A Review on Additive Manufacturing Processes

Jammula Praneeth[1], *Sriram* Venkatesh[1], *and Ledella* Sivarama Krishna[1]

[1]Department of Mechanical Engineering, University College of Engineering, Osmania University Hyderabad, Telangana. 500007

Abstract. Additive manufacturing, well known as 3D printing, is used to fabricate complex geometries and customized products. Freedom to design and waste minimization are key concerns of this technology. Additive manufacturing gains significant interest in many fields which includes aerospace, automotive, navy, and biomedical industries. In this technology, a geometrical CAD model is sliced into a number of layers and then stacked of material in layer-by-layer manner. In this review paper we discussed the various 3D printing methods and materials that are available now and current limitations, future trends of this technology.

1 Introduction

Additive manufacturing (AM) is a process that uses three-dimensional (3D) computer-aided design (CAD) data to create a variety of shapes, structures, and complicated geometries. The process involves stacking successive layers of material created on top of one another. The Additive Manufacturing Process chain consists of five major steps which are geometrical CAD data preparation, STL (Stereolithography) file conversion language which AM system understands Model validation & slicing, building of physical model and post.

Charles Hull developed this technology in 1986 with a process called stereo lithography (SLA), which was followed by advances like powder bed fusion, fused deposition modelling (FDM), inkjet printing, and contour crafting (CC). 3D printing has grown over time and has the potential to alter manufacturing and logistical operations [1]. It uses a variety of procedures, materials, and equipment. AM technology is capable of producing parts ranging in size from micro to macro. The precision of printed parts, on the other hand, is determined by the method's accuracy and the printing scale. In micro scale range 3D printing implies the challenge that with resolution, surface roughness and interlayer bonding, some are recovered by applying different post processing techniques like sintering [2].

*Corresponding author: jpraneeth1202@gmail.com

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The ability to mass customise while retaining a low cost due to mass production is a distinct advantage of 3D printing. As a result, mass manufacture of a few identical parts can be just as cost-effective as mass production of a similar number of varied individualized goods. The issue of increasing printing speed and lowering costs must be addressed through machine improvements. Also, the cost to time of AM process remains to be major challenge that inhibits mass production. Additive Manufacturing became trending technology in biomedical applications, wholers associates predicted that 50 % of 3D printing parts will occupy in commercial applications [3]. This 3D printing trending technology had gained space in medical applications also due to its ability of producing implants from medical imaging like CT, MRI data [4].

One of the current disadvantages of this technique is that it only uses a restricted number of materials. As a result, there is a pressing need to create novel materials that can be used in 3D printing. Further research has to be conducted to enhance the mechanical properties of AM build parts. The advantages of AM technology will continue to emerge through continuing research efforts. With these efforts this AM technology can overcome the constraints to use this technology.
Metals, polymers, ceramics, and concrete are among the materials that are now used in this technique. Liquid, filament/paste, powder, and solid sheet are the four primary forms of AM technology.

The increased demand for 3D printed objects has resulted in the development of new materials. The type of AM process can be used to design and develop issues associated with the process based on the nature of the material to be formed, the size to be produced, and the application for which it is developed. Apart from material savings and product customisation, AM's further benefits include very precise operations and design freedom. However along with benefits there are some drawbacks in this technology like anisotropy and time consuming due to these limitations there is restriction in applicability. Processing parameters have a great influence on properties of 3D printed parts [5]. By using this technology parts from micro level to macro level can be printed easily. Printing of these parts has some challenges like layer resolution, speed, process parameters and post processing methods.

1.1 Additive Manufacturing Types

Earlier Additive manufacturing technologies are classified into three types i.e., liquid based, powder based and solid based systems [6]. According ASTM international standards, Additive Manufacturing systems are classified into seven categories. : (1) Material Extrusion, (2) Powder Bed Fusion, (3) Vat Photopolymerization, (4) Material Jetting, (5) Binder Jetting, (6) Sheet Lamination, and (7) Direct energy deposition [7].

2 Material extrusion process

Stratasys systems developed layer by layer manufacturing in 1988, material was extruding from a nozzle. Thermoplastic material like PLA and ABS are used for the process. High temperatures are required to heat the extrusion system, these systems exhibit high porosities [8-11]. Researchers are concentrating on extending materials (i.e., ceramics, metals, and plastics) used in this technology. Figs. 2(a-e) show the various methods.

