Metal Additive Manufacturing in Space and Aerospace Exploration: Current Processes, Material Selection and Challenges

Balakrishnan Subeshan, Zaara Ali and Eylem Asmatulu [1]

[1] Department of Mechanical Engineering, Wichita State University
1845 Fairmount Street, Wichita, KS 67260, USA, Email: e.asmatulu@wichita.edu

Abstract

Space and aerospace exploration have the highest regulations regarding design and manufacturing processing. As a result, an immense multi-tier manufacturing system has been developed because of the tooling and machinery associated with the production of high-grade spacecraft and aircraft. Furthermore, the nature of the supply chain and hefty capital investments further complicate spacecraft and aircraft manufacturing. Metal additive manufacturing (AM) offers the best solution to produce complex parts from digital information without the need for large amounts of tooling and machinery. MAM represents a promising aspect of innovations to revolutionize the way manufacturing is designed and constructed for many applications. Moreover, various research activities are being carried out in the aerospace industry for MAM process, which produces parts that would be impossible to create using conventional manufacturing (CM) methods. MAM has gained popularity in recent years from its initial stages of development in the research phase to providing a wide range of functional applications in the aerospace industry to manufacture and repair a wide range of components used in spacecraft and aircraft. The significant growth in MAM process can be attributed to its commercial and performance advantages within the aerospace industry. In this paper, a detailed assessment of existing MEM processes is presented, emphasizing the ability to manufacture and repair metal parts for the aerospace industry, providing information about the materials currently in use, as well as identifying possible future applications and challenges. There is no doubt that the information provided in this study will support exploring MAM's new opportunities for future needs in space and aerospace exploration.

Keywords:

Manufacturability, metal additive manufacturing, rapid prototyping, design optimization, space, and aerospace applications

Highlights:

- The *complexity* provided by the AM process is a significant advantage for aerospace applications
- A primary driver for AM technology is the inherent design flexibility and freedom it permits
- AM helps design and manufacture complex geometries while optimizing weight
- AM helps greatly lower the cost and lead time of commercial aerospace activities

Submitted: 20-MAY-24

Accepted: 14-AUG-24

Published: 06-OCT-24

DOI: 10.5455/jeas.2024021104

1. Introduction

The concept of additive manufacturing (AM) has been around for several decades now. It is described in standards ASTM F42 and ISO TC 261 as the procedure for creating a solid three-dimensional (3D) object using a computer-aided design (CAD) model, generally layer-by-layer, with the help of digital information technology, as shown in Fig. 1 [1]. During the 1960s, the first attempts at AM were made. Photopolymers have interacted with laser beams to fabricate solid objects in a resin vat. Over the past few decades, the manufacturing industry has developed many new technologies for producing low-volume, customized, and highly reliable products with high levels of complexity and technical requirements [2]. It has been reported that several AM processes have been developed, such as: stereolithography (SLA), filament fused fabrication (FFF), selective laser sintering (SLS), selective laser melting (SLM), direct metal deposition (DMD), material jetting (MJ), binder jetting (BJ) and direct-ink-writing (DIW).

In AM, material science and part modeling are the two-basic fundamental components for producing 3D-printed parts, followed by knowing which material is appropriate for the application based on mechanical, thermal, and aesthetic standards, followed by being able to design and manufacture that part. There are a variety of materials that can benefit from AM, including metals, polymers, composites, and ceramics. The AM equipment requires a 3D CAD model to operate, and the key to this manufacturing process is the ability to design and manipulate that model [3].

AM endorses various applications in various industries, including component manufacturing, aerospace, military, medicine, dentistry, and architecture [4,5]. Nevertheless, not all AM processes are capable of producing metal parts for the various industries. Here, we refer to metal additive manufacturing (MAM) process currently available for manufacturing components with complex materials (pure metals, alloys, and composites made from metal matrix), that are required by the various industries [6–9].

MAM processes include powder bed fusion–selective laser sintering (PBF-SLS), powder bed fusion–direct metal laser sintering (PBF-DMLS), laser metal deposition (LMD), electron beam melting (EBM), sheet lamination (SL) and wire and arc additive manufacturing (WAAM) as the most efficient and available processes, which are applicable to utilize today [10–12].

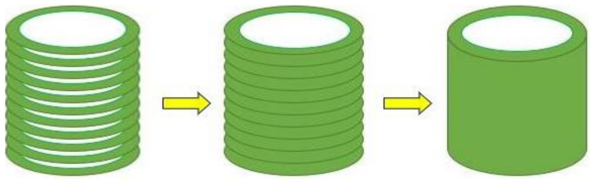

Fig. 1. Layer-by-layer AM process.

MAM permits the production of complex geometry parts, which are difficult to obtain since the procedures for material removal are complicated and time-consuming in conventional manufacturing (CM) methods. Unlike CM methods, which have many limitations in product design, the flexibility of MAM allows manufacturers to optimize a lean production method, which, by its very nature, eliminates waste [13]. Also, MAM can quickly assemble multiple parts into one product instead of creating multiple parts individually. MAM has found enormous success in manufacturing end-products, driven by improved manufacturability and reduced lead time because of the more precise position and manufacturing methods. The 3D-CAD software determines how to create a part by slicing it into small layers and where to add build supports, which allows for tool-free production using MAM [14]. Likewise, there are many advantages of MAM over CM methods. One is the ability to customize products that conform to customers' needs. In addition, customization allows for resetting CM methods. Also, MAM's customization is beneficial to both customers and consumers because it does not entail additional costs. In addition, companies that apply MAM process has the ability to produce end-product components on an as-required basis, which means there is no need for large storage areas [15]. Additionally, MAM is also beneficial to the environment. About 90% of metal and alloy materials are wasted during CM methods, thereby polluting the environment. However, with MAM, 90% of metal and alloy materials can be consumed during production [16].

MAM is a process which traced back as the 1980s, with some aerospace companies beginning this technological experimentation as early as 1988 [17]. Over the years, MAM adoption in space and aerospace exploration has increased and is expected to increase more revenue as technology develops to create more reliable and certified products. Several reasons underlie MAM's relatively widespread adoption in space and aerospace exploration [18]. Original equipment manufacturers (OEMs) are large companies that produce/own spacecraft and aircraft, including Boeing, SpaceX, Lockheed Martin, Airbus, and GE Aviation. The complexities of producing spacecraft and aircraft require OEMs to work with many suppliers. The supply chain involves the production of spacecraft and aircraft consists of a three-tier system. First, tier-one companies manufacture the essential sections of the spacecraft and aircraft, such as frames, fuselages, engines, and necessary gears. Tier-two and three companies supply predominant components to tier-one companies. Over time, a significantly extensive manufacturing company network comprises this three-tier system. The complex nature of producing spacecraft and aircraft results in some of the most demanding supply chain management seen in manufacturing [19].

The aerospace industry is just a few industries showing a high interest in MAM. Reducing the buy-to-fly (BTF) of the material, which is the amount of raw material required per final component, can lower material acquisition costs, embodied energy costs, and fuel costs during production. Several large companies, including Boeing and NASA, use MAM on their spacecraft and aircraft components. The CM method involves fabricating a product from a large billet, which is then machined down following fabrication of the initial billet. Therefore, machining multiple components need more billets, resulting in inefficient materials and a high amount of waste, such as 90% of materials, with high BTF ratios, generally 10:1, which produces poor material productivity [20]. The manufacturing of spare parts for the aerospace industry needs to be responsive and fast to fulfill the requirements. Having an inventory of the desired spare part can be extremely expensive and does not guarantee its use. On the other hand, manufacturing a spare part does not ensure a quick lead time and is exceedingly costlier than the original part. MAM is an evolving process that can help alleviate these problems in the aerospace industry [21–24].

