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A Review on Various 3D Printing Technologies, their Applications and its Implications with Several Materials

G. Naveen Pandi[1], R. Naveen Kumar[2], S. Prakash[3], T. Velmurugan[4]
[1,2,3]*Student, Department of Mechanical Engineering, SREC, Coimbatore, India*
[4]*Professor, Department of Mechanical Engineering, SREC, Coimbatore, India*

***Abstract*: This review paper will help to study the performance and capabilities of additive manufacturing especially in three dimensional printing (3D-Printing). The scope of this research literature survey is limited to comparison of processes that may be specified as additive manufacturing technologies. The study is useful as a basis for matching evaluated 3D printing machine and process capabilities to user requirements, and forming a framework for which future comparative studies can be build. A comprehensive overview of the capabilities of 3D-Printing processes is presented. It shows the application of 3D printing beyond concept modelling. The paper is valuable for researchers as well as individuals, who require adequate and relevant comparative information during decision making. A huge variety of manufacturing applications such as rapid prototyping and rapid tooling using the additive processes directly, as well as further more implementations in design and engineering analysis. To date, 3D printing has primarily been used in engineering to create engineering prototypes. 3D printing has already been proved viable in several medical applications also. In this review, we discuss the potential for 3D printing to revolutionize manufacturing in the same way as the printing press revolutionized conventional printing. The applications, limitations and the production process of 3D printing are discussed.**

***Keywords*: 3d printing**

1. Introduction

The creation of the layer by layer of a 3D object by using computer aided design(CAD) is rapid prototyping, that developed during 1980's for creating models and prototype parts for industrial purpose. Rapid prototyping is an earlier and oldest additive manufacturing process. Now it allows for the creation of parts and the product that we require, contributing to product development at the time and cost reduction, human interaction, and consequently the product development cycle, also the possibility to create almost any complex shape that could be difficult to machine, since it forms like layer by layer [28]. In future it is completely modern manufacturing and growing industries with new processes, technologies, and applications. Not only prototypes, complex components, houses, and even human body parts can also be done using 3D printing. The rapid growth of 3D printing and 3D bio-printing technologies, leads to a huge body of research and practical applications that also exists for these technologies [29]. In future doctors can build a model of a damaged part to examine it and plan better, about the procedure, market analysis's can see what society expects on a particular new product, and how rapid prototyping makes it easier for artists to apply their ideas and find solutions [28]. Rapid prototyping in sand mold and core printing simply substitute the conventional molding and core making process without changing the shape or geometry. 3D printing not only provides a method for conventional manufacturing but also revolutionizes the processing methods and the structural designs. 3D printing technology can also bring make complex designs easier than to casting design and mold design in the casting industry. Kang et al. proposed the application of a hollow mold to aluminum alloy castings according to the idea of a shell-truss mold based on 3D printing technology, and achieved outstanding results [12]. In future layer by layer manufacturing of metal works is a promising technology in industries. The mechanical properties of metal frameworks fabricated by using layer by layer manufacturing methods are altered [16]. In medical field this technique is a recently used method for manufacturing of customized implants and bio-models. Additive Manufacturing presents capacity of building highly complex geometries directly from a CAD model makes possible the fabrication of custom implants from computed magnetic resonance data from the data of a patient. Few advantages of these techniques are shorter surgery times, highly improved bio-mechanical compatibility, reduction of rejection and infection risks, better ergonomic and aesthetic results and increasing the chances of success of the surgery [17]. Nowadays new applications are evolving as better materials and new methods are continuously being researched and applied. The main advantages for this technology are more easily accessible and is contributed to the expiry of earlier affected patents, which has given manufacturers ability to find new solutions and solve issues with new 3D printing devices. Advanced developments have reduced the cost of 3D printers, thereby expanding its applications in schools, homes, libraries and laboratories. At first, 3D printing has been extensively used by architects and designers to produce aesthetic and complex prototypes due to its rapid and cost-effective prototyping capacity. The invention of 3D printing has diminished the additional expenses incurred in the process of product development. Moreover, it is only in the upcoming years that 3D printing will be fully utilized in every industries from prototypes to products. In future, product customization will be a challenge for industrialists due to the high costs of producing complexity products for high end customers [24] but AM is capable of producing 3D printed less quantities of customized products at low affordable cost.

