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Brief Review: Flexible Research – Editorial Paper

Application of Fused Depositon Modelling(FDM) on Bone Scaffold Manufacturing Process

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Abstract: Layer by layer, thermoplastic filament is melted and extruded in FDM, a 3D printing technique. Because of its adaptability, cost, and simplicity of usage, it's well-liked for small-scale manufacturing, prototyping, and customizing. Bone illnesses and fractures are among the health problems that are on the rise in the modern world. Bone grafting is necessary in order to expedite the patient's condition because the natural healing process of the bone is slow. Bone replacement is created by using biomaterials in the form of a bone scaffold because bone grafting techniques including autografts, allografts, and xenografts have limitations. In regenerative medicine and orthopedics, bone scaffolds are essential because they offer a framework for bone repair and tissue regeneration. FDM has therefore developed into a revolutionary technology in the production of bone scaffolds. Bone scaffolds are made using FDM, an additive manufacturing technology. It entails the melting and layering of biocompatible materials to create a specially made scaffold with regulated mechanical and porosity characteristics that supports bone regeneration and patient-specific customization. There are certain difficulties with using FDM in the production of bone scaffolds, though. The porosity, mechanical characteristics, and rates of deterioration of printed scaffolds must be carefully controlled. This requires careful material selection, process optimization, and post-processing procedures. It also takes extensive testing and validation to achieve the appropriate biocompatibility and biomechanical qualities.

Keyword: FDM, PETG,PCL,SLS, PCL/HA, VIKOR Analysis, Bone.

1. Introduction

The human body's bones, which provide its skeletal framework, are amazing living tissues that offer movement, protection, and support. Humans need bones in order to be able to stand, walk, and carry out numerous other daily tasks. Bones are not impervious to damage, despite their resilience. Orthopedic medicine frequently deals with fractures, whether they are the consequence of sports injuries, accidents, or underlying medical disorders. While bone can regenerate itself quite well, it is not able to fully restore large-volume bone abnormalities or specific cartilage damage brought on by injury, infection, or aging. Clinical bone repair and transplantation are mostly indicated for osteoarthritis and bone abnormalities. Although amazing in and of itself, bone mending frequently needs extra assistance to guarantee a full and ideal recovery. Consequently, bone grafting has become a viable therapeutic approach for restoring and reconstructing compromised bone tissues to address the causes of bone deterioration.

Three bone-grafting procedures are available: autografting, xenografting and allografting. The gold standard for bone restoration is an autograft made from the patient's own body. On the other hand, the autograft is rather tiny. In addition, removing the autograft exposes the donor site to a considerable risk of morbidity and additional surgical trauma. Compared to autografts, which are more common, allografts derived from other persons are a superior option. Both immunological rejection and the spread of illness are nearly always the results. For surgical bone tissue restoration, novel bone replacements are therefore highly sought for. Bone tissue engineering techniques show potential in restoring missing or damaged bone tissue when compared to more traditional bone grafting techniques like autografts or allografts. One tissue engineering technique that imitates the inherent characteristics of bone tissue is the creation of a supporting framework or structure, known as the "bone scaffold approach." The purpose of this structure is to help broken or missing bone grow back and heal. The formation of new bone tissue is supported by three-dimensional structures called bone scaffolds.

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Biocompatible materials including metals, ceramics, and polymers are frequently used to create them. A range of bone abnormalities, such as fractures, infections, and tumors, can be treated with bone scaffolds.

Additive manufacturing is one process utilized in the production of bone scaffolds. Using CAD data, additive manufacturing creates parts layer by layer. It is a revolutionary manufacturing process. In contrast to traditional manufacturing, which involves removing material until the desired component is achieved, additive manufacturing creates 3D physical parts by layering on material. This allows for greater printing versatility with additive manufacturing, allowing for items of any geometry and complexity to be produced at a lower cost and faster than with traditional manufacturing methods .

One technology that works well for creating bone scaffolds is additive manufacturing. Scaffolds with intricate geometries and customized attributes can be made with it. This is significant since a bone scaffold's ideal characteristics change based on the application. Customization of bone scaffolds is another benefit of additive manufacturing. This has significance as each patient has a unique bone defect, and it can be utilized to fabricate scaffolds that precisely correspond to the patient's deficiency. Using additive manufacturing, bone scaffolds are created using a variety of processes, including direct ink writing, bioprinting, stereolithography, and fused deposition modeling (FDM).