The advantages of working with MAM products include that MAM produces net-shaped products. As a result, MAM has an extremely low scrap rate and a BTF ratio close to 1:1, which reduces the amount of materials and machine time needed to post-process the parts [25]. Using the MAM process, the structure of the 3D CAD model can be produced immediately in a relatively short time and then converted into an end product. One of the significant factors of spacecraft and aircraft development is the weight reduction of spare parts and aerial parts associated with space and aerospace exploration. In producing parts at a low cost, it is important to emphasize that structural materials within the aerospace industry must be exceptional in terms of strength and durability [26]. The design freedom, energy and material savings, and shorter design-to-production times are among the most prominent advantages of all MAM methods. Several processes can be considered MAM, including some less common in the industry, including powder deposition or sheet lamination. Several different MAM processes are available in the market today, each offering its own set of benefits and limitations depending on the service it provides [27]. Recent advancements in MAM for space and aerospace applications highlight significant progress and promising developments:

- Metal 3D Printing in Space: In January 2024, AddUp and Airbus Defense & Space launched a metal 3D printer to the International Space Station (ISS). This project, Metal3D, aims to test the capabilities of metal additive manufacturing under microgravity, enabling the in-space production of metal parts and reducing reliance on Earth-based supplies.

- NASA's Initiatives: NASA is exploring the use of Mars regolith for 3D printing to create essential structures on Mars, such as habitats and roads. This initiative supports NASA's goal of making in-space manufacturing a critical component of future Mars missions.

Key challenges include miniaturizing equipment for the ISS and ensuring safety due to high temperatures required for metal printing. Airbus addressed these by using a sealed metal box and wire-based printing methods.

Implementing metal additive manufacturing in space can lead to cost savings and logistical efficiencies, making space missions more sustainable and economically viable. This technology is crucial for maintaining a human presence on the Moon and Mars. These developments mark a significant step toward more autonomous and sustainable space exploration [28].

This comprehensive analysis provides novel insights that are poised to drive significant innovations, supporting the industry's quest for enhanced efficiency, performance, and sustainability. In this review, MAM processes have been prioritized because they are the most relevant in the aerospace industry Additionally, the study presents a brief overview of the M AM processes currently in use and provides an overview of their key characteristics. This study also examines the different materials incorporated into the MAM process. Moreover, the aerospace industry's current outstanding issues that prevent MAM process from entering mass production are discussed.

2. Metal Additive Manufacturing Processes for Aerospace Industry

Due to the necessity of metal and metallic composite usage in space and aerospace exploration, mainly MAM processes are widely used. Various MAM processes build layers of metal wire or powder particles in different ways and eventually combine all those layers to manufacture one single product. Some MAM processes are combined based on the thermal properties of metal wire or powder particles. Therefore, the metal wire or powder particles' melting point and sintering temperature control are the most critical considerations in MAM processes. Furthermore, some MAM processes are combined based on the thermal energy of the lasers or electrons that the optical system directs to melt or sinter. These processes use metal powder particles as the primary material to form the final product [29].

Sometimes, industry nomenclatures contradict each other, particularly when it comes to the difference between complete melting and partial melting (sintering). Some companies whose MAM processes fall into a particular MAM category modify their MAM processes slightly or use different terms, making the classification more difficult [30]. All the MAM processes are performed with different levels of energy. From there, it is essential to choose the best quality, most accurate, and functional MEM process that meets the expectations for space and aerospace exploration.

It is essential to divide the possible outcomes of manufacturing according to operating processes and equipment. The quality of the product must be desirable for the application, and the product's value must compensate for the cost without harming the environment or worker safety [31]. Although different MAM equipment uses identical procedures and materials, choosing the process used to manufacture components is also crucial. These differences are generally classified according to the part geometry, specifications of the machine, and materials involved.

In terms of part geometry, MAM processes significantly increases the design freedom compared to CM methods [32]. An essential factor with increased design freedom is the potential to create undercuts, profiles, and overhangs easily. It similarly helps in creating small- and medium-size parts. In the case of more significant parts than the building envelopes during the manufacturing process, the parts must be separated and manufactured smaller to fit the building envelope. Eventually, all small parts must be assembled to form a significant component. On the other hand, small-size components may be produced with exceptional precision and higher accuracy using the MAM process rather than the CM method because more precision can be obtained from a computer-controlled system in the MAM process [33].

MAM's primary attraction is eliminating many of the constraints in traditional manufacturing processes, thereby allowing unprecedented design freedom. Here the time and cost are primarily reduced, making MAM an essential part of impending manufacturing systems. Aerospace companies have started taking advantage of MAM in their wide range of applications for two reasons. First, mass savings are feasible, and mass is directly associated with cost. Second, MAM may produce complicated parts more quickly than traditional manufacturing methods, thereby shortening the manufacturing period from a year to only a few months [34].

Agencies similar to the National Aviation and Space Administration (NASA) have been potentially directing various investigations on employing MAM in creating a collection of aerospace-related products and the likelihood of additive manufacturing a complete space shuttle in orbit! However, mass production of MAM in the aerospace industry has not occurred currently, mainly due to the struggle in modeling the manufacturing process and foreseeing the properties of manufactured components. This brings up the issue of common deficiency and thus confined usage in the aerospace industry [35–37].

MEM process can be based on metal wires or powder particles, depending on the used material. Aluminum, stainless steel, titanium, and cobalt chrome are typical materials used for MAM process. The significant variance among MAM processes is probably in the choice of materials. For example, if one MAM equipment can create titanium components, this does not mean that another MAM equipment can do the same [38]. Each MEM equipment has a detailed group of materials to choose from, depending on the need. Metals and alloys are the most widespread materials used in aerospace industry. The variance in materials generally affects the design freedom and the equipment's specifications [39]. When selecting a different material to create a component, the design or structural engineer must choose from a shortlist of materials available for the MAM equipment.

The MAM process has several stages, from the virtual description of the CAD model to the final physical part. Only the raw material is required at the beginning stage of the product development, and then MAM process is used to handle the rest of the stages to speed up production. In the later stages of the product development, the parts should be thoroughly cleaned and post-processed such as grinding, surface preparation, and painting, which are essential before product use [40]. Fig. 2 shows various stages of the MAM process, and an explanation of each stage follows.

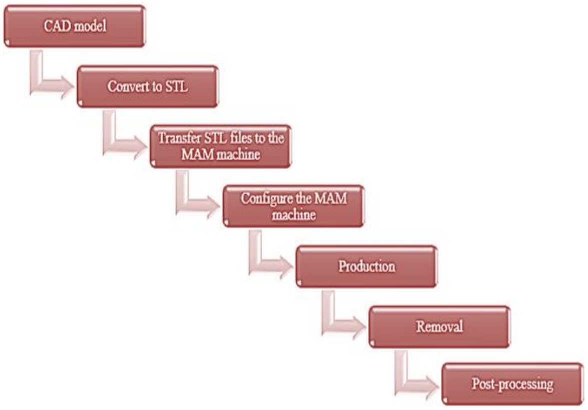

Fig. 2. Seven stages of the MAM process.

Stage 1: Create a model using CAD—Entire MAM components must begin through a CAD structure, which ultimately defines the exterior geometry and may require the utilization of professional 3D CAD software.

Stage 2: Convert the model to Standard Triangle Language (STL) file—Almost all MAM machines adopt the STL file format, which defines the closed surfaces of the original 3D CAD model and serves as the basis for sectional calculations.

Stage 3: Transfer STL file to MAM machine—The STL file relating to the part must be directed to the MAM machine. In this case, the general management of files relies on the creation's size, position, and orientation.

Stage 4: Configure the MAM machine—The MAM machine must be configured correctly before starting the build process. These parameters are associated with design parameters: material constraints, energy source, layer thickness, and duration.

Stage 5: Produce the parts—Parts production is primarily a computerized process whereby the machine can remain virtually unattended. At this stage, only a superficial inspection of the machine should be carried out to ensure that there are no faults, such as the finishing of the material, power problems, or software glitches.

Stage 6: Remove the parts—When the production is completed, the parts must be removed; contact with the machine may be required to remove the parts. There may be safety interfaces, such as low-enough operating temperatures or no active moving parts.

Stage 7: Post-process the parts—When the parts are detached from the machine, additional cleaning may be required before being used. At this point, the parts may be weak, or they may have supported construction that must be detached.

