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A COMPREHENSIVE DETAILED REVIEW OF ADDITIVE MANUFACTURING (3D PRINTING) PROCESSES, APPLICATION AND FUTURE ASPECTS

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ABSTRACT

Additive manufacturing is a layer based manufacturing process aimed at producing parts directly from a 3D model. 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 etc. This paper provides a review of different types of metal additive manufacturing process and application of Additive Manufacturing in aerospace, automotive, medical sectors. This review will help readers understand the different aspects of additive manufacturing and explore new avenues for future research.

Keywords*: Additive Manufacturing, Stereo-lithography, Direct Energy Deposition, Computer Aided Design (CAD) etc.*

1. INTRODUCTION

Additive manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. Additive manufacturing (AM), also known as 3D printing, rapid prototyping or freedom fabrication [1]. Additive manufacturing is a Computer controlled process which produces the object by constructing it layer by layer using different materials such as polymers, composites, ceramic and metallic pastes depending on the requirement using digital data from the computer.

Additive manufacturing (AM) processes fabricate component using 3D computer data or Standard Tessellation Language (STL) files, which contain information regarding the geometry of the object [2]. AM is very useful when low production volumes, high design complexity, and frequent design changes are required.

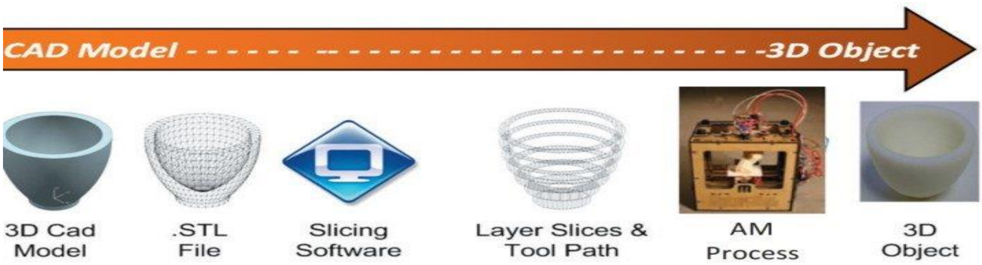

Fig 1.1 Different steps in Additive Manufacturing

AM is very useful when low production volumes, high design complexity, and frequent design changes are required. It offers the possibility to produce complex parts by overcoming the design constraints of traditional manufacturing methods.

Although, AM has many benefits, its applications are still limited because of its low accuracy and long build times compared to CNC machines.

Typically any Additive Manufacturing process includes a combination of following eight steps [3, Gibson *et al*., 2012]

1) Conceptualization and CAD model.
2) Conversion to STL file format.

3) Transfer to Additive Manufacturing (AM) equipment and manipulation of STL file.
4) Machine setup.
5) Build the part.
6) Removal and cleanup of the built part.
7) Post processing of the part.
8) Application.

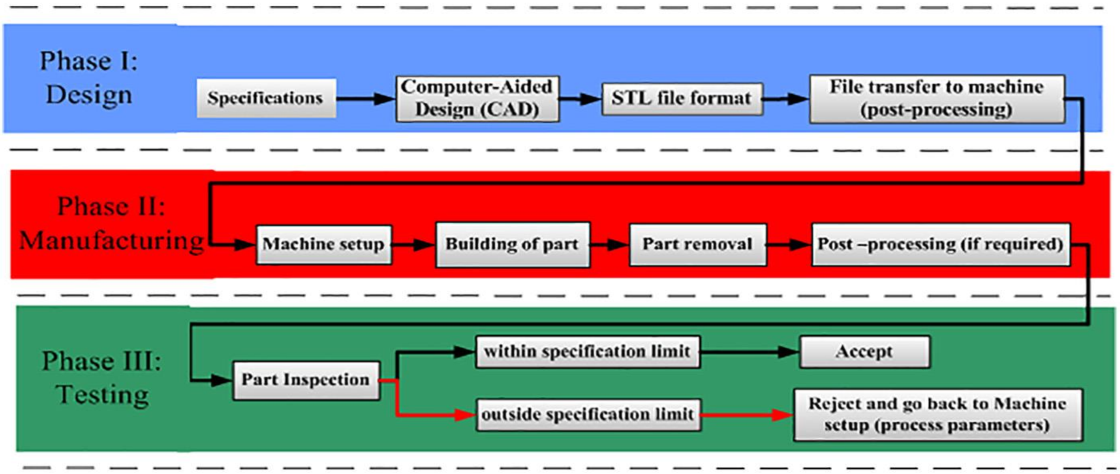

Fig 1.2 Phases in Additive manufacturing (AM) process

2. CLASSIFICATION OF ADDITIVE MANUFACTURING (AM)

Additive manufacturing (AM) process can be classified according to the type of material used [4]. Summarize the existing methods for AM based on the type of material.

