Additive manufacturing: A Review

Shivani

Department of Mechanical Engineering

Kanpur, India.

Abstract: Additive manufacturing is a recent trend in production processes owing to its many benefits. It can be defined as the process of producing parts through the deposition of material in a layer-by-layer fashion. It has been a topic of intense study and review by many researchers. In this work, a comprehensive review pertaining to additive manufacturing has been accomplished. The evolution of additive manufacturing as a prominent technology and its various phases are discussed. The remarkable aspect of this work is the identification of problems associated with different additive manufacturing methods. Because of the imperfections in additive manufacturing, its hybridization with other methods, such as subtractive manufacturing, has been emphasized. This review will help readers understand the different aspects of additive manufacturing and explore new avenues for future research.

Keywords: Additive manufacturing, subtractive manufacturing, hybrid manufacturing.

1.1 Introduction: The evolution of industries depends on innovative and cutting-edge research activities associated with manufacturing processes, materials, and product design. In addition to the customary demands of low price and best quality, the market competition in current production industries is linked to requirements for products that are intricate, possess shorter life cycles, exhibit shorter delivery times, involve customization, and require less skilled workers. In fact, the current breed of products is very complicated and challenging to design. Accordingly, there is a strong incentive toward the design, development, and implementation of new and ingenious manufacturing processes. Manufacturing processes can be categorized into five categories, namely, subtractive, additive, joining, dividing, and transformative.

1. Subtractive technology can be defined as a method in which layers of materials are removed to produce a desired geometry. Over the last 20 years, subtractive technologies have undergone a tremendous change. The introduction of three-dimensional (3D) complex surface modeling software has replaced traditional code generation, such as G and M codes. Unlike the computer numerical control (CNC) machines of the 1940s, the contemporary lineage of CNC machines is highly automated based upon the integration of computer-aided design (CAD)/computer-aided manufacturing (CAM) systems.
2. Additive technology is based on the addition of material layers to create a desired workpiece shape.
3. Joining technology such as welding consists of physically joining two or more workpieces together to produce the required shape.
4. Dividing technology such as sawing is the opposite of the joining process.
5. Transformative technology, for example, forming, heat treatment, and cryogenic cooling, uses a single workpiece to fabricate another workpiece, keeping the mass unchanged.

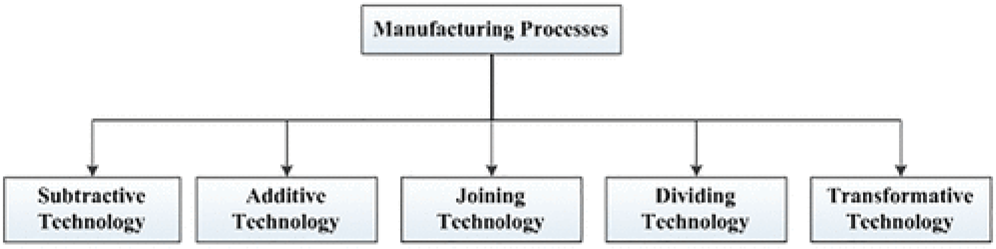

Fig. 1 Classification of manufacturing processes

1.2 Additive Manufacturing: Additive manufacturing (AM) can be described as a technique of blending materials by either fusion, binding, or solidifying materials such as liquid resin and powders. It builds part in a layer-by-layer fashion using 3D CAD modeling. The terminologies such as 3D printing (3DP), rapid prototyping (RP), direct digital manufacturing (DDM), rapid manufacturing (RM), and solid freeform fabrication (SFF) can be used to describe AM processes. AM processes fabricate components using 3D computer data or Standard Tessellation Language (STL) files, which contain information regarding the geometry of the object. 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. It does not have the same constraints as CNC machining because it segregates the part in cross sections with a resolution equal to that of the process. Nevertheless, the accuracy and build time can be improved by employing suitable part orientation. Optimized part orientation can enhance the accuracy and diminish the building time and support volume, which in turn minimizes the part production cost. Moreover, AM in contrast to conventional production processes consists of additional controllable process parameters and higher active interaction between the material properties and process parameters. There are different kinds of AM processes depending on the material preparation, layer generation technique, phase change phenomenon, material type, and application requirements. An AM process involves mainly three phases, namely, the design phase, the processing phase, and the testing phase.

PHASE - I (DESIGN) [Specifications] - [CAD] - [STL file format] - [File transfer to machine (post- processing)]

PHASE - II (MANUFACTURING) [Machine setup] - [Building of part] - [part removal] - Post-processing (if required)

PHASE - III (TESTING) [Part inspection]

1.3 Classification: AM processes or machines can be classified based on machine dimension, nozzle dimension, speed of the nozzle, and workspace dimensions. AM can be categorized in numerous ways based on the functional framework of the material. Although the methods of classification can also include the patterning energy, the technique of generating primitive geometry, the nature of used materials, and the support procedure. However, in broad sense, AM processes can be summarized and classified according to the type of material used. Figure 2 summarizes the existing methods for AM based on the type of material.