2.1 Fused deposition modeling (FDM)

A continuous filament of a thermoplastic polymer is used to print layers of a part in fused deposition modelling (FDM) or fused filament fabrication process. The filament is heated to a semi-liquid condition in the heat chamber before being extruded out the nozzle. The printed layer's resolution is determined by the nozzle diameter. The operation was completed by printing layer after layer. The key processing characteristics that determine the mechanical properties of printed objects are layer thickness, orientation, width, and air gap between layers[12]. Stair stepping (layer by layer appearance) of effect and interlayer distortion are main defects by this process [13]. Interlayer distortion is main source of mechanical weakness. Low cost and high speed are the main advantages of this process when compared to other 3D printing processes [14]. Fiber orientation and bonding between the layers can lead to void formation in composite materials of 3D printing. There are only a few materials available for this FDM technology. Materials like PLA, ABS, PC, and other composite materials are used presently. There is a need to develop new materials to achieve the required mechanical properties [15].

2.2 Powder Bed Fusion

Liquid binder technology well known as Three-Dimensional Printing, the size, shape of powder particles, deposition speed, inter layer bonding after processing methods are major important parameters [16,17]. Part quality and density of parts are main advantages of these powder bed fusion systems. This process has a wide range of applications like tissue engineering, lattice structure, aerospace, and electronics. In powder bed fusion technology fine powder spread over the substrate plate into thin layers. These thin layers are fused with help of laser beam in accordance with cad model. The same process is repeated to the next successive layers. In this powder bed fusion technology sintering and melting of powders takes place, sintering involves low melting of polymer powders. In the melting process metals and alloy powders are melted and fused together with a help high power laser. Selective laser sintering (SLS) is for a variety of polymer powders, Selective laser melting (SLM) is used for different metals and alloy powders. This entire process was carried out in closed chamber and inert environment to avoid oxidation. The parts produced through this type have good strength and stiffness [18].

2.3 Vat Photo polymerization

The first earlier 3D printing method is Stereo lithography (SLA) also known as Vat Photo polymerization was developed in 1986 [8]. In this method it uses UV light as light source for photo polymerization process. When thin Photo sensitive polymer liquid is expose to UV light beam starts a chain reaction and coverts it into polymer chains. The liquid resin starts coverts into solids and it acts as base for the next layer. After printing the solid model is going to post process treatment such as curing, heating to achieve the desired mechanical properties.Mixing ceramic particles in liquid resin monomers can be used to print ceramic-

polymer composites [9]. This method achieves high quality and precession 3D printed parts with resolution of 10µm, drawback of this system is slow and expensive. Materials which are used in this printing method are limited. UV light sources play a vital role in controlling minimum layer thickness.