2.1 Solid based Additive manufacturing (AM)

2.2 Liquid based Additive manufacturing (AM)

2.3 Power based Additive manufacturing (AM)

2.1 Solid based Additive Manufacturing (AM): In solid state additive manufacturing technology input material is in solid raw form various solid based additive manufacturing **(**AM) are as follow:

a) Fused deposition modelling (FDM)
b) Freeze-form extrusion fabrication (FEF)
c) Laminated object manufacturing (LOM)
d) Direct ink writing (DIW)

2.2 Liquid based Additive Manufacturing (AM): In liquid based Additive manufacturing technologies the input raw material is in liquid state. Various type of liquid based AM are as follow:

a) Stereo- lithography (SLA),
b) Multi-jet modelling (MJM),
c) Rapid freeze prototyping (RFP),
d) Digital light processing (DLP)

2.3 Powder based Additive Manufacturing (AM). In powder-based AM technologies the input material is in powder state. Among so many existing powder-based additive manufacturing (AM) technologies:

a) Three Dimensional Printing (3DP)
b) Electron Beam Melting (EBM)
c) Selective laser Melting (SLM)

d) Laser Engineered Net Shaping (LENS)

e) Laser Metal Deposition (LMD)

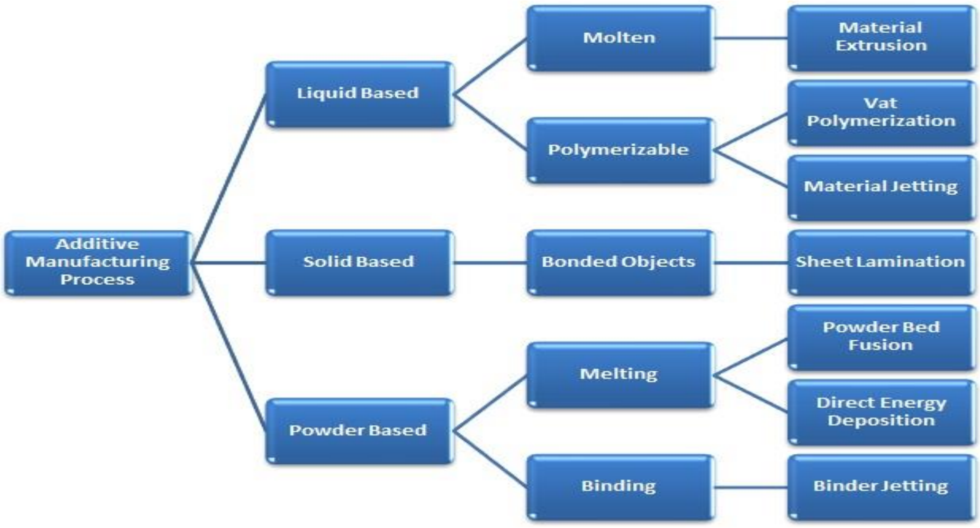

Fig 2.1 Classification of AM processes depending on the state of raw material

3. TYPES OF ADDITIVE MANUFACTURING TECHNIQUES

The basic types of additive manufacturing techniques are listed below [5]:

a) VAT Photo polymerization

b) Material Jetting

c) Binder Jetting

d) Material Extrusion

e) Powder Bed Fusion

f) Sheet Lamination

g) Directed Energy Deposition

3.1 VAT Photo polymerization

VAT Photo polymerization is a Additive Manufacturing process that fabricates the object layer by layer by particularly choosing a vat of curing liquid resin through targeted light-activated polymerization. All VAT Photo polymerization 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. 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 material [7,8,9]