These methods enable these crucial structures to be precisely fabricated. Utilizing biocompatible materials, patient-specific designs, and personalization are made possible by these methods. One popular and adaptable additive manufacturing method that has proven useful in the production of bone scaffolds is FDM. The best method for tissue engineering applications is to use additively produced scaffolds. Scaffolds possessing distinct architecture, pore size, pore distribution, pore interconnectivity, and porosity have been produced through the application of several additive manufacturing techniques, including photopolymerization, binder jetting, powder bed fusion, and extrusion-based systems. Extrusion-based methods are the most widely utilized additive manufacturing approach among these techniques for the creation of bone scaffolds.

The process of melting a polymer-based material and printing it on a movable platform where it will cool down is known as extrusion-based additive manufacturing. The final qualities of the printed scaffolds will be determined by an inherent morphological development process that takes place during this heating and chilling procedure. For the production of bone scaffolds, fused deposition modeling is a useful and adaptable approach. Its capacities to offer biocompatibility, regulated porosity, customization, and cost-effectiveness are very compatible with the particular demands of the bone scaffold production process. Layer by layer, melted filament material is deposited over a construction platform using an FDM 3D printer. Digital design files are submitted to the FDM machine, which then converts them into actual dimensions. The machine feeds polymers like ABS, PLA, PETG, and PCL through a heated nozzle to create materials for FDM.

2. Literature Review

Rochmad Winarso et al.(2022) [1] discussed about how FDM technologies are being used to produce bone scaffolds and how various process variables affect the part's properties. The important process factors that affect the part include extrusion temperature, nozzle diameter, printing speed, contour numbers and more.

Qiliang Zhang et al.(2023) [2] discussed on the creation of bone scaffold for tissue engineering using 3D printing methods like SLS, SLA and FDM. These techniques are difficult, even though they are flexible. Rough surfaces can result from SLS changing material characteristics, and FDM's lack of accuracy necessitates improvements in precision. Post-processing is frequently necessary for SLA scaffolds, which carries a risk of impurity and distortion. In order to fully utilize 3D printing in tissue engineering, several problems must be resolved.

Harshavardhan Budharaju et al.(2023) [3] discussed on bone implants made of 3D printed ceramics. Discovered benefits such as customized mechanical characteristics and decreased stress shielding. But they also have to deal with issues like expensive printing, difficult printing conditions, and perhaps defective materials. More effective and dependable implant solutions for individualized bone tissue regeneration may result from streamlining printing procedures and taking into account material combinations like ceramic-nanomaterial composites.

James Hulme et al.(2023) [4] Investigated the porosity and mechanical properties of four lattice-structured bone scaffold materials: face-centered cubic, body-centered cubic, body-centered cubic with z struts, and simple cubic. The body-centered cubic design was found to be the weakest and the simple cubic design to be the strongest when compressive strength was evaluated using 3D printing and polylactic acid. Simple cubics exhibited the largest porosity, which is important for nutrient diffusion and cell movement, according to porosity measurements.

Laldinthari Suamte et al.(2023) [5] discussed on the various scaffold qualities and techniques for tissue

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engineering. The distinct structures and biocompatibility of various scaffolds are impacted by the processes used in their production. Speed, accuracy, complicated geometries, and resource economy are all provided by additive technologies, but post-processing is necessary, which raises the cost of the final product. While familiar and affordable, conventional methods lack advanced features.

Evangelos Daskalakis et al.(2023) [6] discussed on the extrusion-based additive manufacturing, the viscoelastic characteristics of different mixes containing PCL and ceramic materials. The viscous modulus of these mixes was greater than the elastic modulus at low frequencies, but as the frequency increased, the discrepancy narrowed. Both moduli rose with the inclusion of ceramic materials; the maximum elastic modulus was found in PCL/HA. Because of their reduced loss factor, relaxation periods, and shear viscosities, blends including Bioglass particles were generally more suited for printing than PCL/HA blends, although having a slightly lower elastic modulus overall.

Binglong Li et al.(2022) [7] discussed on the advancements in 3D printing technology and various material types. The main component used to prepare bones is polymer filaments in FDM printing systems, which are the most focused form of 3D printing systems utilized in biomedicine.

Joana Macedoa et al.(2022) [8] discussed on the accuracy and precision of printing tablets in three dimensions using fused deposition modeling. For multiple printing, two distinct mixtures were used, which led to minimal intra-batch variability and negligible changes between batches for the majority of characteristics. Tablet mass varied between batches, possibly as a result of variations in filament diameter. Reproducibility was increased by using a smaller nozzle or a different printer, and multiple printing reduced production time by more than 35% as compared to single printing.