2.1. Powder Bed Fusion - Selective Laser Sintering

PBF-SLS is a process that has developed from being primarily used in research applications into a strategic manufacturing tool for aerospace engine manufacturers. In addition, more than a handful of various aerospace engine components can be pre-produced and tested early by various aerospace suppliers. As a result, this MAM process has now got the market's attention for MAM parts, including various safety-critical structural components, and exploring the possibility of manufacturing large-size components. In the PBF-SLS process, a layer of powder particles is applied, and the layer is melted by a laser beam. Next, the baseplate is lowered, and a new layer of powder particles is applied. After scanning each cross-section, solidification occurs, the powder bed is lowered to one-layer thickness, another layer of metal powder particles is applied, and the procedure is repeated until the component is completed, as shown in Fig. 3 [41].

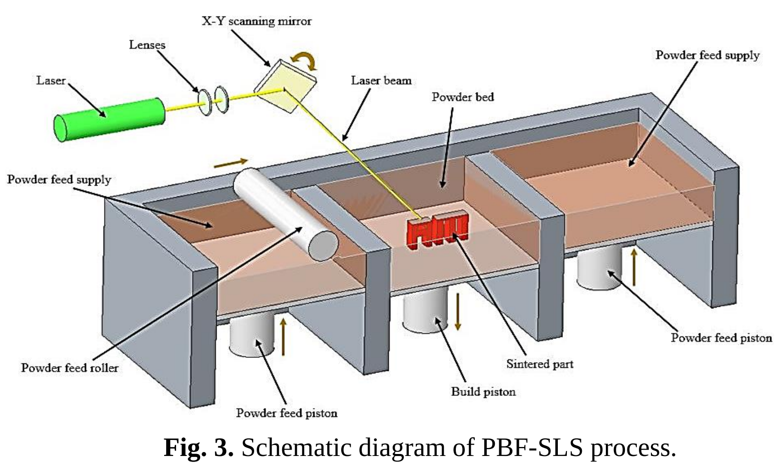

Fig. 3. Schematic diagram of PBF-SLS process.

The profitability of the PBF-SLS process depends on the possibility of recycling the unfused powder after each printing cycle by filtering. Moreover, recycling can change the particle diameter distribution and the chemical composition of the powder. Consequently, this increases porosity and voids after subsequent prints since the mean diameter distributions have changed, resulting in the fine powder being removed in the recycling procedure [42]. While using fine, spherical metallic powders, the parts can still achieve very dense packing, which results in better control over parts and fewer defects [43]. The PBF-SLS process does not require structural supports since the high powder density throughout the building geometry allows the building to stand on its own. In this way, a single print operation allows multiple components within one build volume to be processed and printed simultaneously, increasing the efficiency of MAM process.

Moreover, compared to other MAM processes, the PBF-SLS process offers a higher level of precision. This process employs a vast choice of materials containing metals and composites that are progressively being used to manufacture parts for aerospace exploration. In addition, PBF-SLS-manufactured metal components are long-lasting enough to be utilized in approaches where mechanical loads are an essential factor [44]. Using the PBF-SLS process, Taghipour et al. constructed a model of a wing-body-tail liftoff vehicle structure from glass-reinforced nylon composite [45]. The meta-surface antennas built using the PBF-SLS process by Sharples et al. are optimized for CubeSats and SmallSats.

The power management subsystem of the CubeSat is for the ALSat#1 mission [46]. Soller et al. investigated stainless steel 316L and CoCr for use at extreme temperatures in liquid rocket engine injectors, particularly for an injector head of the expanders and gas generators, resulting in a mass reduction of 25% through an optimized design, as well as a reduction of manufacturing costs using the PBF-SLS process [47]. In addition, it is reported that Tommila et al. have investigated the PBF-SLS process of a nickel alloy to achieve extremely small nozzles with diameters below 1 mm for the electrothermal or chemical thrusters of small satellites [48].

2.2. Powder Bed Fusion - Direct Metal Laser Sintering

PBF-DMLS process uses a metallic powder that is 20 µm in diameter and melts completely by scanning a high-power laser beam to create a component that matches the properties of the original metal [49]. In the case of PBF-DMLS process, the build process is usually carried out in a vacuum or an inert atmosphere, this being done to minimize the formation of oxide layers on the surface of the molten metal layers. Due to this phenomenon of the laser beam providing sufficient energy to melt the powder over its melting point, the melt pool region is created precisely where the 2D projection of the CAD model is projected. One advantage of the PBF-DMLS process over the PBF-SLS process is the excellent resolution of the metal part due to the use of thinner layers, which is possible because of the smaller diameter of the powder that allows for more intricate part shapes [50].

In addition, a primary benefit of the PBF-DMLS process is that the manufacturing duration is not subject to the part's complexity but is controlled by the melted material volume. The PBF-DMLS process can be carried out using a powder dispenser piston, which increases the powder supply; then, the coating arm distributes the powder layer over the powder bed. The laser then sinters the metal powder layer, and after a layer is built, the build piston lowers the build platform, and the next powder layer is set in place, as shown in Fig. 4.

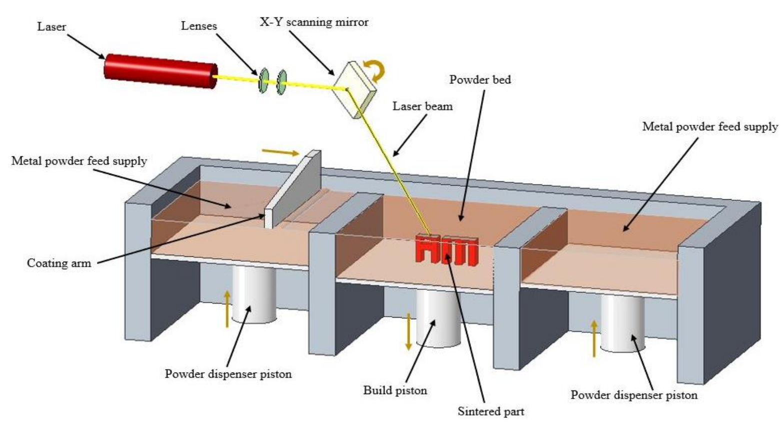

Fig. 4. Schematic diagram of PBF-DMLS process.

Although PBF-DMLS process can use only metals, both PBF-DMLS process and PBF-SLS process cannot fully melt the deposited powder material [51]. There are numerous benefits to PBF-DMLS process in general, one of those being that it can produce components of high quality and resolution, so it is instrumental in the aerospace industry. However, they are generated using the PBF-DMLS process when the laser broadens the material and shrinks after the laser has shifted. Thus, the component is subject to substantial internal stresses at the time of deposition because of the material's shrinkage at solidification. Stresses might make the support structures break down in extreme cases. In order to eliminate this, a stress-relieving heat treatment is required before separating the part from the substrate. The chamber could be heated above the stress-relieving temperature to lessen the effect of residual stresses [52].

It is important to note that the metallic powder used by PBF-DMLS printers is a different kind of powder. Since it is used for ultra-thin printing layers, the metallic powder must be perfectly shaped to even itself out. In addition, the metallic powder must consist of spherical shapes since each printing layer must be the same height [53]. Orme et al. designed, optimized, prepared, tested, and finally launched different components using the PBF-DMLS process for a satellite using the AlSi10Mg alloy [54]. According to Zhang et al., vibration tests were performed on AlSi10Mg manufactured PBF-DMLS process to create a lightweight satellite structure using lattice sandwich panels that could reduce the structure's mass by more than 50% compared to CM satellite structures [55]. Gill et al. prepared antenna feed arrays with PBF-DMLS process using AlSi10Mg alloy for the Ka-band based on high-efficiency horns. This is an example of a typical feed element in high-throughput satellites with multi-beam antennas [56].

2.3. Sheet Lamination

There is also a process called SL process, which represents every layer as a separate sheet or foil. These layers are bonded together to achieve a 3D shape. The company Fabrisonic is one of the companies that manufacture machines that use this process and use ultrasonic welding to bond the foils together. Recently, a patent was published that shows the bonding can be accomplished using diffusion or friction welding [57]. In the SL process, layers of metallic laminates are melted by heat then cut using a computer-controlled laser. Fig. 5 illustrates the SL process. The sheet is adhered to the material using the heated roller. Then, once the laser has followed the desired dimensions of the part, the laser cross-hatches through the non-part areas to facilitate waste disposal. The last step in this process is to lower the build platform to a new location to retrieve the next laser, and the process is repeated until a complete metal part is built [58]. Several additional improvements have been industrialized in the SL process, including various building materials and cutting approaches. However, due to the construction principle, only the exterior contours of the parts and the metallic sheets can be cut and then stacked and then cut again [59]. The SL process equipment is moderate in cost, and no functional parts are obtained.

