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Review

A Review on Metal Additive Manufacturing - Types, Applications and Future Trends

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Abstract

Metal Additive Manufacturing (MAM) process has been established as an industrial process for customized and intricate metallic components. It is one of the growing technologies proving its potential in numerous fields by introducing the latest processing methods. The significant growth in this technology is partially fueled by its ability to manufacture parts that could be performance-beneficial and commercially utilizable in various industries. The adaptability of metal AM processes has prompted innovation across various industries with applications spanning defense, aerospace, medical, dental, automotive, and oil & gas sectors. Each industry benefits from the unique abilities of metal AM; for instance, material efficiency, design flexibility, lead time reduction, and the creation of lightweight and complex structures that were unachievable through traditional methods can now be achieved. Therefore, this review article analyzes metal AM, describing its types, technological challenges, environmental & business considerations, energy consumption, applications, and future trends. Initially, the article introduces primary categories of metal AM, elaborating their mechanism and working principles, later, it focuses on the industrial contributions of metal AM, technological challenges, and business considerations. The outlook of this technology highlights emerging materials and technologies, such as the inclusion of machine learning (ML) and artificial intelligence (AI) to predict defects, optimize process parameters, and enhance the quality of products. Furthermore, advanced materials like high entropy alloys (HEAs) are being discussed to broaden the functionality of AM parts. Metal AM is playing a critical role in shaping the future of manufacturing by offering customization, efficiency, and sustainability in the industries. The article aims to provide a general understanding of metal AM while highlighting key technological advancements and future research directions to expand its applications in various sectors further.

Keywords

Metal additive manufacturing; environmental and business considerations; aerospace sector; automotive industries; medical and dental sector; construction sector

1. Introduction

Additive manufacturing (AM) or 3D printing converts a computer-aided design (CAD) into a physical item by depositing multiple layers and seldom requires post-processing to get the final product. In contrast to subtractive manufacturing technology, ASTM Standard F2792 describes the additive manufacturing process in which 3D model data is used for joining materials to make different components, typically layer upon layer [1]. Previously, AM was used for the production or rapid prototyping of plastic/polymer components; however, in recent years, breakthroughs in this area have enabled different industries, like aviation, automotive, and medical, to make metal components through AM technology, which could be used in real-world applications. Many industrial sectors are now manufacturing geometrically complex structures by using these techniques due to three main advantages: 1- minimum waste of materials, 2- the ability to develop components that cannot be manufactured through casting or machining, 3- time reduction from CAD model to final component production [2].

Generally, three main elements are required for AM: feedstock, heat source, and manipulator. The software slices the CAD model of the desired component, and each slice depicts a deposited layer (Figure 1A). The thickness of each layer is predetermined. A manipulator is used to trace out each layer as programmed which is intended to be deposited (Figure 1B). Finally, the intended part is deposited by a device, usually described as a heat source, providing the necessary energy to melt the feedstock (Figure 1C) [3].

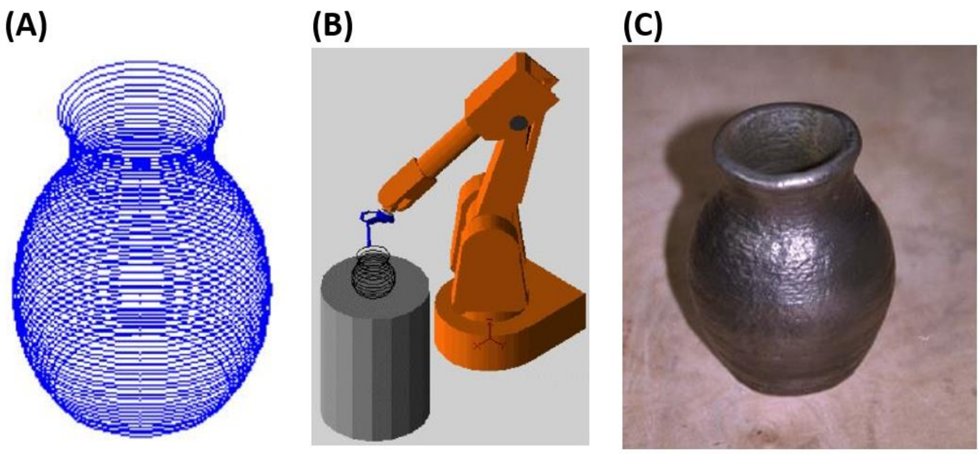

Figure 1 Main steps of AM: (A) the object is sliced into different layers, (B) a manipulator such as a robot or machine is programmed to trace out each layer, and (C) a heat source is used to build the intended object [3].

The ASTM categorization of AM processes appropriate for metals includes material jetting, directed energy deposition (DED), powder bed fusion (PBF), binder jetting, material extrusion, sheet lamination, and VAT photo-polymerization [4]. The grouping of metal additive manufacturing processes based on feedstock form, source of heat, and material consolidation is shown in Figure 2.

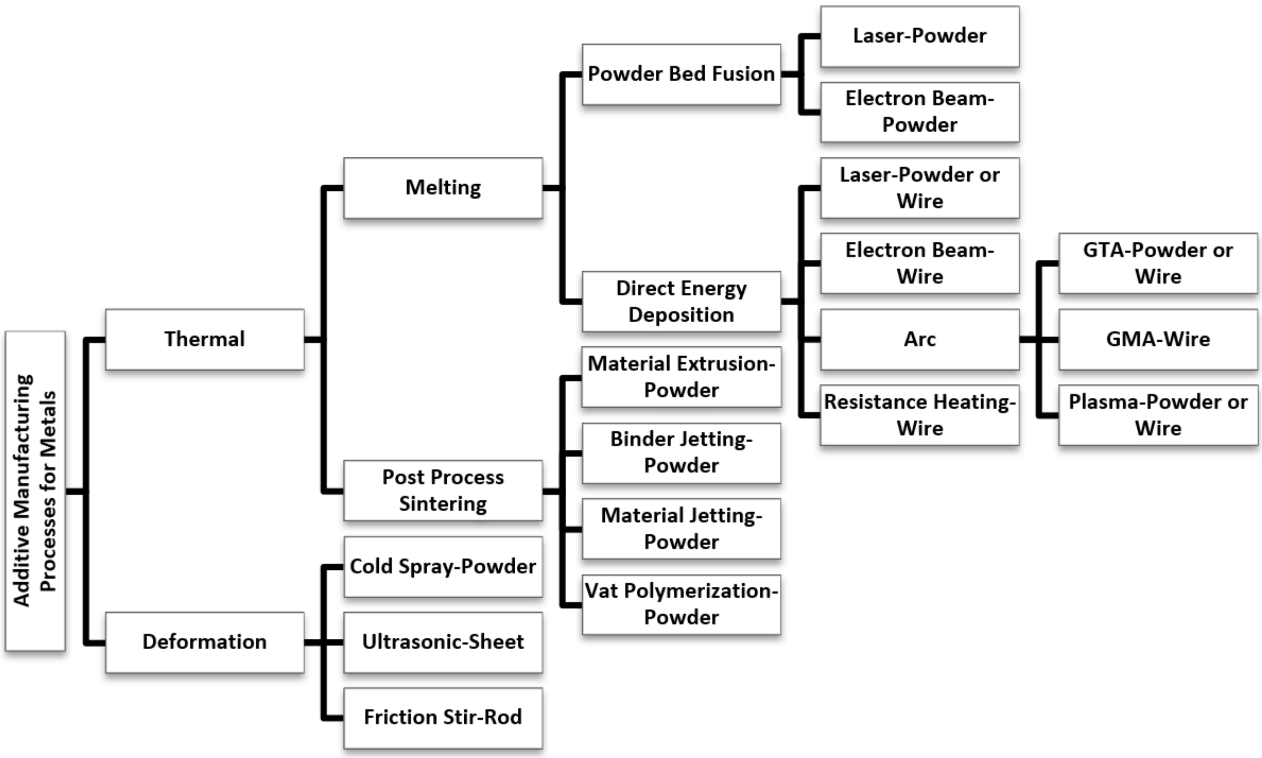

Figure 2 Graphical representation of AM processes applicable to metals [4].

Powder bed fusion and direct energy deposition are very common AM technologies. Recent advancements have given rise to resin, extrusion, and lamination-based metallic AM, although more research is needed in these technologies to achieve properties comparable to those of parts manufactured from conventional methods. The global market report of metal AM technologies in 2024 is shown in Figure 3, and the representation of additive manufacturing equipment and resources is also presented in Table 1.

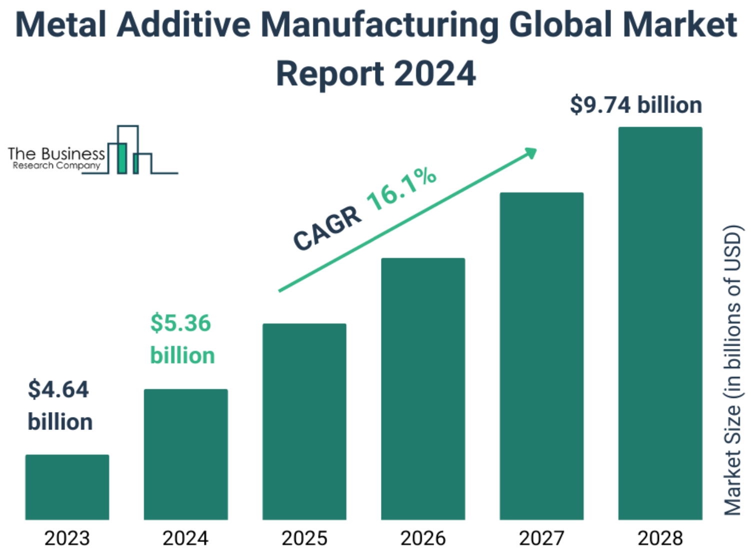

Figure 3 Metal AM Technologies global market report 2024 [5].

Table 1 Metal AM equipment sources and specifications [6].

Brand	Product	Technology	Build size (mm)	Country
TRUMPF	TruPrint 1000	Laser beam PBF	100 × 100 × 100	Germany
SLM Solutions	SLM 125		125 × 125 × 75	Germany
GE Additive	M2 Series 5		250 × 250 × 350	-
Renishaw	RenAM 500Q		245 × 245 × 335	-
Desktop Metal	Production System P-1	Binder jetting (multi-step)	200 × 100 × 40	United States
Digital Metal	DM P2500		203 × 180 × 69	Sweden
Pollen AM	Pam Series MC	Material Extrusion	⌀ 300 × 300	France
Markforged	Metal X (Gen 2)	FFF	300 × 220 × 180	United States
Formalloy	L-Series	Laser beam DED	1000 × 1000 × 1000	United States
XJet	Carmel 700 M	NPJ	501 × 140 × 200	Israel
3D Systems	DMP Flex 100	DMP	100 × 100 × 90	United States
GE Additive (Arcam)	EBM Spectra L	EBM	⌀ 350 × 430	United States
Desktop Metal	Studio 2	BMD	300 × 200 × 200	United States
EOS	EOS M 100	DMLM	100 × 100 × 95	Germany

The provision of material efficiency, design flexibility, and customization in metal AM has revolutionized manufacturing processes across various industries. Despite rapid advancements, the understanding of each AM technology is crucial. Therefore, this review aims to address this gap by summarizing the working principles of metal AM technologies, exploring their potential applications, and identifying the latest trends. The article seeks to assist academic researchers and industrial practitioners in selecting and implement suitable AM technologies for future studies.