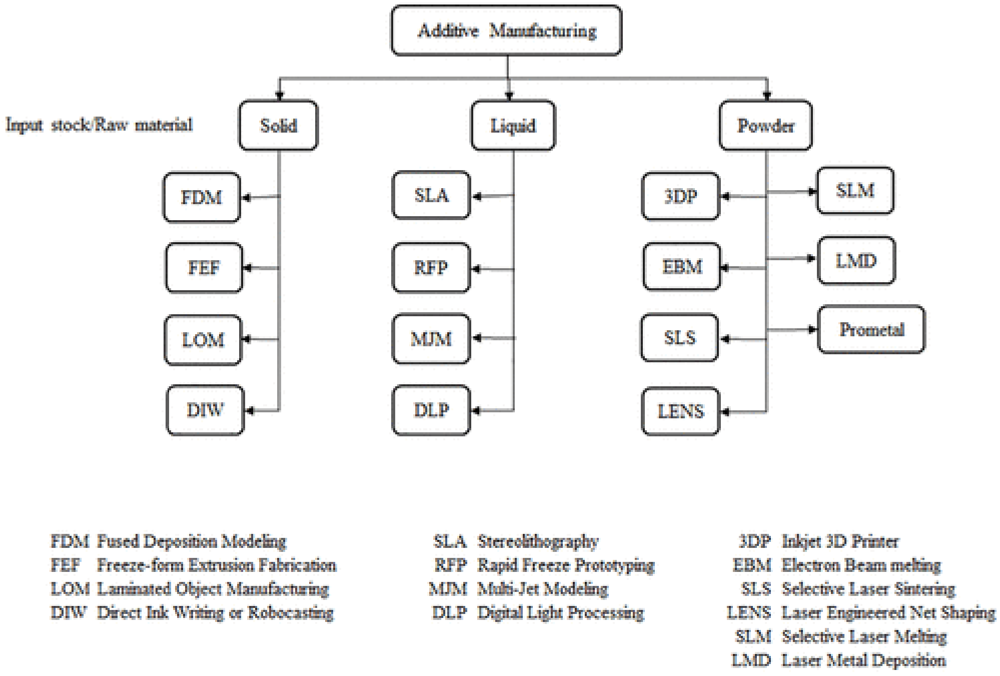

Fig. 2 Classification of AM processes depending on the state of raw material.

Solid-based AM: The AM technologies in which input raw material is in solid state have been discussed in this sub-section. Among so many existing solid-based AM technologies, FDM, freeze-form extrusion fabrication (FEF), laminated object manufacturing (LOM), and direct ink writing (DIW) is the most popular.

FDM: The working of FDM as shown in fig. 3 is based on the principle of layered manufacturing technology. In this technology, the plastic raw materials (filaments) are extruded through the nozzle, which is heated to melt the material. The nozzle head moves according to the tool path, which is generated for each layer.

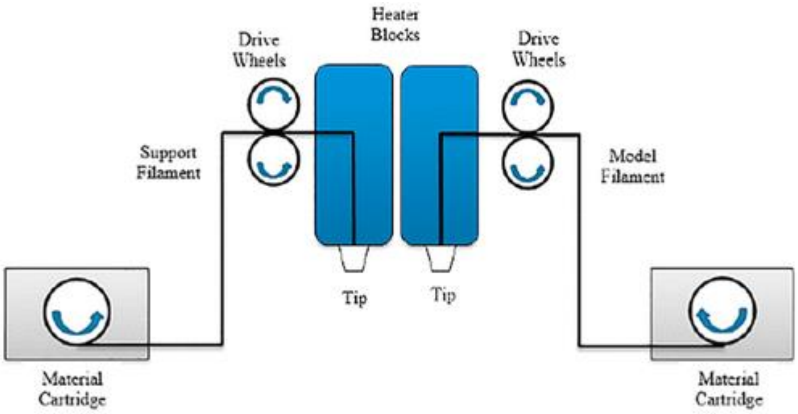

Fig. 3 Schematic of FDM.

FEF: It worked by extrusion of an aqueous ceramic paste. In this technology, the paste was extruded layer-by-layer into a build chamber, which was kept below room temperature in order to achieve the freezing of the paste. It was an environment-friendly approach because only water was utilized as the binding media. Solid loading as high as 60 vol. % had been achieved with this method using aluminum oxide (Al203). Figure 4 shows the schematic FEF process.