Tesfaye Mengesha Medibew et al.(2022) [9] discussed the effects of process variables on component tensile strength and components printed with polylactic acid (PLA). Layer thickness is the primary element influencing the tensile strength of components manufactured with FDM. The tensile strength of FDM PLA-printed products is mostly determined by various factors such as the print speed, infill pattern, raster angle, density, and extrusion temperature.

Hyungjung Kim et al.(2022) [10] discussed about the using deep transfer learning to find faults in FDM printing, such as spaghetti forms. Through picture augmentation and fine-tuning, it employs pre-trained CNN models, such as ResNet50, with a limited dataset to increase accuracy. The findings demonstrate that, in particular, ResNet50 efficiently and with low computational overhead recognizes spaghetti-shape defects.

Nadine Gottschalk et al.(2022) [11] discussed the differences between drop on powder printing and FDM in the context of 3D printing amorphous solid dispersions. It was discovered that FDM is more appropriate for manufacturing because of its decreased tendency toward recrystallization. Even so, printing and producing filaments posed a significant difficulty.

Krishna Mohan Agarwal et al.(2022) [12] Investigates the effects of six critical print parameters on the dimensional accuracy of the printed specimens: wall thickness, extrusion temperature, build plate temperature, print speed, layer thickness, and infill density. The two most important of the six parameters were Print Speed and Layer Thickness, followed by Wall Thickness and Infill Density. It was found that the reaction was mostly unaffected by the extrusion temperature and little affected by the build plate temperature.

Luqman Musa et al.(2022) [13] discussed how using PLA-based TPE material for FDM could improve the features of the existing PLA filament. With the correct ratio, it is feasible to produce TPE filament with PLA and rubbers that may be used with 3D printers. Rubber particles added to PLA material can address problems not addressed by conventional PLA thermoplastic filaments.

Chloé Parulski et al.(2021) [14] discussed potential ways to accelerate the development of products for the pharmaceutical sector as well as the main fused deposition modeling important process factors. The three main crucial process parameters were those that were specific to the material, the operation, and the machine.

Dhinakaran Veeman et al.(2021) [15] discussed the important modifications, trends, and breakthroughs in tissue engineering and regenerative medicine with possible applications, as well as the additive manufacture of biopolymers. While biopolymers are environmentally beneficial and sustainable, they frequently lack the mechanical strength of conventional plastics. To handle applications requiring load bearing, ceramic composites can be used to reinforce them.

Nagireddy Dumpa et al.(2021) [16] discussed about the many steps in FDM 3D printing and how drug delivery uses 3D printing. Individual differences in genetics, metabolism, and physical characteristics present a variety of obstacles for individualized pharmacotherapy and customized drug administration.

Manav Doshi et al.(2021) [17] investigated the printing settings that directly affect the mechanical qualities of the FDM-produced products, such as stress, tensile strength, and Young's modulus. Preference should be given to common materials like nylon, PLA, and ABS, with 100% infill density producing the strongest results. For PLA filament, the ideal temperature is 215°C, and the ideal infill speed is 90 mm/s. While the 0° raster angle provides the best overall performance, the build orientation of 0° yields the highest tensile strength.

Moritz Glatt et al.(2021) [18] discussed on automated technique for removing parts from FDM printers. To get beyond the printed part's adherence to the build platform, it uses blades to slip below it. The system, in contrast to current techniques, has a simple detachment mechanism, requires no separate build platforms, takes up very little room, and uses inexpensive components. It can be modified for printers with glass building plates and front access to the build chamber, while it was originally made for Ultimaker 3 printers.

Srishti A. Deomore et al .(2021) [19] discussed on the VIKOR technique's optimization of the FDM process parameters. It makes use of the VIKOR technique to optimize settings when producing PLA plastic specimens via 3D printing. Using a 0.3 mm layer thickness, 100 mm/hr speed, and a 55% infill percentage, the optimal parameters were determined by the VIKOR analysis, which ranks 6 grams of material weight, 2.13 meters of filament length, and a 20-minute printing time as the top choices.

Dimitris Mourtzis et al.(2021) [20] discussed on the planning and creation of a framework based on the use of DT and cloud technologies for tracking and increasing the parameters of FDM. The framework may be accessed via a mobile application and allows for both online and offline simulations as well as remote machine monitoring through Augmented Reality. The process entails evaluating printed components manually for quality and saving the outcomes in the cloud for later use.

