The Role of 3D Printing for the Growth and Progress of Medical Healthcare Technology

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Edited by

Dinesh Bhatia

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My sincere gratitude to my dear parents for their unconditional love, support and blessings in all my endeavours

Mr. Ashok and Mrs. Kanchan Bhatia

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FOREWORD

I am pleased to write the Foreword for the book *The Role of 3D Printing for the Growth and Progress of Medical Healthcare Technology* by Cambridge Scholars Publishing, edited by Dr. Dinesh Bhatia. 3D printing came into existence in the early 1980s as additive manufacturing and over the years the technology has grown leaps and bounds. The technology gained huge popularity in the 2000s, when its importance came to the limelight and its role was explored to help improve the capability of humans. This additive technology is currently employed in different fields and affecting different aspects of human lives. It is also employed for industrial purposes, as well as in sophisticated fields such as nanotechnology. In the medical field, 3D-printing was seen as one of the biggest breakthroughs and it slowly became an integral part of mainstream medical practice. Different 3D-printed solutions were developed to benefit a large number of patients across different specialties.

I hope this book will help to explore the growth and advancement in 3D printing technology in different areas of healthcare and in improving patient care with better quality, customized designs and lower costs, thereby providing durability and patient comfort. I congratulate all the authors who have spared their valuable time and contributed to the book by sharing their knowledge and expertise in the field with potential readers and researchers to further enhance their skills. It will provide insight to budding researchers and students to explore the field further. I also acknowledge the role of the reviewers and publishers in providing their inputs to help in refining the quality and content of the book before final acceptance and production.

I extend best wishes to all potential users of this book.

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29th May, 2020

PREFACE

This book explores explore the growth and advancement in 3D printing technology in different areas of healthcare and how it is being employed to help in improving patient care with better quality, customized designs and lower costs, thereby providing durability and patient comfort. Despite its existence for a number of years, not many books are yet available on this field, making this text unique. It incorporates knowledge and expertise from professionals who have worked in the field for a number of years to help establish the technology. It will provide insight to budding researchers and students to explore the field further.

In the medical field, 3D-printing is seen as one of the biggest recent breakthroughs and it slowly became an integral part of mainstream medical practice. 3D printing is currently employed in several industrial applications and in different medical fields specifically to replace human organ transplants, improve surgical procedures, develop surgical tools at lower costs, and improve the lives of disabled people reliant on prosthetic limbs. The field is creating huge interest among scientists and researchers and is revolutionizing the medical domain, and has benefits for varied patient populations. One example of this is the first 3D printed implant known as bioprinted airway splints for babies whose lives are at risk due to the collapse of tiny airways around the lungs. This is a special implant as it has the ability to grow with the baby and can be produced in less than an hour's time with minimal costs involved. 3D bioprinted tissues for burns victims, organ transplants, human organs, and liver, kidney and brain tissues can also be easily developed employing this technology.

I would like to extend my sincere gratitude to all contributing authors for their painstaking efforts and helping me in incorporating finer details into the present book. I am grateful to my parents and family members for their kind support in allowing me to complete the book in time. I also acknowledge the support of my present institution/University and Cambridge Scholars Publishing for allowing me to complete this challenging assignment in the prescribed time. I do hope the present book would serve the due purpose for which it was initiated and support people

working in the field to enhance their skills and guide budding researchers in the discipline.

Finally, I thank Almighty God for his kind blessings, wisdom and grace to enable me to complete this book.

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CHAPTER ONE

INTRODUCTION TO 3D PRINTING

DR. NEELAMSHOBHA NIRALA

Abstract

3D printing began in the 1980s, when Charles Hull designed and printed a small eyewash cup. It has generated much interest since then. It is a cost-effective, localized, one-step manufacturing technique that can produce personalized, complex objects with minuscule precision. It has affected almost all industries, from edible cookies to jewellery; kids' toys to house designs; prosthetic limbs to humanoid robots (Kenshiro and Kengoro) that can mimic human activity; pharmaceuticals, and so on. Complicated structures that were impossible to produce with conventional manufacturing methods can now be easily produced by using 3D printing. Even an object which consists of several parts, such as the designing of a car, can be produced in a single operation. The flexibility of 3D printing allows for a reasonably quick and easy way to adjust the design without the need for additional tools or equipment. However, the practical application of, and potential for, 3D printing is to some extent limited because of its slow speed and the time required to fabricate the required 3D objects. In this chapter, we are going to discuss in detail the basic concept of 3D printing, looking briefly at its history, the advantages and limitation of this technique, and drawing a comparison with the subtractive method of manufacturing. We will also discuss various techniques presently being used for 3D printing, along with the materials used in various applications.