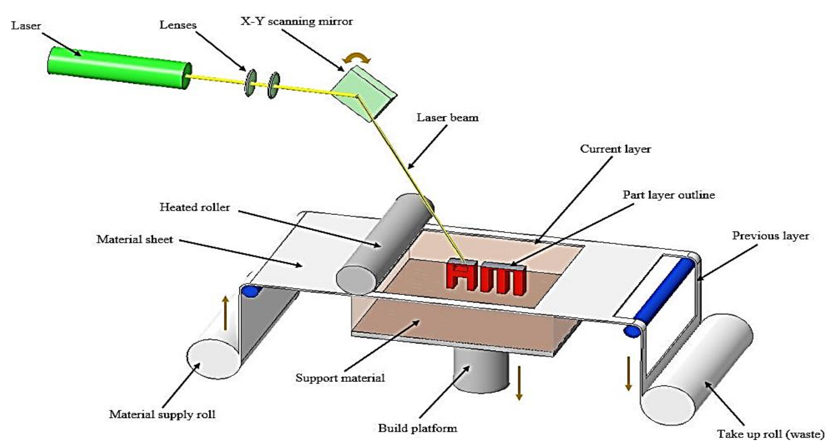

Fig. 5. Schematic diagram of SL process.

2.4. Electron Beam Melting

The EBM process consists of a powerful scanning electron microscope (SEM), whereas PBF-SLS process includes only a lens, mirror, and galvanometer to position the laser beam. In EBM process, the powder is selectively melted under vacuum conditions. It is necessary to add a low-pressure helium atmosphere to protect the powder from electrostatic discharge. As a result of this vacuum condition, corrosion can be almost entirely mitigated [60]. As opposed to PBF-DMLS process, EBM process transfers its energy at approximately 70% of the speed of light thru accelerated electrons kinetically colliding with that located on the powder bed's surface (as shown in Fig. 6). Thus, the energy provided by the electron beam during the melting process is sufficient to melt the powder and can also increase the negative charge of the powder. On the other hand, due to its electronegativity, it can produce a less concentrated beam of energy as the powder's capability of repelling incoming electrons [61].

Here, metal powder is placed in a vacuum and melted by heating with the electron beam. This MAM process distributes a layer of metallic powder onto a build platform that is then melted using an electron beam. The build platform is lowered, and the next metallic powder layer is placed on top [62]. The powder coating and melting process are repeated as necessary, and the metal part accumulates layer by layer in the powder bed. Electron beam initiation is generally a more effective procedure than laser beam initiation. When a potential voltage difference is applied to the heated filament in EBM process, maximum electrical energy is transformed by the electron beam; higher beam energies are accessible at an average cost. EBM process results in high-quality and precision parts, which does not present a problem for obtaining metal parts with overhangs or internal holes since the powder itself serves as support [63].

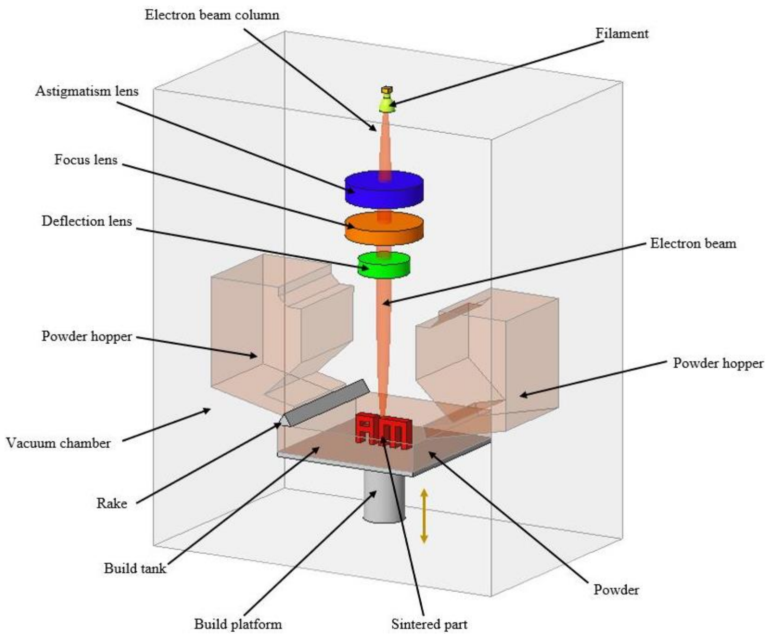

Fig. 6. Schematic diagram of EBM process.

Using the EBM process, a first layer is formed from melted powders in the vacuum. Layers of metallic parts can combine to form a solid structure and a support structure with thin layers. In order to avoid residual stresses on the finished product, whereby the mechanical properties could be harmful, the EBM equipment enhances the process temperature so that it remains invariably high in the chamber throughout the whole process [64]. As a result, EBM process has been reformed the exterior damage of single-crystalline turbine blades manufactured with a Ni-based superalloy, alongside no variation in the ɣ/ɣ' microstructure in the melt-pool zone, expanding channels to printing extensive single crystals with creep and helium repellent [65]. Typically, EBM chambers are pre-heated before operation begins to reduce the large temperature gradients and residual stresses caused by the process and avoid unwanted microstructures forming on the fabricated parts that compromise the quality of the as-fabricated components, e.g., α'-martensite in steels [66]. Using EBM, Arnaud et al. developed an antenna for low-

Earth orbit microsatellites [67]. In addition, Seidel et al. produced a thruster nozzle from γ-TiAl for a cold-gas propulsion system utilizing EBM. According to this study, the material can withstand temperatures greater than 700°C to increase the propellant efficiency in cold-gas propulsion systems [68].

2.5. Direct Energy Deposition

The DED process is another MAM process whereby the material is handled in metal wire or powder mode. Metal wire or powder melts through the medium of a laser, electron beam, or otherwise plasma arc passing over the controlled region. Inert gas is used to inhibit oxidation of the liquefied pool. Metal wire or powder is blown through nozzles, melting and depositing layer by layer on a substrate where it anneals. The nozzle has a multi-axis arm and carries throughout the part [69]. The grain growth direction does not always follow the build direction when using the DED process, and the length and depth are comparable. The above description suggests that the DED process produces columnar dendritic structures due to the shape and size of the melted pools. Even after a part made from DED process, part has cooled to below its solidus temperature, it is still necessary to reach room temperature before undergoing several phase changes [70].

The DED process includes more variety of MAM processes, such as laser cladding (LC), laser engineered net shaping (LENS), and WAAM. The way that material is delivered during the DED process is different from that used in PBF processes. Furthermore, DED process is similar to multi-axis welding processes and has been used to produce components fabricated from superalloys [71]. Because of the localized melting and rapidly cooling processes, the resulting microstructure has the potential to consist of fine and well-defined grains, and the resulting material can be 30% stronger than CM castings [72]. Zheng et al. studied the mechanical traits of deposited IN625 metal matrix composites with Ni-coated TiC. This study indicates that the Ni-coated TiC particles' advantages and the mechanical properties of the deposited metal matrix composites were significantly strengthened [73]. The DED process has a substantial benefit compared to the PBF MAM process and is strongly fitting for large parts with high BTF ratios for aerospace exploration, while the DED process achieves BTF ratios of 1 kg/h to 4 kg/h. Brandl et al. investigated the DED process on Ti-6Al-4V alloy and discovered that the hardness is reduced with the distance that separates it from the top of the part, and the annealing of the metal does not influence this attribute [74].