A. .STL file format

Additive manufacturing 3D printing is used for the rapid prototyping of 3D models that are generated by a computer aided design (CAD) program. At first the original design is drawn in a CAD program, and .STL file is made (Standard Tessellation Language or Stereo- Lithography) file. The standard file format for data transfer between the CAD software and a 3D printer is the .STL file format, and has been accepted. In 1987 the STL file was created by 3D Systems Inc. when they first developed the stereo lithography, and the STL file stands for Standard Tessellation Language. Though there are other types of files, most willingly the STL file is the standard for every additive manufacturing process. The continuous geometry in the CAD file is converted into a header, small triangles, or coordinates triplet list of x, y, and z coordinates and the normal vector to the triangles in the STL file creation process. Since the smaller triangles are closer to reality this process is inaccurate. Surfaces of the objects especially the interior and exterior surfaces are identified using the right-hand rule and vertices cannot share a point with a line. When the figure is sliced additional edges are added. The slicing process also clears inaccuracy to the file as in this, the algorithm is replaced by the continuous contour with discrete stair steps [23]. To reduce this inaccuracy, the technique for a feature that has a small radius in relation to the dimension of the part is to create STL files separately and to combine them for future models.

2. 3D printing methods

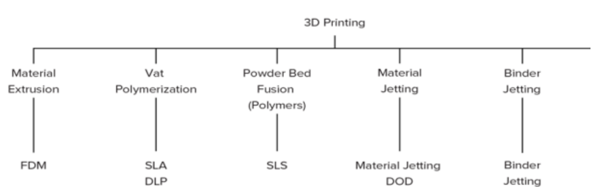

Fig. 1. 3D Printing classification

Various methods of additive manufacturing have been found out to meet the demand of manufacturing complex structures at ultrafine resolutions. With rapid prototyping, the capability to print large geometric structures, reducing printing defects and enhancing mechanical properties are done as some of the key factors. Polymer filaments are mainly used in 3-D printing and the technique is known as fused deposition modelling (FDM) and another method is additive manufacturing of powders by selective laser sintering (SLS), selective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), many as well as inkjet printing, stereo lithography, direct energy deposition (DED), contour crafting and laminated object manufacturing (LOM) are the main methods [24].

A. Stereo lithography

Photo curable polymer resin is employed in Stereo lithography which solidifies into solid while in exposure to high intensity light. At first, medical curing was only possible with UV light, but now recently polymers also cure with visible wavelengths has been developed. After certain level highly focused lasers or LED beams with very high intensity are used, and the spot diameter of the light beam determines the printing resolution obtained. All the layers of the object is printed as a point-by-point 2D cross section cured by the scanning focused beam onto a printing platform immersed in a durable photo curable tank that can hold the liquid resin. In advancements made, projection-based stereo lithography has been introduced with specifications that can decrease print time while maintaining almost 99% of the same resolution as line-based stereo lithography. Photo polymerization is the basic principle of this process, where a liquid monomer or a polymer gets converts into a solidified polymer just by penetrating ultraviolet light which acts as a catalyst for the reactions; this process is also called ultraviolet curing. In this method it is possible to have powder layers released and suspended in the liquid like ceramics. The energy of the light source and exposure are the main factors controlling the thickness of each layer. Complex Nano-composites can be effectively used for the additive manufacturing and can be prepared by SLA method.

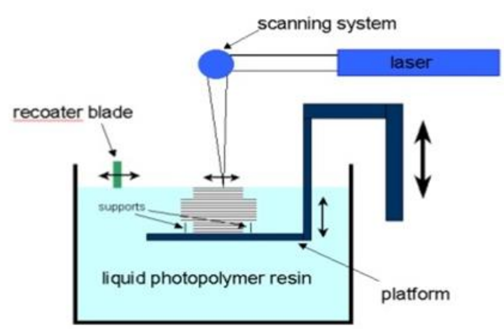

Fig. 2. Stereo-lithography

B. Fusion deposition modeling

A continuous filament of a thermoplastic polymer is used in FDM method, to 3D print layers of materials. At the nozzle the filament is heated to reach a semi-liquid state and then extruded on the platform or on top of previously printed layers. An essential property is the thermos plasticity of the polymer filament for this method, which allows the filaments to fuse together during printing and then to solidify at room temperature after printing. In this process the main advantages are that no chemical post-processing is required, no resins to cure, less expensive machine, and materials resulting in a more cost effective process. The resolution on the z axis is low compared to other additive manufacturing process (0.25 mm) is the disadvantage, so if a smooth surface is needed a finishing process is required and it is a slow process sometimes taking days to build large complex parts. Some models permit two modes; a fully dense mode and a sparse mode that save time but obviously by reducing the mechanical properties.

