A Review on Applications of Metal Additive Manufacturing

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Abstract- *Additive manufacturing is a layer-based manufacturing method aimed at generating elements immediately from a 3-d model. This paper offers a assessment of key technologies for steel additive manufacturing. It specializes in the effect of essential manner parameters on the microstructure and mechanical residences of the ensuing part. Several substances are taken into consideration inclusive of aerospace alloys consisting of titanium (TiAl6V4 "UNS R56400"), aluminum (AlSi10Mg "UNS A03600"), iron- and nickel- based alloys (stainless-steel 316L "UNS S31603", Inconel 718 "UNS N07718", and Invar 36 FeNi36 "UNS K93600").*

Keywords- Metal additive manufacturing, selective laser melting, additive manufacturing processes, rapid manufacturing, aerospace industry.

I. INTRODUCTION

ASTM International [1] defines Additive Manufacturing (AM) as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". There are various classifications of AM processes within the literature. The classifications include: (i) according to the base material, such as polymers, ceramics, and metals [2]; (ii) indirect and direct processes depending on the bonding method [3]; and (iii) according to the state of the raw material input, such as liquid, molten, powder, and solid layer processes [3-5]. This paper presents an overview of various metal AM processes, benefits, and applications. It also provides a comprehensive review of the influence of AM process parameters on the material properties. The paper highlights the main challenges facing the widespread industrial applications, particularly in the aerospace industry.

Additive Manufacturing Processes

ASTM International [1] categorizes the AM processes into seven main categories, according to the adhesion and bonding method. These categories are: (i) VAT photopolymerization, (ii) material jetting, (iii) material extrusion, (iv) powder bed fusion, (v) binder jetting, (vi) direct energy deposition, and (vii) sheet lamination. VAT polymerization or material jetting could be used in liquid AM processes, while material extrusion could be used in filament processes. Powder AM processes could use powder fusion, binder jetting, or direct energy deposition for binding the powder particles. Fig. 1 classifies the bonding techniques according to the state of the raw material "feedstock". AM is a relatively new manufacturing technique, having only been developed in 1986 by Charles W. Hull [6]. Since then various processes have been introduced. Fig. 2 shows a classification of various AM processes according to the state of the raw material. In this section, these AM processes are explained.

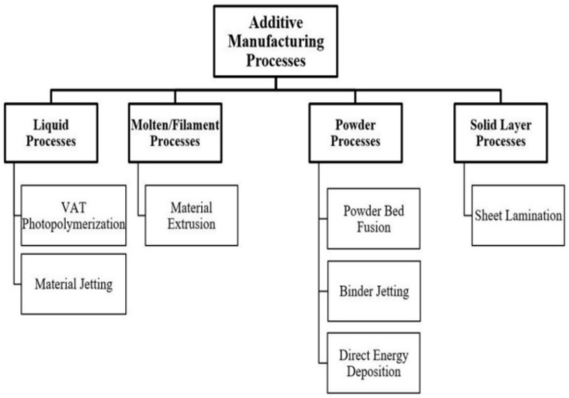

Fig. 1: Adhesion and bonding methods in additive manufacturing [1].

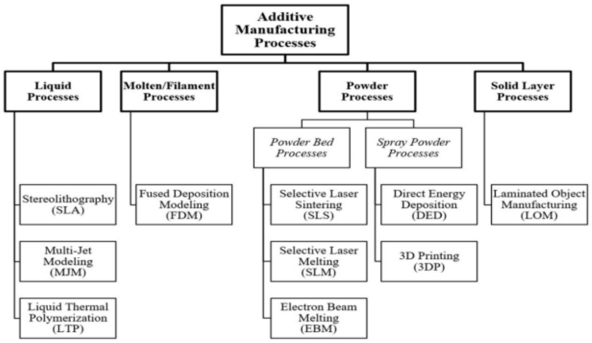

Fig. 2: Various additive manufacturing processes.