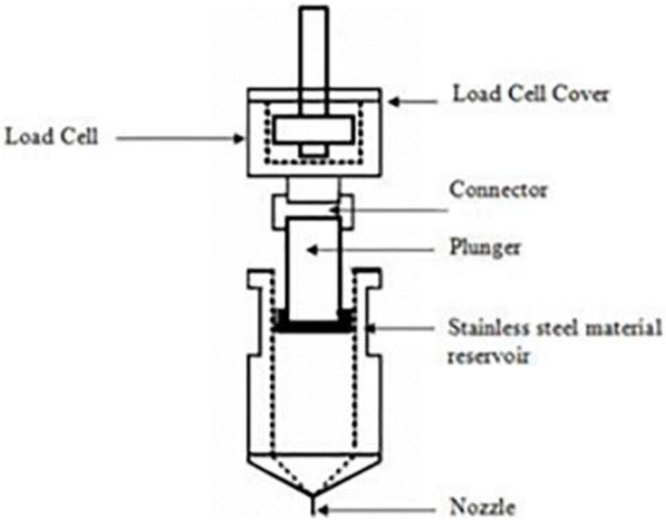

Fig. 4 FEF process

LOM: In LOM process, the metal, paper or a form of polymer in sheet form can be employed as a raw material. The sheet materials are joined together by ultrasonic consolidation and then machined into desired shape. In case of paper as raw materials, the paper sheets are glued together by adhesive and cut in shape by sharp blades. Moreover, the polymer sheets are joined together with the help of heat and pressure. The advantages of LOM include high surface finish, low material requirement, lesser machine and process costs, and high strength.

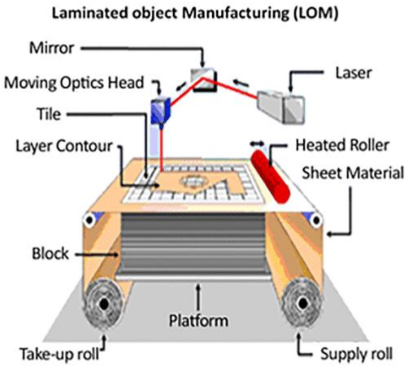

Fig. 5 Schematic of LOM process

DIW: The DIW (also known as ‘Robocasting’ or ‘Robot-Assisted Deposition’ or ‘Direct Write Fabrication’) was first appeared in the mid-1990s at Sandia National Laboratories. In this technology, a pseudo-plastic paste mixed with ceramic particles was extruded to fabricate a part. The movement of the nozzle was controlled through the instructions generated by the software using the information from the CAD model. It is very similar to FDM, but its principle depends on the pseudo-plasticity, in contrary to solidification in order to maintain parts’ shape. The nozzles as fine as 30 µm are required with ceramic pastes and 1 µm with polymer pastes. The larger nozzles (>1 mm) are also compatible with the process in order to build parts faster than other AM processes.

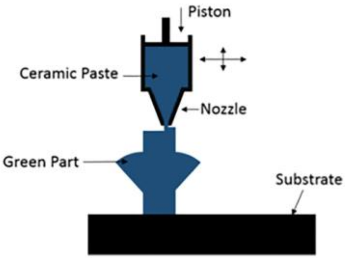

Fig. 6 Schematic of DIW process.

Liquid-based AM: In liquid-based AM technologies, the input raw material is in liquid state. Among so many existing liquid-based AM technologies, stereo lithography (SLA), multi-jet modeling (MJM), rapid freeze prototyping (RFP), and digital light processing (DLP) are the most prominent.

SLA: In SLA, a vat of liquid photopolymer resin is utilized to build parts in a layer-by-layer fashion. This part is subsequently hardened or cured using the UV light. The building platform moves down the object as the layers are being made after each new layer is cured. The principle of SLA can be seen in figure 7. The fabrication of part in SLA technologies requires supporting structures to attach the part on the building platform and hold the object as it floats in the liquid resin. No special material is required for support structures. The support structures are fabricated using the same material as that of the actual part.

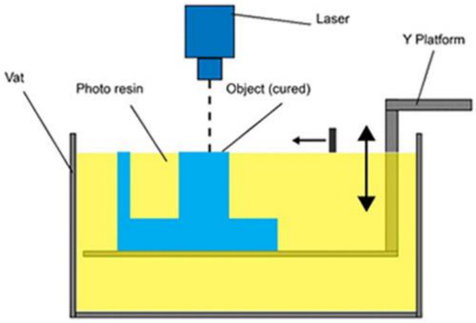

Fig. 7 Vat Photo polymerization process scheme

MJM: This process employs multiple nozzle jets to supply a UV curable polymer or wax as required. When the printed polymer gets out of the head, the UV lamp flashes to cure the material. The MJM prints parts on a moving platform that moves down after the current layer is cured in order to continue the process. It is a cost-effective technique because it can fabricate parts in a lesser amount of time. The MJM process is safe and quiet and therefore can be used for printing polymeric parts in the laboratory environment. However, in this process, the strength of parts and part quality are relatively poor as well as the bottom surface is most often printed parts quality; the part strength is relatively poor and the bottom surface is often indented, rough, or uneven.

