A Detailed Review on Additive Manufacturing

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Abstract: *The demand of additive manufacturing (AM) in manufacturing has been increasing every year. The layer-by layer system of fabricating parts is in high demand for serial production. Nowadays, AM is being utilized to fabricate metallic parts using steel, aluminium and titanium which is being utilized to its fullest. This advancement in technology possible the fabrication of new shapes and geometrical features. AM provides a high degree of design freedom, and the resulting potential for optimization. However, to get the best out of AM, we must study properties of the materials as well as the different ways of putting AM to fabricate parts. In this paper, the current fabrication processes of AM are reviewed.*

1. Introduction

Additive Manufacturing (AM) techniques are used in various industries to create physical prototypes as well as end-use parts. AM has the ability to allow custom-build or personalized production of materials with almost accurate precision and resolution. This method helps produce using metallic or non-metallic products directly by a designing computer software called Computer Aided Design (CAD). The most important feature of AM is the liberty it provides to the product on CAD and hence the liberty in production of the parts with almost any geometry. AM permits the fabrication of advanced part designs which provide additional space, multifunctional parts, and parts that are difficult to machine. AM permits to vary materials in a component according to its suitability, and to control the construction process starting from a digital model. Features like these and the increase in high precision and time saving fabrication process has led to the rapid growth of this 3D Printing technology. These multiple advantages can be utilized if the building components and AM processes are fabricated competently in the designing and drafting phase. The quality of AM to fabricate complex designs which high precision makes it suitable for the aerospace industry. AM has become quite popular in the Biomedical engineering sector as Bioprinting or 3D printing using cells provide a flexible and wide range of methodology to produce cell-laden tissue-like constructs for tissue engineering. The distinctive feature of AM to fabricate products with high precision, complex designs, drop in material wastage, reduction in the need for tools and fixtures with premium materials in such less production times, has reduced the need to use traditional machining means which take up a lot of production time as well as the requirement of using several other processes to get the final product. Polymers and ceramics have primarily been an integral production material in AM. Sometimes, AM uses 3D Printing process to provide more functional parts by improving the materials making use of nanotechnology - particularly using polymer-graphene nanocomposites. AM has made it possible to produce highly advanced micro structured energy devices for self-powered microelectronics by controlling the thickness of electrodes and the optimization of capacitance which plays a major role in energy devices. The potentiality to process renewable carbonaceous materials by 3D printing helps in generating impact of functional materials for commercially viable energy storage applications. The present paper provides an overview of the types of AM processes, its advantages and developments

2. What is Additive Manufacturing?

Additive manufacturing, also known as 3D Printing or rapid prototyping worldwide, is a way to join materials to form 3D models from 3D data. It is a computer-controlled process which produces the product by constructing it layer by layer which is opposite when it comes to subtractive manufacturing, such as machining [1]. Additive Manufacturing, as inferred by its name, suggests that it adds material to produce an object. Each layer sticks to the previous layer of partially melted material. Parts are digitally modified by computer-aided-design (CAD) software that is used to create .stl files that "chop" the part into ultra-thin layers [2]. The data from CAD guides the path of a nozzle as it accurately deposits material on the previous layer. As materials are cured, they fuse together to form a three-dimensional object. It can be used to produce anything, and its application are limitless, whether the product is made of plastic, concrete, or metal, it could someday with more advances also help produce human tissue onto making a human organ. Nowadays, AM helps in the production of end-use products in aircraft, dental restorations, medical implants, automobiles, and even fashion products. Additive Manufacturing is on the verge of bringing digital elasticity ,efficiency and order to manufacturing operations [3]. The usual process of using AM includes, a computer, 3D modelling software (Commonly CAD OR Computer Aided Design), machine equipment and Manufacturing material. Once the design is completed on CAD, the machine reads and starts the process of manufacturing the product by adding or laying down layers of liquid, sheet material or powder. AM has some of its traits when you compare the production of an object by the traditional means, it is frequently a task to carve up parts by extra processes by tapering, milling, drilling and other means, which in turn takes up a lot of time. Some terms like Rapid Prototyping and 3D Printing are used to describe AM but each of these are just subtypes of it. Hideo Kodama of the Nagoya Municipal Industrial Research Institute, had invented two additive methods for construction of 3D models, this is the first known 3D printing manufacturing tool [4,5].