1.1 Liquid Processes Stereolithography.

Stereolithography (SLA) is an AM technology which converts liquid photosensitive resin into a solid state by selectively exposing a resin vat to ultraviolet (UV) light. Layers are made one by one as the building platform lowers after each layer is fully completed. The layers are exposed to the UV light for a specified time to fully adhere to each other. This process was the first AM process to be commercialized [7, 8]. A recent innovation in SLA has been developed by Carbon 3D and provides for continuous curing from a liquid pool and achieves 100x the printing rate of other processes [9]. Not only can SLA fabricate polymeric parts, but it also can conceive ceramic objects with suspensions of ceramic particles in a photo-curable monomer vat [7, 8].

Multi-Jet Modeling.

This process uses multiple nozzle jets to dispense a UV curable polymer or wax on demand. As soon as the printed polymer comes out of the head, the UV lamp flashes to cure it, much like SLA. Multi-Jet Modeling (MJM) prints parts on a moving platform that lowers once each layer is cured in order to continue the process. This is a cost-effective technique that can build objects in a short amount of time. MJM is safe and quiet enough to be used for printing polymeric parts in an office environment. This method has some issues when it comes to the printed parts' quality; the partstrength is relatively poor and the bottom surface is often pitted [10].

Liquid Thermal Polymerization.

Liquid Thermal Polymerization (LTP) is a two-jets system that forms thermo-set layers by feeding liquids to the individual jetting heads that then deposit small droplets on a platform. The jetted material solidifies as it cools. Different materials can be used by each jet to produce multi-material parts or parts with wax support material. After each layer is printed, a milling head removes excess material to assure uniformity. A vacuum then collects the eliminated particles. After printing, the wax support material can be removed by melting or dissolving. The range of material for this process is very limited [2, 11].

1.2. Molten Filament Processes - Fused Deposition Modeling.

Fused Deposition Modeling (FDM) is an AM process in which two separate nozzles, one for model material and another for support material, are used to build a 3D model designed using a CAD tool. In a typical FDM system, the build material is melted and deposited from the build nozzle to create the part layer-by-layer as shown in Fig. 3a. The support material is added to each layer to support the built layer, but it needs to be removed at the end of the building process. One of the limitations in the FDM process is the dimensional inaccuracies and poor surface finish of the fabricated parts. Predicting the dimensional accuracy as a function of process parameters is a heavily researched area within the FDM research field [12-15]. In addition, mechanical and thermal properties are big challenges not only in the FDM process, but in most AM metal processes. For this reason, many researchers focus on studying the mechanical and thermal properties of AM metal parts [16-20].

1.3. Powder Bed Processes - Selective Laser Sintering.

Selective Laser Sintering (SLS) is an AM process where layer by layer, fine powder is spread and sintered to build a part. The powder is distributed and spread evenly with a coater arm to create a level, uniform surface that completely covers the build area, as shown in Fig. 3b. A focused laser beam is then precisely directed at the powder layer and scans over the cross-section of the part. The build platform is lowered and the process is repeated until all layers have been printed [21, 22]. The basic binding mechanisms of the powders can be split into four categories: solid state sintering, chemically induced binding, liquid phase sintering, and partial melting. Solid state sintering occurs at a temperature between the melting point and half the melting point of the preheated powder [23-28]. Chemically-induced binding uses no binder elements, whereas the metal atoms bind with oxygen to create a binding material that fuses the powder. Liquid phase sintering, or partial melting in the last case, combines a structural un-melted material with a melted material as a binder, in some cases, both are often an equivalent material [23-26]. SLS can process a large range of materials and so can extend its field of applications to many other areas.

Selective Laser Melting.

Full melting of powders strives to produce fully dense objects with mechanical properties comparable to bulk materials. The development of the Selective Laser Melting (SLM) process mirrors the method of SLS thereupon goal in mind. All metals may be candidates but some act differently when processed. Such differences include reactions to laser absorption, different surface tensions, and different viscosities. These complications limit the range of available SLM metals [23]. SLM powders can be broken down into two categories: single material powders or alloyed powders. Single material powders contains strictly one sort of metal, like pure titanium. In this case, tests show an almost 100% part density, however high thermal stresses can cause cracks [29]. Alloyed powders consist of alloyed materials such as Ti-6Al-4V and steel powders. The mechanical properties of these materials are comparable to bulk material apart from ductility, which is significantly reduced [30]. A big benefit of SLM is the ability to process non-ferrous metals such as titanium, aluminum and copper. As the process uses higher energy, problems arise with instabilities in the melt pool along with part shrinkage [31].