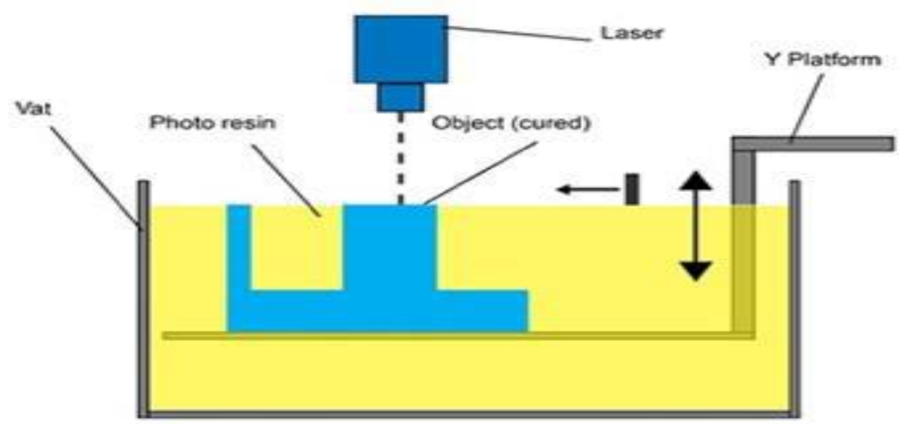

Fig 3.1 VAT Photo polymerization process

In almost all the cases, structural support will be added 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 [10].

3.2 Material Jetting:

Material jetting creates objects in a similar method to a two-dimensional inkjet printer. Material is jetted onto a build surface or platform, where it solidifies, and the model is built layer by layer. The material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light. As material must be deposited in drops, the number of materials available to use is limited [11,12,13].

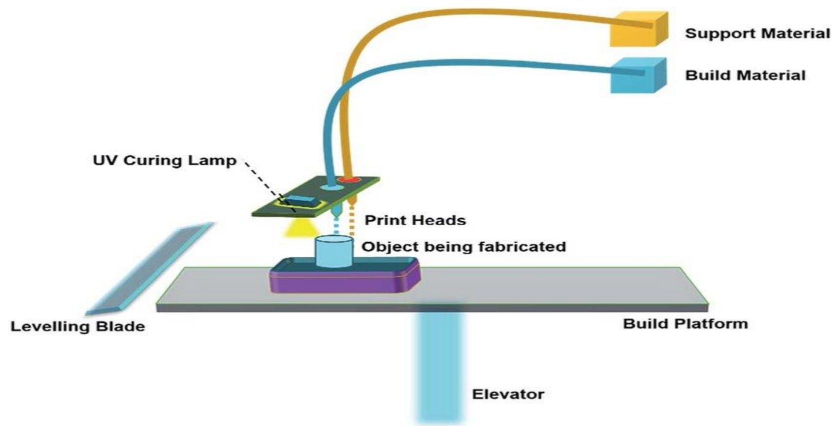

Fig 3.2 Schematic diagram of the material jetting process

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. 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.

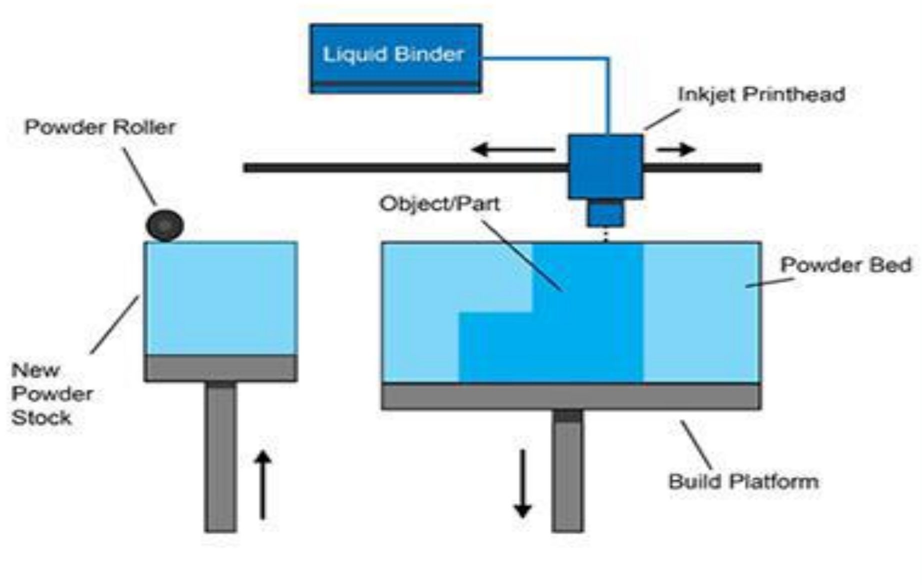

Fig 3.3 Binder Jetting

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 [14].