3. Types of additive manufacturing techniques:

The basic types of additive manufacturing techniques are listed below:

3.1 VAT Photopolymerization
3.2 Material Jetting
3.3 Binder Jetting
3.4 Material Extrusion
3.5 Powder Bed Fusion
3.6 Sheet Lamination
3.7 Directed Energy Deposition

3.1 VAT Photopolymerization

VAT Photopolymerization is a AM process that fabricates the product layer by layer by particularly choosing a vat of curing liquid resin through targeted light-activated polymerization. All VAT Photopolymerization use special resins (viscous substances that convert into rigid polymers through a curing process, and are both naturally occurring and synthetically produced) called Photopolymers as printing material. Stereolithography (SLA), the first AM process to be patented and commercialized in the late 20th century. It uses photochemical processes to produce polymers [6].

Process- An ultraviolet (UV) light is used to harden the liquid resin at specific spots using motor controlled mirrors, while a platform moves the object being made downwards after each new layer is hardened or cured. There is no structural support from the liquid material during the construction period, contrasting powder based methods, where support is given from the loosen materials. In almost all the cases, structural support will be added.

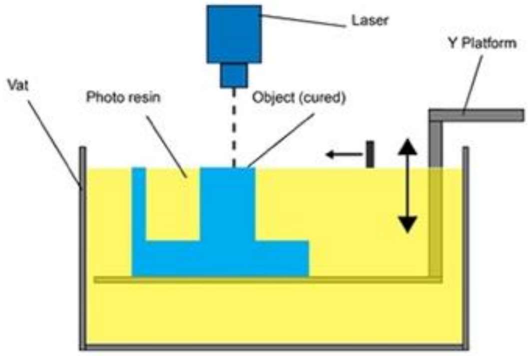

Fig-1: VAT Photopolymerization process

Liquid Resin or liquid photopolymer is kept in a box or vat with the build platform partially submerged near the surface of the liquid. Utilizing the data fed from the CAD file, the printer produces a UV or certain wavelengths of light source to selectively cure the liquid resin into a solid layer. Then the platform is re-immersed into the resin and the whole process takes place again in the next layers until the design has fully printed. This process is very fast and has high precision. It can be used to fabricate large models but they are quite prone to deformation over the years and resins don't have their own structural support. It may also require additional tooling which makes it quite an expensive process [7].

3.2 Material Jetting:

MJ is one of the most fast ways of 3D printing and has high precision. Material jetting is a 3D printing process which uses liquid photopolymer and UV light. It fabricates products almost like a 2D ink printer because it sprinkles liquid resins onto the platform . However, 2D ink jet printer onto squirts a single droplet into the platform whereas MJ builds the product layer by layer until completed. Liquid resin photopolymer is jetted onto the build/construction platform, layer by layer, where it solidifies. Material is squirted from a nozzle, which moves in a horizontal way along the construction platform. MJ is quite similar to stereolithography (SLA) as both use UV light to cure the liquid resin photopolymer. The only way to differentiate these processes is how MJ can squirt thousands of liquid resin onto the platform at one time whereas in SLA, liquid resin polymerisation is held in a container or a vat, which is then particularly (point-wise) squirted and cured by the UV light.

Line-wise deposition-
Another way how MJ is considered unique is the way material is unloaded and therefore cured. MJ printers squirt liquid resin from nozzle heads along an X-axis platform, which sweeps back and forth depositing resin onto it. To help visualize the movement of the apparatus, think of the light source in a windshield wiper of a car [8].

