

Review of Additive Manufacturing Technology: Fundamentals and Processing Techniques

*¹Misbahu Abdullahi Hayatu, ¹Aishat Ometere Salawu and ²Kamilu Adeyemi Bello

¹Department of Metallurgical Engineering Technology, Kaduna Polytechnic, Kaduna, Nigeria.

²Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, Nigeria.

*Corresponding authors' email: mabdullahi8003@gmail.com

ABSTRACT

Consequence to the challenges of conventional materials processing and manufacturing technologies, scientists and engineers are everyday searching for new technologies to improve or replace the existing ones. Additive manufacturing is one of the promising technologies that show the potential in replacing conventional manufacturing processes. This study reviewed the fundamentals and processing techniques of various additive manufacturing technologies such as, directed energy deposition, powder bed fusion, material jetting, etc. Basic working principles, sources of energy, raw and forms of materials as well as process parameters of the various additive manufacturing processes were studied. Recent original works were studied and relevant findings were expatiated. Energy ranges of the various additive manufacturing processes were studied. It is understood from the findings that despite numerous benefits of additive manufacturing various defects still pose processing problems, and therefore mitigation measures such as optimization and use of hybrid sensor defects detection were highlighted for future trend of research. It is further concluded that the integration of artificial intelligence with additive manufacturing is paramount for overall enhancing the performance of additive manufacturing for wider applications in industry 4.0 and 5.0.

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INTRODUCTION

Additive manufacturing (AM) technology is widely drawing attention and substituting conventional manufacturing (CM) technology in the arena of materials processing and manufacturing engineering (Mohayla et al., 2020). This is consequence of the tremendous economic and technical advantages of AM processes (AMPs) over CM processes (CMPs). According to Oskar (2022) and, Balbaa & Elbestawi (2022), complex parts are better produced by AMPs. Ability to produce light weight and customized products, improved functionality and simplified production route are amongst the excelling attributes of AMPs (Baumers, 2012; Samoilenko, 2022).

Unlike CMPs which involve series of production steps to accomplish 3D components or structural parts; AMPs are capable of manufacturing 3D components from a single step operation (Ramachandiran, 2023; Baumers, 2012). In sand casting process for example, a popular CM process, various steps such as pattern making, moulding, melting, pouring and fettling are carried-out on work piece to make castings; metal castings must be further subjected to post removal of feed head and filling system; multiple subtractions of material from work piece leading to too much materials waste in subtractive machining; poor interface quality in dissimilar materials welding. All these contribute to overall costs, time-consuming, high-energy consumption, logistics, poor surface finish and require lots of tooling and consumables (Hasanov et al., 2022; Adoyi et al., 2026).

Quite number of research findings established that parts manufactured by AMPs offer better properties compared to those made by CMPs. Sinha et al. (2021) reported an aeroturbine blade manufactured by AMPs to be better than that produced by CMPs. Oskar (2021) concluded that the fatigue properties of 316l stainless steel printed by wire and arc additive manufacturing (WAAM), a popular AM process, are

better compared to those of cast and rolled samples.

In the ISO/ASTM 52900 standard, AM is defined as "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". AMPs operate on the principle of layer-by-layer adding of materials to build an ear-net-shape 3D object (Sun et al., 2022; Oskar, 2022; Wiikinkoski, 2022). Heating and/or bonding mechanisms are employed in AMPs to fuse materials together layer-by-layer to the desired geometry. Heat source could be laser beam, electron beam or arc energy. Raw materials for printing are any engineering materials in the form of liquid, powder, wire or filaments (Navarro et al., 2022; Hasanavo et al., 2022). There are different types of AMPs and each process has its peculiar working principle, source of energy and state of raw material.

Both AMPs and CMPs largely depend on the physical, chemical and mechanical properties of engineering materials. Metals/alloys, ceramics, polymers and composites are the key engineering materials used as raw materials in AMPs. Size and geometry of the intending 3D components and materials properties such as, melting point, density, thermal conductivity, etc. play significant role in selecting appropriate AM process. The properties of the final product are functions of the applied AM process and process parameters (Sun et al., 2021).

Miller et al. (2026) reviewed defect detection in AM by artificial intelligence (AI) and concluded that AI-driven skills increase defects identification in AMPs. Crapnell et al. (2026) reviewed material extrusion AM but limited his work on fused filament fabrication. Liu et al. (2026) studied the review of powder based AM with limited information on basic working principle of the process. Albahadli et al (2025) investigated previous works on AM of steel without details

on sheet lamination AM.

This paper aims to describe the various AMPs including processes not previously extensively reviewed, process parameters, quantitative range of each process, and current case studies with the sole aim of enriching the understanding of AM technology as a guide for future track of research.