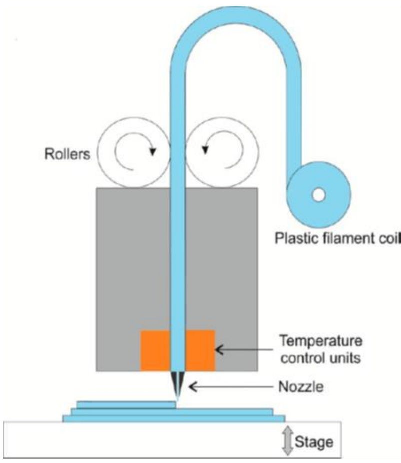

Fig. 3. Fusion deposition modeling

C. Laminated object manufacturing

Laminated Object Manufacturing (LOM) is a process that combines additive and subtractive techniques to build a part layer by layer. In this process the materials come in sheet form. The layers are bonded together by pressure and heat application and using a thermal adhesive coating. A carbon dioxide laser cuts the material to the shape of each layer given the information of the 3D model from the CAD and STL file. This process is low cost, no post processing and supporting structures required, there is no deformation or phase change during the process, and the possibility of building large parts. The disadvantages is the fabrication material is subtracted thus wasting it, low surface definition, the material is directional dependent for machinability and mechanical properties, and complex internal cavities are very difficult to be built. This process can be used for models with papers, composites, and metals.

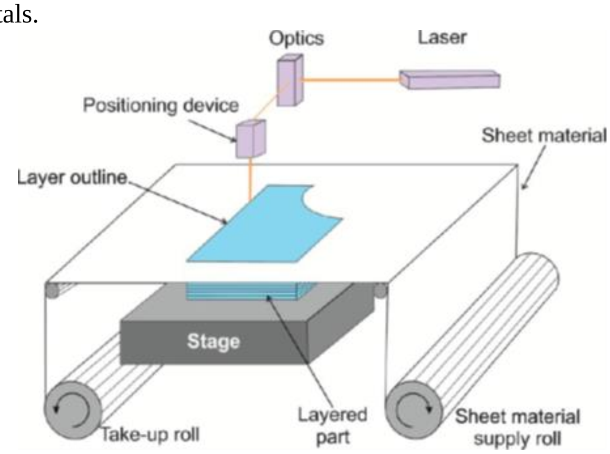

Fig. 4. Laminated object Mfg

This process results in a reduction of tooling cost and manufacturing time, [24] and is one of the best additive manufacturing methods for larger structures. However, LOM has inferior surface quality (without post-processing) and its dimensional accuracy is lower compared to the powder-bed methods. The excess materials after cutting are left for the support and after completion of the process, it can be removed and recycled. This process can be used for a variety of materials such as polymer composites, ceramics, paper and metal-filled tapes. Post-processing such as high-temperature treatment may be required depending on the type of materials and desired properties.

D. Laser engineering net shaping

In additive manufacturing process, a part is built by melting metal powder that is injected into a specific location. It becomes molten with the use of a high-powered laser beam. The material solidifies when it is cooled down. The process occurs in a closed chamber with argon atmosphere. This process permits the use of a high variety of metals and combination of them like stainless steel, nickel based alloys, titanium-6 aluminium-4 vanadium, tooling steel, copper alloys, and so forth. Alumina can be used too. This process is also used to repair parts that by other processes will be impossible or more expensive to do. The problem in this process could be the residual stresses by uneven heating and cooling processes that can be significant in high precision processes like turbine blades repair. Fig. 5, is an illustration of how the part is made in this process.