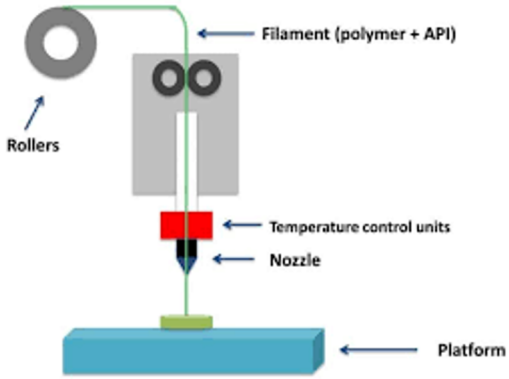

Fig. 2 (a): Fused deposition modelling

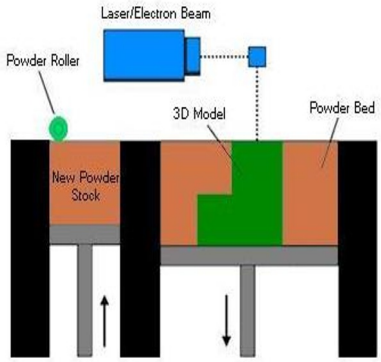

Fig. 2(b): Powder bed fusion

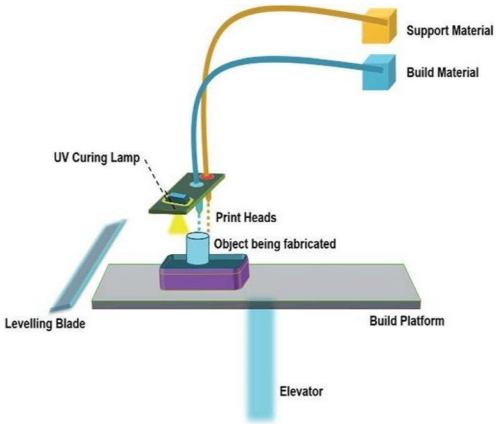

Fig. 2 (c): Material jetting

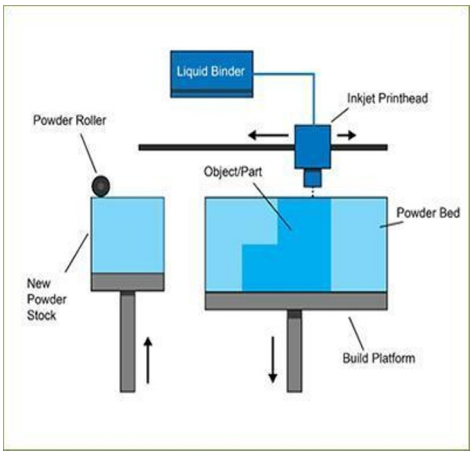

Fig. 2(d): Binder jetting

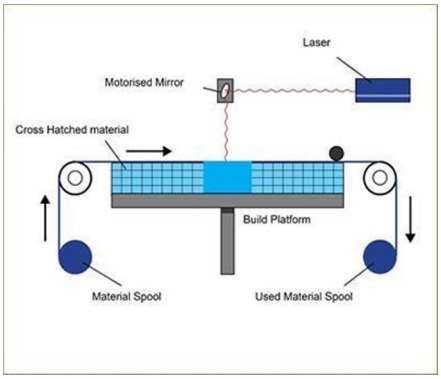

Fig. 2(e): Sheet lamination

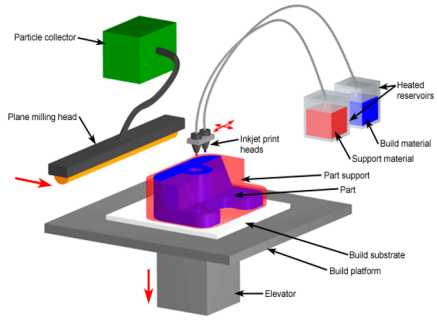

Fig. 2(f): Ink jet process

2.4 Material jetting

In this technology liquid ink droplets sprinkle on the substrate plate by jetting process these fused together by the process of photo curing. In this liquid some materials like ceramics, metals and semiconductors are mixed at Nano level, to get the required strength [15]. A Nano mix of ceramic particles in ink to get required functionality [19-21].

2.5 Binder Jetting

In Binder jetting process a liquid polymer material is spread over onto a powder bed. Surface which results in agglomerate primitive. Recoating of another layer by spreading over on previous layer. These processes have applications in a variety of metals [22, 23], ceramics [24, 25] and various polymer materials [26-30].

2.6 Sheet Lamination

Cubic technologies developed this technology in 1986known as Laminated object manufacturing (LOM). In Laminated object Manufacturing (LOM), sheets of materials are bonded together and cut accurately according to the design. Materials like polymers, metals and ceramic sheets are manufactured by this technique. It is the first commercially available rapid prototyping technique. The excess material after cutting can be recycled [31]. Post processing techniques like heat treatment are employed to get the desired properties. LOM process had applications in paper manufacturing, electronics, and industries. However, this process has limitations in applicability due to poor surface quality and dimensional accuracy.

2.7 Direct Energy Deposition Systems

In Direct Energy Deposition process metallic powders are used to create metal parts from design model [32]. It is called Laser Engineered Net Shaping (LENS). Lasers and electron beams are used to melt the metal powders and achieve 99.99 % of theoretical density of material. When compared to conventional casting process DED produced parts having 30 % high strength [33]. By using this technology, we can repair old parts by adding material where damaged portions can be replaced [34-38]. Limitations of this technology are having low accuracy (0.25 mm (about 0.01 in), less surface quality when compared to other powder bed technologies.