2. Metal AM Processes

This section will cover the working principle, advantages, and limitations of various metal AM techniques such as powder bed fusion, directed energy deposition, jetting-and extrusion-based processes, sheet lamination, and wire arc-based processes. The generic workflow diagram of metal additive manufacturing is shown in Figure 4. Brief details about the materials, benefits, drawbacks, and potential use for each AM technology have been presented in Table 2, and metal AM technologies are presented in Figure 5.

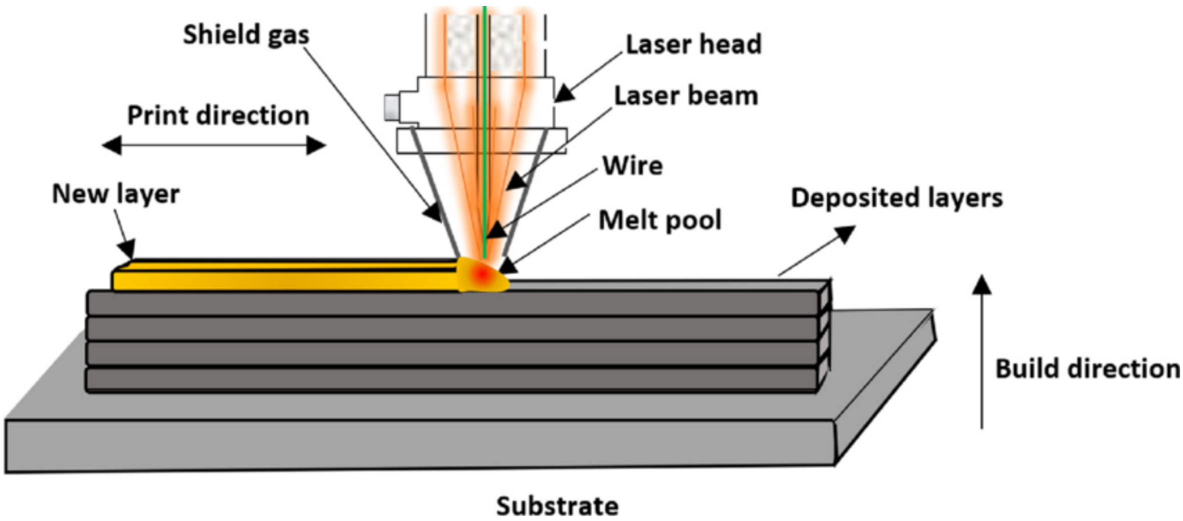

Figure 4 Workflow Diagram of Metal Additive Manufacturing [7].

Table 2 Benefits, Drawbacks, materials, and application of different AM methods.

Methods	Benefits	Drawbacks	Materials	Applications	References
Powder bed fusion	Build high-quality and Fine resolution parts	High porosity in 3D printing, particularly the binder jetting method, Expensive technology with slow printing speed	Available in the form of compacted powders, such as polymers and ceramics for 3DP; metal, alloys, and some polymers for SLS and SLM	Lightweight lattice structures, Heat exchanger, aerospace, biomedical, and electronics	[8]
Stereo-lithography	Build high-quality and Fine resolution parts	Expensive technology with limited materials and a slow printing rate	Hybrid ceramic-polymer Photo-active Monomers	Prototyping and biomedical area	[8]
Fused deposition modelling	Offers a simple printing process with high print speed and low build cost	Issues in layer-by-layer surface finish, limited availability of materials, and exhibit low mechanical properties	Continuous fibre-reinforced and thermoplastic filament polymer	To build composite parts and use them in rapid prototyping	[8]
Laminated object manufacturing	Offers manufacturing of large-scale structures with a vast range of materials and low cost. Decrease the production time.	Complex geometries manufacturing limitations, lower dimensional accuracy, and surface quality	Metal-filled tapes and metal rolls, ceramics, polymer composites, paper	Smart structures and paper manufacturing, electronics, and foundry industries	[9]
Inkjet printing	Offers quick and large structure printing	Layer-by-layer finish Lack of surface finish and bonding between layers, coarse resolution	Concentrated dispersion of particles in liquid paste/ink; material could be concrete or ceramics	Construction of large building structures, biomedical	[10]

Direct energy deposition	Offers excellent mechanical properties with reduced cost and production time. Best for retrofitting and repair, accurate control of composition	Required heavy support structure, low surface quality, and accuracy, limitations in printing complex structures	Metal, ceramics, polymers, and alloys in wire or powder form	Repairing & Retrofitting, aerospace, biomedical	[11]

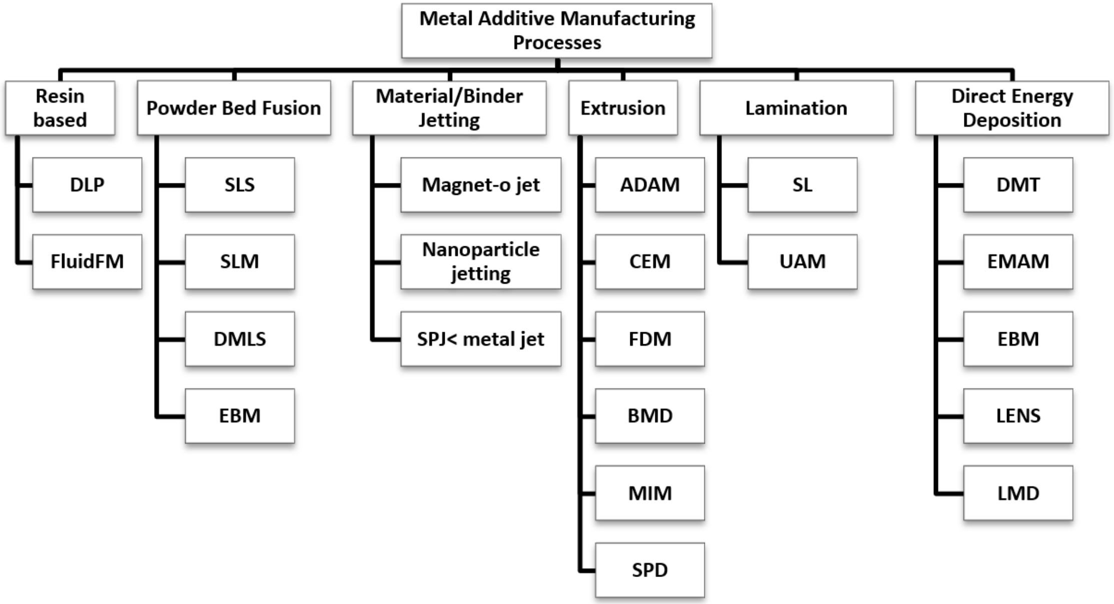

Figure 5 Metal Additive Manufacturing Technologies[1] [6].

[1] DLP (Digital Light Processing), SLS (Selective Laser Sintering), SLM (Selective Laser Melting), DMLS (Direct Metal Laser Sintering), EBM (Electron Beam Melting), ADAM (Atomic Diffusion Additive Manufacturing), CEM (Composite Extrusion Modeling), FDM (Fused Deposition Modeling), BMD (Bound Metal Deposition), MIM (Metal Injection Molding), SL (Sheet Lamination), UAM (Ultrasonic Additive Manufacturing), DMT (Direct Metal Tooling), EBAM (Electron Beam Additive Manufacturing), EBM (Electron Beam Melting), LENS (Laser Engineered Net Shaping), LMD (Laser Metal Deposition).

2.1 Powder Bed Fusion AM

In powder-based technique, a laser beam or electron beam [12] is employed as a heat source to melt or fuse powder materials for different components manufacturing [13, 14]. Powder bed fusion AM technology includes electron-beam melting (EBM), direct metal laser sintering (DMLS), selective laser sintering (SLS), and selective laser melting (SLM). Currently, only fewer alloys, the most appropriate being EOS aluminum (AlSi10Mg), Titanium Grade 5 (TiAl6V4), Cobalt Chrome (CoCr), and Inconel 718, can be definitively printed. Most alloys, more than 5500, are available for use; however, they cannot be manufactured with additive techniques due to the dynamics of melting and solidification during the printing process. This led to unbearable microstructures with enormous columnar grains and periodic cracks. Thus, to develop these alloys, a comprehensive study of the processing and mechanisms is required for microstructural stability and improvement in mechanical properties. However, powder bed-based processes give an advantage in geometrical flexibility to manufacture intricate components [15, 16]. It helps to eliminate the series of processes required in conventional manufacturing for complicated components and consumes less material [17], time, cost [18], and energy [16, 18-20]. The leftover powder can be reused after it is sieved, and it was observed that recycled powder can lead to material use efficiency of up to 95% [21].

Laser beam PBF systems depend on the melt-pool size, laser spot size, and layer thickness and are capable of printing high-resolution parts with a feature resolution of 40-70 microns. It allows the construction of lattice structures, intricate cooling channels, and topology-optimization, which helps make complex geometries. However, care must be taken while handling the support structure and powder removal process. This process typically has a slight build platform and scaling up is challenging due to optics and powder spreading capabilities. For this reason, new machines with multiple lasers are available which helps in speeding up the layer scanning time for a larger built platform. The high cost and limited availability of materials restrict the use of this printing technology [4].

Electron beam PBF, conversely, can make parts with high purity and very high density due to its process in a vacuum. Its high scanning speed makes the process faster, and the splitting of the beam allows the production of multiple parts simultaneously. The parts constructed with electron beams have fewer thermal stresses and require less support. Higher prices of electron beam machines, limited availability of materials, and smaller build sizes are the limitations of this technology [4].

2.1.1 Selective Laser Sintering (SLS)

SLS is a laser-based method that can print both metallic and non-metallic parts. In this process a power source such as laser is used to compact the metal powdered material to manufacture parts without melting [22]. The graphical representation of the SLS process is shown in Figure 6 and can be divided on the basis of the printing mechanism and laser method. The part's qualities, such as surface finish and mechanical and metallurgical properties, depend on the operating parameters like feedstock, geometric, and laser parameters. The parts printed with the SLS technique may have similar properties to wrought materials [23].