Introduction

One of the buzzwords of today's generation, which attracts many individuals ranging from technical researchers and scientists to homemakers, is 3D printing. With this technology it is possible to design customised chocolates at home while also enabling the design of complex physiological models, like prosthetic limbs or fully functioning organs. Its wide application involves almost every industry, from automobile to aeronautics, food production to tissue engineering, and house-building to jewellery making. What is 3D Printing? It is a technology that supports the formation of an object by placing the contoured layers or slices on top of one another. Here, the parts are grown layer-wise from the base to the top until the object is formed.

3D printing began in the 1980s, when Charles Hull printed a small eye wash cup as the first 3D object and, since then, it has generated much interest. This technology is also known by many other names, like Additive Manufacturing (AM), Rapid Prototyping (RP), Solid Free-form Technology (SFF), Direct Digital Manufacturing, or Desktop Manufacturing, based on its specific abilities. When 3D printing was first proposed in the 1980s it was called Rapid Prototyping (RP) because it enabled the production of a prototype of an object without the use of tools, thereby saving both time and money. It provided the ability to evaluate the design in the computer before it went into the stage of actual production.[1] It was faster to generate an altered version of 3D printed designs. It is important to note that the time taken in creating a 3D object depends upon various factors, such as the size of object, the speed of the motor, the thickness of the slice, the type of 3D printer used, and so on. But with the use of computers and software, this has made the process of prototype designing much faster. This method is known as Additive Manufacturing (AM) because it develops an object by adding the layers of material instead of removing the material from the workpiece, as done in traditional Subtractive Manufacturing (SM).

Before comparing Additive Manufacturing with traditional Subtractive Manufacturing (SM) methods, let us see how the manufacturing cycle of the traditional method works. Mass manufacturing by traditional methods include various steps:

1. Collecting raw material or basic resources from various places. Depending on the distance between the source of the resource and the manufacturing plant, this factor consequently adds to the transportation charge.

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[1] Andreas Gebhardt and Jan-Steffen Hotter, *Additive Manufacturing 3D Printing for Prototyping and Manufacturing*, ed. Cheryl Hamilton (Cincinnati: Hanser Publications, 2016); Thomas Birtchnell and William Hoyle, eds., *3D Printing for Development in the Global South: The 3D4D Challenge* (PALGRAVE MACMILLAN, 2014), https://doi.org/10.1057/9781137365668.0001.

2. Transportation of these collected raw materials to locations where refinement takes place.
3. Making initial products or components from refined materials in huge numbers using SM technique to reduce the unit cost. SM techniques include milling, turning, drilling, grinding, cutting moulding, beating, forging, machining, and so on.
4. Shipping of these initial products or components across the world.
5. In the case of components, the need to assemble them into the final products in huge numbers.
6. Transportation of final products into huge warehouses.
7. To reach the actual consumers, shipping is again needed to various distributors and standalone stores.

From the above, it is clear that the above-mentioned method has some areas of inefficiency and is most suitable for mass production, like wheels for four-wheelers of a similar kind, the standard size of clothes worn by a majority of people, or some kind of mobile phone for major needs. This method of manufacturing involves the consumption of huge resources in the form of raw materials, energy production, and distribution of goods among various places, often involving much labour-intensive activity, like an assembly line, warehouse or distributor. As an example, this kind of manufacturing process in the clothing industry works well while a defined mould is required and met, in terms of the cloth material required before the arrival of a new season, but as soon as trends or techniques change, the requirement of a new design group, human power, mould preparation, tools requirement, and fixture may lead to the discarding of obsolete tools and materials.

As the saying goes, necessity is the mother of invention. Society has sought to evolve from its more primitive stage towards a more civilised form, which has been made possible by the earlier industrial revolutions that have reshaped the way our societies function. Enthusiasts of AM or 3D printing see this as the third industrial revolution. Each industrial revolution transforms the world in some way. The first revolution transformed the means of production, whereby the world went from handmade production to automatic production which utilised machines which ran using steam or water. For example, tilling of the land by animals was replaced by tractors and wooden tools were swapped for metal ones. The second revolution raised the application of steam-driven engines for factories, and enabled mass production. The third revolution is expected to support the local production of greatly customized products on-demand at low cost while ensuring limited resource wastage. It is also expected to shorten the traditional release cycles of products and design cycles. In view of the above points, let us observe a few advantages brought about by AM or 3D printing.