Fundamental Principle of Additive Manufacturing Processes

Direct manufacturing of three-dimensional objects from computer aided design (CAD) data is the fundamental and universal principle of AMPs (Navarro et.al, 2022). Layer-by-layer heating and bonding are the two basic mechanisms of repeatedly adding materials to obtain a complete 3D objects. All AMPs operate on these basic principles with differences in the energy and form of materials (liquid, wire, powder, sheet or filament) to be used in printing the 3D

objects, which dictates the type of process to employ; and these lead to different types of AMPs. For instance, in powder bed fusion (PBF), metal powder is selectively melted locally layer-by layer via a movable laser beam solidifying a cross section of the component. This single operation is repeatedly carried-out until the complete 3D object is built. However, in direct energy deposition (DED), metal wire or powder is melted by means of an energy source such as arc welding which is applied locally, in layers, to quickly produce a new near-net-shape metal parts (Oskar, 2022).

In every scenario, AMPs operate on the principle of producing a 3D component by repeatedly single operation contrary to CMPs where in all cases work piece must be subjected to different multiple operations. Figure 1 displays level of steps in AMPs and CMPs.

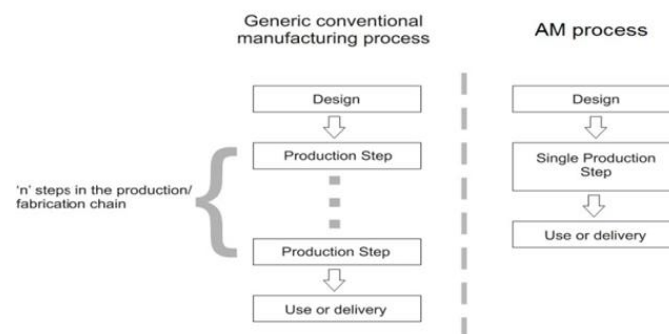


Figure 1: Production Step Sin AM and CM Processes (Baumers,2012)

MATERIALS AND METHODS

Classification of AMPs

The ISO/ASTM 52900 standard categorized AMPs into seven (7) major groups as: powder bed fusion (PBF), material jetting (MJ) binder jetting (BJ), material extrusion (ME) directed energy deposition (DED), sheet lamination (SHL) and vat photopolymerisation (VP) techniques. Each group operates under distinct working principle. This classification is based on the type of applied and source of energy, the nature and

form of materials to utilize in the printing and size of the designed objects. For example, a particular AM process may be suitable for polymeric materials but not suitable for metallic materials and vice-versa. In another angle, one process can print larger objects where others cannot. Hybrid additive manufacturing (HAM) involves the combination of two or more AMPs in printing 3D model parts. Figure 2. illustrates the several AMPs and details of each process will be discussed in subsequent section.

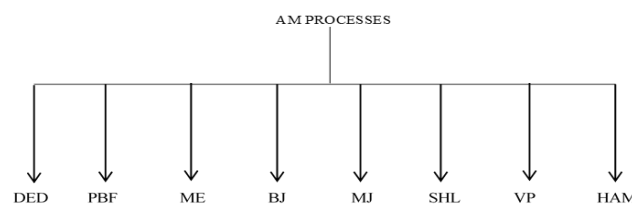


Figure 2: Classification of AM Processes

Raw Materials, Energy Sources and Variable Parameters for AMPs

Raw materials or feedstock for AMPs include metals, polymers, ceramics, hydrogels, biomaterials, elastomers, hybrids, functionally graded materials and composites in the form of liquid, wire, granules, resin, filament, sheet and powder (Savchenko et al., 2022; Hasanov et al., 2022; Sun et al., 2021; Oskar, 2022; Baumers, 2012). Binders are added in some processes to facilitate fusion and layer-by-layer addition of materials. Some processes utilize two or more different materials when producing multi material components, while others can adopt two or more forms of materials.

Arc energy, laser beam, electron beam, kinetic hypersonic speed energy (Oskar, 2022), and plasma are the

key sources of energy in AMPs (Navarro et al.,2022). The energies are derived from other processes such as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), plasma arc welding (PAW), electron and laser beam welding processes. These sources of energy provide the required heat enough to melt/fuse the raw materials in the respective processes that utilize heating for melting. Other AMPs that do not need heat use bonding mechanism in adding materials.

Parameters may be machine-based or material based. Machine based parameters are functions of AM machine while material-based parameters are dependent on the attributes of feedstock. In laser-based processes, laser power, hatch distance, laser scanning speed, layer thickness, scanning strategy, etc. are amongst the critical parameters. Powder size or particle size, morphology and density are

important variables in powder- based processes. In arc- based processes, such as WAAM, wire diameter, wire feed speed (WFS), arc current and voltage, shielding gas, gas flow rate, arc energy, travel speed, etc. are common parameters (Sales

et al., 2022). Table 1. Presents AM raw materials, energy sources and parameters with the irrespective applicable processes.

Table 1: Comparison of AM Processes

AM Variables	DED	PBF	ME	MJ	BJ	SHL	VP
Raw / Form of Materials	Metal powder / wire	Metal powder	Polymeric / metallic filaments	Wax, thermoplastic, thermosetting, elastomeric materials	Powder of metal, ceramic	Metal / polymer sheets / foil	Photo-curable resin polymer
Energy Source	GMAW, GTAW, PAW, laser, electron energy	Laser and electron beam	Hot nozzle	Ultraviolet energy	—	Laser, electrical, chemical adhesive and ultrasonic energy	Visible, ultraviolet light, laser
Parameters	Arc current/voltage, arc energy, etc.	Particle size, laser power, etc.	Extrusion temperature, feed rate, etc.	Build orientation, tray location, layer thickness, etc.	Amount of binder liquid, particle size, layer thickness, etc.	Roller temperature, roller speed, layer thickness, etc.	—

Categories of AMPs

As disclosed earlier, ISO/ASTM52900 standard classified AMPs into seven (7) categories. In this section, each class will be discussed with emphasis on fundamental working principle, materials, energy and parameters.

Powder Bed Fusion

In this process, laser or electron beam thermal energy selectively fuses regions of a powder gradually, layer-by-layer in a build chamber repeatedly until the 3D object is obtained (Wiikinkoski, 2022). This process uses either laser beam or electron beam as sources of energy. Laser power could be low such as carbon dioxide laser or high laser power. The low laser power is used for non-metal based PBF process such as selective laser sintering (SLS), while the high power laser is used for metal-based PBF process such as selective laser melting (PBF-LB/M). In SLS, cross sectional layer of polymer or nylons powders, are scanned and heated below melting by low laser power; thereby sintering the powdered materials layer-by-layer repeatedly until a near-net 3D object is obtained (Sinha et al., 2022).

In PBF-LB/M process, spreaded metallic powders in a build chamber are heated and melted by high power laser on the substrate layer-by-layer repeatedly until the three dimensional parts are produced (Navarro, 2022; Sinha et al., 2022). Low laser energy due to low laser power, large layer thickness, high scan speed and high hatch distance cause defects such as

porosity in the final object. SLM manufacturing of turbine blade showed remarkable low fabrication time contrary to casting (Sinha et al., 2022).PBF-LB/M process is capable of repairing faulty parts such as worn-out portion of jet engine combustion chamber. A PBF-LB/M repairing machine capable of reducing the repairing time by 90% was developed by siemen (Sinha et al., 2022).

Electron beam melting (PBF-EB/M) has similar working principle as PBF-LB/M process with the main difference in the source of energy. Here, energy for melting the metallic powder is generated from electron beam emitted by a heated filament. The energy density of electron beam is capable of melting any known metal (Parmar, 2010)-which is one of the merit of PBF-EB/M over SLM process. The EBM process therefore has higher productivity, less impurity absorption, minimal residual stress, greater layer thickness compared to PBF-LB/M process. An PBF-EB/M made TiAl turbine blade presented 50% and 10% weight reduction and fuel consumption respectively (Sinha et al., 2022) – a quality better than that of SLM-printed Ni-based-super-alloy turbine blade. Quasi- shaped components are possible by PBF-EB/M process. In general, accurate surface finish, high complex and customized metal and ceramic parts geometries are amongst the unique credits of PBF process over all other metal based AM processes (Balbaa & Elbestawi, 2022). Figure 3 illustrates PBF process.

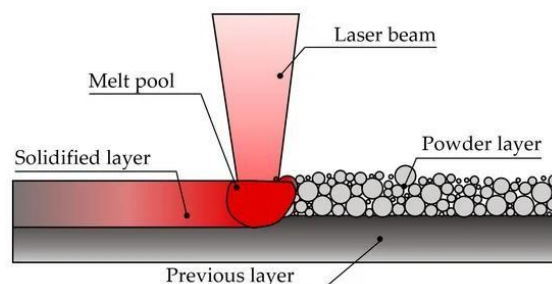


Figure 3: Basic Working Principle of PBF (Ostolazaet al., 2023)

Megahed et al. (2022) studied the potential of printing and repair of 1.2343/H11 tool (a crack sensitive) steel by PBF process. Gas atomised powder of 1.2343/H11 tool steel of size 15-45 μm was used to produce samples of the steels. Laser power, hatch distance and laser scanning speed is varied. According to the result of the work, energy density of 69.93J/mm³ presented highest relative density and lowest crack density for the unpreheated samples. High laser power, fast scan speed and small hatch distance favour better surface roughness. The additive repaired parts presented finer grains and better tensile and hardness properties than the CM made parts. Hadi & Taha (2022) produced 316L/SiC composite samples by PBF-LB/M process using gas atomised powder of 316L and SiC of size <65 μm and < 40 μm respectively. They concluded that; scanning speed, volumetric energy density, laser power, hatching distance and layer thickness of 700mm/s, 136J/mm³, 200W, 70 μm and 30 μm respectively offered best relative density, micro hardness and porosity amongst the varied data. Lower scanning speed and higher volumetric energy give lower micro hardness. The tensile and compressive properties of the AMd composite (1% SiC) are slightly higher than that of the unreinforced 316l stainless steel. Mohayla et al. (2022) additively manufactured AISI 316l by PBF-LB/M technique using gas atomized powder of mean size of 26.33 μm . Laser power, laser scanning speed and layer thickness of 200W, 650mm/s and 50 μm respectively were used for the printing. The relative density and porosity of the produced samples were calculated to be 98.12 and 1.14% respectively.

Directed Energy Deposition

This process is defined by ISO/ASTM 52900 standard as "AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited ".The

focusing energy is provided mostly by arc-welding based processes such as, GMAW, PAW, GTAW, cold transfer welding (CTW).Laser and electron beam energies are also used in this process (Sun et al., 2022; Hasanavo et al., 2022). Metal powders or wire being supplied automatically are the main feed stocks in this process; the feeds are melted and deposited layer-by-layer on the substrate repeatedly until the final 3D object is obtained. There are different types of DED processes such as, WAAM, laser engineering net shape (LENS), laser metal deposition (LMD), direct metal deposition (DMD). DED processes have the outstanding property of manufacturing large components/structural parts not possible by any other AM processes (Rodrigues et al., 2022). This process facilitates repairs and maintenance of failed parts; feed stocks are cheaper compared to those of PBF processes-an advantage that qualifies DED processes to be overall cost effective than PBF processes. The benefits of changing feed stocks at any time during the printing process and the printing of functionally graded materials (FGMs) are unique to DED processes (Hasanov et al., 2022). GMAW process is the most effective and efficient of all other arc-based DED processes due to multiple attributes such as: simplicity of operation, automatic feed supply and high deposition rate among others (Penot et al., 2021; Singh et al., 2022).

Moreover, WAAM is the most popular of all DED processes. Parameters of this process are similar to those of GMAW process with the exception of powders. Arc current and voltage significantly influence wire feed speed in arc-based DED process (e.g. WAAM). Materials and coatings for nuclear applications have been reportedly fabricated by DED techniques (Sun et al., 2022).Figure 4 illustrates DED process.

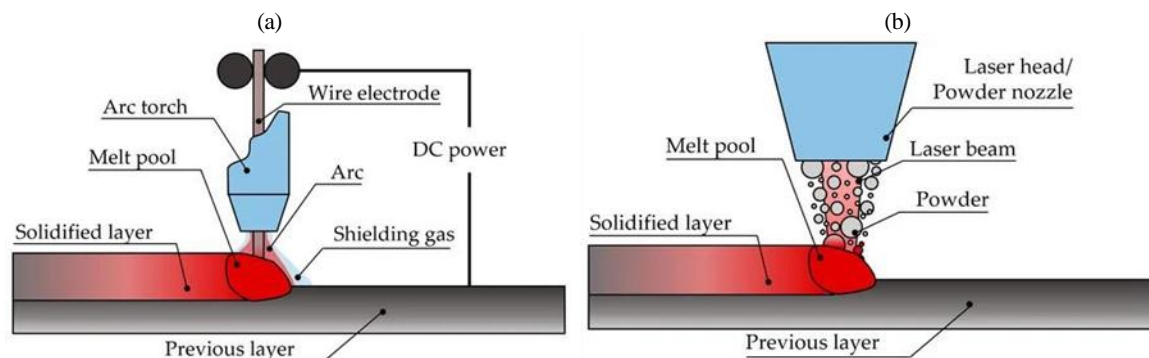


Figure 4: DED Working Principle (a) WAAM (b) LMD (Ostolaza, et al.,2023)

Aydin et al. (2023) investigated the effect of laser powder metal deposition (LPMD) process parameters on the bead geometry and the microstructure of precipitation hardening stainless steel deposits. Gas atomised powder of PH 13-8M was utilised for the printing. The results of the research showed that bead width and depth increase with increase in laser power; powder feeding rate influences bead height while laser scanning speed affects width, depth and height of the deposited bead. The microstructure of the deposited bead was studied under SEM, EDS and BBSD. Martensite, primary ferrite, small amount of retained austenite and aluminum enriched inclusion were observed. Sales et al. (2022) studied the mechanical properties of GMAW - WAAM super duplex stainless steel (SDSS) using 1.2mm diameter ER 2594 SDSS wire. They varied interpass temperature (150 and 100 $^{\circ}\text{C}$) to alter the cooling rates. The study deduced that decrease in interpass temperature resulted

to drop in ferrite content of the SDSS to 36%-a value that meets industrial standard. However, the tensile properties were isotropic irrespective of the change in the cooling rates; while the fatigue properties are weaker in transverse deposition direction, but improve with increase in cooling rate. Internal defects such as gas pores were detected in the test samples.

Rodrigues et al. (2022) investigated the effect of thermal cycles on microstructures and mechanical properties of GMAW-WAAM made high strength low alloy (HSLA) steel. ER110S- G wire electrode of 1mm diameter and heat inputs of 511 and 221J/mm were used to produce different samples of HSLA steel. The findings of the investigation indicated that heat input variations have no significant effect on the microstructures of the manufactured HSLA steel samples, which is evident by the presence of ferrite, bainite, martensite and retained austenite for all heat inputs. The

tensile, hardness and impact properties show isotropic behaviour due to the microstructural homogeneity of the additive manufactured (AMd) HSLA steel samples. Hejripour et al. (2019) produced wall (linear deposition) and tube (orbital deposition) samples of 2209 SDSS by GMAW-WAAM using 0.9mm ER2209 wire. They employed thermal modeling and experimental methods to characterise the AMd samples. Effects of thermal cycles and cooling rates on the microstructure and mechanical properties of the samples were studied. The findings of the study revealed that, ferrite content of the WAAM parts are lower compared to that of the wrought material; and the tensile properties in the layer direction were close to those of base metals manufactured by CM. They further reported that the flexural strength and stiffness of the WAAM made SDSS in deposition direction were higher than those of wrought samples.

Material Extrusion

The basic working principle of material extrusion (ME) according to Hasanov et al. (2020) is that "Filament material is melted inside the extrusion head and deposited onto a build plate using a bead-by-bead and layer-by-layer technique". ME is also called fused deposition modeling (FDM). In this technique, material is dispensed selectively via a heated nozzle or orifice to a heated build platform (Sun et al.,2022). Raw material for this process are usually a filaments made up of elastomers such as PLA and ABS polymers (Savchenko et al.,2022). Metals/ceramics are mixed into the filaments with polymer serving as binders. The filament is a wire shaped metals containing plastic. The most familiar of ME-AM is fused filament fabrication (FFF) which utilizes cheap thermoplastic filament as feedstock. Important variable parameters in ME are layer height, print speed, extrusion rate and nozzle diameter. Figure 5 shows ME process.

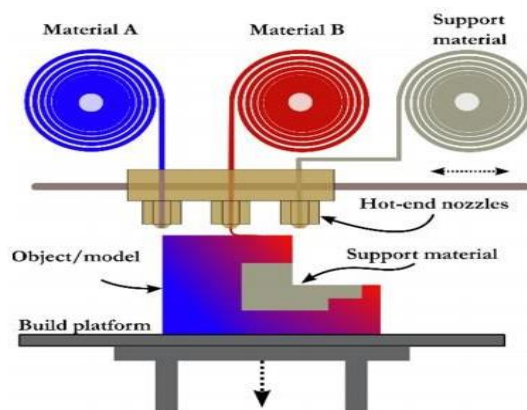


Figure 5: ME Process (Hasanov et al.,2022)

Savchenko et al. (2022) investigated new approach of ME-AM technique using liquid PVC plastisol materials in place of filaments. They concluded that; the new ME technique is capable of printing materials with low shore hardness by rebuilding the traditional FFF equipment with supplement parts; the mechanical properties are dependent of layer orientation. They further stated that selection of right process parameters and additives are important factors in obtaining better part properties.

Binder Jetting

Binder jetting is somehow similar to PBF process; in this method, powder based material is distributed in powder bed by jetting machine while a binder material usually liquid is

being selectively deposited onto the powder layer-by-layer and repeatedly until the 3D object is produced (Wiikinkoski, 2022). The binder materials fuse the powders or granules in layers continuously to build the designed three-dimensional object. ASTM standard described binder jetting as " Additive manufacturing in which a liquid agent is selectively deposited to join powder materials". Sintering, de binding and de powdering operations are involved in this technique. Metals, polymers, and, ceramics and composites can be processed by this technique. Critical variables are layer thickness, amount of binder liquid, velocity of powder spread, particle size and hatch distance (Salari et al., 2022). Figure 6 presents binder jetting process.

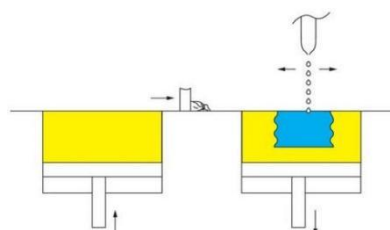


Figure 6: Binder Jetting Process

Salari et al. (2022) investigated the influence of BJ printing parameters on the modulus of rupture of magnesium-oxychloride based components. Powder mixture of (magnesium oxide and porous glass) and (1% rice starch plus 49.5% magnesium chloride hexahydrate deionized water solution) was used as binder. The findings of the work showed that the strength of the material was significantly affected by

the layer thickness, amount of binder and particle size.

Material Jetting

This is an ink jetting printing technique in which a printed head releases droplets of a photo reactive materials that deposits onto a build platform layer-by-layer and solidifies under ultraviolet (UV) or laser light. In this method,

photopolymer materials are stored in air-excluding tanks where they will be deposited as droplets forming a very thin layer on the build platform repeatedly until 3D object is formed (Gulcan et al.2021). Curing of the molten material on the platform is carried out by emitting UV light. Important parameters in MJ are tray location, layer thickness, build orientation, surfaces finish, material type and post processing;

all variables affect mechanical properties, dimensional accuracy and surface roughness (Gulcan et al.2021). Polymers such as thermoplastics, thermosetting and elastomers are the Key materials used in this technique. MJ are employed for fabrication of lithium batteries and multi-functional parts (Sun et al., 2022). Figure 7 is MJ technique.

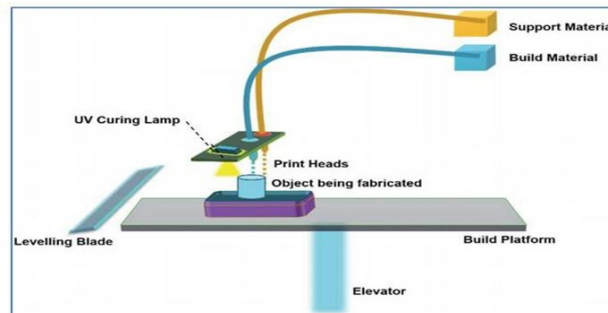


Figure 7: Material Jetting Process (Sireesha et al., 2018)

Gulcan et al. (2021) critically studied MJ technology state of art and found that; mechanical properties, dimensional accuracy and surface roughness are significantly affected by layer thickness, build orientation, surface finish, tray location amongst other parameters; and MJ technology offers better dimensional accuracy and surface roughness compared to other polymeric AMPs.

Sheet Lamination

Sheet lamination is called laminated object manufacturing AM process bonds sheets of material to form a 3D part by using a bonding mechanisms such as: thermal bonding, adhesive bonding, ultrasonic welding and clamping bonding (Gibson et al., 2015; Wiikinkoski, 2022). Mechanical cutter or Laser

(Zhan & Liou, 2021) is utilized to cut the sheets for subsequent bonding layer-layer and repeatedly until the CAD model is obtained. Figure 8 describes SHL. The three types of SHL processes are selective lamination, paper-based and composite-based lamination techniques (Zhang & Liou, 2021). Foils/papers supplied via a feed roller are the feed stocks in SHL. The lamination techniques could be bonding the sheets layer-by-layer followed by forming the 3D part or vice-versa. SHL heavily depends on post processing operations to obtain the final desired 3D component. Air temperature of the chamber, laser cutting speed, base plate temperature, roller speed, roller temperature, layer thickness and number of layers are critical variable sin SHL.

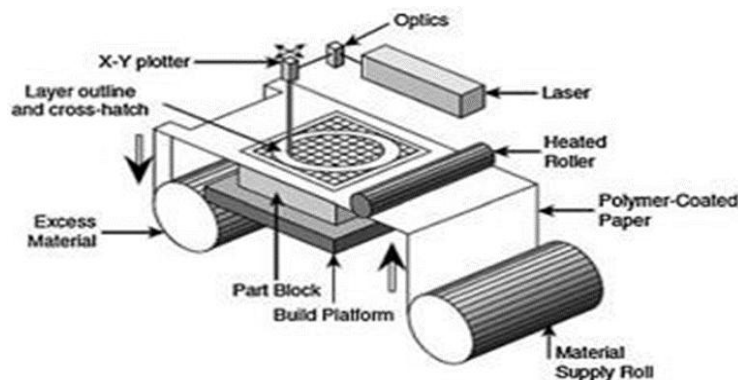


Figure 8: SHL Process (Wiikinkoski, 2022)

Vat Photo Polymerisation

Vat photo polymerisation is described by ISO/ASTM 52900 standard as an “additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.” Photo polymerisation is defined as the process of curing when UV light is exposed to photopolymer materials, transforming them from a liquid or semi-solid state into a solid state (Hasanov et al., 2022). Photopolymers comprise monomers, oligomers, and photo initiators (Nohut & Schwentenwein, 2022). Figure 9 diagrammatically shows the VP process. The photopolymer

materials are swept using a rotating system with liquid resin in vats on a rotating platform. Laser power, visible light, and UV light are used in this technique as sources of energy for curing. VP is extensively employed in the fabrication of FGMs. Common VP methods include continuous liquid interface production (CLIP), stereolithography (SLA), two-photon lithography (2PL), digital light processing (DLP), and continuous digital light processing (CDLP). Nuclear fuel of thorium dioxide has been reported to have been fabricated using the SLA technique (Sun et al., 2021).

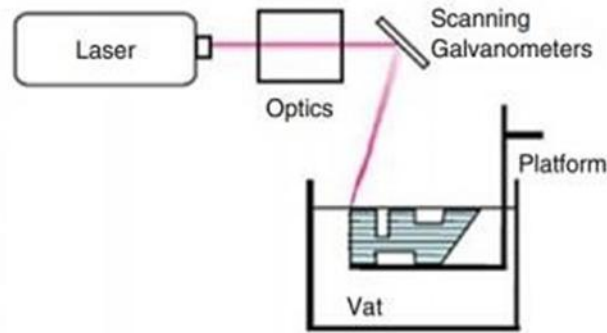


Figure 9: Vatphotomerisation Technique (Wiikinkoski, 2022)

Logo et al. (2020) characterized different VP resins specimens produced by DLP AM technique. The work revealed that resin with 0.6vol% of inorganic load presented tensile strength of 53MPa, compressive strength of 110MPa, 79MPa bending strength and shore hardness of 82.3; the values are close to that of injected polymer.

Hybrid Additive Manufacturing (HAM)

The application of two or more different AMPs and equipment for printing 3D object is termed HAM (Hasanov et al.,2022). In multi-material AM the application of HAM is highly encouraged for printing FGM. Roach et al. (2022)

reported combination of ME, MJ and direct ink writing (DIW) AMPs in printing multi-material heat exchanger. HAM integrates the less material waste AM with precise dimensionally subtractive machining. With the application of HAM many manufacturing challenges and difficulties of the various AMPs could be eliminated. Surface quality improvement, deposition of second material and fabrication of part with various mechanical properties, e.g., hardness are amongst the important benefits of HAM. Table 2 below presents the quantitative ranges of the various AMPs discussed.

RESULTS AND DISCUSSION

Table 2: Quantitative Ranges of AMPs

Process	Accuracy	Building speed	Layer thickness	Surface roughness
PBF-LB\M	±0.1-0.2mm	5-100cm ³ /hr.	20-50µm	5-20µm
PBF-EB/M	±0.2-0.3mm	50-200cm ³ /hr.	50-100µm	15-35µm
DED	±0.5-1.0mm	200-1000cm ³ /hr.	250-1000µm	20-100µm
ME	±0.2-0.5mm	10-150cm ³ /hr.	100-400µm	10-20µm
MJ	±0.05-0.1mm	20-100cm ³ /hr.	16-32µm	1-3µm
BJ	±0.2-0.3mm	1000-5000cm ³ /hr.	10-30µm	10-30µm
SHL	±0.2-0.5mm	200-2000 cm ³ /hr.	100-500µm	15-50µm
HAM	±0.01	-	-	0.8µm

AM Defects and Possible Mitigation Measures

Despite the fact that each AM process renders unique advantages and facilitates the creation of complex shapes and compositions, defects may arise in each method. These defects can lead to variations in parts properties such as lack of fusion, porosity, dimensional inaccuracy strength, composition and other abnormalities that may result in part deviation from design specifications (Miller et al.,2026; Liu et al.,2026). Defects often render components unusable for

their intended industry applications, resulting in significant losses of time, material, and financial resources when detected late in process. Undetected flaws may lead to catastrophic failures posing severe risk and economic risks (Miller et al.,2026). Anisotropy, surface roughness, dimensional error and residual stress are defects common to all AMPs. Table 3 below gives some AM defects, causes and possible mitigation measures.

Table 3: Defects and Mitigation Measures

Process	Common defects	Causes	Mitigation
PBF	Porosity, hot cracking, shrinkage, lack of fusion, anisotropy poor surface, key residual stress and cracks, balling.	Low energy density, uneven bed temperature, old powder, oxidation,wet powder.	Optimize laser power,preheat chamber, HIP, dry powder, defect detecting using AI.
DED	Poor bonding to substrate, cracking, anisotropy, distortion, porosity, cracking, poor surface.	Wrong powder feed rate, high heat input, rapid cooling.	Preheat substrate, optimize parameters, use interpass cooling.
ME	Warping, layer delamination, lower resolution, anisotropy.	Uneven cooling, poor bed adhesion,wrong temperature retraction.	Heated bed and enclosure, incorporate FFF with SLA .

Process	Common defects	Causes	Mitigation
BJ	Lower final density, shrinkage, weak green parts, distortion, anisotropy.	Low binder saturation, droplets pread, uneven sintering, weak green strength.	Binder saturation, compensate CAD for shrinkage, smaller droplets.
MJ	High material cost, limited thermal stability, support removal required, anisotropy, curing.	UV intensity, soluble support removal, layer thickness.	Calibrate UV, print at 16 μ m, waterjet +NaOH for support removal.
VP	Warping, delamination, cracking, incomplete cure, resin trap.	Under exposure, cure shrinkage, poor drainage, wrong supports.	Optimize exposure time, clean dried resin, drainage holes, annealing after cure.
SHL	Limited geometries, delamination, intermediate accuracy, anisotropy	Weak adhesion bond, thick sheets, cutting accuracy.	Optimize pressure and temperature, employ thinner sheets, use CNC machining after lamination.

Future Trends

The fundamentals and processing techniques of various AMPs have been reviewed. The layer-by-layer deposition technique was recognized as the critical basic operating principle of AM technology in producing a near-net shape 3D object. Metal-based AM such as DED, PBF employ metal powder and/or wire as feedstocks for layer-by-layer deposition to obtain the desired 3D object. In all AMPs CAD model of the intended 3D object must be designed which will subsequently be utilized for layer deposition. In SHL and BJ, bonding of materials such as metal sheets, foils and powders is the basic technique of producing the 3D object. However, some AM process such as VP adopts only photopolymer materials as feedstock. Laser and electron beam, arc, electrical, chemical adhesive, visible and UV light, hypersonic and mechanical energies are the main sources of energies in the various AMPs. Each process has critical parameters that strongly influence the properties of the final 3D object.

It is understood from the review that, the mechanical properties of additive manufactured steel parts are anisotropic and in many scenarios are comparably better than those of conventional manufactured ones. In all AMPs, process parameters play significant role in determining the final microstructures and mechanical properties. In PBF process, laser power, hatch distance, laser scanning speed and volumetric energy density significantly affect the properties of the AM made parts. Works on AM of cast iron products are scarce. Effort should be placed in future research to print cast iron by AM. Information regarding weld ability of additive manufactured parts are also scarce in the literature.

For AMPs to comprehensively replace CMPs, future research sought to focus towards improving the build chamber of all AM machines to enable printing of larger sized objects/parts. Likewise, upcoming research should put more prominence in integrating AMPs with AI for improving overall performance of AM technology in industry 4.0 and 5.0. High sophisticated optimization techniques of process parameters must be developed for sustainable AM practice. AM of composites and nanocomposites as well as incorporating nuclear materials and energy need extensive exploration in prospective research works. Incorporating FFF with SLA for high resolution could overcome resolution challenges. It is of utmost importance for subsequent works to explore hybrid defect detection methods that combine multiple techniques in mitigating persistent AM defects. The high cost of AM equipment and raw materials such as powder and printer play significant role in limiting the overall application of the technology; and for this reason, researchers, scientists,

industrialists and engineers must devise a mean of producing affordable AM machines and raw materials for sustainable and wide range of applications.

CONCLUSION

The review of fundamentals and processing techniques of AMPs with respect to basic working principle, feedstock, energy and process parameters were carried out. Recent works on AMPs were also evaluated and the following conclusions were arrived:

WAAM and PBF-LB/M appeared to be the most applicable AMPs in printing metals such as SDSS, 316L stainless steel and other carbon steels. WAAM has the advantage of producing larger objects not possible by any other AMPs. GMAW-WAAM is more common among other arc based AMPs due to its cost effectiveness and automatic wire feeding. PBF processes give high dimensional precision than WAAM, but very expensive than all other AMPs. It is apprehended from the study that HAM gives overall best result of AMPs. Findings from the case studies also reveal that mechanical properties of most AM made parts are better in layer direction, therefore, it is strongly emphasized that AI-driven techniques be integrated with HAM to mitigate anisotropy and all other lingering AM defects in future trend of research.

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