3. Materials

Metals, polymers, ceramics, and concrete are just a few of the materials that are currently being used in 3D printing.

3.1 Polymers and composites

Polymer materials are the most often used materials in 3D printing due to their wide range of applications and adaptability to different 3D printing techniques. Polymer materials are available in the form of filaments, resins, and powder for 3D printing. Composite materials are also used in this polymer for serving different needs in industrial applications.
Polymers are fabricated by different 3D printing technologies like stereo lithography, selective laser sintering, digital light processing (DLP), fused deposition modeling techniques. FDM is the most common method to use polymers in 3D printing [16]. Researchers found that ABS has superior mechanical properties when compared with PLA, but PLA is an ecofriendly material [39]. In addition to polymer materials, adding fiber reinforcement can achieve desired mechanical properties, metal powders are used to increase the strength of the part [40,41]. Nano materials are also used to mix with polymers to improve its mechanical strength [42,43]. The adaptability of polymer-based materials makes it feasible to create a wide range of sophisticated products geometry low-cost products several applications ranging from biomedical, aerospace, navy, automobile, architectural, educational, food industries and much more.
The promising factors from AM technologies are high level accuracy, complex geometry and with no or limited post processing steps. Which offer low cost when compared to traditional methods like molding, casting forming and extrusion. The mechanical properties of these polymer materials are good at applications level in functional applications.
Strength and temperature resistance have been improved as a result of new resin innovations. Various 3D printing processes could be used to manufacture thermoplastic polymers such as ABS (acrylonitrile-butadiene-styrene copolymer), PC (polycarbonate), and PLA (polylactic acid). Although maintaining an optimal resin viscosity at low temperatures is a significant challenge with PLA, there are two techniques that can help: 1. increasing the temperature during processing and 2. using a proper plasticizer.

3.2 Metals and alloys

Metal based AM techniques gaining superior interest from industries, The metal AM systems selling range went from 49 to 97 in the years of 2014 and 2016. This ratio is around 49 % of total AM based systems [44-46]. Metal feed stock which is used in this technology is in the form of powder or wire and which is melted by the surface of a laser beam or electron beam. This technology had high precision about ± 0.02mm (about 0 in) with good density and mechanical properties. Presently few alloys are used because of processing parameters and the cost of these technologies.
Major applications of this metal-based system are aerospace industry, it is also used in research, defense, automobile, and bio medical industries. Applications range from prototypes to real world functional parts. Metals including stainless and tool steels, aluminium alloys, titanium and its alloys, and nickel-based alloys can all be made.

3.3 Ceramics

These materials are used in tissue engineering and lattice structure is an advantage of these materials for processing these materials inkjet method, powder bed fusion, stereo lithography

methods are used. Selective laser sintering (SLS) is the main method used to develop ceramic powders by fully dense parts [9]. Nano ceramic powders are also used to produce highly complex parts with required mechanical properties.
Ceramics materials are used in biomedical industry and tissue engineering such as bones and teeth. The stair stepping effect is one of the drawbacks of this ceramic material printing. Currently a small number of materials are only printing this challenge must overcome. Ceramic materials require post processes like sintering and forming shaping for an effective look. When compared to conventional methods like casting and sintering, this AM technology offers high speed and accuracy. The porous materials are utilized in scaffolds used in tissue engineering,

3.4 Concrete

In this method the high-pressure concrete paste extruded from heavy nozzles and printing layer by layer. To avoid step by step appearance a trowel like shape attached to the nozzle end. This is a revolutionary technique in the construction industry; the efficiency of this method has to be determined. To obtain smooth surface on part a trowel shape arrangement had used to overcome stair stepping effect [47].

3.5 Biomaterials

3D printing is one of the thrust regions for biomedical engineering since patients specific customized parts are required. Very intricate shapes are required to print using this technology. It is associated with challenges like creating 3D models, customized implants [48], tissue engineering, dentistry, organ developing, Prosthetics and other related areas. The traditional methods are not preferable due to its limitations and cost aspects, AM can overcome limitations occurred by traditional manufacturing, with maintaining accuracy and precision [49]. In this bio materials polymers, ceramics and metals are used, by the advantage printing porous materials regeneration of tissue can be achieved. These materials offer superior advantages on the other hand lack of strength to weight ratio, lack of durability, and other characteristics [50-53].