3.4 Material Extrusion (ME-AM):

Material extrusion also known as ME-AM, fused filament fabrication, or fused layer modelling is an extrusion based additive manufacturing technique under the name of fused deposition modelling. 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 semi crystalline 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 re-solidifies. 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 [15,16].

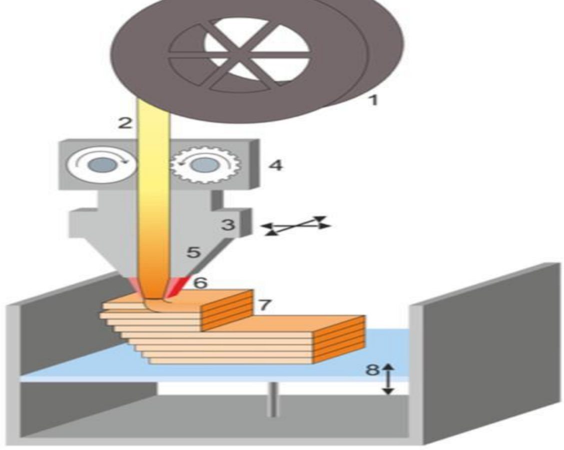

Fig 3.4 Schematic Diagram of Material Extrusion Process

a) Spooled material storage
b) Thermoplastic filament
c) Horizontally movable
d) Counter-rotating driving wheels
e) A liquefier
f) A nozzle
g) Structural element fabricated in a layer-by-layer manner
h) Vertically movable build platform

In contrast to photo polymerization and powered based AM techniques that fulfils the requirement of the material to be used in ME-AM technique, ME-AM allow use of wide range of thermoplastics that 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 process ability, stability and accuracy.

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.

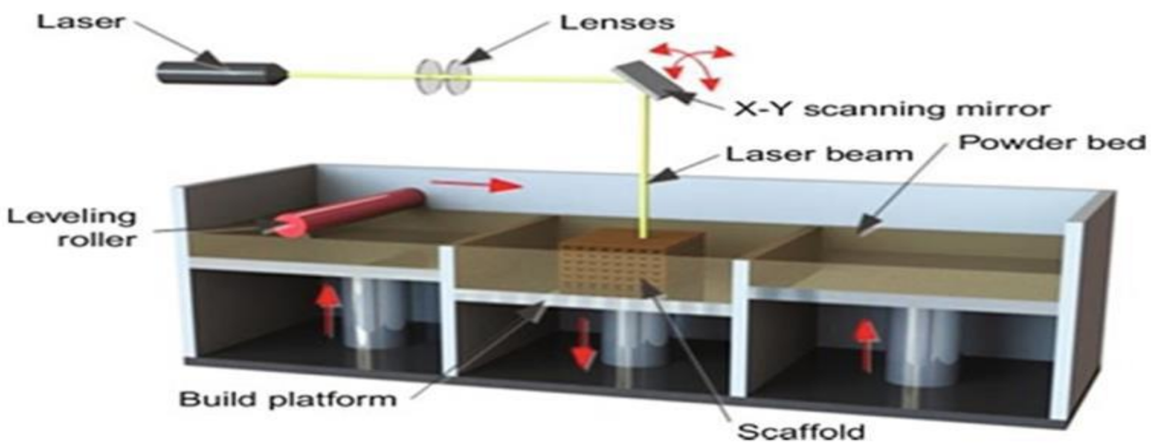

Fig 3.5 Schematic Diagram of Powder Bed Fusion

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). 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 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 [17].

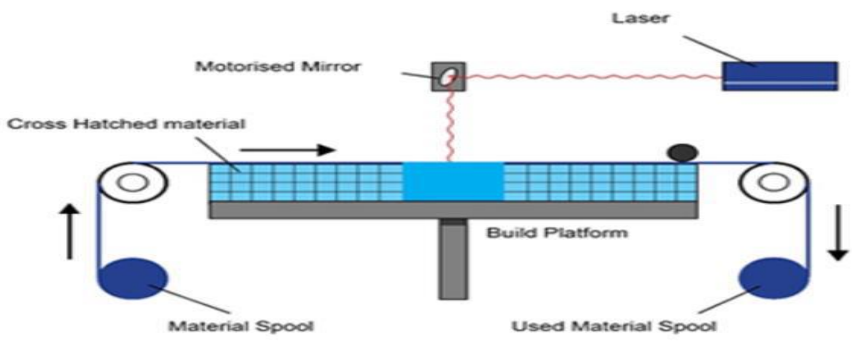

Fig 3.6 Schematic Diagram of Sheet Metal Process

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.