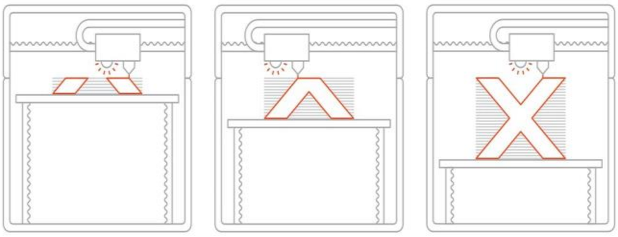

Fig-2: Multiple print heads deposit droplets in an X-axis line, which scans back and forth along the Y-axis. Source: 3D Hubs

Pros and Cons
High dimensional accuracy and fast speed make MJ the preferred choice for 3D Printing. We can produce multiple parts using MJ without disrupting its speed. This proves to be a plus point for small scale production. Parts made from MJ have a very polished surface which helps in producing creative and aesthetic parts. Entire colour pallet and multi-material usage also is as added benefit. With so many appealing qualities of MJ, it comes at a cost, the entire process it quite costly as both the machine as well as the material are costly. Because the parts are made of liquid resin and cured by UV light, structural support has to be added, it can't carry immense load and could deteriorate over time.

Applications-
It is mostly used for fabricating prototypes. Doctors use this to produce realistic body parts. Similarly, architects and students would fancy the prototypes of their designed projects like buildings. MJ could also be used to fabricate moulds [9].

3.3 Binder Jetting –

The binder jetting procedure makes use of two materials; a powder based material and a liquid binder. The binder jetting process is similar to material jetting, except that the nozzle puts down alternate layers of powdered material (metal, sand, ceramics or composites) and a liquid binder. The liquid binder plays the role of adhesive between powder layers. The nozzle moves horizontally along the x and y axes of the machine and puts down alternating layers of the building powder material and the liquid binding material. After each layer, the object being printed is lowered on its construction platform. It uses a map from a digital design file from CAD, until the object is fabricated completely [10]. It has relatively high speed of fabrication. This process doesn't necessarily have 100% proper structural support as compared to the other processes which use only powdered build powder material. It does provide self-support but not fully. The technology is often referred to as 3DP technology and is copyrighted under this name. Depending on the application, some materials, like sand, require little to no additional post-processing [11].

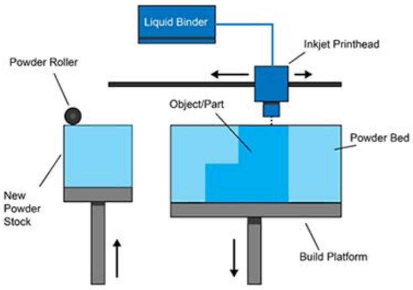

Fig- 3: Binder Jetting

Binder jetting does not use heat or light to curate parts during the build process and it prints quickly entire layers of many parts using a various nozzles. The parts are supported by the loose build powder material, eliminating the need for a build plate or supports. Thus, binder Jetting has the ability to print a large number of parts or large parts in a quick and cost effective manner. Finally, parts printed in metal powder are sintered together at one time after the shape has been formed, resulting in a high-quality microstructure with superior grain isotropy [12].

3.4 Material Extrusion (ME-AM):

Material extrusion also known as ME-AM, fused filament fabrication, or fused layer modeling is an extrusion based additive manufacturing technique that was developed in late 198s by Stratasys Inc. under the name of fused deposition modeling. Material Extrusion based additive manufacturing (ME-AM) is an emerging manufacturing technique which is characterized by the selective deposition of thermoplastic filaments in a layer-by-layer formatted based digital part models. This technique has manifold benefits over conventional manufacturing technologies and hence has attracted considerable attention [13]. In the course of a state-of-the-art ME-AM process, a solid thermoplastic filament is trailed into a hot die by two counter-rotating driving wheels. The spooled filaments, typically prepared by extrusion of any thermoplastic polymer, are transported through a moving deposition unit onto a heated build platform thus resulting in layer-by-layer fabrication of the structural element according to CAD-defined layer. For the material to be extruded through the nozzle, the filament is heated up in the liquefier and the nozzle up to a temperature at which it can easily flow, which is mostly above the melting temperature of semicrystalline thermoplastic filaments. Once the material leaves the nozzle, the extruded material is deposited onto a build platform or a previous layer in the horizontal plane. The deposited material cools and resolidifies. Once the required deposition of a layer is completed, the built platform is lowered by the amount of one layer height in order to print subsequent layers [14,15].