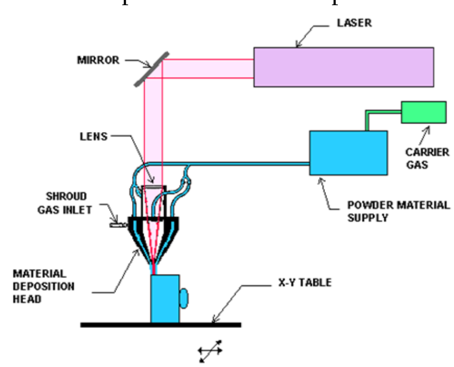

Fig. 5. LENS

E. Selective laser sintering

Since it is a three-dimensional printing process in which a powder is sintered or fuses by the application of a carbon dioxide laser beam. In this, the chamber is heated to almost the melting point of the material. The laser fused the powder at a specific location for each layer specified by the design. The particles lie loosely in a bed, which is controlled by a piston, that is lowered the same amount of the layer thickness each time a layer is finished. In this process offers a great variety of materials that could be used: plastics, metals, combination of metals, combinations of metals and polymers, and combinations of metals and ceramics. Examples of the polymers that could be used are acrylic styrene and polyamide (nylon), which show almost the same mechanical properties as the injected part. It is also possible to use composites or reinforced polymers, that is, polyamide with fiberglass. It also could be reinforced with metals like copper.

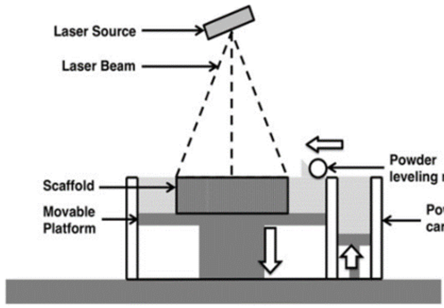

Fig. 6. DML's

F. Inkjet printing

Inkjet printing is one of the main methods for the additive manufacturing of ceramics. This is used for printing complex and advanced ceramic structures for applications such as scaffolds for tissue engineering. This method is a stable ceramic suspension e.g. zirconium oxide powder in water is pumped and deposited in the form of droplets via the injection nozzle onto the substrate. The droplets then form a continuous pattern which solidifies to sufficient strength in order to hold subsequent layers of printed materials. This method is fast and efficient, which adds flexibility for designing and printing complex structures. Two main types of ceramic inks are wax-based inks and liquid suspensions. Wax-based inks are melted and deposited on a cold substrate in order to solidify. On the other hand, liquid suspensions are solidified by liquid evaporation. The particle size distribution of ceramics, viscosity of the ink and solid content, as well as the extrusion rate, nozzle size and speed of printing, are factors that determine the quality of inkjet-printed parts. Maintaining workability, coarse resolution and lack of adhesion between layers are the main drawbacks.

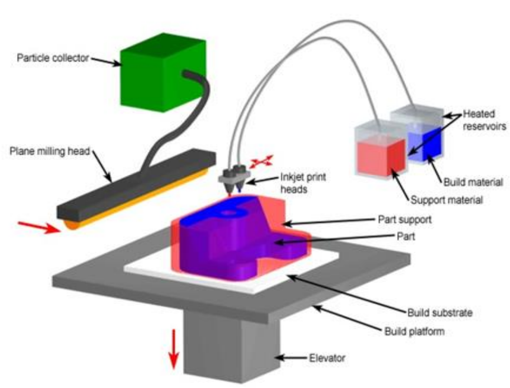

Fig. 7. Inkjet printing

3. 3D printing materials

Materials in additive manufacturing technology systems are defined by the fabrication processing technology. Each 3D printing technology transforms material through external heat, light, lasers and other directed energies. The ability of a material's mechanical composition to react positively to a certain directed energy marries that material to a technology which can deliver the desired change. The material-technology partnerships will expand as materials are advanced and material chemistry explored. Advancing technologies encourages more positive material reactions, layer by layer, to directed external energies. The mechanism of material change-unique to individual 3D printing technologies and processes-defines the material in terms of state changes, final mechanical properties and design capabilities. By extension, developments in 3D printing materials correspond with developments in 3D manufacturing; as the build process improves to encourage more positive reactions from materials, material selections will expand. The 3D printing materials are available in different material types and states such as powder, filament, pellets, granules, resin etc.