DED process offers many benefits, one of the most well-known of which is the shorter development process and time to market. DED process streamlines the design process, thereby allowing users to rapidly manufacture the prototype, review, test, optimize, and repeat quickly, with a less financial commitment. Designs can go from concept models to final product design with nothing more than digital information. This also eliminates the need for large amounts of tooling and machinery. Equipment is self-contained in the sense that a large amount of cutting tools, dies, and fixtures are not required to operate it [75]. The Norwegian company Norsk Titanium fabricated components for the commercial B787 Dreamliner using the DED process [76]. The company utilized the DED process for building components that experience in-flight stress loads. Airbus produced titanium brackets to be used inside the pylons of the A350 XWB aircraft using this process, which links the wing and the engine [77]. Furthermore, the Comac C919 was the first to manufacture central wing spars from titanium using the DED process [78].

3. Material Trends of Metal Additive Manufacturing

During the past few years, MAM has been using common metallic materials to fabricate parts for the aerospace industry, such as steel, aluminum, titanium, stainless steel, cobalt, nickel, copper, and alloys of these metals [29]. Depending on the MAM process, these metals are typically used in pre-alloyed powder form, produced via gas atomization or in wire. Particularly, nickel-based superalloys have become increasingly popular due to their extreme temperature properties, which are ideal for aerospace components generally used in harsh surroundings [79]. For example, nickel-based superalloys have been progressively crucial in producing disks and blades used in high-pressure turbines for gas turbine engines. In addition, they are extensively used in a wide variety of applications that involve high temperatures and cryogenic conditions, including injectors, turbomachinery, igniters, and valves. Furthermore, modern aircraft engines have become significantly efficient due to this metal's excellent mechanical properties despite extreme temperatures, high pressures, and corrosive environments [80].

Additionally, titanium alloys are particularly attractive to aerospace companies because they combine high strength and fracture toughness, as well as low density and coefficient of thermal expansion. Furthermore, its high corrosion resistance makes it a lightweight material for aerospace applications. Due to these reasons, manufacturers are increasingly implementing the MAM process to manufacture titanium components. MAM provides a wide range of design and processing options, significantly reducing manufacturing costs and the amount of waste generated [81]. For example, as titanium alloys exhibit excellent mechanical properties at high temperatures, they have been processed to manufacture turbine blades used in commercial aircraft. It is also possible to use titanium alloys for cryogenic application components, such as rocket propellant tanks, since they do not exhibit ductile-to-brittle transition under very low temperatures [82].

The use of stainless steel in many aircraft and space components is due to the metal's high strength-to-weight ratio, its high durability and hardness, as well as its remarkable mechanical and corrosive properties at high temperatures. With MAM, various stainless-steel classes are commonly used, including austenitic and precipitation hardened (PH) steels [83]. Stainless steel is used across various components, including landing gear systems, hydraulic components, heat exchangers, engines and exhaust systems, and structural joints. Stainless steel, specifically 17-4PH, is frequently used in aerospace exploration, but many metal alloys are being developed, such as stainless steel 316L, H13 steel, and other tool steels along with copper, titanium, aluminum, and nickel-based superalloys [84]. For example, in the combustion chambers of liquid rocket engines, copper alloys are commonly used in heat exchangers. A high-pressure propellant or oxidizer must effectively cool the thrust chamber walls within this high heat flux environment. Copper alloys are preferable for this application with their high strength and conductivity. Other metals, such as cobalt-based alloys including Co-Cr and Stellite, are also utilized for extreme temperature applications [85].

Many of the metals mentioned above are available in the market as feedstock for MAM machines and have been subject to extensive research into the material properties and characteristics produced by the MAM process, some of which are superior to those associated with CM methods. Therefore, the operations and post-processing parameters must be adjusted to reduce porosity, crack occurrence, residual stress, as well as include optimized post-processing options to improve the material properties, such as heat treatments that are suitable for the material. Generally, the cost of materials for MAM is higher than for CM, but optimized AM processes can offer lower BTF ratios and recycle capabilities, thereby lowering manufacturing costs [86].

In the early stages of MAM, materials were traceable to common alloys which were used. However, these alloys are frequently not the best-fit alloys for the intended application, and several of them are present challenges in the MAM process due to their potential cracking or porosity formation, oxidation, or other undesirable properties. In addition, MAM presents an excellent opportunity to develop new alloys, which, along with better processing, are better suited for minimizing cracking and other risks and being optimized further for the final application [87]. Additionally, NASA recognized the need to develop advanced alloys for use in the MAM process and developed GRCop84 and GRCop-42 copper alloys that can be used in high heat flux environments, as well as the iron-based superalloy NASA HR-1 alloy, which is intended for use in conditions of high pressure and hydrogen [88]. In addition to superalloys, aluminum, and refractory metals, several other examples of custom superalloys explicitly developed for the MAM process have also been found, providing further evidence that the industry requires more materials in the near future [89]. Additionally, to monolithic alloys, the MAM process also offers the possibility of developing custom bi-metallic and multi-metallic materials and incorporating materials locally into designs to optimize their thermal and structural performance. Depending on the required material, it is also possible to compute discrete transitions or function gradients [90].

4. Metal Additive Manufacturing Applications in Aerospace Industry

MAM has a great potential to revolutionize space travel by allowing astronauts to make components, including replacement parts for repairs, specialized equipment for scientific research, and structures. NASA's Rapid Analysis and Manufacturing Propulsion Technology project, or RAMPT, is pioneering the development of the DED MAM process for rocket engine parts. DED MAM process could reduce prices and lead times for large and complex engine components like nozzles and combustion chambers. NASA's Langley Research Center has funded the manufacturing of an EBM 3D printer that will feature real-time monitoring, control, and flaw-detection capabilities, which will enable NASA to adjust 3D printing parameters from Earth to space conditions [91,92].

Additionally, the potential of using MAM for producing propulsion components has been explored. Some propulsion components, such as injectors, nozzles, combustion chambers, and thrusters, have been manufactured to optimize geometry and high performance. MAM process offers new structures and an upgraded catalyst design and cross-sections for ideal thermal/weight management. Another component produced via MAM is a thruster of platinum-rhodium, which increases the propulsion performance [93]. Finally, MAM has significantly benefited the internal rotation and attitude control system bracket, even under a highly loaded launcher structure. MAM has made it possible to replace high-strength aluminum alloy with Ti6Al4V alloy, gaining substantial mass savings. MAM applications and sustainable outer aerospace exploration and energy storage have been investigated for over a decade [92].

MAM process benefits outer space applications substantially over CM method with optimized designs that reduce materials usage and waste generation, offer high-quality complex geometry production, and operate at high speed with less energy. In 2006, the European Space Agency (ESA) experienced a valve failure at the International Space Station (ISS). This became a case study for investigating the potential of MAM involving metallic material methodologies. This revolutionary assessment revealed the ideal potential of MAM in aerospace applications [94]. Furthermore, the aerospace industry perfectly illustrates how MAM can manufacture stronger and lighter parts than CM parts in a shorter time. As a result, the aerospace industry was an early adopter of MAM and made significant contributions to its growth. Common MAM parts used in aerospace industries include jigs and fixtures, surrogates, mounting brackets, and highly detailed visual prototypes [95].

In 2019, Boeing turned to MAM for satellite production and created the first metal additive manufactured satellite antenna. The new Boeing 777x, equipped with two GE9X engines, incorporates more than 300 MAM parts, reducing the engine's weight and lowering the fuel consumption by 12%, thus making it the most efficient engine globally. Airbus has become one of the primary users of MAM technology by incorporating more than 1,000 MAM parts in its Airbus A350 XWB. Two and a half years ago, Airbus included its first titanium MAM part for a serial production aircraft. Its next venture is to metal additive manufactured drones and self-driving cars. MAM has the potential to revolutionize low-volume aerospace production. A new technology used only for prototyping is now being leveraged and used as a full-scale tool for manufacturing end-use parts. Table 1 summarizes MAM applications in space and aerospace exploration [96].