Electron Beam Melting. Electron Beam Melting (EBM) is typically similar to SLM except that an electron gun is used for melting preheated powder instead of using a laser source for melting a powder, which makes the EBM more powerful because its build rate is faster than SLM [32, 33]. Powder bed processes are commonly used for metallic applications, especially for complex designs.

EBM is currently the preferred process for fabricating metals, but it is limited by the electrical conductivity of the material and the need to conduct the process in a vacuum. Because of these issues, however SLM is considered more versatile [34]

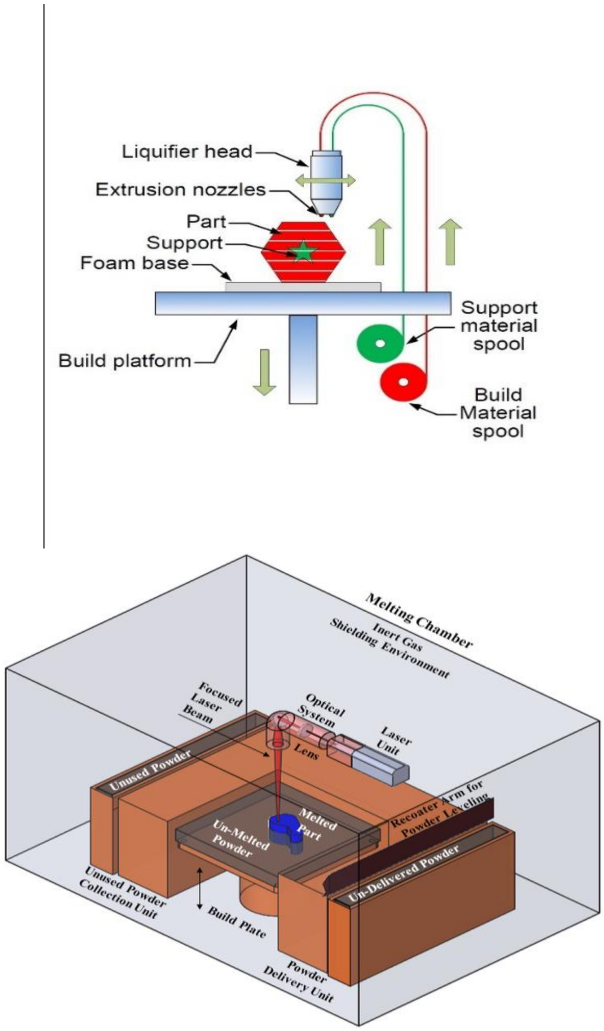

Fig. 3: (a) Fused deposition modeling [14, 15], and (b) selective laser sintering [21, 22] processes

1.4. Spray Powder Processes - Direct Energy Deposition.

Direct Energy Deposition (DED) is an AM process that uses two different techniques; 3D Cladding and 3D Welding. In 3D Cladding, a metal powder is fed through a nozzle and then melted using a laser or plasma beam forming a layer as shown in Fig. 4 [35]. The laser-based method is mentioned as Laser Metal Deposition (LMD) [31], Laser Engineered Net Shaping (LENS) [36], and Laser Consolidation (LC) [37]. LMD or LC occurs through the process of a nozzle feeding metal powder that is subsequently laser melted onto the substrate layer. It is a versatile process that has the unique ability to repair metal parts which are difficult to be repaired by other conventional methods. This process can coat, build, and rebuild very complex components from laser-consolidated materials, such as nickel-based superalloys, cobalt alloys, titanium alloys, and steels [36, 37]. The plasma-based method, which is named Plasma Deposition Manufacturing (PDM), starts by supplying a continuous powder feed to a plasma-melted zone in an inert gas environment composed of argon, helium or nitrogen, to help reduce oxidation. Since no commercially supplied gas can be 100% free of oxygen, some oxidized particles can still form when the powder is melted and solidified as the plasma beam scans across the deposited layer. PDM is a technique for 3D part creation, suitable for low production metals [38]. 3D Welding, commonly known as Shaped Metal Deposition (SMD) [39], is a wire-based process in which a wire of small diameter is fed and melted, binding to the previous layers through welding. SMD is particularly noteworthy because it can use a wider range of metals than laser deposition or electron beam welding. Also, since the surface area of a wire is less than a powder there is less opportunity for oxidized particles to form. Although it is promising in terms of producing parts with good ultimate tensile strength, there are several difficulties reported in the literature including mostly related to weld pool control and its impact on dimensional and geometrical accuracies [40, 41]. This process also boasts very dense and large parts with mechanical properties that are competitive with cast material.