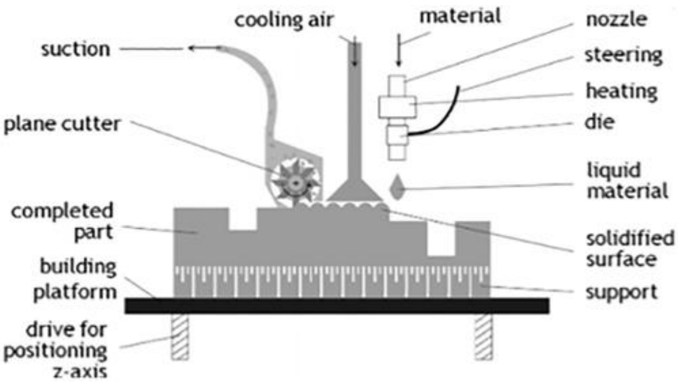

Fig. 8 MJM process

RFP: This process fabricates part by selectively depositing and freezing the water or brine in a layer-by-layer manner. Two types of techniques such as continuous deposition and drop-on-demand deposition can be utilized to deposit water. The building environment is kept at a low temperature, well below the waters freezing point. In this process, the pure water or brine can be used as the support material which is ejected from the nozzle and deposited on the previously solidified ice surface. The nozzles and feeding pipes are maintained at a particular temperature to pre-cool water near to its freezing point as well as kept them in the liquid state to allow material flow freely and smoothly.

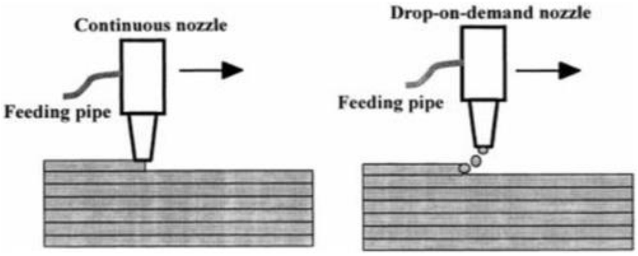

Fig. 9 Principle of RFP

DLP: This process is quite similar to SLA in the sense that it also utilizes photopolymers. The primary difference lies in the light source. In DLP, a conventional light source (an arc lamp) and a projector (DLP projector) are utilized. One of the benefits of DLP over SLA is that a shallow tub of resin is needed to carry out the process, causing less wastage and lower running costs.

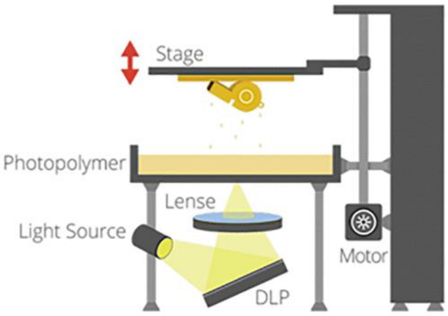

Fig. 10 Principle of DLP

Powder based AM: In powder-based AM technologies, the input raw material is in powder state. Among so many existing powder-based AM technologies, three-dimensional printing (3DP), electron beam melting (EBM), SLS, selective laser melting (SLM), laser-engineered net shaping (LENS), and pro metal and laser metal deposition (LMD) are the most extrusive.

3DP: In 3DP, a liquid binder is utilized to bond the powder materials. The powder layer is spread on the building platform and the binder liquid is extruded through nozzles depending on the cross section of the 3D model. This process does not require additional support structure, instead the support is provided by the unbound powder particles.

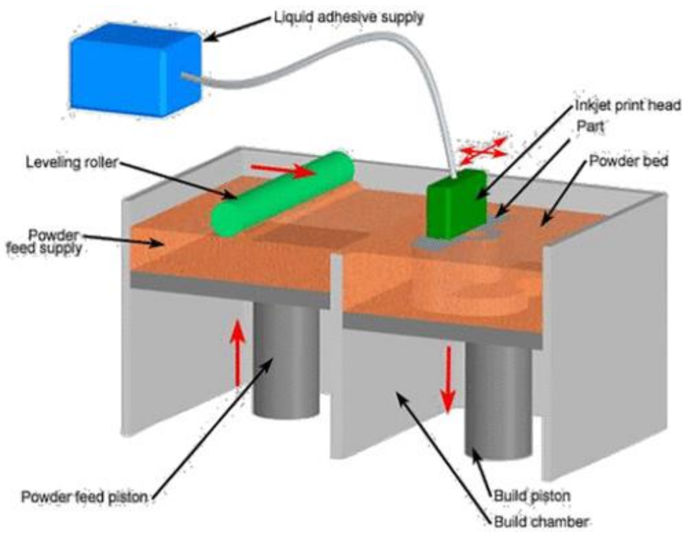

Fig. 11 Schematic of 3DP

EBM: EBM technology is a relatively new AM process with majority of applications in medical and aerospace industries. It was a technology patented by ARCAM for 3DP primarily. The electrons are emitted from a filament, which is heated at above 2500°C. These high-energy electrons are accelerated through the anode. The magnetic field of lenses focuses the beam and electromagnetically scans the layers. The powder particles are fed by gravity from hoppers and are raked into layers across the building table. The entire process is carried out under vacuum, which eliminates impurities and yields high strength.