3.7 Directed Energy Deposition (DED):

Directed Energy Deposition process (DED) 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 directions 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 [18].

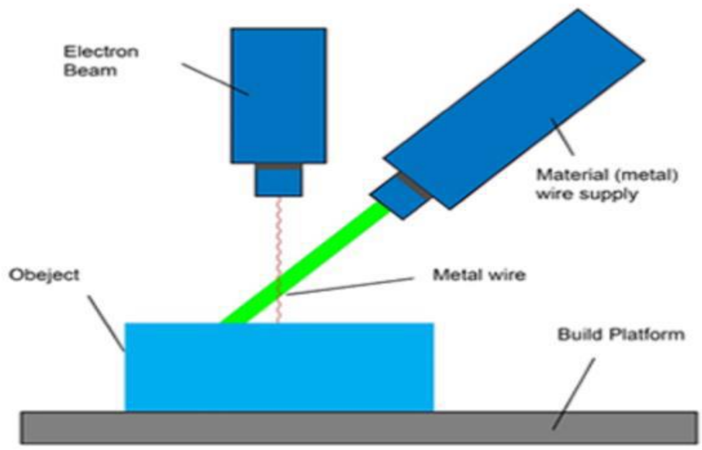

Fig 3.7 Schematic Diagram of Directed Energy Deposition

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.

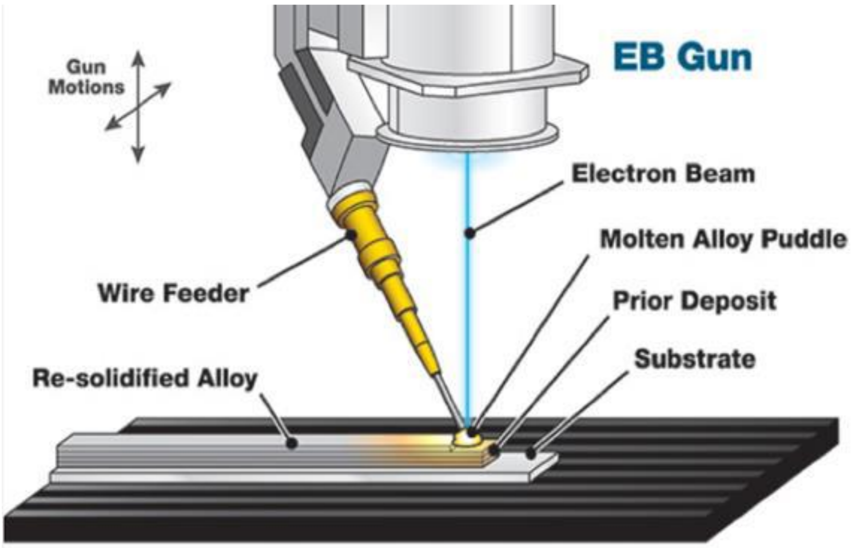

Fig 3.7.1 Wire Directed Energy Deposition [19]

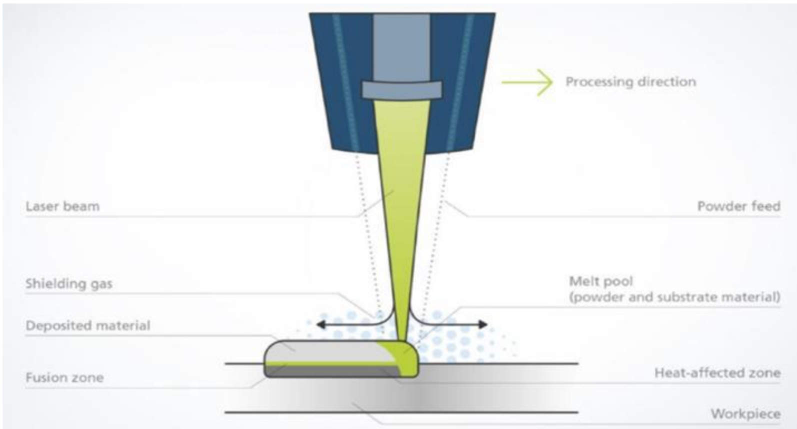

Fig 3.7.2 Powder Directed Energy Deposition [20]

4. APPLICATION OF ADDITIVE MANUFACTURING (AM)

1. **Aerospace sector:** AM is particularly suited to aerospace applications due to its weight saving capability and ability to produce complex geometry.