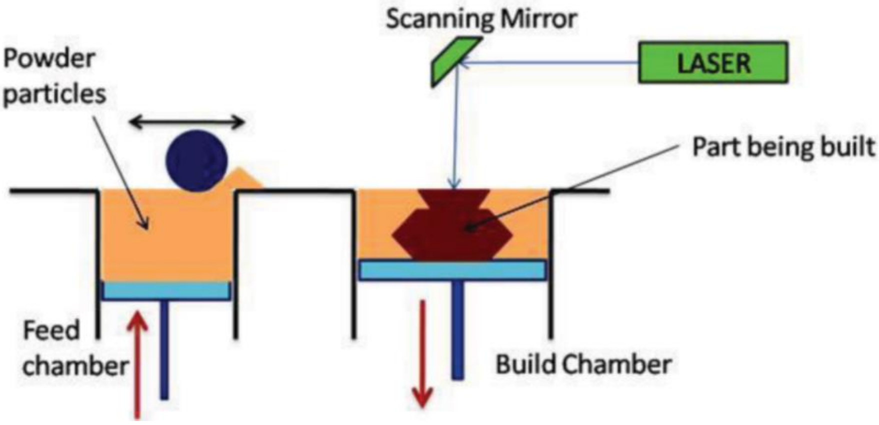

Figure 6 Schematic of SLS Process [23].

2.1.2 Selective Laser Melting (SLM)

In SLM, metal powder is spread on a substrate and then a laser heat source scans the given path which melts the powder to build the required layer. This process is repeated multiple times until the desired shape is achieved. The working process of SLM is shown in Figure 7. This technique has the ability to construct components from the powder which have comparable mechanical properties to conventionally manufactured components [24].

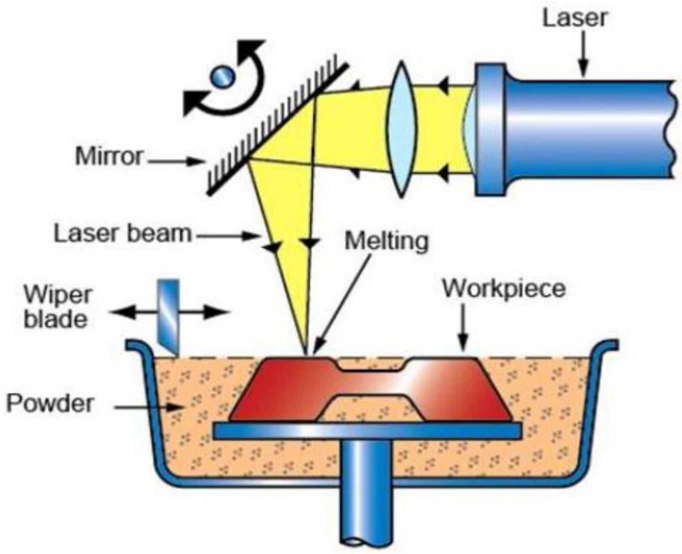

Figure 7 Selective Laser Melting [25].

SLM can manufacture complex objects that are difficult to build by traditional methods [26] is very useful for manufacturing customized components and can manufacture multi material components [27]. Carbon footprints can also be reduced by using AM compared to conventional manufacturing [26]. Additionally, SLM has various applications in different fields, such as shock absorption, thermal insulation, and biomedical implants [28]. In short, SLM endorses “performance design” instead of “design for manufacturing” [17].

2.1.3 Electron Beam Melting

In EBM, electron beam is used for melting the metal powder and creates a layer of the metal inside a vacuum chamber [29, 30]. It is produced from an electron-beam gun by heating the tungsten filament to a very high-temperature until it starts to release electrons. These electrons are speeded by creating an electric field and then the electron beam is directed with various electromagnetic coils as shown in Figure 8.

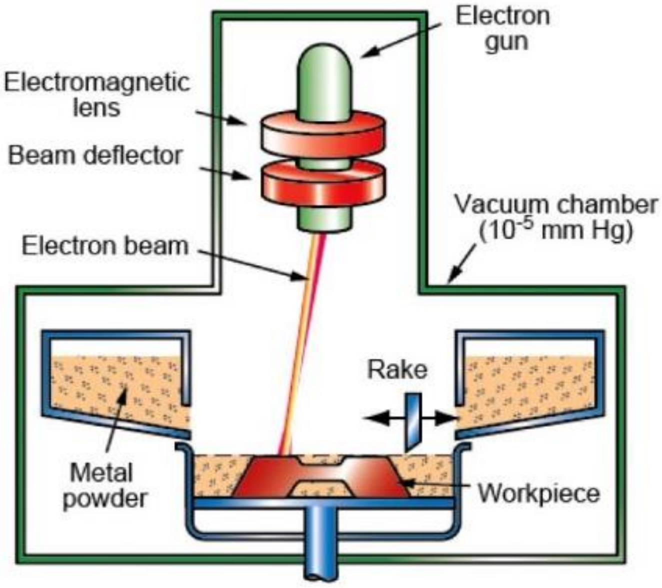

Figure 8 AM based on Electron Beam Melting [31].

2.2 Jetting Based AM Processes

The jetting processes include binder and material jetting and are explained as follows.

2.2.1 Binder Jetting (BJ)

The binder jetting process (Figure 9) uses two materials: a metallic material from which the actual part is to be made and a binder which acts as an adhesive to glue the metal powder between different layers. This binder is mainly in the form of a liquid. First, metal powder is spread on a substrate, and then the binder is deposited on the metal powder wherever directed by the CAD 3D model. The process is reiterated until the required component geometry is achieved. Several post-processing processes may be required in this technology, such as de-powdering, curing, infiltration, sintering, and finishing [32, 33].

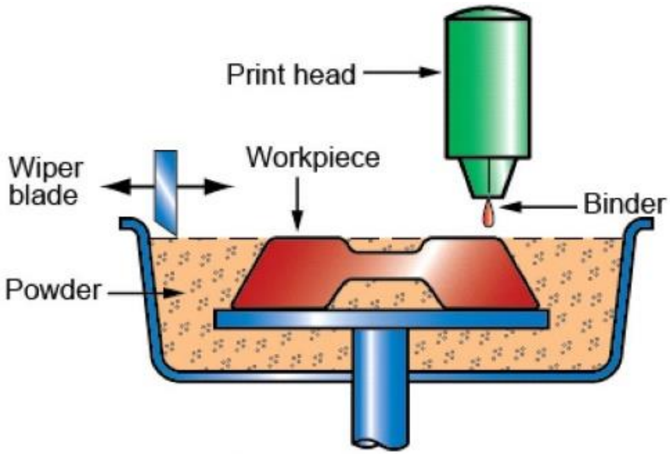

Figure 9 Schematic of binder jetting [34].

There is no need of controlled environment because the BJ process does not need high temperature heat source for building green parts. Moreover, the powder bed processes give the support for overhanging areas and enables full nesting within 3D volume. The parts manufactured with sintering process are not completely dense and typically have more porosity than DED and PBF printed parts. Whereas the infiltration or hot isostatics pressing (HIP) with low melting alloys are employed to increase the density of parts. Material choices are limited for this sintering process; however, it keeps on increasing as the research is going on [4].

2.2.2 Material Jetting (MJ)

In MJ process (Figure 10), build material is deposited layer wise selectively on the substrate usually in a vertical direction and the process is carried out many times to get the final geometry [35]. Multiple variants of material jetting machines are available in the market [36], mostly, machines have two or more print heads. A support structure is created with one print head, and the other one build the components. To get the better surface finish, hybrid machines are being used particularly for the miniature metal parts. In direct write method, an inert gas with an atomized nanoparticle-size material is jetted into a focused beam to create the droplets. Machines having this technique could print both non-metal and metal parts. Some machines, particularly direct-write process, combine the material jetting with material extrusion process for creating electrical circuit boards.

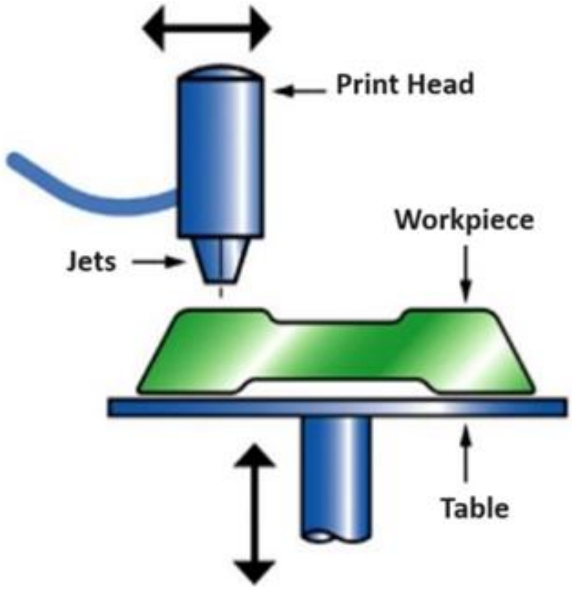

Figure 10 Schematic of Material jetting AM [34].

2.3 Extrusion-Based Process

In extrusion process, fused deposition modelling (FDM) is most widely used technology which is developed by the Stratasys USA [37]. In this type of AM, a filament type material is deposited with a nozzle or an orifice. First, material is extruded and dispensed through a heated head/nozzle where the material is melted and then deposited on the build plate. The extruder is moved upward, or plate is lowered after the completion of each layer equal to layer thickness. This process is reiterated until the final shape is attained [38]. The schematic of extrusion-based process is shown as Figure 11. The applications of this simple and low-cost printing technology are not only limited to visual aids, prototype productions and conceptual models' formation but also used to build practical parts, for instance drilling grids manufactured with this technique used in aerospace sector [39]. FDM has shown a significant potential of shifting from prototyping to manufacturing [40]. This technology is famous for plastic materials, but researchers are also working to manufacture metal-based components. There may be more than one nozzle creating structures or support materials [41].

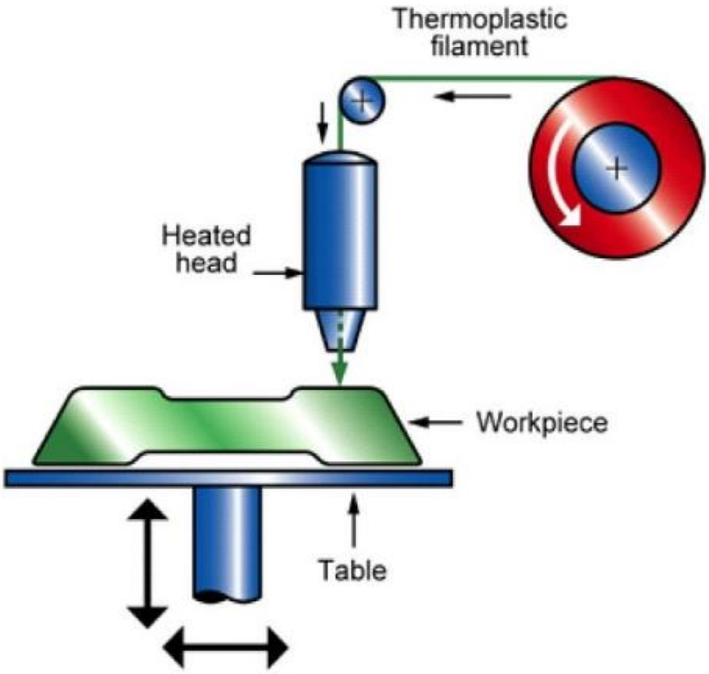

Figure 11 Schematic of extrusion base AM technology [34].