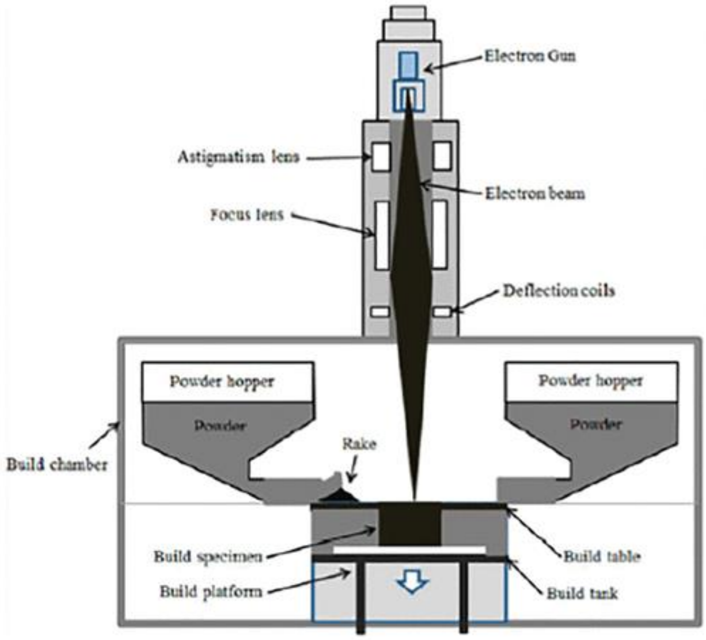

Fig. 12 Schematic diagram of electron beam melting process

SLS: In SLS, the laser beam is used to sinter or melt the spread layer powder particles. The energy beam selectively sinters or melts the powder particles through scanning the layers on the building platform. Once the layer is scanned, the building platform is lowered and the new powder layer is spread on top, and the process is repeated until the part is finished.

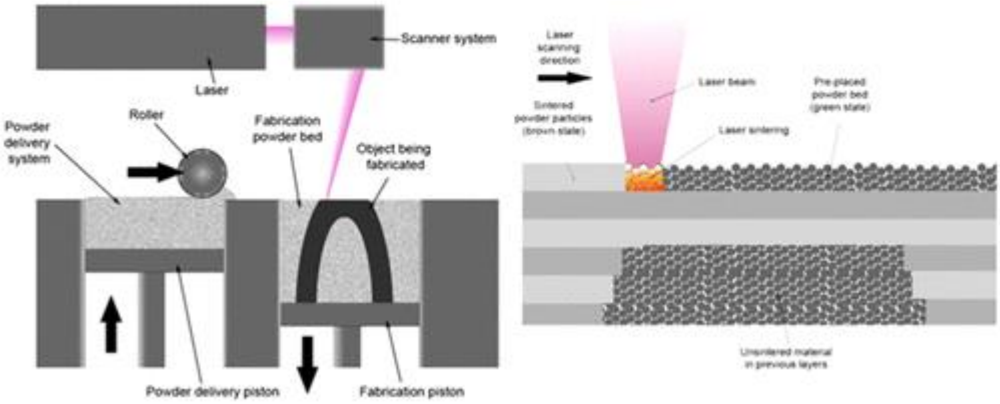

Fig. 13 Selective laser sintering system

SLM: The part is fabricated layer-by-layer through selectively melting the metal powder using a laser in SLM. The mechanical properties of parts manufactured by SLM are nearer to those produced through conventional manufacturing techniques. Indeed, the previous works have asserted that parts with densities up to 99.9% can be produced using SLM. Although this technology possesses a great potential, however, the implementation in industries is limited due to several obstacles. One of the primary hindrances is the presence of high residual stresses and large deformations in the part. The residual stresses significantly contribute to the formation of thermal cracks. Moreover, it is difficult to maintain consistent quality during the build-up process, thus causing varying porosity within the part.