Table 1: Metal additive manufacturing applications in space and aerospace exploration

MAM Process	Materials Used	Part Produced	Year	Reference
PBF-DMLS	CuCrZr (C18150)	Rocket engine combustion chambers	2021	[97]
PBF-DMLS/DED	Inconel 718	Test parts (spacecraft)	2021	[98]
PBF-DMLS	Titanium Alloy	Impeller	2020	[99]
PBF-DMLS	Aluminum and Titanium Matrix Composites	Experimental study	2020	[100]
PBF-DMLS	Titanium Alloy	Heavy-loaded aerospace bracket	2020	[101]
PBF-DMLS	Niobium Alloy	Propulsion Thruster	2020	[102]
DED	Titanium Alloy	Access door latch	2019	[103]
PBF-DMLS	AlSi10Mg	Flat plate pulsating heat pipe	2019	[104]
EBM	Metallic Composite	Rutherford Engine	2019	[105]
DED	Titanium Alloy	Spacecraft component	2019	[106]
DED	Inconel 625	Channel-cooled combustion chambers	2019	[107]
DED	Inconel 625 and JBK-75	Liquid rocket channel wall nozzles	2019	[108]
WAAM	Titanium Alloy	Rear frame	2019	[109]
PBF-DMLS	AlSi10Mg	LEROS engine support structure	2018	[110]
DED	Metallic Composite	Terran 1 Fuel Tank	2018	[111]
PBF-DMLS	AlSi10Mg	Experimental study	2018	[112]
PBF-DMLS	N/A	Multifunctional panel	2018	[113]
DED	Inconel 625 and 718	Turbines and heat exchangers	2018	[65]
PBF-DMLS	AlSi10Mg	Experimental study	2017	[114]
PBF-SLS	AlSi10Mg	Sentinel antenna bracket	2016	[115]

MAM Process	Materials Used	Part Produced	Year	Reference
EBM	Titanium Alloy	Low-pressure turbine blade	2016	[109]
PBF-DMLS	Copper Alloy	Thrust chamber assembly	2014	[116]
DED	Inconel 718	Helicopter engine combustion chamber	2014	[117]
PBF-DMLS	Inconel Alloy	Super Draco engine chamber	2014	[118]
PBF	Inconel 625	Double Nozzle	2013	[119]
EBM	Titanium Alloy	Bleed air leak detector on F-35	2013	[120]
EBM	Titanium Alloy	Experimental study	2012	[121]
PBF-DMLS	Titanium Alloy	Nacelle hinge bracket	2011	[122]
PBF-DMLS	Nickel-based Superalloy	Industrial gas turbine blade	2004	[123]
PBF-SLS	Co-Cr	LEAP engine fuel injector nozzle	2003	[109]

Figure 7 features various MAM components. Fig 7. (a) shows Boeing 787 structural components provided by Norsk Titanium. In 2016, Norsk Titanium delivered their first Federal Aviation Administration (FAA)-approved MAM Ti-6Al-4V component for installation on the Boeing 787 using the rapid plasma deposition (RPD) technique. Parts manufactured by this technique have fewer defects and better mechanical performance [124].

Fig 7. (b) exhibits the MAM of fuel nozzles for a GE9X engine. The aircraft engine GE9X, designed for the Boeing 777X-8/9, is believed to be the world's largest jet engine and has made news by carrying 3D printed fuel nozzles certified by the FAA. The Morris machine, used by GE to fabricate the nozzle, combined all 20 parts into a single unit, weighing 25% less than a regular fuel nozzle. In addition, this part was manufactured using an electron beam, which is much more powerful than a laser, enabling faster printing and fusing layers as thick as 100 microns. In another application, GE consolidated 855 parts into just a dozen parts using additive manufacturing for its turboprop engine, reducing the fuel burn by 20% and increasing the power by 10%. Textron Aviation later picked this engine for its new plane Cessna Denali [124,125].

Fig 7. (c) shows Space-X's Super Draco rocket engine, the first MAM engine of its kind to enter service in 2013. The thrusters successfully delivered 5,000 lbs. of supplies to the International Space Station. MAM is also utilized in the Dragon spacecraft/Falcon 9 rocket combination to transport passengers to the ISS. In addition, SpaceX used PBF-SLS to make impellers for the Merlin engines that power its Falcon 9 launch vehicles, which are currently undergoing certification for human space flight [109].

Fig 7. (d) shows titanium clamps for a satellite produced by Airbus Defense and Space. This division manufactured these clamps for satellites through the Electro-Optical Systems (EOS) GmbH technique. First, they connect the satellite's body to the feed and sub-reflector assembly at the top end. Then, a laser fuses the titanium metal powder to generate a sturdy part using the PBF-DMLS process. The manufactured component can resist a temperature of 330 ℃ under 20 kN force. Furthermore, using the MAM technique, the manufacturing time is less than five days, the cost is ~20%, and component weight was significantly reduced [126].

Fig 7. (e) shows a Cell Core prototype rocket nozzle featuring internal cooling channels. Cell Core explains the benefits of the PBF-DMLS technique and how it may be applied in the aerospace sector by designing a thrust chamber for a rocket propulsion engine. The monolithic component was designed in partnership with the PBF-DMLS process and printed in a nickel-based superalloy. The extremely high temperatures developed in the chamber during combustion must be cooled to prevent the wall from burning. The liquid fuel (such as kerosene or hydrogen) is supplied upward through cooling ducts in the combustion chamber wall before entering the injection head. The fuel is mixed with the oxidant and ignited by a spark plug. The cooling is integrated as part of the design and manufactured in one step with PBF-DMLS. Traditional manufacturing processes, which are also cost-intensive, take about a year and a half to manufacture this component, whereas, with the MAM process, it was manufactured in less than five days [127].

Fig 7. (f) exhibits an antenna feed array (AFA) manufactured by MAM for space applications. The PBF-DMLS process is one of the acceptable options that can be studied for space applications focused on developing an AFA using the PBF-DMLS process. This array usually consists of high-efficiency horn elements for feed elements in high-throughput satellites employing multi-beam antennas used for the Indian Space Research Organization's (ISRO) GSAT series of satellites [56].

Fig 7. (g) shows the rocket engine produced by MAM for NASA. The PBF-DMLS method has been used by the Marshall Space Flight Center (MSFC) to create rocket 3D printing technology. NASA has created and tested various injectors and combustion chambers during the last few years. The MSFC recently 3D printed an enhanced spark igniter for the RS-25 engines used on NASA's Space Launch System. The cost of the igniter is predicted to drop by a factor of four with the new design. A liquid hydrogen turbopump was also 3D printed and tested by the MSFC for use in an upper-stage engine. Thanks to MAM, the turbopump's part count has been reduced by 45%. The MSFC also created a breadboard liquid rocket engine with additive-manufactured injectors, turbomachinery, and valves to understand how the 3D printed parts work and to certify them for flight. Engineers learned to design for the new manufacturing technology, using its potential while also cognizant of its limitations and subjecting the hardware to severe environments. For example, laser melting of titanium powders (laser cussing technology) is used to manufacture the cabin bracket connector (Fig 7. (h)) for the Airbus A350 XWB. Initially, this part was milled and machined out of aluminum alloy, but it is currently a 3D printed titanium that provides a 30% weight reduction. In addition, milling airplane parts generates 95% scrap/waste, while laser cussing generates only 5% waste [126].