Main applications of these polymers include aerospace, medical, educational, and toy making. These materials are printed in AM machines by thermochemistry property, commonly used materials are PLA (poly lactic acid), PA (poly amide), PC (Poly carbonate), Photopolymer resins. Because of the advantage of easy processing these are considered, but due disadvantage in mechanical properties. The advantages of using metal-based materials and alloys for complicating functional parts that are not possible by traditional manufacturing methods, and avoiding assemblies. Ceramic materials are employed in the form of powders and inks, which are sintered or cemented together using a laser. The microstructure and content of the component can be better controlled by 3D printing ceramic powders. Dimensional precision and quality are two issues that come up while working with ceramic materials.

4 Printing Parameters of AM

The build time, resolution, surface resolution are the main parameters which are to be considered while selecting suitable AM technology, Other factors, including as materials, orientation, and position of the item, can have an impact on the final product.

4.1 Build time

Building time for an individual part or an assembly part depends upon part size, layer thickness, orientation of the part, and printing speed. In 3D printing technology, the height of the part is a major attribute for the total building time.

4.2 Feature resolution

Resolution of the part depends on the AM system energy/material patterning principle. In FDM process nozzle deposition head (~0.4 mm (about 0.02 in)) to extrude the material. And other AM systems like vat photo polymerization process and powder bed fusion the layer thickness is very fine so the final part resolution is finer.

4.3 Surface quality

Surface quality of the 3D printed part determined by the layer thickness, the defective surface quality leads to stair stepping effect. In extrusion systems like fused deposition modeling the layer thickness is approximately 0.4 mm (about 0.02 in), other systems like powder bed systems layer thickness are around 0.2 mm (about 0.01 in) and vat photo polymerization systems had minimum of 0.1 mm (about 0 in).

4.4 Support Structures

Design freedom is the main advantage in additive manufacturing systems, support structures are needed to create intricate parts which have complex geometry like overhang surfaces and undercuts. All additive systems should have support structures; support structure material depends on the type of system used part which is to create. No extra support material is needed in powder bed fusion AM systems because the surrounding powder itself acts as support.

5 Main challenges

Though 3D printing technologies have many advantages there are some barriers while adapting this technology. Powder based fusion (PBF) technologies and stereo lithography are more time consuming when compared to inkjet printing. The main advantages of this technology are creating complex structures and cost-effective processes for some applications [54]. The main challenges in the additive manufacturing systems are part size, build speed, mass customization, and defects in the printed parts. The research is going on to reduce costs and speed of printing apart from these the defects in printed parts are main challenging to overcome. The major defects are void formation, anisotropic behavior, and layer by layer effect.

5.1 Void formation

Porosity is formed between the layers and due to that reduction on mechanical properties. Inter layer void formation depends on the AM system which is used to print and print material. In FDM process this void formation leads to delamination of layers after printing. In powder bed method this porosity can reduced by controlling layer height [16]. Porosity also had an advantage in tissue engineering [55].

5.2 Anisotropy

One of the most difficult aspects of AM is anisotropic behaviour. Because parts in AM technology are manufactured layer by layer, the microstructure of each layer differs from the microstructure of the layers' borders. Heating prior layers again in metals and alloys leads in distinct grain structures, resulting in anisotropy.
In powder bed fusion (PBF) technologies like SLM or SLS, cladding of material in layer-by-layer manner results in anisotropy [56]. Anisotropy observed in materials like ceramics [57] and polymers [58,59]. Building direction is also effective in anisotropy of final part [60]. Might be anisotropy is also advantage in some applications.

5.3 Layer-by-layer appearance

It is also called stair-stepping effect, due to the layer height and printing method observe layer by layer appearance, this can overcome the controlling layer height and reducing the no of layer which to complete the part. Along with this there are other challenges like lack of test standards, printing speed, layer resolution, and low no. of materials need to be overcome. Some post processing technologies are used to control this defect [61]. In concrete printing technology a trowel like instrument is used to prevent this effect [48].