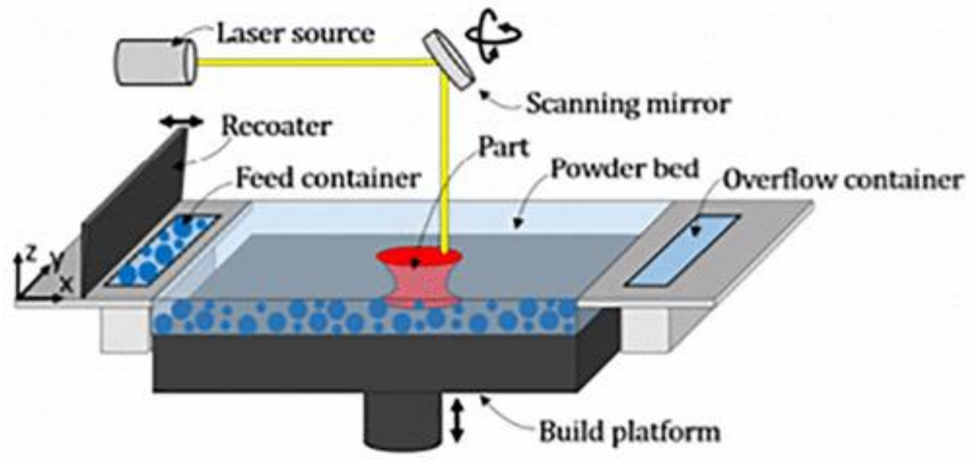

Fig. 14 Schematic overview of an SLM machine setup

LENS: The LENS technique was developed by Sandia National Laboratories and commercialized by Optomec Inc. (Albuquerque, NM, USA) since 1997. It can be identified as laser cladding process, in which a laser is employed as a heating source to melt the powder particles to be cladded onto a substrate. The materials that can be processed by LENS may include steel, aluminum, titanium alloys, nickel-based alloys, and metal matrix composites. The extremely rapid cooling in this process generates a fine-grained microstructure, producing a high tensile strength and high ductility.

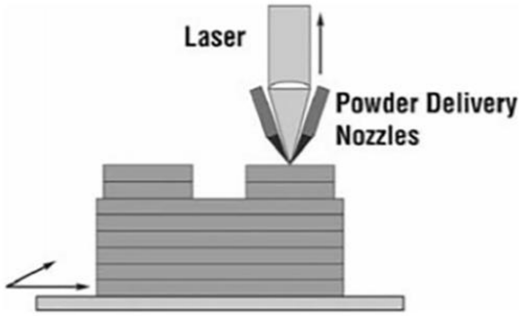

Fig. 15 Laser engineered net shaping principle process scheme

Pro metal: Pro metal can be defined as a 3DP process to build injection tools and dies. It is a powder-based process in which mainly stainless steel is used as the raw material. The printing process occurs when a liquid binder is sprayed on to the steel powder. The powder is located in a powder bed which is controlled with the help of pistons. After fabrication of each layer, the bed lowers down and the feed piston provides the material for the subsequent layers. In case of a mold, no post-processing is needed; however, the building of a functional part requires sintering, infiltration, and finishing processes.

LMD: In this technology, the 3DP head is generally connected to a robotic arm, which comprises nozzles to deposit metal powder on the building platform. The laser beam provides the required energy and melts the powder particles to fabricate the desired geometry.

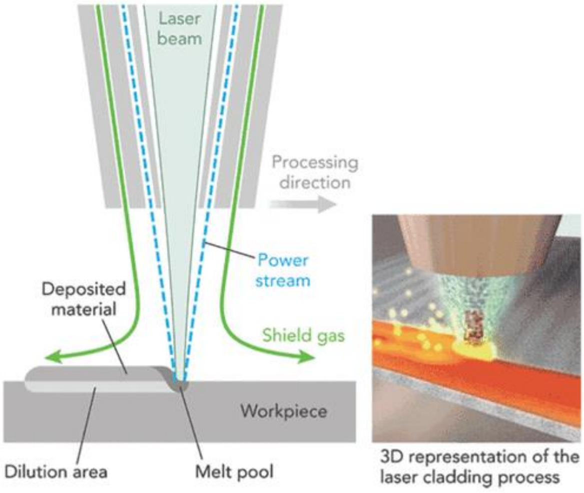

Fig. 16 Laser metal deposition.

It has been observed in the literature that many researchers and academicians have primarily adopted AM classification based on a functional framework. This includes the categories of material, AM technologies, AM material preparation, and layer creation technique, phase changes in AM, patterning energy, phenomena of creating primitive geometry, support mechanisms, and AM applications. The main classifications of AM depend on the material used and the applied technology. The preparation of these materials before actual fabrication varies. The layer creation phenomenon can also vary depending on the technological methods used. After the creation of a layer, the phases can also be classified as full melting, partial melting, or solidification phases. The application of these parts, such as for prototyping or final product, is different, depending on the technology used.

The design tools for AM can be organized in four categories. Three categories, namely, point cloud processing, solid modeling (CAD) systems, and process-oriented design software, allow the modeling, visualization, meshing, and conversion of 3D model into STL files. The STL files have issues associated with handling interior volume to generate internal structures. Therefore, a fourth type of design tool was introduced which was further divided into two sub-categories: topology-optimization-based software and cellular structure design software. There have been several unresolved problems associated with the characterization of part properties (i.e. stiffness) and specification of material distribution.

A four-step procedure that considered the manufacturing capabilities and constraints of AM was developed by Vayre et al. to investigate the design process. The different steps can be identified as design methodology, design analysis, tuning up, and validation of final geometry. For an effective selection of production strategies in AM techniques, Achillas et al. proposed a decision-making framework. This framework integrated a multi-criteria decision aid (MCDA) and data envelopment analysis (DEA) to assist manufacturers in the selection of optimal production techniques among several alternatives.