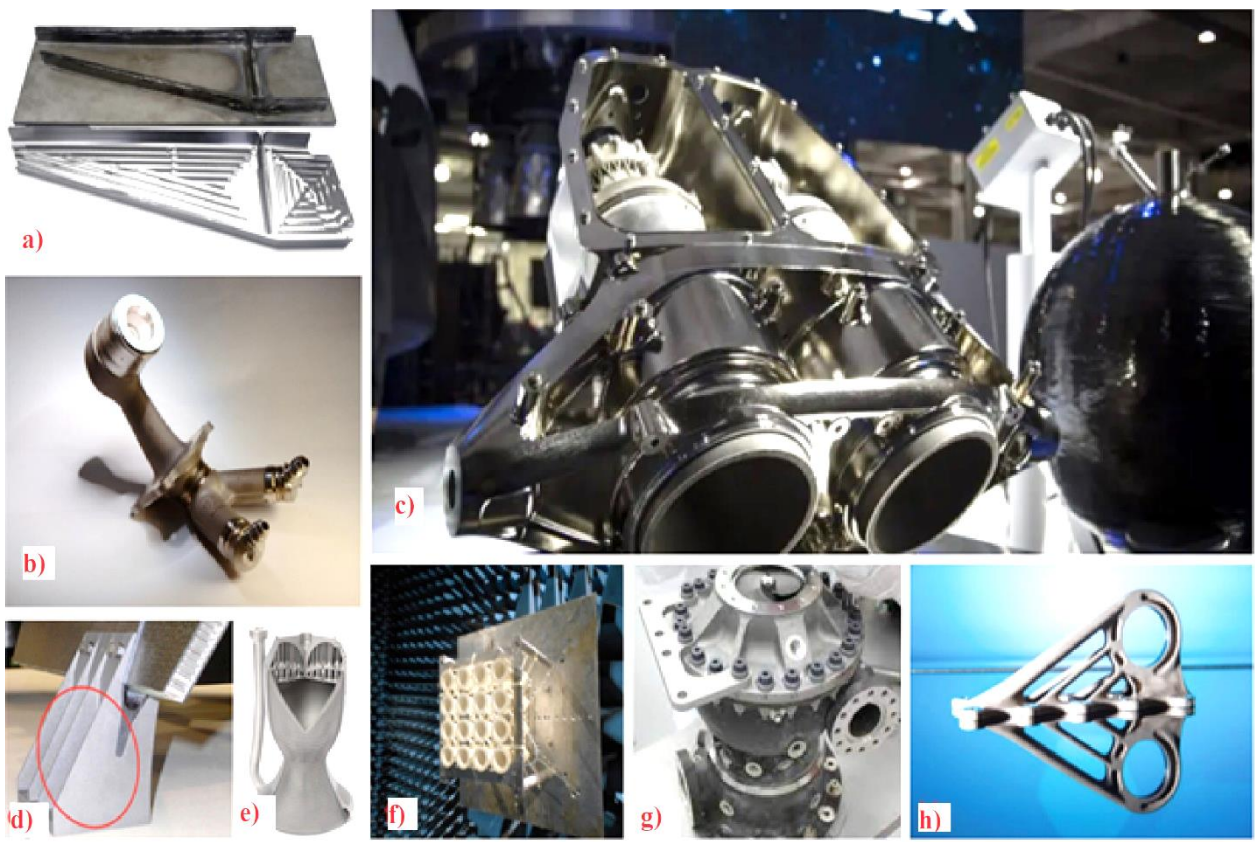

Fig 7. (a) FAA certified additive manufactured Ti-6Al-4V component made by Norsk Titanium; (b) GE's additive-manufactured nozzle; (c) Space-X's 3-D printed Super Draco rocket engine; (d) titanium clamps for satellite produced by Airbus Defense and Space; (e) rocket propulsion engine built with PBF-DMLS process; (f) PBF-DMLS-built AFA; (g) additive-manufactured turbopump at NASA; (h) titanium cabin bracket manufactured via laser cussing technology for Airbus A350 XWB.

5. Challenges of Metal Additive Manufacturing

MAM offers excellent opportunities in many aspects compared to CM methods. With MAM, the production of any component can be started immediately, thereby saving an enormous amount of time and money. Compared to CM methods, it also allows for more complex components with total design freedom, which is essential for reducing assemblies by producing complex parts. As a result, many new aerospace companies in this field are emerging and are becoming increasingly competitive [128]. In today's market, there are many options for MAM processes, and it seems that more and more are becoming available every day. Nevertheless, it is necessary to explore further how these all-MAM processes work. Although MAM is a breakout process that can modify component manufacturing in the aerospace industry, its usage is still in its infancy, and there are numerous challenges to applying MAM in a way that allows for its substantial development [129].

Despite all the positive benefits of MAM, some drawbacks prevent more widespread adoption of this technology, including size, scaling, and cost limitations. The smaller volume part can be manufactured quickly, but build time increases as the size and complexity increase. The size is an important factor for the manufactured parts, which adds cost. MAM printers can manufacture only smaller objects than the size of the printer casing, limiting the size of parts produced. Large-build-area equipment can manufacture more larger sized parts. However, they are costly, several times more than a traditional machining equipment and larger printers must be stored in a large space to accommodate their size. The equipment's high prices make it difficult to extend the use of MAM. Equipment manufacturers treat some of the statistics as a trade secret. Some small parts of the product are made in segments, without an adequately large printer. However, it takes a longer time to assemble the parts for a finished product, this negates the benefits.

Another most considerable challenge with MAM is that the high cost of metal materials has been a significant barrier to introducing and expanding its use, which reflects that MAM metal materials are five times more expensive than their counterparts. Problems also include the choice of metal materials and their influence on design. In frequent cases, the choice of a part's material combined with the process used to determine the geometric limits of the part design [130]. Since the MAM process is moderately new to design and structural engineers, a general understanding of its design and structural integrity is lacking, creating significant misperception and an iterative nature when using MAM processes [131]. If the design and structural engineers do not identify what limitations exist, they must modify their designs several times before the parts are classified as manufacturing. It is essential to change the knowledge of manufacturing processes and start to design for metal additive manufacturing (DFMAM). Prior to the total cost of ownership, the cost of producing parts is a combination of raw metal material and printer costs. However, the printer costs influence the printing speed and quality of the end part. So having a less expensive printer could result in a much slower printing speed and bad quality parts [132].

Quality is also a concern, especially on solid sintered parts under high internal stresses. After being removed from the build plate, they risk destroying themselves. Such high internal stresses can be diminished or avoided with proper heat-treating cycles. After the stress-relieving cycle, surface finishing similar to any CM method is required [133]. Furthermore, one problem with surface finishing in the MAM process is when the metal material does not have the same finishing properties as CM method metal materials [134]. Consequently, in most cases, components manufactured with MAM require secondary operations to create corresponding surfaces, which is yet another step in the manufacturing process and therefore increases the cost. The cost-driven nature of the aerospace industry makes it desirable to reduce the manufacturing time of MAM components or the price of the feedstock materials. As an alternative, increasing the speed of production or decreasing the quality of input materials may increase defects. The quality of the part should always be high in industrial standard, which attracts the attention of industrial users. However, PBF-DMLS process is relatively slow and not ideal for the mass production of large-component volumes. As a result, many companies are introducing innovative sub-technologies that combine high production speeds and excellent product quality [135].

The aerospace industry also believes that identifying the possible uses of MAM is a significant challenge. Since most organizations are inexperienced with MAM or are still experimenting with this technology, it is essential to find the proper-use cases and identify their adoption benefits. However, this is usually a long manual task, not perfectly organized and automated. In general, the aerospace industry agrees that there is a significant gap in practical application knowledge regarding MAM processes and how to apply these to commercial products. The training, education, change in mindset among engineers and executives in a company on the MAM are considered necessary and are presently under progress [136]. Among the most significant challenges surrounding certification guidelines is the lack of information about the failure mechanisms exhibited by MAM-fabricated components and especially the fatigue properties, which are highly important to aerospace manufacturers since aerospace components are subject to repeated cyclic loadings. Today, there are no part-driven data available on printing process variables, material properties, and microstructures, in addition to their mechanical properties, which is further complicated by the lack of process control on-site and prohibitively expensive non-destructive testing (NDT) methods [137]. However, the excellent design flexibility of MAM processes offers many prospects to a combination of hybrid AM/SM approach, design for additive manufacturing, and topology optimization, and these, in addition to benefiting manufacturing and quality of MAM fabricated aerospace structures [138]. MAM may present challenges, but the aerospace industry has already been exploring it to produce many complex components. Aerospace companies are also attracted to the ability to reduce weight and improve functionality [139,140].

6. Safety Regulations in Metal Additive Manufacturing

In the aerospace industry, the intense certification process is essential for the safety of workers. Most OEMs have an enormous research base for the existing MAM process and a close connection with safety regulatory agencies. As technology advances, certification and qualification for certification continue to be a key challenge in integrating MAM into market [141]. All MAM processes discussed so far require safety regulations to achieve proper aerospace exploration certification, which necessitates consistency and repeatability of the production process. Some of the metal materials used in MAM process are non-standard metal materials. Therefore, the materials themselves must be certified to a certain standard. Metal materials must go through a series of tests to meet the expectations of regulations for strength, fatigue, damage tolerance, flammability, and other parameters [142].