2.4 Resin-Based Process

This metal resin-based AM technology (Figure 12) uses photosensitive resin which is filled with metal particles and laser/light source is used to harden the desired layer. This process is reiterated many times until desired part geometry is obtained [6]. The SLA process of metallic materials involves a curable metallic suspension with UV rays made up of a pre-polymer, metallic powder, additives and photo-initiator. To obtain the metallic matrix during polymerization process, the polymer joins the metallic particles. The binder is removed from the7 obtained matrix structure through sintering and thermal treatments that ensures the final properties of the part [42].

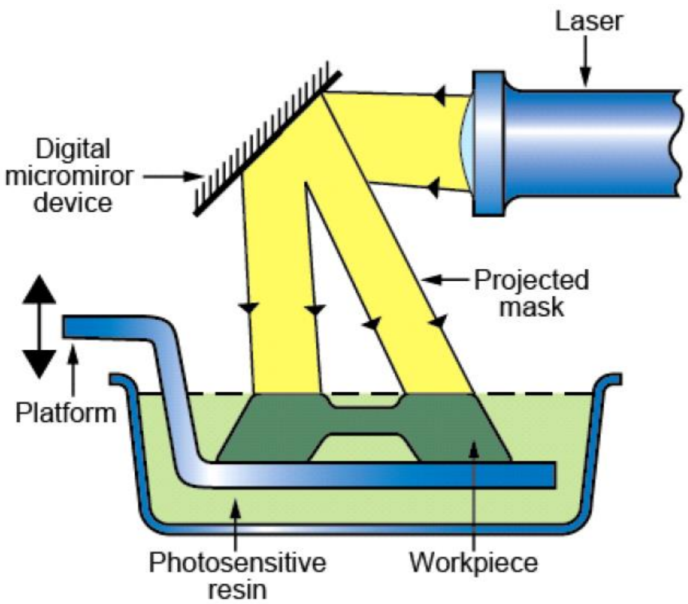

Figure 12 Schematic of the metal resin process [43].

2.5 Sheet Lamination

In this AM technology, material sheets are joined together to manufacture a part [35]. This technology includes two methods, laminated object manufacturing (LOM) (Figure 13) and ultrasonic manufacturing (UAM) (Figure 14) [43]. In UAM, metal sheets join by vibration and the sonotrode vibrates in a very high frequency which causes the sheet layers to melt due to friction. A mill head can be utilized to enhance the surface finish as a post processing [36]. Laminated object manufacturing (LOM) uses pre-laminated sheets with an adhesive which is heat sensitive. Selective heating technique is used to get the desired shape and the excessive contours can be cut by using a laser or a knife [2].

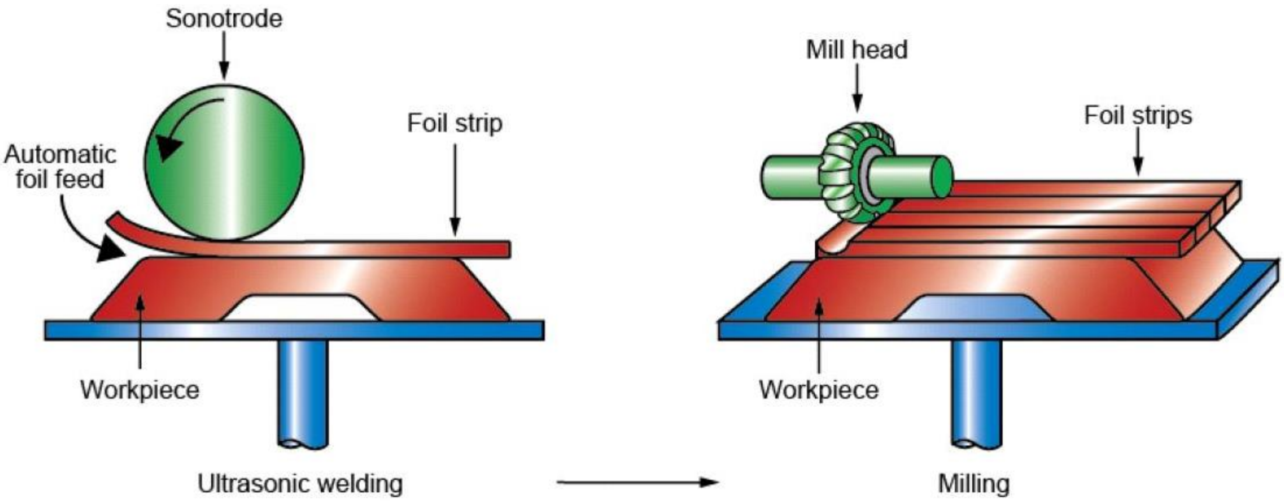

Figure 13 Sheet Lamination AM by UAM technology [34].

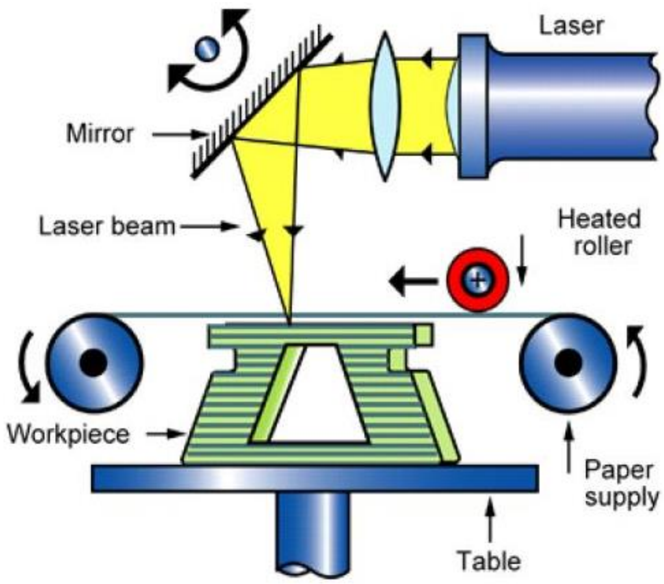

Figure 14 Sheet lamination AM by LOM technology [34].

2.6 Directed Energy Deposition (DED)

In DED process, material (metal wire or powder) is fed into a melt-pool which is created by thermal energy [35]. The thermal energy can be an electron/laser beam or an arc welding torch. When powder is used as a build material, the DED can be referred as blown powder [36, 43]. The workflow diagram of DED process is shown in Figure 15.

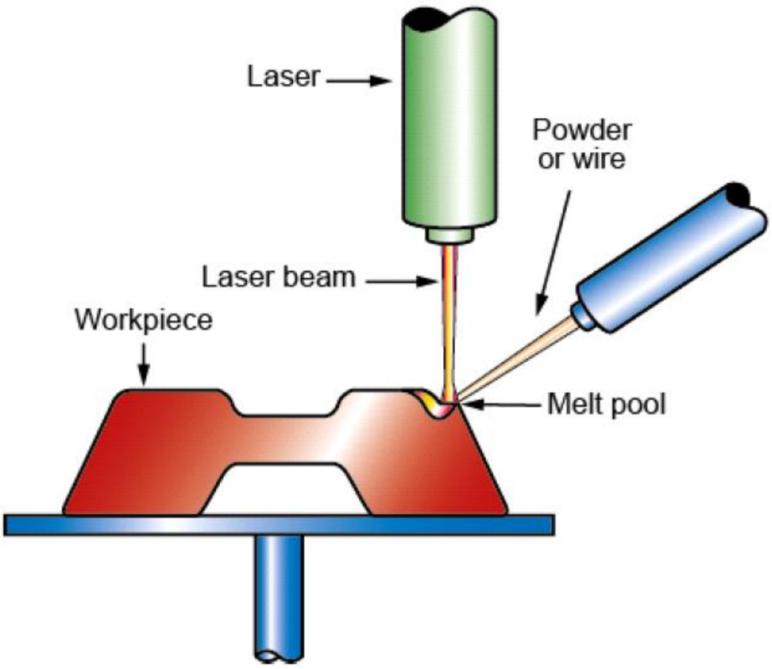

Figure 15 Schematic of the directed energy deposition process [34].

The process that uses gas metal arc, plasma arc, and gas tungsten arc as a source of heat along with filler wire as a feedstock material is termed DED-GMA, DED-PA, and DED-GTA, respectively, as shown in Figure 16(A). The process in which laser is used as a heat source is termed DED-L, in which powder material/wire [44] as feedstock is fed into a melt pool, as shown in Figure 16(B) [45, 46], which creates the part layer by layer on a substrate plate. Argon is usually used as shielding gas to protect the pool of metal from oxidation which also carries the powder particles stream into the pool of metal.

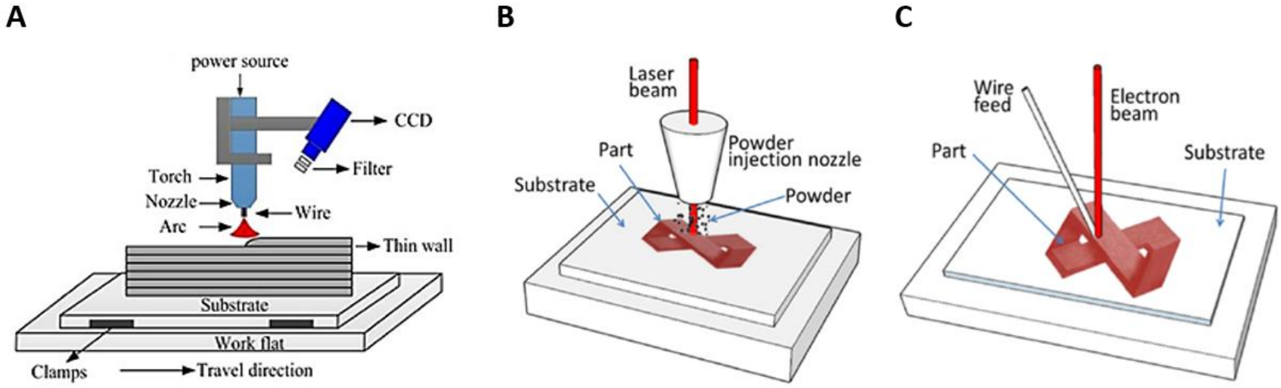

Figure 16 Schematic of direct energy deposition by using laser beam and electron beam, respectively (A) DED-GMA [47]; (B) DED-L; (C) DED-EB [48].