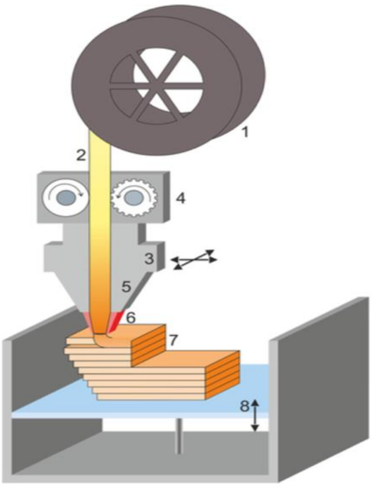

Fig- 4: Schematic Diagram of Material Extrusion Process (1)Spooled material storage, (2)Thermoplastic filament, (3)Horizontally movable, heated deposition of, (4)Counter-rotating driving wheels, (5)A liquefier, (6)A nozzle, (7)Structural element fabricated in a layer-by-layer manner, (8)Vertically movable build platform.[15]

In contrast to photopolymerization and powered based AM techniques that fulfils the requirement of the material to be used in ME-AM technique, ME-AM allows use of wide range of thermoplastics thar are commercially available in spools and which satisfy all the material requirements. Apart from Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS), particularly Polyethylene Terephthalate and Polycarbonate (PC) can nowadays be declared as standard ME-AM materials. The other materials that are available cannot always be used trouble free and needs plenty of hands-on practice and thus needs improvements in terms of part processability, Stability and accuracy [16,17].

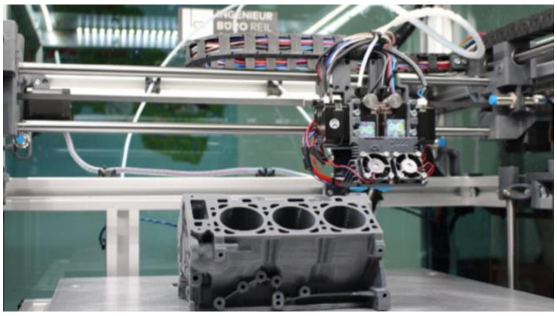

Fig- 5: Material Extrusion Process in Additive Manufacturing

3.5 Powder Bed Fusion (PBF):

Powered Bed Fusion (PBF) is one of the most used techniques in Additive Manufacturing. Since this has low-cost quality, it has grown a lot in past few years. There is no need for support in this process since the powder itself acts as support. This process allows selecting various materials including plastics, glass metals, and its alloys. This process is recyclable and the powder used can be recycled and used. In this process, a heat source is used to fuse powder to form material that is used to make a 3D product. Thermal, electrical and laser are the three techniques for heat source generation in PBF. The laser fusion technique is sub-divided into Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), SLS process is capable to fuse for only plastic parts whereas, SLM is for metal. PBF is the process of spreading the new layer of powder on the previous layer for which there are various mechanism available, like blade or a roller. There are two chambers for powder bed fusion printers, one is for Powder chamber and the other is Build chamber (Simply table or platform on which product is build) with a roller or blade to spread the powder evenly as required [18]. There are certain steps that are to be followed for PBF, A 3D cad model is generated into cross section and saved in suitable file format i.e. stereo lithographic file (.STL file), with the help of desktop or printer the required files are loaded and correctly placed on the bed of the printer, Multiple copies can be filled at a time in order to increase the productivity, powder chamber is then filled with powder manually or automatic process, then by using the heat source which is either laser or electron or thermal, the powder is fused. The blade or coating roller then spreads a layer of powder which is generally around 0.1 mm on the platform as per the 2D cross-sectional data from the STL. File. A new layer of powered material is added or spread upon the previous layer again and the process is repeated until the whole product is created. When the final product is produced, the parts are removed from the platform by the means of different machining process. PBF technique is relatively less expensive process, suitable for visual models and prototypes and is capable to integrate support structure. This process is time consuming because it needs pre heated powder, vacuum generation and build time is very high. Surface and structural properties are poor compared to other manufacturing process. [19]