Inkjet 3D Printing.

Inkjet 3D Printing (3DP) is mainly divided into two different processes; binder jetting 3DP and material jetting 3DP. In the binder jetting 3DP, a binder liquid is selectively sprayed and printed onto a powder bed using an inkjet head in order to bind the powder particles layer by layer. Post processing is required to obtain sufficient mechanical strength in the fabricated parts. On the opposite hand, typical material jetting 3DP uses droplets of the building material in a liquid state to build the required model layer by layer through the inkjet head. These jetted droplets are then cured by passing a UV light through each layer [42-44]. The selection of the binding material is the most challenging aspect of 3DP because the binder has a significant effect on the mechanical strength and properties of the fabricated part. The 3DP process is widely used in biomedical applications including clinical studies, surgical trainers, custom reconstructive and orthopedic implants, tissue engineering, and dental repairs because of its ability to fabricate custom bio compatible devices [43]. Another challenge in 3DP processes is surface finish. For this reason, improving the surface finish through either smart powder distribution or using small particle sizes is one among the most research issues for this process [44, 45].

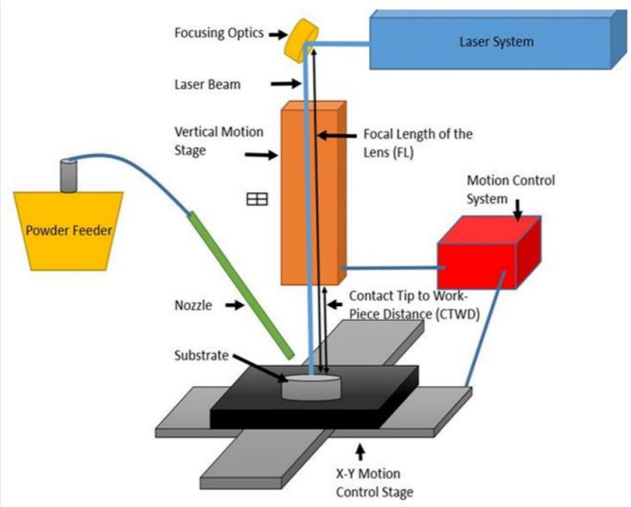

Fig. 4: Laser cladding process [35].

1.5. Solid Layer Processes - Laminated Object Manufacturing.

Laminated Object Manufacturing (LOM) is a solid state AM process invented by Helisys Inc. in 1991 [46]. The LOM system consists of a laser system to cut the part layers into the desired shape and a bonding tool to fuse and laminate the solid layers of the building material using heat and pressure [47]. LOM is considered a high speed process as it is five to ten times faster than other AM processes, but it has many challenges with realizing geometric accuracy, surface finish and desired material properties [48].

II. APPLICATIONS OF METAL ADDITIVE MANUFACTURING

Aerospace Industry. An important requirement for the aerospace industry is to consistently produce light complex geometries with good mechanical properties in small quantities. These reasons make AM a really efficient manufacturing method for aerospace applications. The most common AM processes utilized in the aerospace industry are FDM [49], DED [50], SLM [51], and EBM [52]. These techniques are used to fabricate low-volume complex aerospace parts, aircraft wings, and replacement parts in the aerospace industry along with fabricating specialized parts, lightweight structures, parts with minimal waste, on-demand parts, and replacement parts to support long term space exploration [53]. Advanced materials such as aluminum alloys, titanium alloys, nickel super-alloys, and special steels have been manufactured in the aerospace industry using AM technologies [3]. AM technologies open the door for developing new materials and designs in the aerospace industry. The main challenges reported in the literature include mechanical anisotropy, microstructural inhomogeneity, residual stresses, dimensional accuracy, and surface finish [54-60].