Similarly, the process that uses electron beam as heat source is termed as EBAM or DED-EB which creates a solid structure by feeding feedstock material in the form of filler wire inside a vacuum chamber as shown in Figure 16(C) [49-56]. Arc-based AM techniques consist of an energy source, multi-axis control system, and a wire-feeding system, also termed as wire-arc additive manufacturing (WAAM) [47, 57-59]. These multi axis motion system can be used to manufacture complicated geometries and could be used to repair intricate objects [36, 60].

The ability of DED technique to consolidate material on existing surfaces makes it appropriate for repair applications. It allows multiple axes process execution for non-planner layers, thus removing the requirement of support structures. The use of multiple powder feeders permits the creation of alloys and functionally graded materials. The DED can deposit larger layer thickness; hence, increased deposit rate could be achieved using higher powder feed and laser power rates. This technique could also be used in hybrid systems as it can be operatable with shielding gas instead of environmentally enclosed chamber. This process has a few limitations as higher deposition rates limit the feature size and require post-machining for achieving tolerance and dimensional requirements. The powder capture efficiency could be low and lead to high power losses [4]. The DED techniques based on heat source and feedstock are shown in Figure 17.

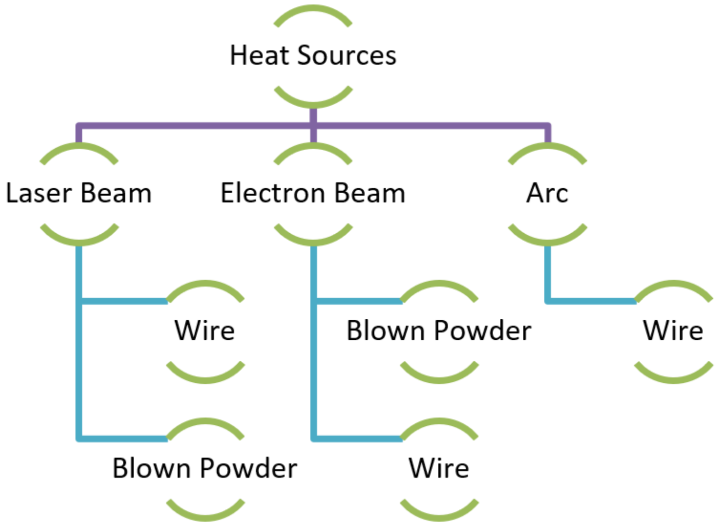

Figure 17 Directed Energy AM techniques based on heat source and feedstock [3].

2.6.1 Wire Arc based AM Processes (WAAM)

The wire-arc AM which is termed as WAAM system contains a wire-feed system, power source, robotic system, which is numerically controlled, and few accessories such as preheating, shielding gas, etc. WAAM can be divided further in different groups such as gas metal arc welding termed as GMAW [61], Gas tungsten arc welding which is termed as GTAW [62] and plasma arc welding which is termed as PAW [63]. Generally, the WAAM system consists of following elements (Figure 18):

1. Computer interface
2. Robot controller - used to synchronize the welding and robot motions
3. Programmable welding power source
4. An industrial robot manipulator
5. GMAW torch implementation
6. GTAW

7. Metal deposition

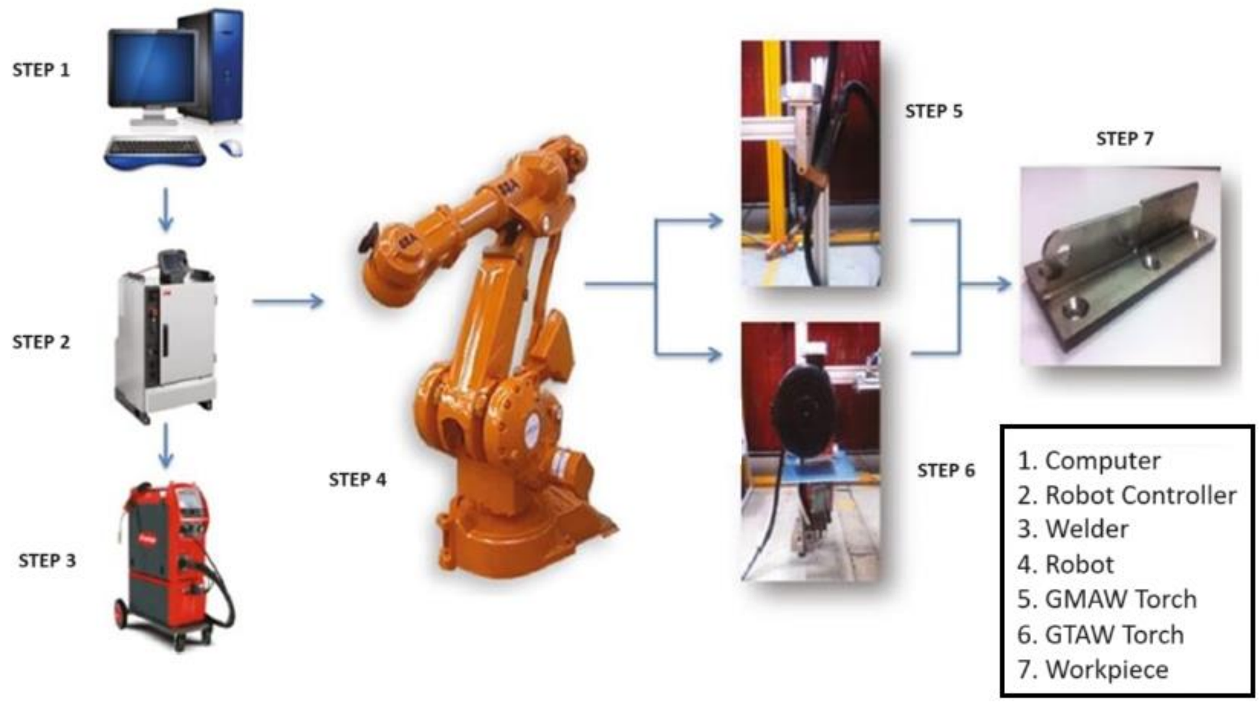

Figure 18 Schematic of WAAM system [64].

The process comparison of different AM is made in Table 3 and it can be seen that the filler wires are cheap and easily available which makes the arc additive manufacturing cost effective comparative to metallic powder. Moreover, wire AM offers high deposit rates in contrast to powder based material and suitable for very large components, especially for object heavier than 10 kg [59].

Table 3 Process comparison [3].

	Deposition Rate kg/h	Maximum Size mm^3	Accuracy μm	Equipment Cost £	Material Cost[a] £/kg
SLM	0.2	350 × 350 × 350	25	500	500
Laser Cladding	1	1000 × 300 × 300	25	1000	500
EBM	0.2	350 × 200 × 200	25	500	500
WAAM	10	-	1 mm to 2 mm	200	180

[a] Prices are for Ti-6Al-4V.

WAAM process rapidly deposits large amounts of material and uses large molten melt-pools. These melt pools often cause problems such as sagging, low deposit accuracy due to gravity, and surface tension that leads to rounded deposition, which results in high surface roughness. Since post-machining is usually applied to the parts, these problems could be solved by employing the near-net shaping production process pursued by subsequent machining.

This technique is considered effective in terms of material consumption and is appropriate for repair of damaged surfaces. Multiple wire feeds could be used to incorporate the different materials.

The limitations of this process include huge thermal and residual stresses; however, residual stresses could be reduced by printing on both sides of the part [4].

2.6.2 GMAW Based AM Systems

GWAM technology makes an electric arc between a consumable wire electrode and workpiece and has different transfer modes such as pulsed, globular, short-circuiting, spray, etc. Cold metal transfer (CMT) is a widely used WAAM process that is based on the controlled dip transfer mode. This mode of transfer has a higher deposition rate and lower heat input [65]. Both single wire process and twin wire process (Tandem GMAW) are used for parts manufacturing; the latter has a higher deposition rate [66]. A double electrode of GMAW by using GTAW is used to increase the material efficiency and deposition rate. It is reported that this technique increased material utilization up to 99%, especially for thin-walled components [67]. The Tandem GMAW and double electrode GWAM is shown in Figure 19 and Figure 20, respectively.

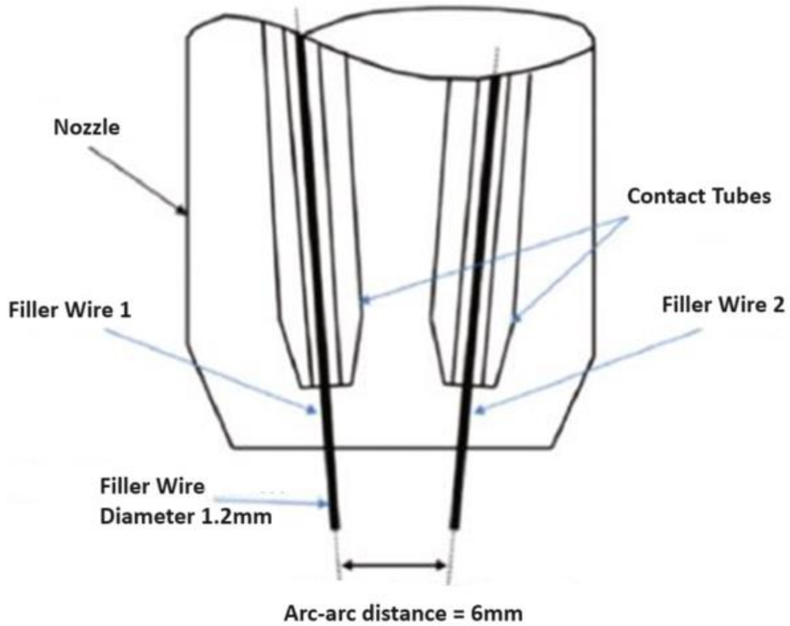

Figure 19 Schematic of tin wire WAAM process [66].