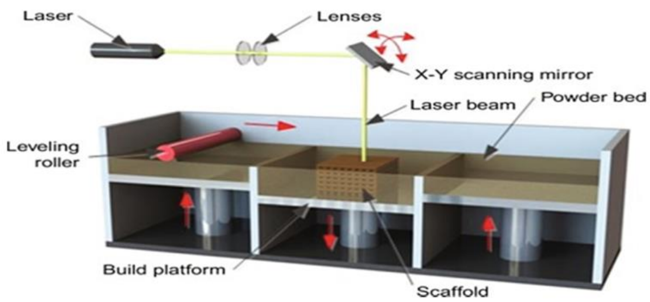

Fig- 6: Schematic Diagram of Powder Bed Fusion

Powder Bed Fusion technique use any powder-based materials, but the common metals and polymers used are:
SLS, SLM: Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel
EBM: Titanium, Cobalt Chrome, Stainless Steel, Aluminium, Copper. [19]

Fig- 7: Part manufactured by PBM Technique

3.6 Sheet Lamination:

Sheet Lamination process includes Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM). Sheets are ribbons of metal which are bounded together by ultrasonic welding are used in Ultrasonic Additive Manufacturing. This process requires additional cnc machining and removal of unbound metal often during the welding process. Layer by Layer approach used by paper material and adhesive instead of welding is used in Laminated Object Manufacturing (LOM). For easy removal post build, cross hatching method is used in LOM process. This process of laminated objects is used for aesthetic and visual models and aren't suitable for structural use. UAM is a low temperature process and allows for internal geometries to be created. This process uses metals and includes aluminium, copper, stainless steel and titanium. In Sheet Lamination process the material is first positioned in place on the cutting bed, the material is then bonded in place, over the previous layer using the adhesive. The shape required is then cut from the layers by the help of laser or knife after which the next layer is added. Similar process is repeated and the desired output is generated.

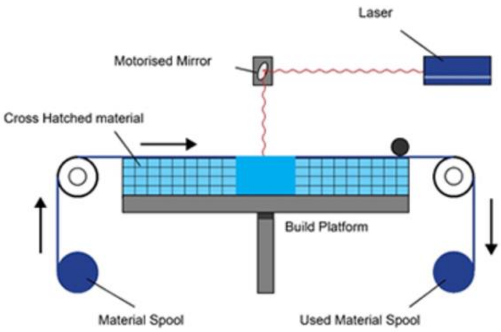

Fig- 8: Schematic Diagram of Sheet Metal Process

LOM is the process which uses variety of sheet material, namely paper. The main benefits of this process are that it includes A4 size paper which is readily available and it isn't that expensive. UAM process uses sheets of metals that are bounded together using ultrasonic welding. UAM process is difficult and expensive compared to LOM process since there are metals used and post processing is a long process. [20]

Fig- 9: Sheet Lamination Process

3.7 Directed Energy Deposition (DED):

Directed Energy Deposition process is a complex printing process and is used to repair or add additional material to existing components. This process covers a range of terminologies like Laser engineered net shaping, Directed metal deposition, 3D laser cladding. Typical DED machine includes a nozzle which is mounted on multi axis arm which deposits melted material onto the specified surface where it solidifies. This process is somewhat similar to Material Extrusion Process but the nozzle in this process can move in multiple direction and isn't fixed to a specific axis. The material that can be deposited from any angle due to axis machines is melted upon the deposition with the help of laser or electron beam. This process can be used with polymers and ceramics but gives best result when used with metals in form of powder or wire. In this process the nozzle moves around a fixed object, the material is deposited from the nozzle onto existing surfaces of the object. The deposited material is either in form of power or wire. Material used is melted using a laser, electron beam or plasma arc upon deposition. The material keeps on getting added layer by layer and it solidifies, creating or repairing new material features on the existing object.