Automotive Industry. Metal AM has significant implications on part design as well as supply chains and inventory systems, which is particularly relevant for the automotive industry. An important feature of using metal AM processes in the automotive sector is fabricating complex lightweight structures. The weight of the automotive parts can be reduced significantly by leveraging the ability of AM processes to produce parts with complex geometries while maintaining relative strengths. samples of automotive parts produced by AM include structural composite components, engine valves, and turbocharger turbines. A significant advantage is in-house and on demand production, which reduces inventory needs, shipping costs, and material procurement costs [63]. Notwithstanding the capabilities of the AM processes in the automotive industry, the parts produced should comply with the standards to perform a certain level of performance. The main challenges in the AM of automotive components are: (i) the thermal stresses induced in the AM parts which affect the repeatability and performance of these parts, (ii) the surface finish and dimensional accuracies, and (iii) the size of the parts produced [42, 56] in addition to this, processing speed is critical due to typical production volumes.

Tooling Industry. For the tooling industry, AM can offer time saving through the reduction of the fabrication steps and cost reduction through the elimination of material loss associated with traditional subtractive manufacturing. In addition, the AM technology offers the ability to produce customized molds with optimized cooling channels which can impart unique properties to parts and reduce production cycle time. AM molds made with integrated conformal cooling also prolong their service life as it provides the designer with the ability to reduce the thermal stress loading that the die experiences. The mechanical behavior of the tools fabricated by AM affects the performance and service life of these tools. In general, performance tests are highly recommended for the tools fabricated by AM to fully assess their cost and performance benefit for an application.

Healthcare Industry. The use of metal AM processes in the healthcare industry is briefly reviewed. In the dental industry, AM processes are used for creating precise dental crowns, bridges, and implants. The capability of the SLM process to manufacture custom, complex, accurate, and fully dense objects makes it suitable for dental applications. The process of creating crowns and bridges consists of scanning the dental impression of the patient's teeth, digital modeling of the part, and then SLM production. This process provides a competitive market for AM of dental implants that rivals traditional casting and milling production methods. Additionally, a similar process is used for the manufacturing of personalized prosthesis and supports for artificial teeth made of titanium or cobalt-chromium [60]. Moreover, metal AM processes are used in the medical sector due to its ability to quickly produce highly custom components. The technology is very useful for fabricating custom-made medical implants as well as surgical tools and fixtures for use in operation rooms. There is no doubt that fabricating custom implants is more accurate than the previous traditional methods [60]. the most advantage of AM within the medical industry is its capability to supply very complex components with low production cost as well as customized components [60].

Nanomanufacturing. Recently, AM technologies have been integrated with nanotechnology to fabricate parts from new nanocomposites. The main benefit of using nanomaterials in AM processes is enhancing the material properties of the fabricated parts. Parts with better optical, thermal, electrochemical, and mechanical properties have been obtained. Over the past few decades, a wide variety of nanomaterials were used in AM processes, including carbon nanotubes, nanowires, metal nanoparticles, nano-graphene, and quantum dots [60]. Nanoscale AM plays a vital role in producing metal parts with nanopores, thus eliminating or minimizing the formation of pores and voids.

III. INFLUENCE OF PROCESS PARAMETERS

From the above survey of AM processes, FDM, DED, SLM, and EBM are the most commonly used processes for metal fabrication. In this section, the influence of process parameters on the microstructure and mechanical properties of selected aerospace materials are reviewed.