Advantages of AM

1. AM initiates the direct conversion of design to product. AM can produce a complete product, including finishing and processing within a timeframe (which may include interlocking of moving parts, holes, cavities, or bearings within the wheel) that is greatly reduced when compared to the SM method.
2. Approach towards zero waste manufacturing by reducing material wastage.
3. No tooling—3D printing eliminates the need for costly and time-consuming tools for the production of an object.
4. AM is especially suitable for the shortening and improvement of the product development process.
5. Since 3D records are available for access in the desired format, it eliminates the data exchange problems which arise with pre-processor in the subtractive manufacturing process.
6. Personalisation or customisation—with the availability of the internet and the ease with which data across the globe may be shared, AM allows the personalisation of goods at the time of fabrication by a consumer's choice in terms of design, colour, shape, and size. These initiate the manufacturing of a customised product.
7. Design flexibility—the unique feature of 3D printing is the layer-wise sequential fabrication approach that makes it promising to create complex geometrical structures. With the help of 3D printing, fewer load-bearing structures can be easily made with additional support material. In the case where weight is a considerable factor, where strength is required, the honeycomb-like structure can help to produce lightweight products, for example, the bones of birds. Overall, 3D printing provides the designer with the flexibility to selectively place the material at a precise location to obtain design functionality with lower material consumption.
8. Reduction in the cost of geometric complexity—3D printing provides freedom to the designer in the realisation of complex structures. In traditional manufacturing, there is a direct proportionality between the complexity of the shape and moulding cost, whereas in AM an increase in geometrical intricacy does not affect costs.
9. Sustainability—by altering the strength and flexibility in the design of an object, 3D printing can reduce the material utilisation and

conserves resources and money. Further utilisation of degradable material may reduce the consumption of petrochemical-based polymers.

10. Reduction in obsolescence—with the advance of technology, old products become obsolete and raise the inventory of old parts. With 3D printing, we can design the 3D models of obsolete parts of automobiles and machines which are no longer available.
11. Economies of scale—in traditional manufacturing, mass production is required to overcome the cost involved in the transportation of goods, long storage periods, distribution networks, manufacturing in low-cost areas, and labour costs, so that per product costs drop-down at the consumer end. In AM, however, the above-stated costs are not going to be as affected by the number of products manufactured. Moreover, it reduces the costs associated with manpower, consumption of raw material, human error, transportation, and inventory.
12. Avoids the assembling of parts—with the flexibility in the design of intricate shapes by 3D printing, it is possible to produce shapes that would otherwise need assembling of various parts by traditional methods. In the future, it will be possible to produce products with "single part assemblies", which means a single product will be fabricated in which the parts and joints will be present in their respective places with support material. During post-processing, these support materials can be easily removed.
13. Reduces the delivery time of the product. With local fabrication of 3D objects, the delivery time of the product can be reduced.

Since we are now familiar with extensive advantages of AM, let us see what a 3D printer is made up of, and how it works on the design part. The most widely used 3D printer is based on the Fused Deposition Modelling (FDM) technique. In FDM, thin filaments of melted plastic will be placed in layers to form a 3D part. Fig1.1 shows the basic component of the FDM-based 3D printer. It consists of a frame or chassis, build plate or area, a filament spool, an extruder, linear movement components, and a controller unit. The chassis is the frame of a 3D printer; it can be made up of wood or metal plates to support the movement and vibration during working, as well as to hold the printed object. The build area is a flat, levelled plate where the actual printing takes place. A thin filament of thermoplastic is coiled in the filament spool to feed the extruder. The extruder is the main part of the FDM technique which melts the filament supplied to it, and then pushes the melted filament out from the small diameter nozzle to place it in the desired location in the build area. The extruder can move in both x and y direction, which means it can move from left to right and front to back or vice-versa to reach a particular x–y coordinate. It is essential to level the build plate perfectly parallel to the extruder so that the built part will be level. The linear movement component helps in the movement of the extruder in a defined direction through the stepper motor. End-stops are placed to limit the linear movement of the extruder in each axis. A controller unit guides the whole movement of the 3D printer. In 3D printing, we directly fabricate a physical model of an object from its digital design. So, let us consider the steps involved in the fabrication of a part by 3D printing.