Daniele Pierantozzi et al.(2020) [21] discussed on the use of 3D printing to produce PCL, PCL/HA, and PCL/SrHA composite scaffolds. Their porosity matched human cancellous bone, as proven by microCT examination. Adding ceramic has no influence on stiffness from a biomechanical standpoint. Mechanical qualities, which could be modified by scaffold design, were largely independent of material formulation. Each scaffold allowed for the development of cells and was biocompatible. Promising for bone tissue engineering, scaffolds incorporating SrHA demonstrated better mineralization potential.

Alice Melocchi et al.(2020) [22] discussed how the settings of the FDM process affect the efficiency and quality of the parts. Important considerations are mentioned, including layer height and raster orientation. The thickness or layer height is thought to be an essential component in determining the part quality. Raster orientation is a key factor in determining the mechanical properties of polymer components.

Ankita Jaisingh Sheoran et al.(2020) [23] discussed on the qualities and quality of FDM printed parts, such as surface roughness, finishing, and dimensional accuracy, as well as the effects of the process settings. In order to determine which FDM process variables significantly affect a given desired output, current DOE methodologies and statistical optimization tools are employed.

Naiju C D et al.(2020) [24] discussed the precision of FDM in the creation of medical components using CT scan data, with a particular emphasis on components for the hand and thumb (Hallux). Reconstructing these implants with FDM produced an average deviation of 0.303 for the distal implant and 0.361 for the primal implant. Deviations were ascribed to many causes, including the monitoring of CT scan data and the staircase effect on curved surfaces. Nevertheless, FDM demonstrated cost-effectiveness and efficiency, cutting production time without sacrificing quality.

Sunil J. Raykar et al.(2020) [25] discussed on VIKOR technique for choosing the best printing settings for fused deposition modeling (FDM). 3D printed specimens made of ABS plastic are used to test various factors, including printing time, filament length, and material weight. The highest settings yield a material weight of 3.39 grams, a filament length of 1128.7 mm, a printing duration of 16 seconds, and a layer thickness of 0.25 mm at 40°C in bed temperature, 100 mm/h speed, and 40% infill percentage.

3. Materials and Methods

3.1. Materials

Filament Material: A long strand of composite or thermoplastic material coiled onto spools, filament material is essential to 3D printing. Materials commonly utilized in Fused Deposition Modeling (FDM) include composites such as Hydroxyapatite (HA), PLA, PCL, and PEEK. The physical characteristics of the product that is 3D printed are greatly influenced by these materials.

Supporting Material: During 3D printing, supporting materials like PVA and HIPS are used to give structural support for overhanging or intricate elements. These supplies make it easier to create complex designs and keep the finished product's structural integrity.

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3D Printer: Three-dimensional things can be created with a variety of 3D printers, including the Prusa i3 MK3S, Ultimaker 2+, Creality Ender 3, and MakerBot Replicator Z18. These printers use precise instructions from digital models to deposit layers of molten thermoplastic material onto a build platform.

Software for 3D Modeling: 3D modeling software is essential for designing scaffolds that are mechanically optimal, biocompatible, and tailored to each patient. Utilizing programs such as Autodesk Fusion 360, SolidWorks, Tinkercad, Blender, and SketchUp, engineers and designers can precisely customize 3D data collected from medical imaging.

Slicing Software: Slicing software is essential for converting 3D models (in STL format) into G-code so that the models are ready for 3D printing. Software like Ultimaker Cura, PrusaSlicer, and Simplify3D are noteworthy because they let users adjust details like layer height and infill density.

3.2. Methods

Obtaining Patient Data: For the purpose of manufacturing bone scaffolds, medical imaging methods—specifically, CT and MRI scans—are the main source of patient data. The precise creation of computer models is aided by the detailed photographs of the patient's bone structure provided by these scans.

3D Modeling Process: The segmentation process is the next step in the 3D modeling software's workflow after data collection. In order to create a thorough model of the patient's bone architecture, it is necessary to identify and isolate particular structures or regions of interest within the 3D data. Designers then modify the 3D model's size, shape, and porous components using specialist software to meet the patient's needs.

Material Selection: Selecting biocompatible and resorbable materials for FDM, like PCL or PLA, is essential to guaranteeing that the 3D-printed scaffolds are compatible with human anatomy.