Titanium Alloys. Many researches are focusing on studying the characteristics of titanium TiAl6V4 (UNS R56400) produced by different AM processes to meet aerospace standards. A study showed that the mechanical and fatigue behaviors of the SLM TiAl6V4 parts are significantly affected by the internal voids as well as the residual stresses in the parts produced. The tensile strength and fatigue strength are strongly affected by the pores size, however the crack growth is influenced by the residual stresses [60]. Another study demonstrated that the microstructure of the SLM TiAl6V4 components also alters the mechanical properties of those parts [60]. The SLM process parameters such as scanning parameters, scanning strategies, and laser melting parameters exhibited a robust influence on the surface quality, voids characteristics, microstructure, and mechanical properties of TiAl6V4 parts. Moreover, few studies were performed to find the optimum SLM process parameters for fabricating TiAl6V4 parts suitable for the aerospace industry Similar studies performed using other AM processes such as DED [40,] and EBM achieved similar results. In EBM production of TiAl6V4, a function is developed to control the beam speed and energy during the fabrication process in order to enhance the thermal properties of the parts produced.

Aluminum Alloys. Although AM has gained considerable popularity in aerospace and automotive applications, it still faces many challenges with processing aluminum alloys [60]. Many investigations were performed to find the process parameters required to produce high dense aluminum AlSi10Mg (UNS A03600) parts by SLM [60]. Few studies focused on investigating the quality of the aluminum parts produced by AM processes. These studies showed that the microstructure of the SLM AlSi10Mg and AlSi12 parts has a significant effect on the mechanical properties such as fatigue behavior, strength, elongation, etc. Moreover, the microstructure of these parts is influenced by the imperfections formed during the process and the post-processing procedures. The AlSi10Mg still manifests fatigue strength lower than that of a corresponding wrought material. Internal voids and/or large internal precipitated particles serve as fatigue crack initiation sites. However, this material also does show a very fine microstructure and anisotropic mechanical properties along the building direction.

Iron- and Nickel- Based Alloys. Stainless steel 316L (UNS S31603) is the most used material in powder-based AM processes. Starting from the raw material, the powder grain size affects the density and consequently the mechanical properties of the produced parts. In SLM of stainless steel 316L, some studies showed that time distance, exposure time, scan speed, layer thickness, and building direction have a strong influence on the quality of the parts produced. These parameters should be controlled during the fabrication process in order to get reasonable surface finish and mechanical properties [22, 60]. AM technology opens the door for fabricating special alloys such as nickel-based alloys. Some studies showed that AM produced Inconel 718 (UNS N07718) parts contained small cracks that may affect mechanical properties in all directions especially in the building direction. These cracks can be attributed to the phase transition and the formation of columnar dendrites during the melting process. On the other hand, few studies illustrated the selection of the process parameters for fabricating dense parts from Invar.

IV. CONCLUSIONS

This paper aimed to review various additive manufacturing processes and their applications. The above survey showed that additive parts differ from wrought parts in that they can have many defects including, but not limited to, voids, lack of adhesion between subsequent printed layers, and substandard mechanical/fatigue properties. Developments in metal additive manufacturing offer significant possibilities for the creation of new types of products. Research and development priorities have been discussed in the literature. A summary of the main research issues includes:

1. Studying the influence of process parameters on surface features, mechanical properties, and material characteristics of the parts by modeling studies and/or experimental work.
2. Developing new materials supported the capabilities of the additive processes.
3. Establishing rules and protocols to style for additive manufacturing.
4. Creating a real-time process control for the additive manufacturing systems.
5. Exploring the hybrid manufacturing and multi-materials additive manufacturing
6. Improving the productivity of the additive manufacturing systems

Newly emerging metal additive manufacturing processes have many limitations and challenges compared to extensively studied subtractive manufacturing processes. Process repeatability, complex thermal stresses, and material microstructural implications of the process are the largest challenges to industrial applications of additive manufacturing, especially in the aerospace industry. These factors affect the density of additive parts and consequently all the mechanical properties and material characteristics. There are currently two options to overcome these challenges. The first, and most common solution is to refine the quality of the additive parts through carefully controlled post processing techniques. The second, and less established solution is to optimize and control the process parameters to produce high quality parts.

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