1. To print any 3D object or its prototype, we first need a 3D model of an object, material to fabricate, and a 3D printer.
2. There are three possible sources for the 3D model of an object. First, the use of 3D modelling software, like CAD (Computer-Aided Design) software that allows you to create your model. Second, the use of a 3D scanner that allows you to construct and virtualise 3D models of the real object. Last, by downloading 3D files from many open websites.
3. The material used for the AM process includes a wide variety, ranging from photopolymers, thermoplastics, resins, metal powder, ceramics, sand, fibres and glass, even to biomaterials. However, the choice of material depends upon various factors, like the type of available 3D printer techniques, cost, and so on.
4. A 3D printer can use different ways to build up staggered layers of materials, like a fusion of liquid polymers by laser, binding minute granular particles by laser, or by using a binding material or the extruding of liquefied material.
5. Once all three things are obtained, fabrication starts with the 3D model of an object. The 3D model is the digital representation of an object which tells the printer what to print. The most common type of file format used in 3D printing is STL which stands for "Stereo lithography". The STL file defines the special coordinates and connects those coordinates to form a series of triangles or mesh objects. The STL file is then sent to the slicer software.
6. The slicer software will cut the digital file into numerous thin layers or slices. It generates a printer-readable digital file, commonly called a G-code file. This code will direct the movement of the printer. Slicer software also creates a supporting structure to avoid the dropping of hanging parts.
7. The G-code is uploaded to the 3D printer so that printer can print an object.

8. Sometimes post-processing is required to clean and finish the printed object.

With the reduction in the cost of computers, CAD software, lasers, and inkjet printing, there is democratisation in the design process which initiates engineers as well as lay people into how to utilise this technology.[2] Furthermore, projects like "RepRap", which stands for "replicating-rapid-prototype", introduced in 2006, make this technology available to hobbyists and consumers by providing freely open code-bases.[3] However, apart from the ease of fabrication and various advantages, AM also has certain limitations. One of the biggest disadvantages is the high cost of a 3D printer. For small objects and prototype design it is good, but designing bigger objects is still challenging. The cost of materials is another limitation, especially in the case of moulds, as 3D printed moulds usually degrade with time and are sensitive to environmental exposure. Even though 3D printing can produce complex designs, they can lose their functionality and resistance over time. The material properties of the object are generated during the production of the 3D object and may vary with its orientation. AM is a computer-controlled technique which can significantly affect the workforce requirements in production. Certain other economic effects of AM include a reduction in economic imbalance due to the demand on local production, giving rise to job opportunities and industries related to 3D printing. The use of 3D printing for unchecked production of dangerous items raises intellectual property issues. Large distance transportation used for shipment of goods and resources will be affected.[4]

History of 3D printing

The history of 3D printing is quite interesting and was started almost 40 years ago, in May 1980, when a Japanese doctor, Dr Hideo Kodama, from

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[2] Wei Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering," *Computer-Aided Design* 69 (2015): 65–89, https://doi.org/10.1016/j.cad.2015.04.001.

[3] Liza Wallach Kloski and Nick Kloski, *Make: Getting Started with 3D Printing*, ed. Roger Stewart, *Journal of Chemical Information and Modeling*, vol. 53 (Canada: MakerMedia, San Francisco, CA, 2019), https://doi.org/10.1017/CBO9781107415324.004.

[4] Alexandru Pîrjan and Dana-Mihaela Petroşanu, "The Impact of 3d Printing Technology on the Society and Economy," *Romanian-Economic Business Review, Romanian-American University* 7, no. 2 (2013): 360–70; Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering."

the Nagoya Municipal Industrial Research Institute, filed for a patent for Rapid Prototyping technology, which is now known as 3D printing. He was the first to invent the curing of photopolymers by a single laser beam. Unfortunately, he was unable to submit the full patent requirements by the deadline. After that, this technology was picked up by a French team of engineers (which consisted of Alain Le Méhauté, Olivier de Witte and Jean-Claude André), and filed the patent for the stereo lithography process in 1984. Due to a lack of proper funding, along with the absence of a well-thought-out business perspective, they had to abandon the patent. Meanwhile, an American named Charles Hull, who held a Bachelor's degree in Engineering Physics, and who was working for a company that made a tough coating for table tops and furniture using an ultraviolet lamp, suggested a new way of using ultraviolet technology for placing many thin layers of plastic on each other. After 2 months of experiments, he submitted a patent for the stereo lithography technique, which was issued in 1986. After obtaining the patent, he founded the company called 3D Systems Corporation, in 1988, and released its first commercial 3D printer, called Stereo lithography apparatus (SLA-1), which was delivered to only a few selected customers. Later on, with the feedback obtained from those customers, an improved version called SLA-250 was released by the company. The first 3D object made by Charles Hull from his 3D printer was an eyewash cup.

