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# Additive manufacturing of biomaterials

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ABSTRACT

Biomaterials are used to engineer functional restoration of different tissues to improve human health and the quality of life. Biomaterials can be natural or synthetic. Additive manufacturing (AM) is a novel materials processing approach to create parts or prototypes layer-by-layer directly from a computer aided design (CAD) file. The combination of additive manufacturing and biomaterials is very promising, especially towards patient specific clinical applications. Challenges of AM technology along with related materials issues need to be realized to make this approach feasible for broader clinical needs. This approach is already making a significant gain towards numerous commercial biomedical devices. In this review, key additive manufacturing methods are first introduced followed by AM of different materials, and finally applications of AM in various treatment options. Realization of critical challenges and technical issues for different AM methods and biomaterial selections based on clinical needs are vital. Multidisciplinary research will be necessary to face those challenges and fully realize the potential of AM in the coming days.



**Contents**



*Abbreviations*: AM, Additive Manufacturing; SFF, Solid Freeform Fabrication; LM, Layered Manufacturing; RP, Rapid Prototyping; CAD, Computer Aided Design; FDM, Fused Deposition Modeling; ASTM, American Society for Testing of Materials; TCP, Tricalcium Phosphate; PCL, Polycaprolactone; LENS™, Laser Engineered Net Shaping; EBDM, Electron Beam Direct Manufacturing; CNC, Computer Numeric Control; LBMD, Laser Based Metal Deposition; EBAM™, Electron Beam Additive Manufacturing; FDC, Fused Deposition of Ceramic; PBF, Powder Bed Fusion; SLS, Selective Laser Sintering; SLM, Selective Laser Melting; EBM, Electron Beam Melting; SLA, stereolithography; DMD, Digital Micromirror Device; CaPs, Calcium Phosphates; HA, hydroxyapatite; BMP-2, Bone Morphogenetic Protein 2; TTCP, Tetracalcium Phosphate; DCP, Dicalcium Phosphate; VEGF, Vascular Endothelial Growth Factor; CMC, Carboxymethyl Cellulose; DLP, Digital Light Processing; PVA, Polyvinyl Alcohol; ALP, Alkaline Phosphatase; BCP, Biphasic Calcium Phosphate; DLF, Direct Laser Fabrication; LAM, Laser Additive Manufacturing; HIP, Hot Isostatic Pressing; DLF, Direct Laser Forming; SBF, Simulated Body Fluid; PBS, Phosphate Buffer Saline; BSA, Bovine Serum Albumin; ECM, Extracellular Matrix; PGA, Polyglycolic Acid; PLA, Polylactic Acid; PLGA, Poly(lactic-*co*-glycolic acid); PLLA, Poly-L-lactide; PDLA, Poly-D-lactide; PLDLLA, Poly(L-lactide-*co*-D,L-lactide); PEG, Polyethylene Glycol; SSLS, Surface Selective Laser Sintering; PPF, Polypropylene Fumarates; PEEK, polyetheretherketone; CPP, Calcium Polyphosphate; THR, Total Hip Replacement; TKR, Total Knee Replacement; FGF-2, Fibroblast Growth Factor-2; DMLS, Direct Metal Laser Sintering.

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## 1. Introduction

Additive manufacturing (AM) means processing or prototyping approaches that are capable of fabricating metallic, polymeric, ceramic or composite structures in a layer-by-layer manner from a computer generated design file. AM is also referred to as 3D Printing, Solid Freeform Fabrication (SFF), Layered Manufacturing (LM) or Rapid Prototyping (RP). In any AM process, parts are first designed using a computer aided design (CAD) software. Surface features of the three-dimensional CAD files are then exported to a file typically with a .STL extension. The .STL file is the main input file for an AM fabricator where the part is built. The surface file is sliced in a virtual environment into many two-dimensional (2D) layers. An AM machine then uses those 2D layers of the design file and creates the necessary tool-path along the X and Y directions for direct manufacturing. Finally, each layer is processed sequentially one on top of the other to form a three-dimensional part. Since each part is fabricated by adding layers on top of a previous layer, this type of manufacturing approach is called "additive manufacturing (AM)". AM fabricators utilize many conventional manufacturing techniques to build each layer. For example, Fused Deposition Modeling (FDM) is one of the most popular AM methods for polymeric materials. FDM works basically by softening a thermoplastic polymeric material and then extruding it through a nozzle to create a layer. Extrusion is a common manufacturing technique for polymers. However, extrusion of multiple layers based on a computer file to create a 3D object is the novelty for FDM. Thus, it can be seen that additive manufacturing borrows conventional manufacturing concepts and utilizes them in a non-traditional way to directly build 3D parts without using any part-specific tooling.

However, there are many differences between additive and conventional manufacturing. Conventional manufacturing processes are evolved to manufacture a large variety of parts as fast as possible, maybe even in high volume. Starting from raw materials to a finished part, processes are optimized for the highest yield. A simple example of such manufacturing principles is the steel industry, where high volume, low-cost fabrication processes like casting, forging or rolling are commonly practiced. After fabrication, parts are machined per customer requirement. In this machining stage, the material is removed and sometimes can be expensive as well as time-consuming. Finally, different components are assembled into a single system. The entire process from the design stage to the actual part realization is long but cheap for large volume production. AM, on the other hand, is a material-specific and design-specific system. Realization of high yield and low cost are not always mandatory. AM methods are unique in the situations where the production volume is not high, the cost of production is not the big-