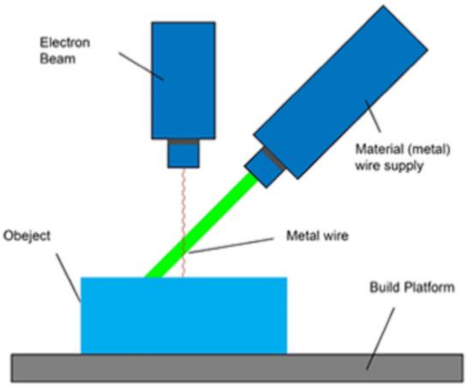

Fig- 10: Schematic Diagram of Directed Energy Deposition

Wire used in this process is less accurate due to the nature of its pre-formed shape but is more material efficient when compared to powder. The electron beam melting process in this type use metals and not polymers or ceramics. Metals like Cobalt Chrome, Titanium is used in EBM process used in Directed Energy Deposition. [21]

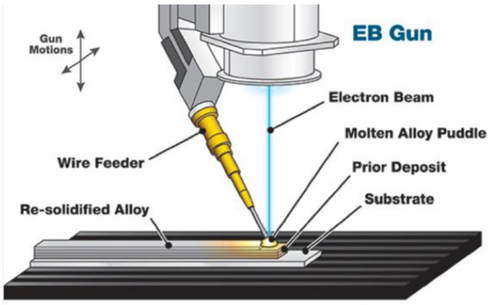

Fig- 11: Wire Directed Energy Deposition [22]

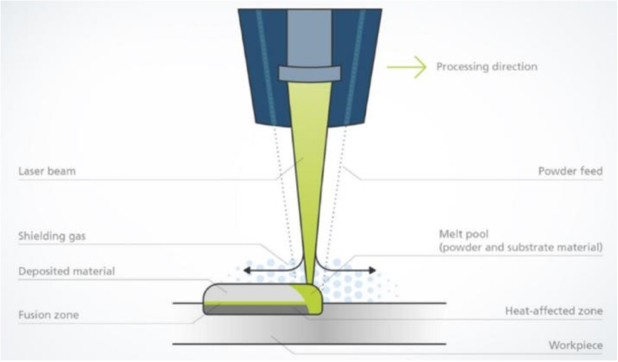

Fig- 12: Powder Directed Energy Deposition [23]

4. Advantages and Disadvantages of Additive Manufacturing:

- Rare shape making ability: Additive Manufacturing is attractive because of its unusual or complex component shapes that can be difficult to use with other processes. Any complex geometry that is difficult to manufacture with the help of other geometries can be manufactured with the help of this process.
- Manufacturing and Assembly in 1: In additive Manufacturing, many components can be produced at a time. In additive manufacturing, manufacturing and assembly is combined in one single process thus helping cut down the time used for two separate methods.
- Less Waste: In traditional manufacturing process the material is removed from larger material to get the final product thus increasing the amount of waste but in additive manufacturing the required amount of material is added on layer by layer thus reducing the amount of waste.
- Cost Prohibitive: Additive manufacturing is rarely the most cost-effective path to an end product. There is considerable amount of capital costs to purchase the equipment necessary to support additive manufacturing. When specified additive manufacturing, very fine or small particles or distribution are noticed.
- No Mixing: The final product from additive manufacturing depends on characteristics of the material used in the process and to prevent the machines used from any harm, mixing of materials cannot be done.
- Slow Process: Additive manufacturing is still not an efficient way to produce parts at high volume. The shape manufactured by conventional manufacturing in 15-20 second will take around 3 hours in additive manufacturing. [24]

5. Uses:

5.1 Medical Industry:

With the help of additive manufacturing, complex anatomical parts can be fabricated which helps provide better visualization of specific anatomies. [25,26] Additive manufacturing was also used for separation of Siamese twins by performing precise pre-surgical planning on additive manufacturing-built modes [27].