Because CNC machining possesses several limitations associated with shape complexity, many research activities have concentrated on shape complexity in AM using non-metallic prototypes, rather than functionality. The domain of applications in metallic prototypes has been growing at a rapid rate. A lot of effort has been focused on AM of metallic objects based on functional classification. Figure 17 summarizes some of the current techniques for AM of metallic components based on functionality.

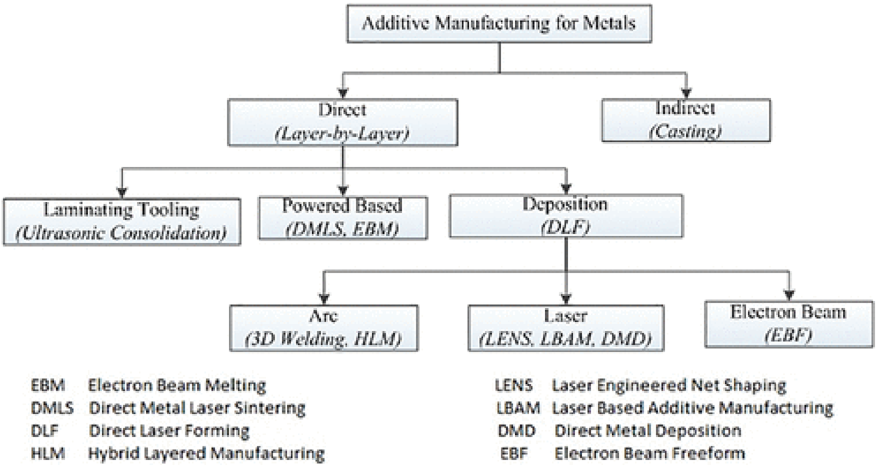

Fig. 17 Prevailing techniques for additive manufacturing of metallic products

1.4 Problems in additive manufacturing: It is observed that none of these technologies are ideal in every dimension. For example, the energy consumption in FDM is low compared to EBM; however, EBM surpasses FDM in terms of high material strength. Certainly, it is not feasible to compare two entirely different AM processes such as EBM and FDM. The objective here is to emphasize the selection of appropriate AM technique depending on the application requirement. For instance, in some manufacturing applications or machines, even parts with low strength are sufficient to achieve desired mechanism. In that case, it is always preferable to employ low-cost FDM part. Similarly, in medical industries, plastic parts (FDM) cannot be used as implants. Therefore, EBM parts, irrespective of their cost or energy consumption, have to utilize. The greatest benefit that can be associated with AM is the ability to manufacture a wide variety of very complex parts. However, the limitations of AM, such as poor accuracy, low surface quality, and low speed, can be overcome when AM is combined with other manufacturing processes such as subtractive manufacturing. This concept led to the development of hybrid manufacturing (HM) processes where different AM methods are combined or subtractive methods are added.

HM processes: HM can be carried out either in parallel or in a serial manner depending on the requirements. These processes can significantly improve tool life, material removal rate, and dimensional and geometric accuracy and reduce production times. The primary objective of hybridization is overcoming the limitations associated with individual processes. For example, in hybrid AM, multiple techniques such as mixing of different materials during deposition and melting of deposit material at various temperature conditions can be used to overcome various limitations. The hybrid processes can be categorized in terms of four hybrid and three sub-hybrid types. HM can be described as an approach that integrates more than one manufacturing operation from different manufacturing technologies. In contrast, sub-hybrid manufacturing is the combination of operations of a single manufacturing technology. The sub-hybrid classification is intended to overcome geometrical issues.

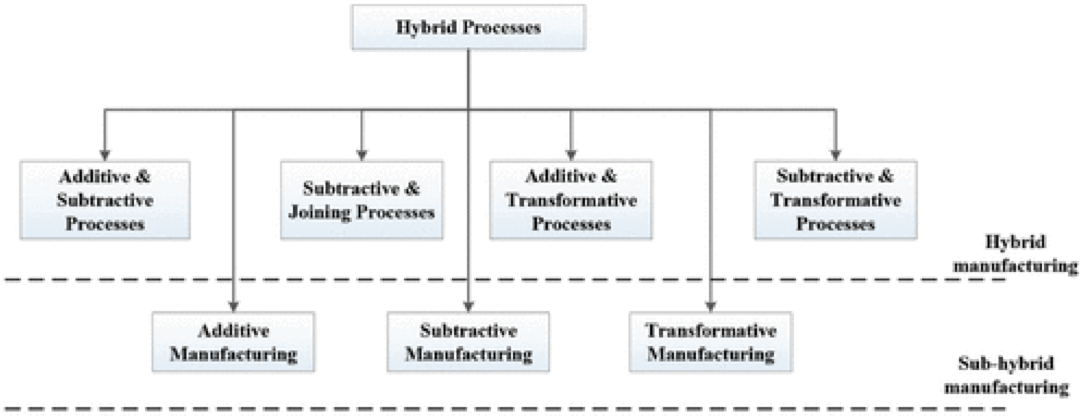

Fig. 18 Categorization of hybrid processes

1.5 AM challenges: Certainly, there are numerous benefits, such as design flexibility, ability to print complex structures, ease of use, and product customization that can be associated with AM. However, AM technology has still not matured enough so that it can be employed in real world applications. There have been drawbacks and challenges that need investigation as well as advanced technological development. The limit on the part size, anisotropic mechanical properties, building of overhang surfaces, high costs, low manufacturing efficiency, poor accuracy, and warping, pillowing, stringing, gaps in the top layers, under-extrusion, layer misalignment, over-extrusion, elephant foot, mass production and limitation in the use materials are the challenges that need further analysis and exploration. Some of the limitations and challenges related to AM are described as follows.