Preprocessing: Using slicing software like as Cura or PrusaSlicer, 3D models can be made ready for printing by modifying parameters like layer height and infill density. For the selected 3D printer, this step guarantees ideal printing circumstances.

3D Printing: It involves loading the chosen filament material into the printer and heating it to the melting point. The 3D digital model's exact outlines are followed by the printer as it deposits the molten material onto the build platform, layer by layer. The production of intricate and personalized geometries is made possible by the layer-by-layer deposition that progressively constructs the bone scaffold from the bottom up.

Sterilization: It is crucial to guarantee the security of bone scaffolds that are 3D printed. Microorganisms are eliminated by the use of sterilization techniques such as autoclaving, ethylene oxide gas, and gamma radiation. When using these scaffolds for medical purposes, adherence to validation procedures and regulatory criteria is essential.

4. Result and Discussion

The developments and difficulties of FDM and other 3D printing technologies for the production of bone scaffolds are examined in depth by Rochmad Winarso et al. (2022) and Qiliang Zhang et al. (2023). Although FDM is versatile, accuracy is still an issue, therefore improvements in precision are required.

The promise of 3D-printed ceramics-based bone implants is highlighted by Harshavardhan Budharaju et al. (2023). They address issues like printing conditions and prices while also recognizing benefits like customized mechanical properties and decreased stress shielding.

James Hulme et al. (2023) Examine the mechanical functionality of lattice-structured materials for bone scaffolds, highlighting the import of design decisions in determining compressive strength and porosity, which are essential for cell migration and nutrient transport. Emphasized how critical material selection and process optimization are in order to determine if PCL and ceramic mixes are suitable for extrusion-based additive manufacturing,

Evangelos Daskalakis et al. (2023) investigate the viscoelastic properties of these materials. Binglong Li et al. (2022) concentrate on the advancement of 3D printing technology, stressing the importance of polymer filaments and FDM systems as essential elements for bone preparation. The impact of printing parameters on reproducibility is highlighted in the work by Joana Macedoa et al. (2022), which investigates precision and accuracy in tablet 3D printing.

Krishna Mohan Agarwal et al. (2022) and Nadine Gottschalk et al. (2022) further address the problems related to FDM, including accuracy and material properties. In order to highlight FDM's production suitability, the former contrasts it with drop-on-powder printing for amorphous solid dispersions.

In their investigation of the effects of several print parameters on dimensional accuracy, Krishna Mohan Agarwal et al. (2022) highlight the importance of elements

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such as print speed and layer thickness. Furthermore, the investigation of new materials is facilitated by the progress made in 3D printing.

In order to address problems that conventional thermoplastic filaments encounter, Luqman Musa et al. (2022) explore the possibility of using PLA-based TPE material to improve the characteristics of standard PLA filaments. As demonstrated by Chloé Parulski et al.'s work from 2021, the survey also includes studies that are specifically focused on the pharmaceutical industry. These studies address important process characteristics and potential solutions for accelerating development in the pharmaceutical sector.

5. Conclusion

A complex picture of the state of the field is presented by combining several literature studies on FDM and 3D printing technologies for the creation of bone scaffolds. With an emphasis on creating new PLA-based TPE materials to improve current filament quality, the careful consideration of material selection highlights the critical role of polymers such as PCL, PLA and composite materials.

Critical process parameters are thoroughly investigated; these include layer thickness, raster angle, build orientation, and other variables. With techniques like the VIKOR approach and statistical tools to fine-tune the desired output properties, such surface roughness and dimensional accuracy, the optimization landscape is broad.

It is openly known that these technologies have drawbacks, including post-processing requirements in SLA, material property changes in SLS, and accuracy problems in FDM. In response, researchers have developed creative strategies to tackle these problems head-on, such as automated detachment techniques and deep transfer learning for flaw detection.

In order to clarify the best scaffold design considerations for efficient tissue regeneration, mechanical performance assessments examine a wide range of lattice-structured materials, including porosity and compressive strength. Examining the viscoelastic characteristics of mixtures of PCL and ceramics reveals a more complex picture of the behavior of materials during the extrusion-based additive manufacturing process, with implications for medical applications.

Personalized pharmacotherapy and tailored medication delivery are also possible with the use of 3D printing in pharmaceutical and drug delivery systems, which is emerging as a promising topic. Overall, this extensive body of work represents not only the complex aspects of FDM and 3D printing technologies for the creation of bone scaffolds, but also the dynamic field of tissue engineering and customized medical solutions, propelled by ongoing innovation and thorough investigation.

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