**
↓							
⇓							
SD	0.01462	0.00005	0.00000	0.00022	0.06288	0.00015	0.00321
RSD	2.72	8.35	0.00	9.00	14.36	1.88	29.31

	P [%]	Ce [%]	La [%]	Mo [%]	Sc [%]	Ba [%]
1	0.0114	0.0421	0.0173	0.0139	>0.0600	0.0019
2	<0.0015	0.0489	0.0182	0.0151	>0.0600	0.0019
⇑						
↑						
Ø	**0.0065**	**0.0455**	**0.0178**	**0.0145**	**>0.0600**	**0.0019**
↓						
⇓						
SD	0.00702	0.00480	0.00069	0.00085	0.00000	0.00002
RSD	108.61	10.54	3.89	5.82	0.00	0.86

Fig. 14. Spectroscopy Analysis of the AlTi printed components

Key Observations:

- Surface texture: Rough, requiring post-processing.
- Material composition: Consistent AlTi distribution, low impurity levels.
- Structural integrity: Good fusion with some minor un-melted particles. Comparison of 3D Printing Methods in Biomedical Engineering.

Table 2

Comparison between FDM, SLA DED 3D printing technologies

Aspect	FDM (Markforged X7 Onyx with Carbon Fiber)	SLA (Formlabs Form 3 White V4 Resin)	DED (InssTeld MX-Mini AITi Metal Powder)
Surface Finish	Moderate smoothness with visible layer lines typical of FDM	Exceptionally smooth with minimal surface defects best finish overall,	Rough surface with visible layer formations: requires post-processing
Micro-structure	Continuous carbon fiber reinforcement provides strong internal structure	Dense, uniform resin polymer structure with occasional voids	Good fusion of metal powder but with minor un-melted particles.
Dimensio-nal accuracy	High precision with excellent layer adhesion slight surface unevenness	High accuracy; very few dimensional deviations; best consistency	Dimensional stability affected by powder layering: moderate accuracy.
Material compo-sition	Reinforced with carbon fibers, enhancing strength and stiffness	Homogeneous resin matrix with consistent polymerization	Consistent AlTi distribution essential for biomedical mechanical properties.
Defects observed	Minimal warping surface texture due to deposition lines.	Minor micro-cracks and voids likely from post- curing shrinkage.	Roughness and occasional un-melted powder; structural impurities are minimal.
Post-processing need	Minor post-processing for smoothness; sanding or coating may be required.	Minimal; post-curing addresses most surface issues.	Significant post-processing needed for surface finish (e.g. machining).
Strengths	Strong internal reinforcement good overall mechanical properties.	Superior surface quality and detail ideal for small, complex geometries.	High material strength and load-bearing capabilities; suitable for implants.
Weaknesses	Surface finish inferior to SLA; visible layer lines.	Resin micro-cracks could impact long-term durability.	Rough surface texture; post-processing intensive.
Suitability for biome-dical applications	Suitable for functional prototypes tools, and devices requiring reinforced strength	Ideal for detailed anatomical models surgical guides, and custom prosthetics	Best suited for load- bearing implants and metallic components with strict material needs.

Surface Finish and Detail: SLA printing with Formlabs Form 3 stands out with its highly smooth and detailed finish, making it the best choice for applications needing precise, high-quality surface detail. In contrast, FDM and DED methods lag behind in surface quality, with DED requiring significant post-processing.

Structural and Mechanical Integrity: The FDM process offers robust parts due to carbon fiber reinforcement, which can withstand high stress. The DED method provides strong metal components but often at the cost of surface quality, making it ideal for implants but less so for cosmetic applications.

Material Composition and Suitability: DED excels in producing components with consistent metal compositions critical for biomedical implants, while FDM and SLA are better suited for non-load-bearing applications, prototypes, or guides. The choice of material and printing method should align with the functional demands of the intended biomedical application.

4. CONCLUSIONS

Biomedical engineering can use 3D printing technologies to process a variety of materials, including biomedical polymers, metallic biomaterials, bio ceramics, biomedical composites, and living cells, as well as non-biomedical materials in liquid, filament, paste, powder, or sheet form, to create biomedical products. The usage of 3D printing in biomedical engineering is dependent on criteria such as precision, efficiency, material needs, product quality, and cost. Each technology has advantages and disadvantages.

While selecting a material for a biomedical product using 3D printing, factors such as printability, biocompatibility, biodegradation, mechanical and structural characteristics,

interfacial bonding, and cellular considerations play a crucial role. 3D printing is rapidly being applied in biomedical engineering, including surgical applications which covers planning, medical implants, prostheses, and pharmaceutical applications.

3D printing allows for personalized implants and prostheses, such as dental implants, cranial implants, spinal implants, vascular stents, and artificial limbs. 3D printing enables the creation of biomimetic structures for drug screening, as well as controlled-release medication delivery systems tailored to particular patients. 3D printing is being used in tissue engineering to create biological alternatives for various bodily tissues and organs, including skin, bone, cartilage, vasculature, and nervous systems.

Advances in 3D printing, materials science, biology, and clinical science are paving the way for new and improved 3D-printed biomedical products to be clinically available in the near future.

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Imprimarea 3D în ingineria biomedicală

În această lucrare vă vom prezenta in amănunt imprimarea 3D precum si utilizarea acestei tehnologii in medicină. Noi vom arăta si discuta despre printarea 3D, materialele, celulele si aplicațiile care au legătură cu ingineria medicală. Lucrarea prezintă cercetarea si concluziile noastre despre problemele printării 3D in ingineria medicală, precum si potențiale îmbunătățiri. Este cert faptul ca printarea 3D devine din ce in ce mai importantă in ingineria medicală, cu un mare potențial de a produce o gamă variată de produse calitative.

Această lucrare detaliată poate ajuta să ne dăm seama unde ne aflăm si unde putem ajunge in viitor cu printarea 3D in domeniul ingineriei medicale, precum si îmbunătățirea procesului de printare 3D pentru fabricarea unor produse mai bune in medicina.

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