In the same year, 1988, another 3D printing technology, called Selective Laser Sintering (SLS), was submitted for patent by an undergraduate, Carl Deckard, from the University of Texas. Whilst the SLS patent was waiting for approval, another 3D printing technology, called Fused Deposition Modelling (FDM), was filed for patent by Scott Crump. A year later Scott Crump co-founded a company called Stratasys with his wife Lisa Crump. Both 3D Systems Corporation and Stratasys are currently the leading companies in the 3D printing industry. In 1993, the Massachusetts Institute of Technology patented another technology called 3-Dimensional Printing (3D Printing) Techniques, and that is how the term 3D printing originated. Another milestone in the popularity of 3D printing was in 2006, when Dr. Gordan initiated an open-source project called RepRap to develop a self-replicating 3D printer (a 3D printer which is capable of producing another 3D printer similar to itself).[5]

[5] C Lee Ventola, "Medical Applications for 3D Printing : Current and Projected Uses," *P&T* 39, no. 10 (2014): 704–11; Elizabeth Matias and Bharat Rao, "3D Printing : On Its Historical Evolution and the Implications for Business," in *2015*

Even in the field of Biomedical Engineering, the breakthrough of 3D Printing can be seen when a scientist from the Wake Forest Institute for Regenerative Medicine prepared a 3D-printed synthetic scaffold of a human bladder, in 1993, which was later coated with the patient's cells and successfully implanted in a patient who was undergoing a urinary bladder augmentation. In 2002, a working miniature kidney was developed by 3D printing that could filter blood and dilute urine. Later, in 2008, a first prosthetic leg, which included a knee, a foot and a socket, was 3D printed and successfully implanted. Many other 3D printed inventions have been made. Successful 3D prints include an implantable 3D prosthetic jaw; a 3D printed prototype of the car, Urbee; 3D printed food; and a 3D printed house of 1022 square feet into which a family moved.

Different techniques of 3D printing

The first three AM technologies that emerged were Stereo lithography, Selective Laser Sintering (SLS), and Fused Deposition Modelling (FDM). Later on, they were broadly classified into four categories, which include extrusion, granular, laminated, and light polymerised. However, the American Society for Testing and Materials (ASTM) and International standard organisation have divided the AM technologies into seven categories.[6] Fig.1.2 shows the categorisation, and names of all AM techniques. The working principle, advantages, and limitations of each of these technologies are set out below.

Stereo lithography (SLA) – Stereo lithography is the first technique proposed to build a 3D object, by Charles Hull. This works on the principle of photopolymerisation of photopolymers or light-activated resins, by application of a UV light source. Light-activated resins or photopolymers are light-sensitive polymers that harden when exposed to a defined energy of UV light. The interesting part is that only the exposed polymer undergoes solidification, while the rest remains in the liquid phase. Some of the known photopolymers are polyamide, polyacrylate, polyisoprene, epoxies, and

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Portland International Conference on Management of Engineering and Technology (PICMET) (Portland International Conference on Management of, 2015), 551–58, https://doi.org/10.1109/PICMET.2015.7273052; Swati B Nale and Prof A G Kalbande, "A Review on 3D Printing Technology," *International Journal of Innovative and Emerging Research in Engineering* 2, no. 9 (2015): 33–36; Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering."

[6] Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering."

polyimides. Resins initially used in this process were polymers with low molecular weight, which have now been replaced by hybrid polymers to overcome limitations, like high-temperature resistance, shrinkage and high absorption of moisture.[7] Fig.1.3 shows the arrangement made in SLA.

It consists of a vat that holds the polymer, an elevator that holds the working platform used for 3D object making, a UV-laser source for the emission of focused UV light, and an x-y scanning mirror that guides the movement of the laser beam in the defined x-y direction. The movement of the laser beam depends on the 2D pattern given by the STL file for each layer. Initially, the platform is placed in such a way that a thin layer of resins will be available for light exposure. Based on the 2D design of a single layer, the laser beam will be focused on resins. As soon as light falls on the resins, they will solidify and form the first layer, while the rest of the unexposed part will be in liquid form. Now, the platform will go down by the length equal to the thickness decided for each layer (approximately 0.02mm to 0.15mm), allowing the fresh liquid resin to pour on top of the solidifying resin. Once again, the light will expose and help to solidify a new layer of resin which combines with the initial layer. This process will continue until the entire object is ready, and the platform is then raised out of the vat for removal. Support parts are manually removed from the final object, which is then submerged into the chemical bath for removal of excess resins, and finally dried in the UV oven.