A. Plastics

Nylon, or Polyamide, is a strong, flexible, reliable and durable plastic material commonly used in powder form with the sintering process or in filament form with the Fusion Deposition Modeling (FDM) process. This is naturally white in color but it can be colored pre -or post-printing. This material can also be combined (in powder format) with powdered aluminum to produce another common 3D printing material for sintering- Alumide. ABS is another strong plastic used for 3D printing, in filament form. It is available in a wide range of colors useful option for some applications. Lay Wood is a specially developed 3D printing material for entry-level extrusion 3D printers.

This special filament is a composite material of recycled wood and polymer parts that can create wood-like objects that have the look, feel and even the smell of wood. It can be printed between 175-2500^{O}C. It is available in light and dark color wood.

B. Metals and alloys

The most common metals and metal composites like titanium, aluminum and cobalt derivatives. Metal additive manufacturing is showing excellent perspectives of growth. It is also used in the biomedical, defense and automotive industries. Metal AM provides great freedom for manufacturing complex geometries with special connections compared to conventional manufacturing methods. In particular, multi-functional components can be developed to provide solutions to structural, protective engineering and insulation problems at the same time. Many metallic materials such as stainless and tool steels, some aluminium alloys, titanium and its alloys, and nickel-based alloys can be manufactured using PBF-based AM processes. PBF technologies can manufacture components with good mechanical properties and complex shapes with high accuracy (±0.02 mm).

Titanium and its alloys, steel alloys, a few aluminum alloys, nickel alloys, and some cobalt-based and magnesium alloys have been optimized for AM. In particular, titanium and its alloys are high-performance materials commonly used in various industries. They are characterized by high machining costs and a long lead-time based on conventional manufacturing methods.

C. Ceramics

Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. The ceramic parts need to undergo post-processing processes same as any ceramic part made using traditional methods of production — namely firing and glazing. Extrusion of ceramic paste or filament is also known as extrusion free-forming of ceramics (EFF), fused deposition modeling of ceramics (FDC) or rapid prototyping (RP). The main methods of post-curing for extruded ceramics are phase changing (i.e., crystallization of liquid phase by freezing or freeze-drying), evaporation of water or solvent and UV or heat curing. Besides the particle size distribution and packing of particles in the paste, the liquid to solid ratio, air-entrapment, temperature, drying and de-binding procedure, solidification kinetics and inter-layer adhesion can affect the properties of 3D printed ceramics. Stereo lithography, in spite of being developed for 3D photo polymerization (UV, laser or LEDs can also be used) of monomer into polymers, has been extended.

D. Concrete

3D printed models made with concrete are safe, environmentally friendly, and easily recyclable and require no post-processing. 3D printed fiber reinforced concrete composites bring the benefit of controlling fiber orientation in a printed structure compared to traditional fiber-reinforced concrete. Freedom of the orientation of carbon fibers along different printing paths significantly increased flexural-strength by up to 30 MPa. A mix of rapid hardening cement and poly vinyl alcohol (PVA) composite was used in order to print with a finer resolution. However, layer delimitation and void formation between the layers were observed, which became less distinct after post curing of the samples in water.

4. Testing methods

A. Four-point flexural test

The four-point bending test provides values for the modulus of elasticity in bending, flexural stress, flexural strain and the flexural stress-strain response of the material. This test is very similar to the three-point bending flexural test. The major difference being that the addition of a fourth bearing brings a much larger portion of the beam to the maximum stress, as opposed to only the material right under the central bearing.

The difference is of prime importance when studying brittle materials, where the number and severity of flaws exposed to the maximum stress is directly related to the flexural-strength.

This is one of the most widely used apparatus to characterize fatigue and flexural stiffness of asphalt mixtures. The test method for conducting the test usually involves a specified test fixture on a universal testing machine. Details of the test preparation, conditioning, and conduct affect the test results. The sample is placed on two supporting pins a set distance apart and two loading pins placed at an equal distance around the center. These two loadings are lowered from above at a constant rate until sample failure.

B. Three-point flexural test

The three-point bending flexural test provides values for the modulus of elasticity in bending, flexural strain and the flexural stress–strain response of the material. The main advantage of a three-point flexural test is the ease of the specimen preparation and testing. However, this method has also some disadvantages: the results of the testing method are sensitive to specimen and loading geometry and strain rate.