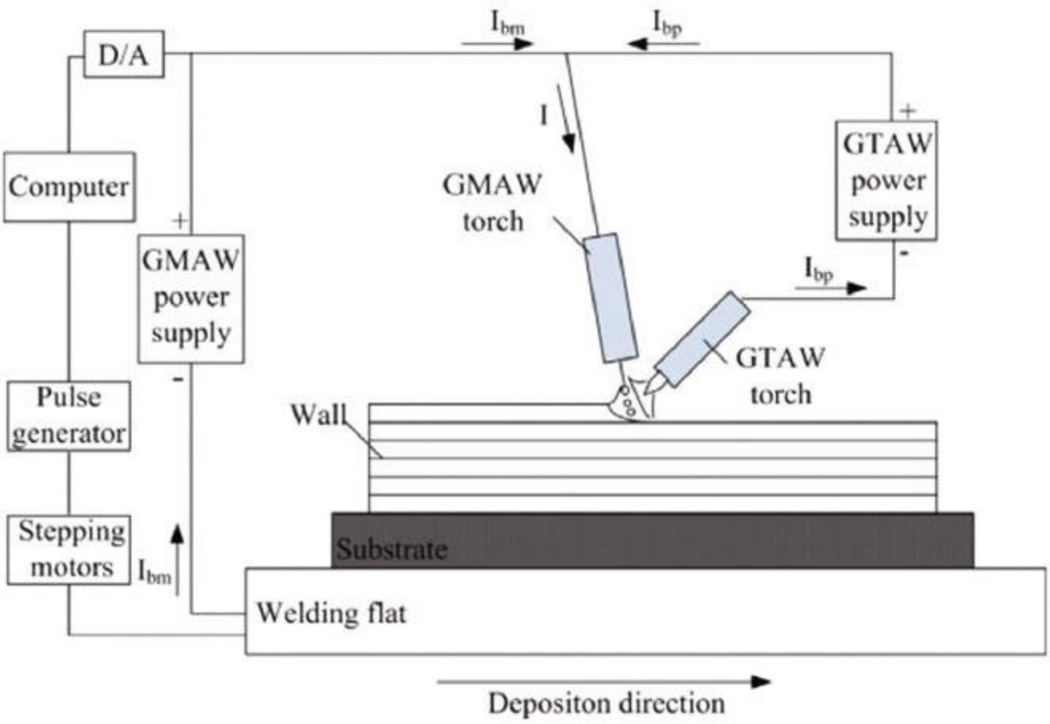

Figure 20 Schematic diagram of double electrode GMAW-based AM [67].

2.6.3 GTAW Based AM Systems

This technique uses a separate feed wire and a non-consumable electrode made of tungsten to produce the deposited layer, as shown in Figure 21. Back feeding, front feeding and side feeding wire may be used for material transfer. Wire feeding influences the material transfer such as Ti and Fe based systems use front feeding technique for better efficiency [68]. To reduce oxidation, a gas lens is used to create a laminar flow of the shielding gas [69]. Twin wire-based GTAW AM was developed to manufacture intermetallic materials. In this technique, two separate wires are fed into a melting pool. The composition is controlled by the wire feed rate of the wires. Trailing gas is used to prevent oxidation, and preheating is used to control interpass temperature [70-72].

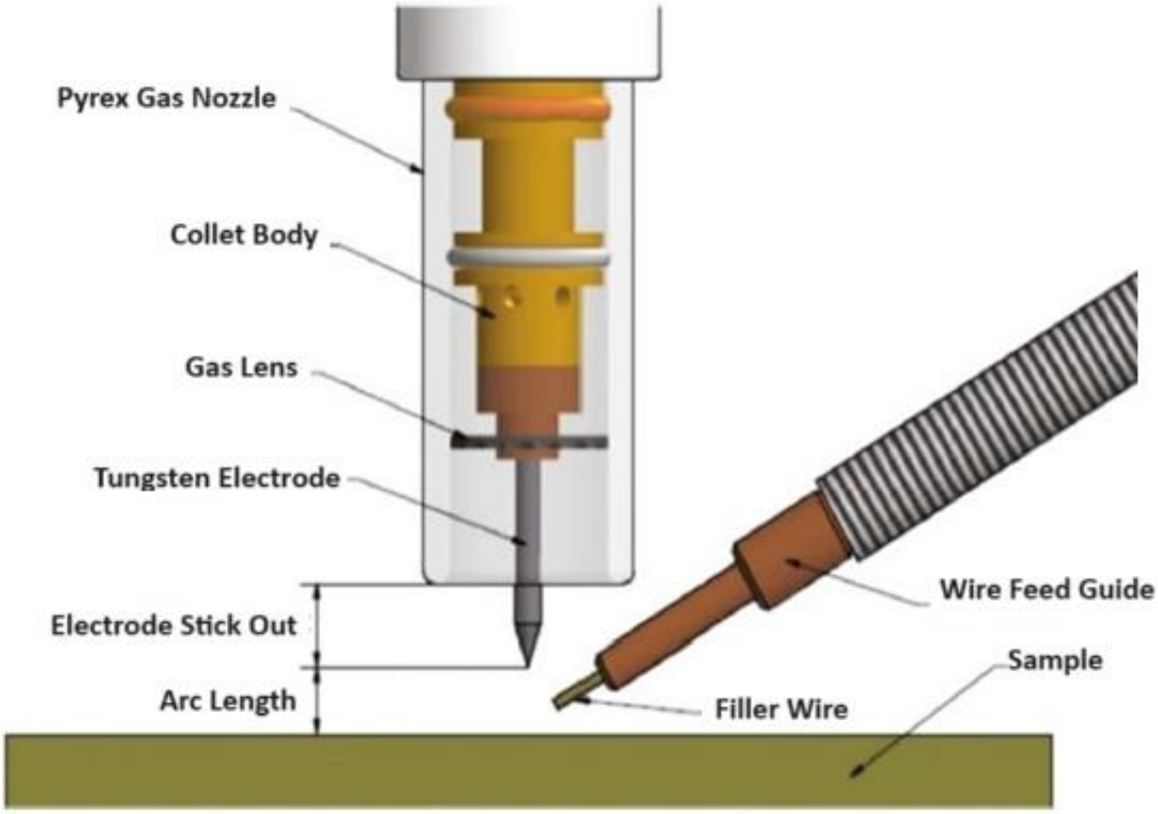

Figure 21 Schematic of GTAW [69].

2.6.4 PAW-Based WAAM System

Plasma arc welding (PAW) technique for AM has been widely investigated [73-75] in which plasma is used as heat source. The energy density in this technique is three times the GTAW energy density. This energy density improvement leads to higher welding speeds with less distortion [76]. The PAW based AM system is shown in Figure 22.

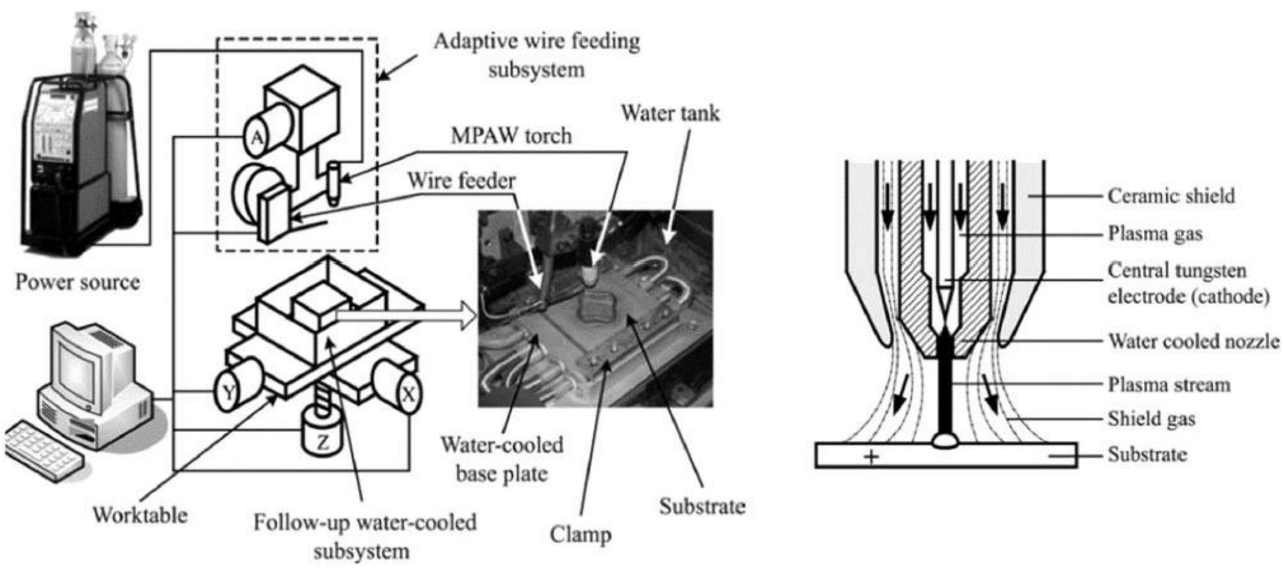

Figure 22 Schematic of PAW based AM [63].

3. Technological Challenges in Metal AM

The technological challenges include process control, metallurgy, porosity, surface roughness, and mechanical properties, which significantly affect the adoption of AM for high-performance and industrial applications where part strength, material consistency, and quality control are critical [77].

3.1 Process Control

The AM processes often observe problems in adjusting the uniform deposition of material. Changes in heat input, material properties, and cooling rates lead to significant challenges in attaining high-quality outputs. Additionally, handling temperature gradient is critical in processes like PBF and DED. The uneven heating and cooling influence the mechanical properties of printed parts, leading to wrapping, residual stresses, and cracks [78].

3.2 Metallurgy

The solidification rate in AM leads to variations in microstructures such as grain size and phase distribution and is quicker than traditional manufacturing processes. This may cause the difference in mechanical properties of AM parts comparative to traditionally manufactured parts. For instance, it is challenging to precisely control the formation of metal phases in the electron beam melting (EBM) process. It can cause defects such as incomplete fusion of particles or undesirable phase formation [79].

3.3 Mechanical Properties

The AM parts mostly show anisotropic mechanical properties, which means the strength of the parts depends on the build direction. This mainly occurs in material extrusion processes where layer-by-layer manufacturing can lead to inter-layer bonding. The build parts may also face reduced fatigue resistance due to defects like incomplete bonding or porosity between layers. These defects operate as stress concentrators and reduce the durability of parts under cyclic loading conditions [80].

3.4 Porosity

The formation of pores in metal AM processes, particularly DED and PBF, is one of the common problems that occur due to insufficient energy input, incomplete melting of powder particles, or poor powder quality. Porosity leads to a reduction in density, which considerably affects mechanical properties such as corrosion resistance and tensile and fatigue strength [79]. Trapped gas pockets, resulting from material vaporization during the melting process, could also form in the parts printed through laser-based systems. This can affect the structural integrity of the parts and lead to undesirable properties.

3.5 Surface Roughness

The AM build parts mostly have high surface roughness comparative to the parts made with conventional ways like casting or machining. This is specifically true for the processes like FDM where staircase effects and visible layer lines are in-built due to the layer-by-layer material deposition. Therefore, to acquire a fine surface finish, post-processing, like polishing and machining, is often required. This increases the cost, time, and complexity of the manufacturing process. For instance, the natural surface roughness of LPBF affects the part performance, particularly from a structural and fatigue perspective. Therefore, the researchers must understand the impact of part performance and its consideration during the design phase [81].

4. Environment & Business Considerations, Energy Consumption and Life Cycle Assessment (LCA)

The environmental impacts are multifaceted in metal AM, involving considerations of carbon footprint, energy consumption and business implications [77]. The lower material waste, efficient use of resources, and no tooling in AM offer environmental benefits. Nevertheless, its energy consumption remains a concern during the manufacturing process, particularly in metal powder bed systems. The impacts from material extraction to end-of-life disposal could be evaluated through a lifecycle assessment approach (LCA). The eco-friendly potential of the process can be enhanced through the optimal utilization of machines, the development of eco-friendly materials, and the use of renewable energy [82]. Metal AM offers both opportunities and challenges from a business perspective. Though the costs associated with energy may be high, the ability of this technology to produce complex geometries with less material waste can lead to cost savings in other areas, such as inventory management and material procurement. Furthermore, companies could explore sustainable practices by connecting renewable energy sources and green technologies into their operations. This could improve the environmental performance and line up with increasing consumer demand for eco-friendly solutions [83].

4.1 Environmental Considerations

Metal AM usually has greater CO_2 emissions per kg of material than conventional manufacturing methods such as wire drawing, forging, casting, rolling, and extrusion. This is due to high energy consumption linked with AM processes, including laser melting and other energy-intensive techniques. Metal AM can be more sustainable in certain contexts despite its higher CO_2 emissions. For instance, AM produces lightweight parts in aerospace due to the design freedom. Lightweight parts can help reduce the carbon footprint and overall material consumption, particularly in areas that require fuel efficiency. Regarding raw material processing, the metal AM was generally less sustainable than traditional manufacturing. Nevertheless, it offered benefits in some instances, particularly in industries where efficiency improvement during usage and weight of the build parts could offset the greater material processing emissions [84].

4.2 Energy Consumption

Energy consumption is one of the critical factors in metal AM, particularly in the processes where high-energy beams are utilized to melt the feedstock materials such as EBM or SLM. These processes affect the overall sustainability and can consume a considerable amount of energy. Though AM reduces material consumption, the energy intensity of these processes remains a concern [83].

4.3 Business Consideration

AM offers the flexibility to achieve rapid prototype and cost savings without significant upfront for startups. It allows us to produce the minimum order quantities and launch the products even during the design-changing phase. Furthermore, it could serve as a pathway for small businesses or individuals to become manufacturers of their products. Starting with prototyping and progressing to applications, the adoption of AM is generally more incremental for established businesses. These companies may face challenges in integrating the AM in existing workflows due to equipment, incumbent processes, and supply chain relationships. However, this technology makes it a valuable addition to the manufacturing capabilities and can offer significant benefits in new product designs and the production of spare parts. In both cases, the transition to AM requires a long-term investment and a cultural shift, as strong leadership support is crucial to driving adoption. Furthermore, in some businesses, outsourcing AM needs could be more cost-effective rather than investing in in-house printing capacity. This model is gaining popularity as it leaves the production to specialized AM service providers and prefers to focus on design and marketing [85].

4.4 Life Cycle Assessment (LCA) of Metal AM

The LCA metal AM products provide a detailed understanding of their social, economic, and environmental impacts. This methodology assesses the whole product lifecycle, including stages such as extraction of raw material, production feedstock, AM processing, post-processing, utilization, and end-of-life management. The ability of AM to reduce waste and enable lightweight designs is a considerable advantage during use phases. It presents challenges like high energy consumption and environmental impacts from feedstock material production. Post-processing operations are necessary to meet the surface quality standards and desired mechanical properties, contributing to the overall environmental footprint. End-of-life considerations, like the recyclability of waste products and materials, are crucial for increasing the sustainability of AM. Studies highlight that adopting repair-based approaches instead of replacement may extend the lifecycle of AM products. They can significantly reduce the energy and material demands over multiple cycles. Comprehensive research is needed to develop predictive models for cost and environmental impact and integration quality considerations into LCA frameworks to leverage the sustainability potential of AM fully. Such methods may help industries reduce environmental hotspots, optimize their processes, and make informed decisions about sustainable manufacturing practices [86].

5. Applications of Metal AM

Metal AM has reformed various industries by enabling optimized, more flexible, cost-effective production methods. The detailed applications of this technology across various sectors are as follows:

5.1 Aerospace Sector

Metal AM is critical in defense and aerospace by providing lightweight and durable parts. Aerospace manufacturers used 3D printing to create components such as light housings, door handles, power wheels, and even full interior dashboards that prioritize functionality and aesthetics. It is valuable for making aerospace components from costly materials like titanium, where reducing waste is a significant cost-saving factor [87]. To achieve more than 30,000 seconds of hot-fire time and significant cost and time savings, NASA has widely applied AM for engine parts, including nozzles and combustion chambers made from high-temperature alloys such as Inconel 718. In addition to that this technique is employed to manufacture static and dynamic engine components to withstand extreme operating conditions [88]. A NASA liquid oxygen (LOX) turbopump, an example of a stator from NASA, can be seen in Figure 23.

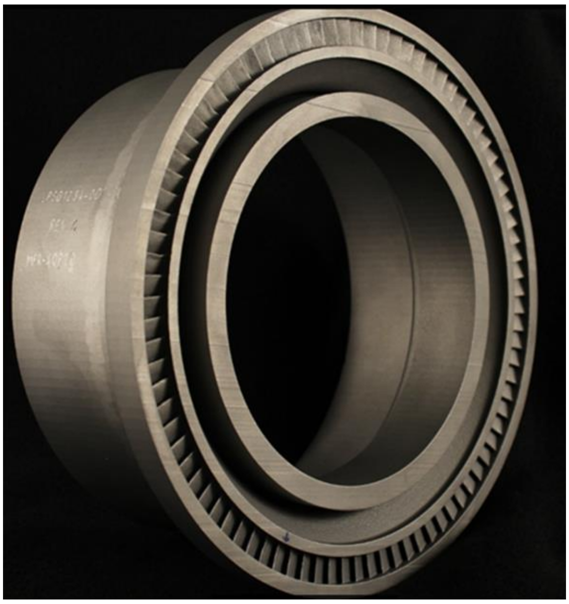

Figure 23 Engine Liquid Oxygen (LOX) Turbopump - AM Demonstrator [89].

The aerospace industry was among the primitive adopters of additive manufacturing technology, particularly metal AM, which is valuable due to its ability to build consolidated parts, complex geometries, and utilization of materials that are hard to machine. General Electric (GE) aviation's manufacturing of fuel nozzles for LEAP engines is one of the notable applications in aerospace [90, 91]. Similarly, Airbus manufactures bleed pipes, metal brackets, and large-scale airframe parts built using additive manufacturing technology, which helps reduce weight and improve fuel efficiency [92].

5.2 Automotive Industries

Metal AM is extensively used in the automotive industry for tooling, rapid prototyping, and even manufacturing finished parts with an average increase of 3.6% in the latest years [93]. It allows the designers to quickly change their digital designs into physical prototypes, ranging from simple interior parts to full-scale car models or complex dashboard assemblies. The rapid prototyping capabilities enhanced the overall manufacturing process efficiency by significantly reducing the product development cycle. Moreover, metal AM allows the production of durable and lightweight parts that help in reducing the overall weight of the vehicle, which in turn increases the performance and fuel efficiency. Its ability to make on-demand parts also minimizes waste and reduces production costs, providing economic benefits to automotive manufacturers [87]. It is advantageous for making parts with complex shapes, such as thin walls, internal channels for cooling, and curved surfaces that are critical for minimizing weight and improving aerodynamics, used for prototyping and validation that allows the rapid creation and testing of numerous design iterations. For instance, high-detail prototypes such as wing mirrors and dashboards can be produced using material jetting technologies and SLA, which provide a smooth surface finish suitable for aerodynamic testing and aesthetics. In the context of production, metal AM has been adopted for manufacturing spare parts on demand, improving supply chain efficiency and reducing inventory costs [94]. For example, the BMW Group used a 3D-printed fixture for soft-top attachment and a window guide rail in the i8 Roadster [92]. Similarly, Bugatti also used metal AM to enhance the efficiency and performance of their vehicles by producing parts like a topology-optimized bracket with integrated water-cooling circuits and Ti6Al4V brake caliper [95].

5.3 Medical and Dental Sector

Metal AM has vast applications in the dental and medical sectors [96]. It is used to build surgical tools, medical devices, and patient-specific implants using the medical imaging data of patients. This technological development allows us to make anatomical models that enhance the precision of surgical procedures by assisting in decision-making and better preoperative planning. Additionally, 3D printing aids in developing custom implants and prosthetics according to the anatomy of individual patients, improving the comfort and fit for the patient. Furthermore, innovations in bio-printing are leading toward the fabrication of tissue scaffolds and transplant-ready organs. These developments pave the way for the latest medical research and treatments in regenerative medicine [87]. Medical companies such as Nexxt Spine and Lima Corporate use metal AM to build porous titanium spinal implants and orthopedic devices, respectively [92]. A commercially available orthopedic device is shown in Figure 24(a), and A Titanium AM spinal cage is another example in Figure 24(b).

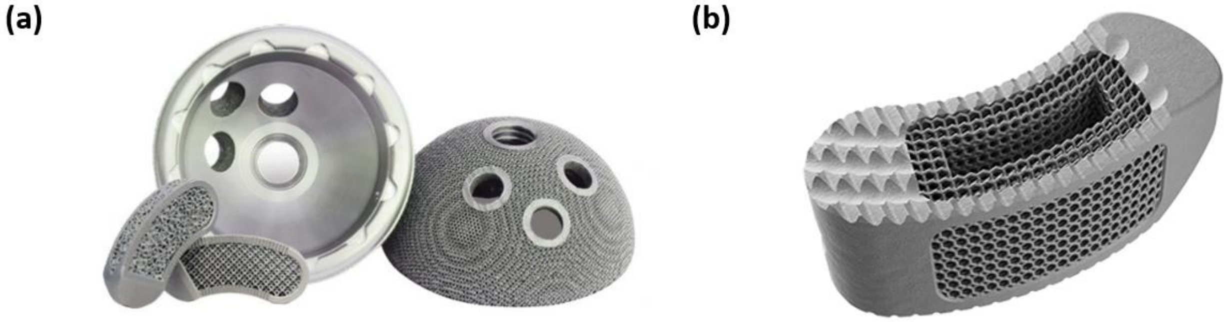

Figure 24 (a) Orthopedic Implant [97], (b) Spinal Cage produced by Nexxt Spine [98].

A study showcases the utilization of LPBF to build pure zinc (Zn) with hierarchical heterogeneous microstructures for implant applications. The microstructural control at multiple scales, including micrometer-scale bimodal grains, millimeter-scale molten pool boundaries, and nanometer-scale dislocations, helps achieve superior strength ductility synergy. These microstructural features increase the ductility and tensile strength. For example, the produced Zn material showed a unique bimodal grain structure that balances the ductility and strength through grain boundary strengthening and deformation twin formation. Furthermore, the LPBF process allows precise customization of implant geometry, mechanical properties, and porosity, crucial for promoting osseointegration and cell proliferation in medical applications [99].

Another study focuses on Voronoi based architected metamaterials manufactured with LPBF, tailored for bone implant applications. The research precisely controls porosities and unit cell topologies, considerably enhancing permeability and mechanical properties. These lattice-inspired voronoi-based metamaterials (LIVMs) show specific energy absorption values from 3.81 to 14.29 J/g and yield strengths from 3.35 to 17.59 MPa, making them ideal for load-bearing conditions in medical implants. Additionally, LIVMs show permeability values consistent with human trabecular bones, promoting cell proliferation and effective nutrient diffusion. This control over mass transport and mechanical behavior is acquired through novel design strategies enabling reduced stress concentration, optimized stress distribution, and increased load-bearing capacity [100].

5.4 Construction

The use of metal AM for construction applications is comparatively low due to its limitations of printing small volumes, long printing times, environmental issues and high initial costs [101]. Although still evolving, metal AM has revolutionized the construction sector by enabling large-scale and complex structures that were previously difficult to construct with traditional methods [102]. Techniques like direct energy deposition (DED) and powder bed fusion (PBF) are specifically utilized due to their ability to construct parts with complex geometries and high precision [103]. Early uses of this technology in construction have focused on components like structural connections and façade nodes, allowing for innovative designs and more optimized geometries [104]. For example, the Nematox façade node (Figure 25) was developed with aluminum powder using powder bed fusion (PBF) for creating intricate geometries that increase the aesthetic appeal and structural performance. This application emphasizes producing high-precision parts that integrate seamlessly into existing building systems, potentially minimizing costs and construction time [105].

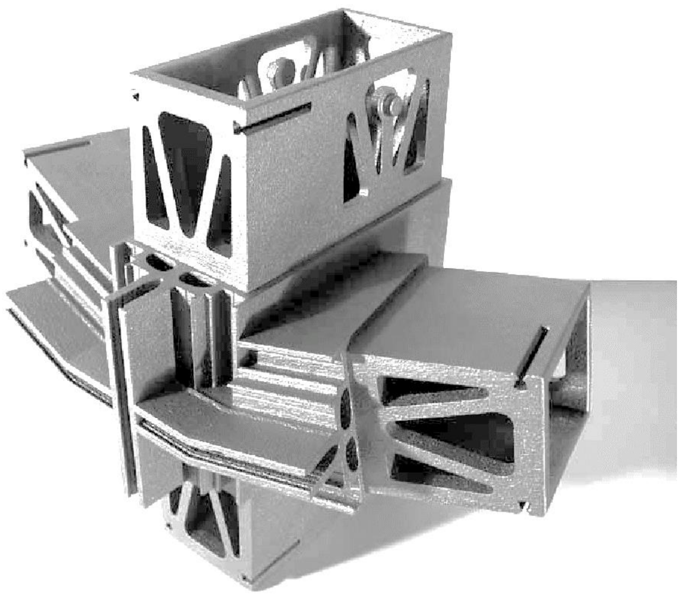

Figure 25 Nematox facade node mock-up [104].

Another considerable application is the improvement of optimized structural nodes, such as redesigning the Arup lighting node [106] using topology optimization to reduce manufacturing costs and material usage. This node was manufactured with powder bed fusion (BPF) using ultra-high strength steel powder, and it demonstrated a significant weight reduction (75%) compared to its conventionally manufactured counterpart. Similarly, the MX3D bridge project in Amsterdam is another example of 3D printing where wire arc additive manufacturing (WAAM) was used to construct a full-scale metal pedestrian bridge. These projects show the growing role of AM in producing lightweight, optimized, and sustainable construction parts [102].

5.5 Other Industries

AM is an emerging stage in various other industries to revolutionize them, too. For instance, it is beneficial in defense applications where it aids the rapid production of critical components and spare parts of missiles. It reduces the dependency on original equipment manufacturers (OEMs) and traditional supply chains by manufacturing customized and on-site parts. The parts can be produced as needed rather than being stored in massive amounts, which contributes to reducing material consumption and lowering warehousing costs [87]. The space industry also benefits from AM by constructing spacecraft structures and components that must bear harsh environments. It aids in creating waveguide brackets and antenna brackets on the sentinel satellites of Juno's mission to Jupiter. It has also been used in creating lattice structures for satellite applications. For example, Altair Engineering and RUAG collaborated to create optimized satellite brackets with enhanced performance characteristics [88]. AM also helps produce thermal devices such as heat sinks and heat exchangers [107]. For instance, NASA’s Perseverance rover uses AM-built heat exchangers designed to withstand the utmost temperatures on Mars [89].

The reduction in cost and improvement in supply chain efficiency highlights the importance of metal AM in the oil and gas industry [108]. Some companies like Siemens have effectively produced complex parts using AM technologies such as turbine blades and burner heads [92]. In the communication and electronics sector, metal AM is used to build novel parts like waveguides, antennas, and RF filters [109, 110]. For example, Optisys LLC offered a significant reduction in lead time, cost, and weight by producing lightweight RF antennas using metal AM [92]. Metal AM is also being adopted by the railway sector for producing spare parts and lightweight components with an addressal of challenges such as long lead times for replacements and discontinued parts [111]. Deutsche Bahn AG and Webtec use AM technologies to build spare parts and components for older fleets [92]. The capability of Metal AM to produce on-demand spare parts, maintain continuous operations, and reduce downtime benefits industries located in remote areas like the mining industry [112]. Companies like Sandvik and Aurora Labs are discovering the applications of this technology for manufacturing components of mining equipment to enhance the efficiency of the supply chain and reducing lead time [92]. The tools and molds industry are also using metal AM for creating optimized tools with conformal cooling channels. It enables manufacturing complex mold inserts and other tooling components that are difficult to make using traditional ways [113, 114].

6. Latest Trends in Metal AM

The recent trends in metal AM uncover noteworthy improvements changing industries from biomedical to aerospace engineering. Considerable advancement has been made in applying high-entropy alloys (HEAs), especially in making nickel-based HEAs using EBM, SLM, and LMD processes. These materials show corrosion resistance, superior strength, and mechanical properties, making them the best for critical applications in the energy and aerospace sectors [115].

HEA products have the ability to build geometrically complex shapes with increased performance characteristics. Notably, they are made up of multiple principal elements that are ideal for use in high-performance applications such as energy, aerospace, and tooling. They exhibit high corrosion resistance, exceptional thermal stability, and superior mechanical properties under extreme conditions. The methods such as mechanical alloying and atomization considerably impact the quality of printed products. Printing technologies such as EBM and SLM enable the precise control of phase formations and HEA microstructures. These techniques ensure that HEAs continue their unique properties in their printed forms. The consistency of HEA's unique properties in the printed form opens up new ways for industrial applications [116]. A recent study shows the potential of doping aluminum with HEAs to reduce the SFE, which inhibits the formation of cracks during the LPBF process. The Al-doped FeCoCrNi HEA showed improved elongation and superior crack resistance without compromising the tensile strength. This development makes HEAs highly suitable for complex applications by providing valuable insights into creating high-performance crack-free products with superior strength-ductility synergy [117].

Meanwhile, the role of metal AM, especially utilization of stainless-steel alloys, cobalt and titanium in biomedical implants is becoming more prominent. This printing technique has the potential to print the customized patient specific solutions such as direct metal laser sintering are vital in constructing 3D scaffolds for implants [118].

Modifying material microstructure is a pivotal aspect of AM, especially for medical applications. A titanium alloy-based 3D printed Anatomical Assembly Thin Bone Plate (AATBP) exemplifies precise control over microstructure in AM and increases mechanical performance. This bone plate shows more biomechanical stability compared to traditional methods. Using LPBF for production enables the optimal microstructural features and creation of complex geometries, including resistance to fatigue under dynamic loads and uniform stress dispersion. These improvements are keen for medical applications as they ensure superior fit, high precision, and effective load distribution in orthopedic implants. The AATBP’s optimized microstructure reduces the complications such as implant failure and increasing osseo-integration, which supports better post-operative and improves its mechanical properties [119].

Another key area is the growth of multi-material AM through DED which integrates various metals into a single structure. It helps in reducing stress concentrations and optimize mechanical performance particularly in nuclear power plant applications [120]. These advancements exhibit the evolving role of metal AM in forming complex and high-performance parts efficiently. It may offer new paths for future research and applications in different industries.

Latest developments in metal AM have also seen a significant integration of artificial intelligence (AI) and machine learning (ML) technologies to improve the processes and quality of products. Machine learning plays a critical role in material design and process optimization. It helps the engineers overcome the challenges of high costs and complex experimental cycles. It is specifically effective in predicting and guiding AM processes that substantially accelerate manufacturing efficiency and material discovery. Studies show that the assistance of ML models in designing and process development ensures better control over processes and improved production time and mechanical properties [121].

Furthermore, surface roughness is a critical quality metric for metal parts in industries like automotive, aerospace and medical devices and could be predictable with the help of AI. Deep learning methods offer a novel approach to predicting surface quality, minimizing re-processing time, and ensuring product compatibility with technical specifications. These developments enhance manufacturing efficiency and reduce cost by reducing errors [122]. Thus, a blend of AI/ML with metal AM holds massive potential to change industrial manufacturing methods by delivering improved productivity and performance across sectors.

7. Limitations of Review

This study provides a broad overview of metal AM technologies, aiming at their working principles, environmental and business considerations, energy consumptions, applications, and latest trends. However, it is essential to acknowledge certain limitations. The discussion on each technology is comparatively brief and does not explore profoundly explicit use cases, performance comparisons, or industrial challenges. Furthermore, material-specific aspects such as cost analysis and compatibility are not extensively covered. The review concludes recent advancements; it does not provide comparative data on the efficiency or feasibility of the technologies. These limitations highlight the scope of this review as a primer anticipated to guide further in-depth research and exploration.

8. Conclusion

Additive Manufacturing (AM) has now become a tangible part of industrial processes particularly famous for custom-made metal components. It has been developed as a transformative technology for various industries by offering customization, unique design freedom, and material efficiency. The review showcases how several metal AM methods, for example, PBF and DED, are being used to build complex parts in industries like medical, automotive, defense, and aerospace. It addressed aspects relating to the business and environmental considerations, technological challenges, and energy consumption associated with metal AM. The ability of AM's techniques to build complex shapes with reduced production time and weight helps these industries contribute to considerable advancements in production development. Regardless of extensive adoption, there remain challenges associated with process reliability, cost, and material limitations. However, the future of metal AM holds vast potential with the integration of machine learning (ML) and artificial intelligence (AI) into the AM processes. These inclusions promise to increase the precision of this technology by optimizing process parameters, enabling real-time monitoring, and predicting product defects. Furthermore, the development of new materials such as stainless steel and high entropy alloys could further grow the capabilities of metal AM and make it suitable for a vast range of applications.

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Author Contributions

Muhammad Qasim Zafar: Performed literature search, writing - original draft. Ramisha Sajjad: writing - review and editing. Muhammad Tuoqeer Anwar: conceptualization. Anas Bin Aqeel: formal analysis. Muhammad Salman Mustafa: methodology. Naveed Husnain: writing - review and editing.

Muhammad Bilal Khan: data curation. All authors have read and approved the published version of the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

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