The major advantages of this technology include the ability to fabricate objects with high accuracy, and this technology also enables the production of excellent smooth surfaces. This made the application of SLA in biomedical engineering and jewellery design a very viable technique to be utilised. It is usually used for prototype fabrication because it is not as time-consuming. Prototypes made by SLA are strong enough to withstand machining, and may be used as a master pattern for various casting and moulding processes. SLA also needs the support part to hold hanging features that can be manually removed. However, the material used for SLA is still limited to polymers and a few ceramics and is quite expensive.[8]

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[7] Shiwpursad Jasveer and Xue Jianbin, "Comparison of Different Types of 3D Printing Technologies," *International Journal of Scientific and Research Publications* 8, no. 4 (2018): 1–9, https://doi.org/10.29322/IJSRP.8.4.2018.p7602.

[8] Sandeep and Deepak Chhabra, "Comparison And Analysis Of Different 3d Printing," *International Journal of Latest Trends in Engineering and Technology* 8, no. 4 (n.d.): 264–72; Richard Horne and Kalani Kirk Hausman, *3D Printing for*

Some of the manufacturers of 3D printers using SLA technology are: Envision technology GmbH, Laser solutions, Objet Geometries, and 3D Systems.

Material extrusion – This category of additive manufacturing designs 3D objects by extrusion of materials. It is of two types: Fused Deposition Modelling (FDM) and Contour crafting.

Contour crafting is one of the more recently developed 3D printing methods, and has been exclusively created for the construction sector. This method was researched by Dr. Behrokh Khoshnevis, at the University of Southern California's Information Science Institute. He is also the founder of the company, Counter Crafting Cooperation. Here, they build buildings using cranes and a robotic arm in a layer-by-layer manner. The materials involved are quick setting concrete and sand. This method has great potential in building government offices, as well as houses for people during migration or facing disasters, at a fast rate.[9]

Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF)

Scott Crump was the one who proposed this technique of AM; soon after obtaining the patent for this technique, in 1989, he co-founded the company, "Stratasys". Crump invented this technology to prepare a toy frog for his daughter using glue gum and a mixture of polyethylene and candle wax.[10] This is one of the most widely used AM techniques and is prominently used for model preparation, rapid prototyping, and rapid manufacturing. Fig.1.4 shows the setup for FDM.

Here, we have spools holding thin filaments of plastic or metal. These filaments are uncoiled and supplied to the extrusion nozzle. The nozzle is heated to the specific temperature required to bring the filament in a semi-liquid state and the flow is then turned on. The 3D object or part is produced by extruding small droplets of material to form layers. The thermoplastic

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Dummies, ed. Richard Horne and Kalani Kirk Hausman, 2nd ed. (New Jersey: John Wiley & Sons, Inc., Hoboken, New Jersey, 2017).

[9] Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering."

[10] Vinod G Gokhare, "A Review Paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing," *International Journal of Engineering Research & Technology* 6, no. 06 (2017): 953–58.

nature of the material allows the filament to fuse during printing and solidify at room temperature immediately after extrusion from the nozzle. The nozzle can move in both a horizontal and vertical direction, where its movement is guided by a controlled mechanism directly through the CAD software. Stepper or servo motors are used for the movement of the nozzle head. Once a layer of material is extruded at the desired location, the extruder head will move up or the platform can push down for placing the next layer. Each new layer hardens as it extrudes and bonds with the previous layer until the final object is prepared.

Compared to SLA, FDM is simple and cost-effective due to the use of thermoplastics, but less accurate. Moreover, the process can be time-consuming for designs having a complex geometry. Commonly used thermoplastics include polylactic acid (PLA), polyvinyl alcohol (PVA), acrylonitrile butadiene styrene (ABS), nylon, or composite materials. These kinds of thermoplastics are usually sold in spools of thin filament with a diameter of 1.75mm and 3.00mm. After the expiration of the patent for this technology, a huge number of open-source communities developed, and many commercial variations of this type of 3D printer have appeared on the market. Moreover, the low-cost and flexible extrusion system of this technique has contributed to its rising popularity among people interested in this technology.