The test method for conducting the test usually involves a specified test on a universal testing machine. Details of the test preparation, conditioning, and conducting affect the test results. The sample is placed on two supporting pins a set distance apart and two loading pins placed at an equal distance around the center. These two loadings are lowered from above at a constant rate until sample failure.

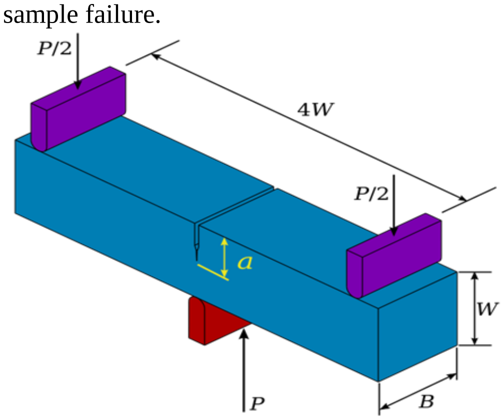

Fig. 8. Three point flexural test

Where, P is the applied load, B is the thickness of the specimen, is the crack length, and W is the width of the specimen. In a three-point bend test, a fatigue crack is created at the tip of the notch by cyclic loading. The length of the crack is measured. The specimen is then loaded monotonically. A plot of the load versus the crack opening displacement is used to determine the load at which the crack starts growing. This load is substituted to find the fracture toughness K.

C. Split Hopkinson pressure bar testing

Using the split Hopkinson pressure bar (SHPB) test the horizontal and vertical samples can be tested under different compressive strain rate conditions. It is noted that, the samples were setup such that, the direction of compressive shock loads was parallel to the longitudinal axis of all the samples. The samples can be tested at each strain rate ranging from 180 s^{-1} to 3200 s^{-1} to ensure consistency and repeatability. It is important to note that all testing was performed at room temperature.

Using compressed gas, a striker was fired to strike the incident bar in order to rapidly deform the test specimen sandwiched between the incident and transmitter bar. By increasing the gas pressure in the firing chamber, a higher impact velocity is achieved, which results in a higher strain rate. When the incident bar was struck, a strain wave travelled through it until part of it passed through the sample to the transmitter bar while the other part was reflected. These strains were measured by placing strain gauges on the respective bars.

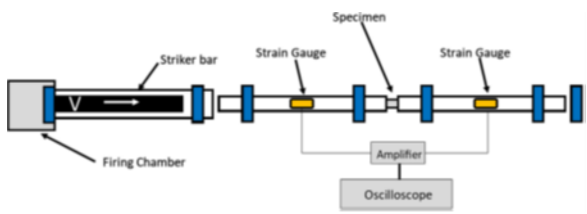

Fig. 9. Hopkinson pressure bar test

D. *Wetting test*

The wetting tests were carried out by classical sessile drop technique upon contact-heating under vacuum. The experimental device has been described. The TiB2 substrate (12×12×2.5 mm3) with Al-12Si sample (a weight of 46 mg) was placed on a boron nitride support situated in the middle of a molybdenum resistance furnace inside a stainless-steel chamber. The chamber was evacuated to about 10-5 mbar at room temperature. The Al-12Si/TiB2 couple was constantly heated from room temperature to 1200 °C and then cooled down to room temperature. The wetting behavior of the liquid alloy on the solid substrate was recorded in steps of 10 °C using a charge-coupled device (CCD) camera. The contact angles were determined at both sides of the drop by analyzing the digital photographs using DROP software. The total uncertainty of the average contact angle was about ±5°.

E. *Vickers hardness testing*

The Vickers hardness test method, also referred to as a micro hardness test method, is mostly used for small parts, thin sections.

The Vickers method is based on an optical measurement system. The Micro hardness test procedure, ASTM E-384, specifies a range of light loads using a diamond indenter to make an indentation which is measured and converted to a hardness value. It is very useful for testing on a wide type of materials, but test samples must be highly polished to enable measuring the size of the impressions. A square base pyramid shaped diamond is used for testing in the Vickers scale. Typically loads are very light, ranging from 10gm to 1kgf, although "Macro" Vickers loads can range up to 30 kg or more.