2. **Automotive sector:** A variety of materials are widely additive manufactured for the automotive_industry as they can be rapidly prototyped while offering weight and cost reductions. 3D printing application in the automotive industry are found in assembly line to develop lightweight car parts, components, replacement, spare parts and prototypes. Car manufacturing companies such as BMW, Mercedes-Benz, Bugatti, Chrysler, Honda, GM, Kia, Toyota and Diamler are embracing 3D printing of automotive parts with complex designs. Local Motors, one of the pioneers in 3D printing and autonomous vehicles debuted Strati, first 3D printed electric car in 2014. Recently the world's first 3D printed autonomous shuttle (Olli) in fig.4.1. Olli is a safe, smart and sustainable self-driving vehicle integrated with the IBM Watson’s advanced cognitive computing capabilities (Rogers, 2014), (Boissonneault, 2019).

Fig. 4.1 3D Printed Shuttle (Olli) [(Rogers, 2014) Copyrights © Local Motors]

3. **Medical sector**: The medical sector is finding an increasing number of applications for additively manufactured parts, especially for bespoke custom-fitted implants and devices.

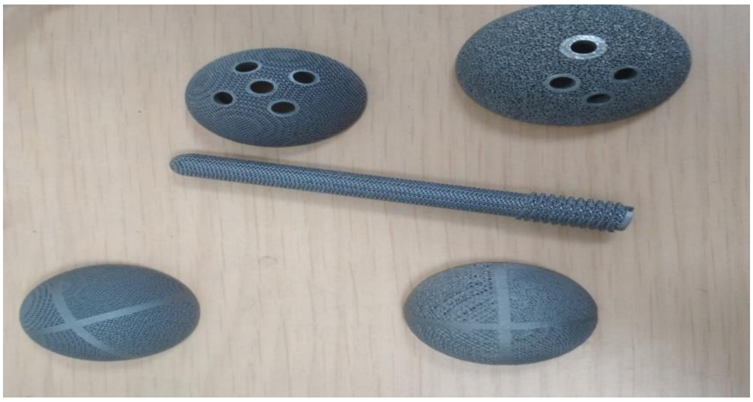

Fig 4.2 Use of Additive Manufacturing in Medical Industry

5. JEWELLERY AND ARCHITECTURAL INDUSTRY:

High degree of manual effort and time is required for complex designs by jewellery and architectural industry.

Fig 4.3 Use of Additive Manufacturing in jewellery and Architectural Industry

Advantages of additive manufacturing technology:

a) Increased data design freedom as compared to the conventional process like casting and machining.

b) Light weight structure can be made with additive manufacturing technology.

c) New function such as internal channel or several parts built in one.

d) Net shape process means less raw material consumption, upto 20 times as compared to the conventional process.

e) In additive manufacturing part can be made in only in one piece i.e. no need of sub assemble of the product..

Disadvantage of additive manufacturing technology:

a) Additive manufacturing processes are generally used for unitary series component i.e. not relevant for mass production.

b) Parts made by additive manufacturing show different property in Z –axis (construction direction)

c) In additive manufacturing processes 99.9% density can be reached but there can be internal residual porosities in the object.

d) Mechanical properties can be better than casting parts but inferior to the wrought parts.

6. FUTURE PROSPECT

In the coming years, AM will boost the advancement of Industry 4.0 in shaping the future of global industrial market. Industry 4.0 is an adaptive, cognitive and largely self-optimizing factory. Combining AM with Internet-of-Things, cloud computing, robotics and big data will revolutionize all industry sectors. The professional 3D printers developed so far will continue to advance innovation and promote businesses in diverse industry sectors such as electronics, healthcare, manufacturing, aerospace, and automobile, construction, fashion, jewellery, entertainment and food industry. In future aspects there is highly scope of Additive Manufacturing of quartz and glass materials and this can be highly useful in industrial application[21,22]

7. CONCLUSION

Additive Manufacturing (AM) has advanced from a rapid prototyping tool to a manufacturing technology capable of producing functional end-user products.

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.

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