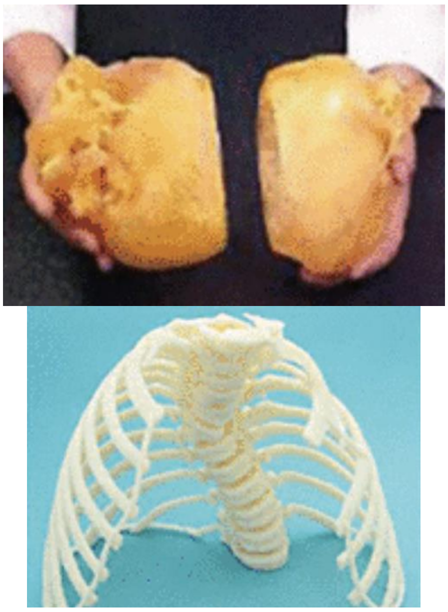

Fig- 13: Use of Additive Manufacturing in Medical Industry

5.2 Jewelry and Architectural industry:

High degree of manual effort and time is required for complex designs by jewelry and architectural industry. Good resolution is possible by additive manufacturing process for complex structures [28].

Fig- 14: Use of Additive Manufacturing in jewelry and Architectural Industry

5.3 Aerospace and Automotive Industry:

Interest has been shown y aerospace industry in these technology because of its ability to fabricate metal parts directly using material like titanium and because of its ability to manufacture complicated shapes [29]. An investigation was carried out by Ding et al. with thin-walled structures of varying and comprising several crossings using arc welding-based AM process [30].

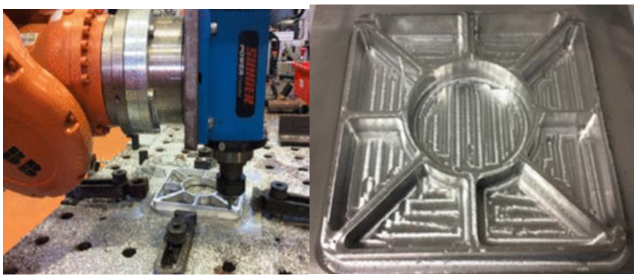

Fig- 15: Process of post-processing and Final finished part with the desired dimensional accuracy.

6. Conclusion:

In this paper we have discussed about the various types of additive manufacturing techniques and how each of them works. Additive manufacturing takes the information from the CAD file which is then converted into STL file format. The information of various layers is read and the final product is manufactured in layer-by-layer form. There is relevant discussion about the advantages and disadvantages of additive manufacturing. Various uses of additive manufacturing are also mentioned with example of how and why the process was used. With the continuous growth of additive manufacturing over the past few years, there is optimism that additive manufacturing has a significant place in the future of manufacturing. Additive manufacturing technique has been welcomed in Automobile, Aerospace and many other industries because of its lighter structure, complex parts production and versatility. There is still a lot of research to be accomplished before additive manufacturing process become standard in manufacturing industry. The accuracy and finishing are the necessary areas where improvement needs to be made.

7. References:

[1]N. Labonnote, A. Rønnquist, B. Manum, P. Rüther Additive construction: state-of-the-art, challenges and opportunities Autom. Constr., 72 (2016)

[2] P. Wu, J. Wang, X. Wang A critical review of the use of 3-D printing in the construction industry Autom. Constr., 68 (2016)

[3] S.H. Ghaffar, J. Corker, M. Fan Additive manufacturing technology and its implementation in construction as an eco-innovative solution Autom. Constr., 93 (2018)

[4] R. Duballet, O. Baverel, J. Dirrenberger Classification of building systems for concrete 3D printing Autom. Constr., 83 (2017)

[5]S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe Developments in construction-scale additive manufacturing processes Autom. Constr., 21 (1) (2012)

[6] Adam G, Zimmer D. Design for Additive Manufacturing—Element transitions and aggregated structures. CIRP Journal of Manufacturing Science and Technology 2014;7:20–28.