Some of the limitations of this technique include the need for high operating temperatures, as well as the fact that the finished products exhibit high porosity and warping. Poor surface finish, weak mechanical properties, and limited resolution are other drawbacks. The layer thickness, air gap in and between layers, width, and orientation of filament are major factors in deciding the mechanical properties of the printed object. The removal of supporting parts leaves marks that need removing and sanding. The use of water-soluble supporting material can be worked without leaving marks. Only limited testing is possible in thermoplastic material. Some examples of 3D printers that used FDM technology are the Cube, the Mojo, the Buccaneer®, and the MakerBot Replicator 2X.[11]

Powder bed fusion – In general, the powder bed fusion technique contains a thin layer of fine powder spread on the packed platform. The fine powder in each layer is fused with the use of an energy beam, which can be a laser

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[11] Horne and Hausman, *3D Printing for Dummies*; Jasveer and Jianbin, "Comparison of Different Types of 3D Printing Technologies"; Sandeep and Chhabra, "Comparison And Analysis Of Different 3d Printing."

or an electron beam. The application of an energy beam causes selective melting and fusion of the powder bed as per the cross-section design generated by digital data. Once a layer is scanned, the powder bed thickness is reduced by one layer. Subsequent layers of powder are spread on top of the prior layer through a rolling mechanism and scanned until all the layers are fused, and the final 3D part is prepared. Finally, the printed part is removed and allowed to cool down, and excess powder can be easily removed. One of the major requirements in this technique is the need to maintain the temperature of the sealed chamber equal to the melting point of the powder material.

Based on the type of energy source used, this category is further divided into 2 groups. The first group contains Electron Beam Melting (EBM), where melting of powder takes place with an electron beam of energy up to 60kV. The second group contains a list of three techniques, called Selective Laser Sintering (SLS), Selective laser melting (SLM), and Direct Metal Laser Sintering (DMLS). In these groups, a high-powered laser is a source of energy. The main advantages of this method include the fact that it can work with fine resolutions: it does not need support material, and can produce printing of a high quality. Such qualities increase its use in biomedical engineering, aerospace, and electronics. However, its limitations include the fact that it is a slow process, is high in cost and the challenges in powder size distribution and packing which ultimately determine the density of the final printed part. What follows is an overview of each of these techniques.[12]

Selective Laser Sintering (SLS) – SLS is a very economical and time-efficient technology. The overall process in this technique is the same as mentioned for powder bed fusion. Fig.1.5 shows the working principle of the SLS technique. SLS supports a wide range of material utilisation for processing, like plastic, ceramic metals, or glass. The laser used in SLS is a high energy CO2 laser. In SLS, laser scanning does not fully melt the powder but raises its surface temperature so that fine particles of powder can fuse at a lower molecular level. The speed of scanning and power of the laser used are major factors to be considered in SLS. In SLS, the quality of the surface and the strength of printed parts are greatly affected by the power of the laser, the temperature achieved, and the part orientation. The major

[12] Jasveer and Jianbin, "Comparison of Different Types of 3D Printing Technologies"; Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering"; Sandeep and Chhabra, "Comparison And Analysis Of Different 3d Printing"; Horne and Hausman, *3D Printing for Dummies*.

advantage of SLS is that it does not need any structural support for the design of complicated parts, as the part itself lies on the bed of the powder material. As a result, this technique prevents material loss, and eliminates the post-processing which would otherwise be required for supporting material removal, thereby reducing the production cost and saving on assembly time. In case a metallic support structure is made, then its removal is highly time-consuming and even its proper removal needs the same level of accuracy as an SLS process. Based on the material used, 100% density can be achieved with comparable material properties. SLS permits rigorous testing of the prototype. SLS makes it possible to design a complex internal structure and passage that would be otherwise difficult to cast or machine. Due to the use of metals, functional prototypes can be made from the same material as that used for product design. Parts printed by SLS are robust and durable compared to traditional production methods, like injection moulding. This is one of the AM techniques used for tailor-made production in the dental, prosthetic, and aerospace sectors. A few factors that need consideration while printing include feature details, particle size distribution, and printing through an error in the z-axis. To achieve an extremely smooth surface, polishing can be done.

Selective laser melting (SLM) – SLM is an advancement over SLS with a similar method used for layer deposition. While SLS may be used for a wide variety of materials, SLM is used for limited metals, like steel, cobalt, chromium, titanium, tungsten, and aluminium. Unlike in SLS, in SLM metallic powder is heated till complete melting is achieved, which results in superior mechanical properties. To avoid metal oxidation, the whole printing process takes place in a vacuum or an inert gas environment. Complete melting of metal in SLM helps in the reduction of porosity, thereby achieving greater control over the crystal structure to prevent part failure.