There are many potential safety hazards due to the different MAM processes. General safety regulations can be made based on existing protocols, and any additional precautions can be determined using hazard and risk assessments. Types of safety risks include fumes, chemical exposure, flammability, and radiation. Safety also goes beyond occupational hazards, including environmental impacts, sizing, costs, consistency of production, and other hazards.

Existing research suggests that personnel who work with MAM equipment and infrastructure could suffer from adverse health effects [143]. Several studies have demonstrated that the direct contact or inhalation of ultrafine metal powder particles may cause various health problems, such as injuries to the lungs and nervous system, many different forms of cancer, and mental impairments [144]. Moreover, if the metal powder particles in MAM equipment is not adequately grounded, personnel might have to bear the hazards of electrostatic discharges or sparks, which can lead to fires or explosions, as well as endanger their lives at risk. These kinds of health and safety risks can be mitigated by operating MAM process under vacuum or in an inert atmosphere and allowing time for residual powder particles to settle before removing the part from the build area [145]. Moreover, it may be possible to introduce an MAM cleaning system together with associated breathing apparatuses for the post-processing, such as drilling, deburring, and handling of parts, to reduce the impact that can be generated from the metal particles and dust [146].

In MAM, studies have presented that the PBF-SLS process uses a laser, it applies to metal powder particles, and the laser fuses the metal powder particles. PBF-SLS printers often use class 4 laser systems, which cause direct radiation hazards. Notably, a company which uses this process should cautiously monitor these devices, assess them for safety hazards, and form appropriate limitation usage with the guidance of properly trained personnel. The repaired parts utilized in the aerospace industry where the safety of the part is vital should be tested and verified by professionals. In the case of spare parts, in-situ inspection methods should be employed to evaluate part quality to prevent unpredictable failure. Furthermore, NDT methods are essential in verifying key parts [147]. Drizo and Pegna pointed out that one of the most irresistible research areas is the exploration of toxicity and the harmful effects of metal materials used in MAM [148]. Various institutions such as the American National Standards Institute (ANSI), Occupational Safety and Health Administration (OSHA), International Organization for Standardization (ISO), and others continually develop standards to mitigate risk to workers and the environment. As MAM continues to grow, these institutions frequently evolve their standards to ensure that this process remains safe and viable in industrial and consumer settings [149].

Relative to safety considerations, one probable advantage of using MAM versus the CM method is the potential for low sound levels in the workplace, in contrast to high sound levels from lathes and milling machines, which creates severe hearing problems to workers. Additionally, the high energy input required to process components during MAM implies that MAM probably cannot be regarded as an eco-friendly alternative to CM method. Nevertheless, MAM remains superior to CM method due to its ability to produce near net-shaped components, resulting in improved manufacturing efficiency. As a result, waste rates and input material are significantly reduced. Further, numerous studies have been dedicated to comparing the differences in CM methods with MAM processes from the aspect of environmental concerns [150,151]. MAM uses raw materials efficiently and reduces the waste of resources that need to be used. Therefore, MAM implies that it significantly benefits environmental factors and reduces the amount of waste [152]. MAM's higher environmental impact in comparison to CM method is expected to be offset by enhanced functionality of MAM-built aerospace components, including reduced component mass and increased aerodynamics, as well as improved durability [153,154].

Another important safety-related factor is that unconventional tools used in industrial applications may cause harm in the long run. Recent studies emphasize the gap in knowledge regarding long-term effects, and more research into this area is recommended. With MAM, customized tools could reduce the chances of injury for the users. In addition, MAM's safety measures to produce parts versus CM methods could be increased. Further investigations in safety regulations are required to avoid any severe health and ecosystem damages caused by handling, using, and disposing of MAM raw materials. Overall, it appears the MAM process has an enormous impact on the aerospace companies who occupy the MAM processes.

7. Future of Metal Additive Manufacturing

The term MAM has become essential in industries over the past few years. There have been considerable developments concerning the aerospace exploration, and huge strides have been made in developing the process to make it more productive and profitable [155]. Excellent MAM processes in various aerospace applications can substantially impact product manufacturing and business operations. Specific future trends in MAM can be envisioned, especially when considering the growing demand for high-performance materials with a unique combination of mechanical, physical, and chemical properties [156]. Mainly MAM process should become increasingly accepted by a broader range of industries, including those that will benefit most from its development. A significant portion of the growth of MAM processes using materials that are already a tradition in the aerospace industry, like titanium, ferrous, and aluminum alloys will revolve around the capabilities of manufacturing parts that are complex in shapes and integrated with lightweight structures. In this case, the benefits will mainly be seen in the weight and cost savings experienced per manufactured part [157]. Additionally, there will be an added benefit in reducing the costs of handling spare parts since, in many cases, the need to store large quantities of different parts can be replaced by producing them as needed from computer data (CAD) that has been saved.

The trend towards using MAM processes as a method to manufacture parts made from highly desirable materials will continue to grow over time. This trend has been established towards using MAM to fabricate materials that would be impossible or extremely difficult to produce by other manufacturing methods, either due to the component's complexity of the shape or the material's nature and characteristics [158]. Additionally, the trend of integrating MAM into unified automated and robotic processing lines in conjunction with post-processing will continue to develop. There are already several such systems in the development process, and they have already demonstrated that they can provide better integration of the MAM components when applied to existing industrial processes. Another further trend in the aerospace industry is the MAM of components made from materials with controlled properties through their entire volume by precise control of material composition and microstructure, adding 4th dimension to 3D printing [159].

MAM improves existing parts and allows spacecraft and aircraft companies to make entirely new components that could not have been produced previously. Although MAM has primarily started to build prototypes, the latest developments and applications of the MAM process suggest revolutionizing many aspects of everyday life. The increased demand for complicated metal components such as rotor turbine vane assemblies, fuel nozzles, combustion chambers, and turbine discs with blades have made MAM processes the most appropriate for aerospace industry [160]. There are many future works is required for the certain challenges preventing MAM processes to gain wider acceptance in the market, such as finding different methods of acquiring raw materials, reformulating design processes, launching new methods of quality control and standardization, development of different mechanisms of post-processing, and the integration of MAM components into existing systems, identifying new ways of implementing life-cycle analysis, and developing new ways of managing costs and resources, etc. In recent years, there have been many studies that have wanted to develop more adaptive and safer MAM processes, including more cost-efficient innovative materials [161–163]. Uninterrupted innovations and the development of MAM will play a major role in the future of aerospace exploration.

8. Conclusion

This review paper has demonstrated various MAM processes for aerospace exploration over the last ten years including successful examples. Relative to utilization for aerospace industry, PBF-SLS, PBF-DMLS, EBM, and DED are the most popular MAM processes. Most applications of MAM in the aerospace industries have revealed cost compensation and schedule reduction. Special mention to this technological process, MAM grows in manufacturing spare part tools and final-end components in aerospace exploration. Many MAM machine suppliers are out there, and the market is overgrowing. The MAM process has been developed to create functionally classified metal components with similar properties to CM components. It has been observed that the mechanical properties of the components produced by MAM are better than their counterparts brought in, but repeatability, as well as standardization, remain challenging issues.

This study also further investigated the challenges and limitations in MAM processes. With MAM, the amount of waste generated from the materials can be significantly reduced compared with CM methods, offering greater design freedom. Compared to CM method, MAM processes offer many advantages for the aerospace industry. The existing MAM processes, material trends, challenges, and future research needs for MAM are discussed in this paper. Although the MAM process offers many benefits over CM methods, most companies still do not accept this process. Research and development in materials, processes, equipment with CAD modeling, process control, applications, and sustainability are needed to expand and increase the level of the MAM process into a mainstream technology. MAM also has the challenge of part certification, unique quality control requirements, poor high-volume production rates, post-processing challenges, potential reduced fatigue properties, high cost of machines, and expertise required to produce functional components. It is perceived that the more profound research and development desired in the design of MAM processes, and material interfaces from MAM are essential. In addition to each MAM process, several opportunities and restrictions must be understood if the development of the process is to be entirely exploited. Moreover, based on the rapid growth of MAM process in the industrial world, it is apparent that MAM process will have a long-term impact on the aerospace industry, contributing to the development of advanced product design.

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