[7] VAT Photopolymerisation: Additive Manufacturing Research Group: Loughborough University. (n.d.). Retrieved from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation

[8] Access denied | all3dp.com used Cloudflare to restrict access. (2019). . https://all3dp.com/2/what-is-material-jetting-3d-printing-simply-explained/

[9] Material jetting: Additive Manufacturing Research Group: Loughborough University.(n.d.). Retrieved from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/

[10] Binder Jetting: Additive Manufacturing Research group: Loughborough University. (n.d.). Retrieved from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/

[11]C. Gosselin, R. Duballet, P. Roux, N. Gaudilliére, J. Dirrenberger, P. Morel Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders Mater. Des., 100 (2016)

[12] G.W. Ma, L. Wang, Y. Ju State-of-the-art of 3D printing technology of cementitious material-an emerging technique for construction Sci. China Technol. Sci., 61 (4) (2018)

[13] Gebhardt, A.; Kessler, J.; Thurn, L. 3D-Drucken: Grundlagen und Anwendungen des Additive Manufacturing (AM); Carl Hanser Verlag GmbH & Co. KG: München, Germany, 2016.

[14] Gibson, I.; Rosen, D. W.; Stucker, B. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing; Springer: New York, NY, 2015.

[15] Gurr, M.; Mülhaupt, R. In Comprehensive Materials Processing; S. Hashmi; G. F. Batalha; C. J. Tyne; B. Yilbas, Eds.; Elsevier: Oxford, UK, 2014; p 77.

[16] Tseng, J.-W.; Liu, C.-Y.; Yen, Y.-K.; Belkner, J.; Bremicker, T.; Liu, B. H.; Sun, T.-J.; Wang, A.-B. Mater. Des. 2018, 140, 209.

[17] Ligon, S. C.; Liska, R.; Stampfl, J.; Gurr, M.; Mülhaupt, R. Chem. Rev. 2017, 117, 10212.

[18] L.E. Murr, Metallurgy of additive manufacturing: Examples from electronbeam melting, Addit. Manuf. (2015),https://doi.org/10.1016/j.addma.2014.12.002.

[19] "Powder Bed Fusion | Additive Manufacturing Research Group | Loughborough University." University of the Year | Loughborough University.

[20] Sheet Lamination | Additive Manufacturing Research Group | Loughborough University

[21] Directed Energy Deposition | Additive Manufacturing Research Group | Loughborough University

[22] Wirefeed Additive Manufacturing vs. Powder Methods | Sciaky

https://www.sciaky.com/additive-manufacturing/wire-vs-powder

[23] Directed Energy Deposition (DED) | Digital Alloys

https://www.digitalalloys.com/blog/directed-energy-deposition/

[24] Advantages & Disadvantages of Additive Manufacturing Process

https://www.horizontechnology.biz/blog/advantages-and-disadvantages-of-additive-manufacturing-process-vs-powder-metallurgy

[25] Dhakshyani, R, Nukman, Y, Osman, A. Preliminary report: rapid prototyping models for dysplastic hip surgery. Centr Eur J Med 2011; 6: 266–270.

[26] Liu, Q, Leu, MC, Schmitt, SM. Rapid prototyping in dentistry: technology and application. Int J Adv Manuf Tech 2005; 29: 317–335.

[27] ukuru, N, Gowda, SKP, Ahmed, SM. Rapid prototype technique in medical field. Res J Pharm Technol 2008; 1: 341–344.

[28] Wong, KV, Hernandez, A. A review of additive manufacturing. ISRN Mech Eng 2012; 2012: 208760.

[29] Campbell, I, Bourell, D, Gibson, I. Additive manufacturing: rapid prototyping comes of age. Rapid Prototyping J 2012; 18: 4255–4258.

[30] Ding, D, Shen, C, Pan, Z. Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part. Comput-Aided Des 2016; 73: 66–75.