Direct metal laser sinister (DMLS) – Also known as the Laser Powder Bed Fusion (LPBF) technique, it is mainly used for making extremely difficult metallic geometries, with accuracy within a reduced timeframe that is not otherwise feasible using other metal manufacturing methods. Similar to SLM, DMLS supports many metals and alloys, like Monel®k500, stainless steel 316L, stainless steel 17-4, nickel alloy 178, and so on. Here, the temperature is raised to heat the metal but not completely melt it. DMLS printed parts are much stronger, corrosive resistant, and denser than traditional casted metal parts. To get a better finish, post-processing may include machining and heat treatment. Apart from the above-mentioned advantages, DMSL suffers from the high price of the printer; it is more porous than SLM, and is limited to printers having a small build volume which end up designing only small structures. The major application of DMLS can be seen in making medical and dental implants and in the aerospace industry.

Laminated object manufacturing (LOM) – The LOM technique was developed by California-based, Helisys Inc. in 1986, and was patented in 1987. Cubic Technologies is now the successor organisation of Helisys Inc. LOM uses a continuous sheet of materials, like paper, plastic, fibre, or even metals. The material is initially coated with an adhesive material. The feed roller mechanism helps to spread the material sheet onto a build platform. Then, by passing the heated laminating roller over the material surface, the adhesive will melt and pressure is applied by the roller pressing the material layer onto the platform. After this, a computer-controlled laser or sharp blade will cut the material as per the design given by the slicer. Excess material that is left after cutting provides support to the structure and can be removed after printing. As soon as the first layer is formed, the build platform will go down, depending upon layer thickness. Then the successive layer will similarly be spread out unless the whole object is printed. When the final object is formed, the printed material is removed from the build platform and excess materials are removed. Finally, post-processing, like sanding, painting and varnishing can be done, based on the type of material and the desired features. Advantages of LOM include low material, machine and process cost, material availability, high surface finished details, low internal tension, and fragility. This technique does not require any support structure due to the use of solid sheets which are left out after cutting. Unlike other techniques, LOM does not depend on solidification of materials but depends only on cutting the sheets to the desired contour, which can be done by multiple layers at a time, increasing the speed of this technique. A few drawbacks of this technique include the limitation of the strength of the printed object as it needs to be similar to the sheet material used, and poor resolution in the z-axis. Removal, recycling, and describing of waste material in LOM still needs to be considered as well. Non-involvement of any chemical reaction and no maintenance of the enclosed chamber, and availability of material make this technique suitable for printing big models and rapid prototyping.[13]

[13] Gokhare, "A Review Paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing"; Tuan D Ngo et al., "Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications, and Challenges," *Composites Part B* 143, no. December 2017 (2018): 172–96,

Material Jetting (MJ) – The MJ technique was patented as PolyJet by Object Ltd. in 1999, and merged with Stratasys in 2012. This technique combines the features of inkjet technology with photopolymers, to design multicolour and multi-material 3D printed objects. The working principle of the MJ technique is elaborated in Fig.1.6. The MJ printer needs a build platform, multiple movable nozzle print heads filled with different UV sensitive thermoset photopolymers, and a UV light source. The process starts with the heating of a photopolymer from 30ºC to 60ºC to achieve the required viscosity for printing. The print head then jets numerous micro droplets of photopolymers at the desired locations. With the exposure of UV light, photopolymer cures and forms the first layer. The rest of the process is similar to other techniques, which involves moving down the build platform spraying successive layers on top of the previous layer until the model is printed. This technique provides excellent resolution of up to 0.016mm, with no staircase effect, enabling high dimensional accuracy and surface finish. It also provides a varied choice of colours and materials at a relatively lower cost, and with a reduced printing time. MJ is most suitable for preparing realistic visual and haptic prototypes with a smooth surface finish. MJ provides the option to choose a matte or glossy finish. Other than the above-mentioned advantages, it does, however, suffer from a smaller build volume, post-processing step (due to the need of support structure), and needs printing media. The support structure can be easily removed by immersion in an ultrasonic bath or by cleaning with water at high pressure. Sometimes warping may occur. The material cost of photopolymers is high, and they also suffer from poor mechanical properties that degrade with time. This technique has wide applications in the production of realistic prototypes, especially in the medical and jewellery making fields. The main market players for the MJ printer are Stratasys and 3D Systems and XJet.[14]

Binder Jetting (BJ) – Binder jetting is also known as powder bed inkjet printing. Here, a thin layer of powder is first spread on the build platform. The powder is either of ceramic (like glass or gypsum) or metal (stainless steel). There are two ways to spread the powder: either through the roller shaft, or through the jetting reservoir or blade. The roller shaft method is more efficient in spreading the low mobility dense powder, with consistent layer thickness. The adhesive material is then selectively deposited onto the powder layer to bind with it. When a single layer is completed, the powder bed moves down slightly, and once again a new layer of powder is spread,

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[14] Gao et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering."