REVIEW OF ADDITIVE MANUFACTURING TECHNOLOGY: FUNDAMENTALS AND PROCESSING TECHNIQUES

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Abstract. Sequel to the challenges of conventional materials processing a0nd 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 summarised. It is deduced from the review indicated that additive manufacturing processes produce 3D objects by basic principle of layer-by-layer addition of material from a CAD model. Findings of the case studies proved that the properties of the additive manufactured parts are better compared to those of the traditional wrought ones and WAAM is the most popular metal based additive manufacturing process. Additive manufactured parts have isotropic properties.
Keywords: *3D printing, layer-by-layer deposition, 3D object, feed stock*

Introduction

Additive manufacturing (AM) technology is widely drawing attention and substituting conventional manufacturing (CM) technology in the arena of materials processing and manufacturing engineering (Mohyla et al., 2020). This is consequence of the tremendous economic and technical advantages of AM processes (AMPs) over CM processes (CMPs). Accordingly, 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 (Samoilenko et al., 2021; Baumers, 2012). 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 workpiece 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 toolings and consumables (Hasanov et al., 2022).

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Quite number of research findings established that parts manufactured by AMPs offer better properties compared to those made by CMPs. Sinha et al. (2022) reported an aero-turbine blade manufactured by AMPs to be better than that produced by CMPs. 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 a near -net-shape 3D object (Wiikinkoski, 2022; Sun et al., 2021).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 (Hasanov 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). This paper aims to describe the various AMPs, process parameters and current case studies with the sole aim of enriching the understanding of AM technology as a guide for future track of research..

Results and Discussion

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. Layer-by-layer heating and bonding are the two basic mechanisms of repeatedly adding materials to obtain a complete3D 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. In every scenario, AMPs operate on the principle of producing a 3D components by repeatedly single operation contrary to CMPs where in all cases workpiece must be subjected to different multiple operations. *Figure 1* displays level of steps in AMPs and CMPs.

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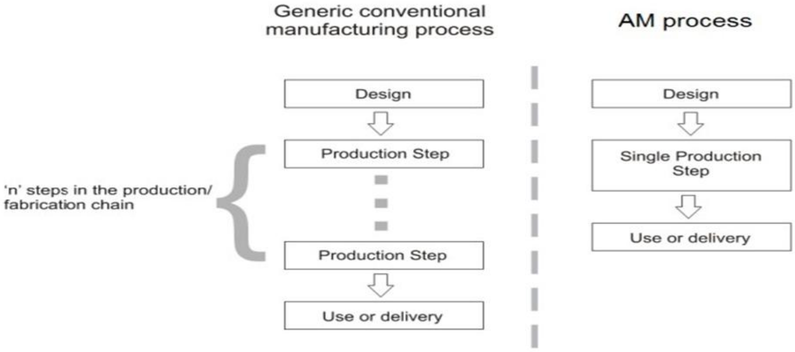

Figure 1. *Production steps in AM and CM processes.*
Source: Baumers (2012).

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.

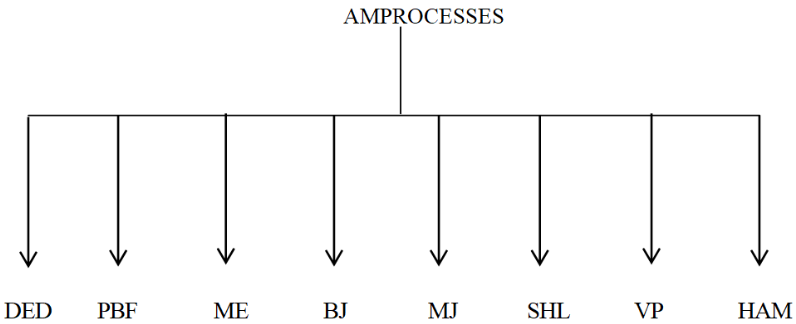

Figure 2. *Classification of AM processes.*

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; 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, and plasma are the key sources of energy in AMPs. 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 feedstocks. 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. *Table 1* presents AM raw materials, energy sources and parameter swith their respective applicable processes. 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.

***Table 1**. Comparisonof 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	-	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 temperatur, feed rate, etc.	Build orientation, tray location, layer thicknes, etc.	Amount of binder liquid, particle size, layer thicknes, etc.	Roller temperature, roller speed, layer thickness, etc.	-

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 (SLM).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 SLM process, spreaded metallic powders in a build chamber are

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heated and melted by high power laser on the substrate layer-by-layer repeatedly until the three dimensional parts are produced (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).SLM process is capable of repairing faulty parts such as worn-out portion of jet engine combustion chamber. A SLM repairing machine capable of reducing the repairing time by 90% was developed by siemen (Sinha et al., 2022). Electron beam melting has similar working principle as SLM 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-which is one of the merit of EBM over SLM process. The EBM process therefore has higher productivity, less impurity absorption, minimal residual stress, greater layer thickness compared to SLM process. An EBM 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 EBM 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. *Figure 3* illustrates PBF process.

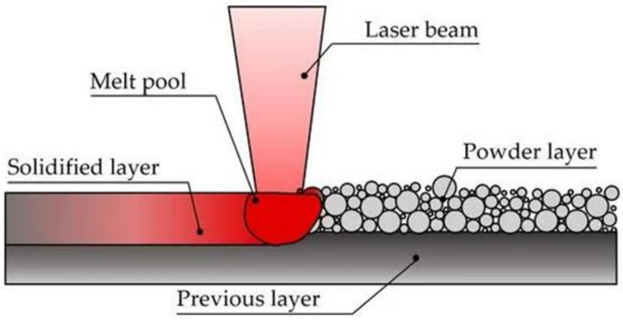

Figure 1. *Basic working principle of PBF.*
Source: Ostolazaet al. (2023).

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 (Hasanov 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 3Dobject 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., 2019). This process facilitates rapairs and maintenance of failed parts; feed stocks are cheaper compared to those of PBF processes-an advantage that qualifies DED processes

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to be overall cost effective than PBF processes. The benefits of changing feed stocks at anytime 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 of operation, automatic feed supply and high deposition rate among others(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., 2021). *Figure 4* illustrates DED process.

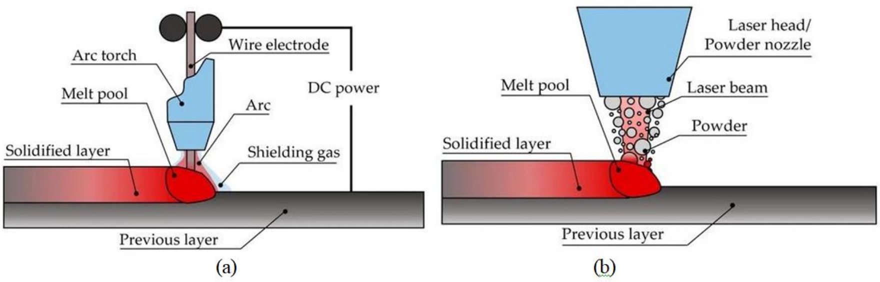

Figure 4. *DED working principle (a) WAAM (b) LMD.*
Source: Ostolaza et al. (2023).

Material extrusion

The basic working principle of material extrusion (ME) according to Hasanov et al. (2022) 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., 2021).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 in to 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.

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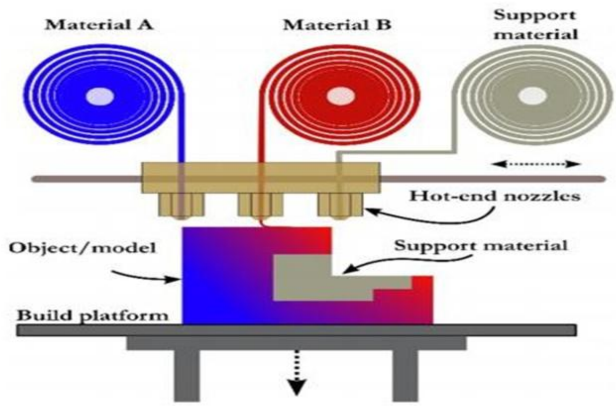

Figure 5. *FFF process.*
Source: Hasanovet et al. (2022).

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.ISO/ASTM standard described binder jetting as" Additive manufacturing in which a liquid agent is selectively deposited to join powder materials". Sintering ,debinding and depowdering operations are involved in this technique (Ki et al., 2022).Metals, polymers, sand, 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.

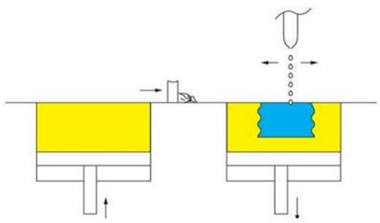

Figure 6. *Binder jetting process.*

Material jetting

This is an ink jetting printing technique in which a printed head releases dropets of a photoreactive 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 (Gülcan 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,

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dimensional accuracy and surface roughness (Gülcan et al., 2021). Polymers such as thermopalstics, thermo setting and elastomers are the key materials used for this technique. MJ are employed for fabrication of lithium batteries and multi functional parts (Sun et al., 2021). *Figure 7* is MJ technique.

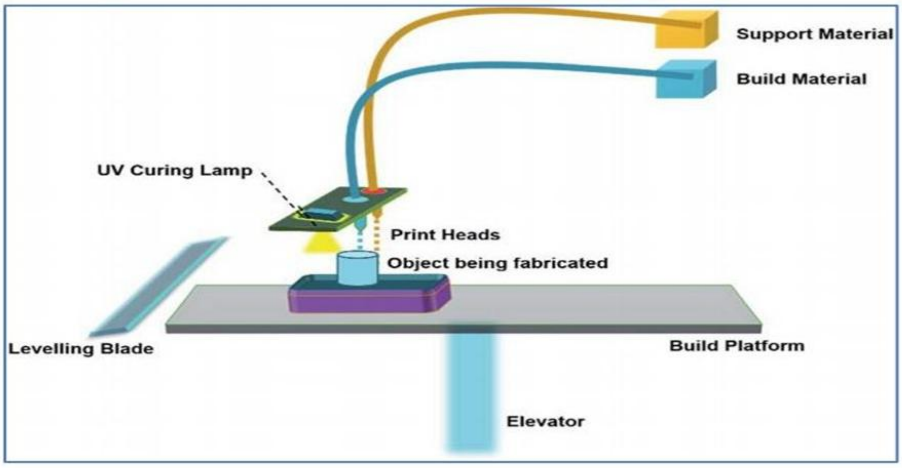

Figure 7. *Material jetting process.*
Source: Sireesha et al. (2018).

Sheet lamination

Sheet lamination also 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 (Wiikinkoski, 2022; Gibson et al., 2021). Mechanical cutter or Laser (Zhang and 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 and Liou, 2021). Foils/papers supplied via a feed roller are the feedstock sin 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 variables in SHL.

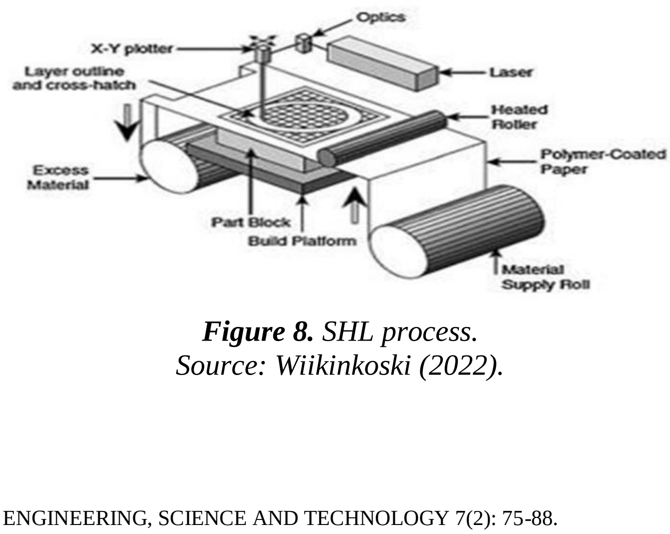

Figure 8. *SHL process.*
Source: Wiikinkoski (2022).

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Vatphotopolymerisation

Vat photopolymerisation 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.” Photopolymerisation 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 photoinitiators (Nohut and 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).

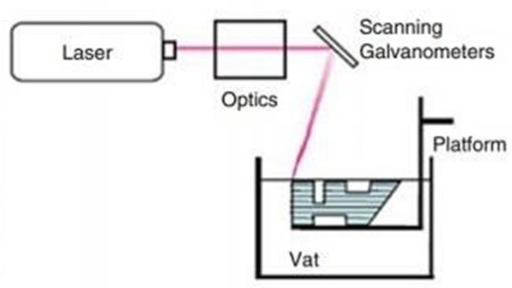

Figure 9. *Vat photomerisation technique.*
Source: Wiikinkoski (2022).

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. Combination of FFF, 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..

Case studies

In this section, recent works on different AMPs were reviewed with respect to the level of improvements and advances in various processes and process parameters. Processing challenges and difficulties were also studied with the intent of proffering possible solutions in future researches. 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 100ºC) 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

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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. (2019) 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. 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 13-8Mo 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. 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 15-45um was used to produce samples of the steels. Laser power, hatch distance and laser scanning speed was 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 and Taha (2022) produced 316l/SiC composite samples by SLM process using gas atomised powder of 316l and SiC of size <65µm and < 40µm respectively. They concluded that; scanning speed, volumetric energy density, laser power, hatching distance and layer thickness of 700mm/s,136J/mm3,200W,70µm and 30µm 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. Mohyla et al. (2020) additively manufactured AISI 316l by SLM technique using gas atomised powder of mean size of 26.33µm. Laser power, laser scanning speed and layer thickness of 200W, 650mm/s and 50um respectively were used for the printing. The relative density and porosity of the

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produced samples were calculated to be 98.12 and 1.14% respectively. 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 futher stated that selection of right process parameters and additives are important factors in obtaining better part properties. Gülcan 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. 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 asbinder .The findings of the work showed that the strength of the material was significantly affected by the layer thickness, amount of binderand particle size. Different VP resins specimens produced by DLP AM technique. The findings of 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.

The fundamentals and processing techniques of various AMPs have been reviewed. The layer-by-layer deposition technique was recognised 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 utilised for layer depositioning. 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. From the case studies, WAAM and SLM 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. Furthermore, 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..

Conclusion

The review of the fundamentals and processing techniques of additive manufacturing processes (AMPs) with respect to their basic working principles, feedstocks, energy sources, and process parameters was carried out. Recent works on different AMPs were also evaluated to understand their developments, applications, processing characteristics, and associated challenges. The review established layer-by-layer deposition as the fundamental working principle of additive manufacturing for producing near-net-shape three-dimensional (3D) objects from computer-aided design (CAD) models. However, the mechanisms of material deposition, bonding, melting, and solidification vary according to the specific AM process. Different forms of feedstocks, including metal powders, wires, filaments, sheets, polymers, ceramics, and photopolymer materials, are employed depending on the selected process. Similarly, different energy sources, including laser beams, electron beams, arc energy, ultraviolet light, and other forms of energy, are applied for material fusion, bonding, deposition, or curing. The review also demonstrated that process parameters have considerable influence on the quality and properties of additively manufactured components. Parameters such as laser power, scanning speed, layer thickness, hatch distance, wire feed speed, arc current, voltage, particle size, deposition rate, and build orientation vary according to the selected AM technique and influence the resulting material characteristics. Therefore, appropriate selection and control of processing parameters are important for achieving the required dimensional accuracy, surface quality, microstructure, density, and mechanical properties of the manufactured components. The different AMPs consequently provide different capabilities and limitations, indicating that the selection of an appropriate process should consider the feedstock, energy source, component geometry, required properties, and intended application.

The reviewed case studies further demonstrated the potential of additive manufacturing for processing metallic materials, particularly stainless steels and other engineering materials. Additive manufacturing of super duplex stainless steel (SDSS) resulted in a decrease in ferrite content, possibly due to temperature changes associated with the thermal cycles and cooling conditions during processing. Studies on wire arc additive manufacturing (WAAM) also demonstrated the importance of thermal cycles, heat input, cooling rate, and deposition conditions in determining the microstructural and mechanical characteristics of manufactured components. WAAM provides an important advantage in the production of relatively large metallic components, while gas metal arc welding-based WAAM offers benefits associated with automatic wire feeding and cost effectiveness. Powder bed fusion (PBF) processes, particularly selective laser melting (SLM), provide comparatively high dimensional precision and have demonstrated potential for producing and repairing metallic components. Nevertheless, processing defects such as porosity, cracks, and variations in surface quality may occur when process parameters are not appropriately controlled. The reviewed studies showed that laser power, scanning speed, hatch distance, energy density, layer thickness, and other processing variables significantly affect the quality of components manufactured using PBF and related techniques. Other processes, including material extrusion, binder jetting, material jetting, sheet lamination, and vat photopolymerisation, also provide distinct processing capabilities for different materials and applications. Overall, the reviewed studies demonstrate that AMPs provide considerable opportunities for manufacturing complex and customised components while reducing material waste. Further improvements in process optimisation, parameter control, material selection, defect reduction, and post-processing techniques are required to improve the quality, reliability, and broader application of additively manufactured components.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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