1. Void formation
2. Stair- stepping
3. Anisotropic in mechanical properties and microstructure
4. Small build volume
5. Fabrication of weapons or drugs for crime purposes
6. Compliance with food & drug administration safety standards

1.6 Conclusion: Advancements in manufacturing industry depend on leading edge research associated with manufacturing processes, materials, and product design. As product complexity increases, there is a need for new and innovative manufacturing processes. AM is a recent trend in production processes because of the many benefits it provides as well as the challenges it has to overcome. It has been subjected to intensive investigation and in-depth review by the research community. In this work, an exhaustive review related to AM has been carried out. The most important feature of this work is the identification of the problems associated with different AM methods. Among the primary AM challenges, part size limitation, anisotropic mechanical properties, building of overhang surfaces, high costs, poor accuracy, warping, layer misalignment, mass production, and limitation in the use materials need further research and investigation.

Based on this review, the various aspects of AM technology can be summarized as follows. It can be asserted that the selection of suitable part orientation is crucial in AM. It helps to improve geometrical and dimensional error, reduce build time, and minimize support volume and part production costs. The staircase effect has been identified as the most important factor affecting the part accuracy. Indeed, the staircase effect is directly proportional to the layer thickness. It has also been observed that build time, which possess greater significance in improving productivity, depends on machine speed, part size, layer thickness, and build orientation.

It has been noticed that there is a need for the development of an effective and ubiquitous cost model for the AM. Meanwhile, the costs of AM can be categorized in terms of material, machine, manufacturing, and labour costs. The summation of these costs represents the overall unit cost. It is important to incorporate the following requirements in the new cost model: reused or wasted material, support design and arrangement, build time, maximum possible number of parts that can be produced simultaneously, level of complexity, post-processing time, and quality management.

Lately, the concept of HM has emerged in order to further expand the applications of AM. The limitations of AM, such as poor accuracy, surface quality, and low speed can be overcome when combined with other manufacturing processes such as subtractive manufacturing. HM can significantly improve tool life, speed up material removal rate, enhance dimensional and geometric accuracy, and reduce manufacturing times. The primary objective of hybridization is to overcome the limitations of the individual processes. In fact, the absence of Computer-Aided Process Planning (CAPP) systems restrict proper utilization of additive - subtractive HM in many industrial applications due to the complexity of designing system inputs at the design phase. Therefore, the development of CAPP for additive - subtractive hybrid systems will encourage further implementation and increase the application of AM in the future.

1.7 References

1. Wong, KV, Hernandez, A. A review of additive manufacturing. ISRN Mech Eng 2012; 2012.

2. Petrovic, V, Gonzalez, JVH, Fernando, OJ. Additive layered manufacturing: sectors of industrial application shown through case studies. Int J Prod Res 2011; 49: 1061–1079.
3. Mognol, P, Lepicart, D, Perry, N. Rapid prototyping: energy and environment in the spotlight. Rapid Prototyping J 2006; 12: 26–34.
4. Luo, Y, Ji, Z, Leu, MC. Environmental performance analysis of solid freedom fabrication processes. In: Proceedings of the IEEE international symposium on electronics and the environment, Danvers, MA, 13 May 1999, pp.1–6. New York: IEEE.
5. Telenko, C, Seepersad, C. A comparison of the energy efficiency of selective laser sintering and injection molding of nylon parts. Rapid Prototyping J 2012; 18: 472–481.
6. Sreenivasan, R, Bourell, DL. Sustainability study in selective laser sintering–an energy perspective. In: 20th solid freeform fabrication symposium, Austin, TX, 3–5 August 2009, pp.3–5. Austi, TX: The University of Texas at Austin.
7. Drizo, A. Pegna, J. Environmental impacts of rapid prototyping: an overview of research to date. Rapid Prototyping J 2006; 12: 64–71.
8. US EPA HPV Challenge Program. Test plan for propylene carbonate. United States Environmental Protection Agency, 2006,
9. HK Wentworth PTY Limited. Safety data sheet: polyurethane resin 5617A. WES components, 2003,
10. The Dow Chemical Company. Product safety assessment: tripropylene glycol. The Dow Chemical Company, 2008
11. Edwards Limited. Material safety data sheet: isopropanol anhydrous. Edwards Limited, 2007.