6 Post-processing

After printing of the part, it must go for post processing operation like support material removal, curing, polishing and coatings. For removing the support structure's part is merged into water if support structures id soluble in water, otherwise gentle scrubbing and breaking or peeling applied for polymer materials. For metals and alloys using conventional cutting tools. Curing is used for getting enough strength to the part, in this the part is exposed to UV light for some time. Polishing and coating applied for the smooth surface finish. Application of post processing techniques increased use of AM technology, due to improvements in material and mechanical properties. Heat treatment process is also used to improve properties and reduce the porosity of metal printed parts.

7 Trending applications

7.1 Biomedical

In Additive manufacturing, high complexity and innovative approaches are achieved in biomedical area. In these tissues, organs and new biomedical implants and drug-controlled systems are used [62,63]. The main advantages are customization and patient specific requirements can be achieved. AM is used as tool for guiding surgeries [64]. AM can be used to print very complex shapes easily. Small volume production can be achieved.

7.2 Aerospace

The aerospace industry is considered the most promising application for AM technology, in these complex shapes are created easily. Strength to weight ratio and customization of parts easily achieved by using AM systems. Both metallic and nonmetallic materials are used, titanium is the most used material for aerospace metallic parts. Plastics, ceramics, and composites materials are also used. Complex geometries like optimized blades and fuel nozzles [65] and other functional parts can easily print [66].

7.3 Automobile

The automobile industry used AM technology for manufacturing individual parts to complete assembly. It uses metallic and polymer materials, plastics like PLA, ABS materials are used in interiors. Sports vehicles parts are also manufactured by using AM technology.

7.4 Buildings

In construction industry using of AM technology increasing day by day, it improves construction quality simultaneously reduction time. Cement and glass fiber materials are used in this industry. Large opening pipe nozzle used for concrete printing.

8 Discussion and future trends

Additive manufacturing has unique capabilities to create complex parts and design to freedom, design for additive manufacturing is an important field in manufacturing industry. Research work carried out on different printing techniques. Materials that are presently used in these technologies are limited, need to develop more materials and cost optimization is also one of the key areas that can be spread applications area.

9 Conclusions

The key advantages of 3D printing include design freedom, mass customization, and the capacity to build complicated structures with minimal waste. Design of freedom, mass customization and ability to print complex parts are main advantages of 3D printing. Fused Deposition Modeling (FDM) is a commonly used 3D printer to print polymer materials like PLA and ABS. By using this we can print prototypes. In powder bed fusion technology powder materials are used, thin layer of powder materials fused together with the previous layers, a laser beam is used to complete this process.

In Ink jet printing liquid with ceramic particles are printed and some curing process need to complete the process. In laminated object manufacturing (LOM), sheets are binder together and with help of laser, these sheets are cut according with CAD model. Contour crafting is used to carry out concrete printing in construction industries. Several types materials are used in the form wires, powder, inks, and sheets can be used in additive manufacturing. Most common materials are polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), polyamide (PA) and polycarbonate (PC). Reinforcement of fibers and Nano materials to enhance the required mechanical properties. Powder type materials are used in Selective laser sintering (SLS) and selective laser melting (SLM). Polymer powders like poly amide (PA) and metal powder like Stainless steel, titanium, copper, and nickel and other alloys to print the metal parts. Ceramic powder is used to get high strength of printed parts.

Industrial usage AM systems increasing, because of customization parts with strength to weight ratio, construction industry also utilizes the benefits of AM technology but limits due to high costs and low performance when compared with conventional methods. Other industries like automobile, biomedical, textile and food industries have also adopted AM systems in their supply chain for meeting customer requirements. The major challenges associated with this technology are void formation between the layers, due to this delamination between the layers which led to reduced mechanical performance. Anisotropic behavior is another major challenge faced in AM; mechanical performance varied in different directions.

The stair stepping effect is also one of the drawbacks in AM technology, layer by layer manner appearance due to layer thickness and the no.of layers, controlled by minimum layer height and part orientation. Design model errors are occurred during transfer of geometric

CAD model into 3d printed final part, degeneration of surfaces and missing of surfaces and other errors occurred due to tessellation.
Presently research work is going on to overcome these challenges and simultaneously developing the new materials and methods for high strength and light weight of the printed parts. Focusing on developing strength in printing axis i.e., Z- direction and reduce the anisotropy.

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