The Micro hardness methods are used to test on metals, ceramics, and composites - almost any type of material.

Since the test indentation is very small in a Vickers test, it is useful for a variety of applications: testing very thin materials like foils or measuring the surface of a part, small parts or measuring individual micro structures, or measuring the depth of case hardening by sectioning a part and making a series of indentations.

Sectioning is usually necessary with a micro hardness test in order to provide a small enough specimen that can fit into the tester. Additionally, the sample preparation will need to make the specimen's surface smooth to permit a regular indentation shape and good measurement, and to ensure the sample is held perpendicular.

5. Applications

A. *Bio materials*

The biomedical market represents 11% of the total AM market share today and is going to be one of the drivers for AM evolution and growth.

Biomedical applications have unique necessities:

Biomedical applications need to be patient specific, from implants to drug dosage. AM presents great potential for patient-specific biomedical products, from hearing aids to biomedical implants and from customized orthotics to prostheses. AM is also used for planning surgeries, improving efficiency and effectiveness, and reducing the necessity of further operations to adapt the implant to the patient. AM will also be used for customizing drug dosage forms and releasing profiles.

Bio-fabrication involves the generation of tissues and organs through bio printing, bio-assembly and maturation .The main difference between bio-fabrication and conventional AM is the inclusion of cells with the manufactured biomaterials for producing the so-called bio-inks. Bio-printing with bio-inks is integrated with the laser induced forward transfer (Lift), inkjet printing and robotic dispensing. These specialized techniques are well discussed in the literature. The biomaterials combined with bimolecular and cells are then matured in the desired shape and tissue. The biomaterials are used as support and physical cues for the generation of the tissue structure while the bimolecular guide the tissue regeneration process. Multiple bio-inks and cells will be combined with more complex tissues and organs. Advanced imaging will make it possible to obtain the precise shape, size and composition of defective parts. Moreover, using antilogous cells from the patient will reduce the risk of rejection of the generated organ/tissue.

B. *Aerospace*

AM techniques are ideal for aerospace components as they have the following peculiar characteristics:

Complex geometry: Complex shapes are necessary for integrated functions i.e., structural, heat dissipation and airflow. For example, GE Aviation is developing fan blade edges with optimized airflow. Moreover, it is possible to simplify parts by combining multiple components, such as GE fuel nozzles. Finally, functional electronics can be implemented (or printed) easily as AM parts.

Customized production: The aerospace industry is characterized by the production of small batches of parts. AM is more convenient economically than conventional techniques for small batches as it does not require expensive equipment such as molds or dies.

Both metallic and non-metallic such as meta-materials parts for aerospace applications can be manufactured or repaired using AM such as aero engine components, turbine blades and heat exchangers. Non-metal AM methods such as stereo lithography, multi-jet modeling and fused deposition modeling (FDM) are used for the rapid prototyping of parts and for manufacturing fixtures and interiors made of plastics, ceramics and composite materials.

C. Buildings

The possibility of building infrastructure on the Moon with the use of lunar soil (regolith) and the application of D-shape printing were assessed. With the design requirements of the outpost identified, a preliminary design of the habitat has been developed. One of the crucial-aspects of using 3D printing involves the capability of the material to withstand the lunar environment. Recently reviewed the use of AM in the proposed Moon Village of the European Space Agency. Lunar regolith was also the raw material to be used with the various AM technologies that were assessed. Powder bed fusion was deemed to be the appropriate and feasible technology for the mission.

Another technique is mesh molding, which utilizes a six-axis robot control to manufacture elements without temporary support. The mesh-mold technique also utilizes thermoplastic polymers where the printed structure also acts as reinforcement for concrete.

Furthermore, the density of the printed mesh can vary depending on the forces that will act upon the structure. The possibility of replacing steel reinforcement is also reported as the presence of a mesh in the structure helps to increase the tensile strength of the concrete.

3D printing has also become a vital process for cultural preservation and reproduction, process for reproducing a component of a historic structure where 3D scanning was integrated with cement mortar-based 3D printing. Utilizing this technology resulted in cost-effective and labour efficient construction as compared to traditional methods.

6. Conclusion

Thus, this paper gave an overview on various 3D printing technologies, their applications and its implications with several materials.

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