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Metal Additive Manufacturing: Processes, Applications in Aerospace, and Anticipated Hurdles - A Comprehensive Review

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Abstract - Additive manufacturing has emerged as a game-changing technology in the manufacturing industry, particularly in the aerospace sector. [1] Metal additive manufacturing, in particular, has garnered considerable attention due to its unique ability to produce complex geometries with high precision and accuracy. This review paper focuses to provide a comprehensive overview of the common metal additive manufacturing processes, their applications in the aerospace industry, and the challenges that lie ahead. The study begins with a brief introduction to metal additive manufacturing, followed by a detailed analysis of the most commonly used processes, such as laser bed melting, powder bed fusion, directed energy deposition, and binder jetting. Next, the paper explores the various aerospace applications of metal additive manufacturing, including engine components, structural parts, and tooling. Finally, the review concludes by discussing the current limitations and future challenges of metal additive manufacturing, such as the need for improved material properties, cost reduction, and standardisation. Overall, this paper provides valuable insights for researchers, practitioners, and policymakers interested in the potential of metal additive manufacturing in aerospace and beyond. [2]

Key Words: Additive Manufacturing, Ti-6Al-4V, EBM, LBM, Post Processing, Aerospace, Microstructure, etc.

1.INTRODUCTION

Additive manufacturing methods: -

1.1. Laser beam melting (LBM)-

Metal laser beam melting (LBM) is a widely used additive manufacturing technique that employs a high-power laser to selectively melt metal powder layers to create three-dimensional (3D) components. The process typically involves the deposition of metal powder in thin layers onto a build platform, followed by the melting of the powder layer using a laser beam. The melted metal solidifies rapidly upon cooling to form a solid layer. The build platform is then lowered to allow for the deposition of the next layer of powder, which is selectively melted using the laser. This layer-by-layer process continues until the 3D component is complete.

One of the main advantages of metal LBM is its ability to produce complex geometries that are difficult or impossible to achieve with traditional manufacturing techniques. This process enables the creation of intricate designs with internal structures, such as lattices and honeycombs, that can improve the mechanical properties of the final component. Furthermore, metal LBM allows for the fabrication of custom components with minimal material waste, which makes it a more cost-effective and sustainable manufacturing process compared to traditional methods. However, metal LBM does have some limitations, such as the need for post-processing to achieve the desired surface finish and the relatively slow build time for larger components. Additionally, the quality of the final product can be affected by factors such as powder quality, laser power, and process parameters, which require careful monitoring and optimization to ensure consistent and high-quality parts.

In summary, metal LBM is a powerful additive manufacturing technique that enables the production of complex geometries with improved mechanical properties. The ability to make custom components along with minimal waste makes it an attractive option for various industrial applications. Despite its limitations, metal LBM continues to be an area of active research and development, with ongoing efforts to improve the process efficiency, scalability, and reliability to expand its potential applications in various fields, including the aerospace, medical, and automotive industries.

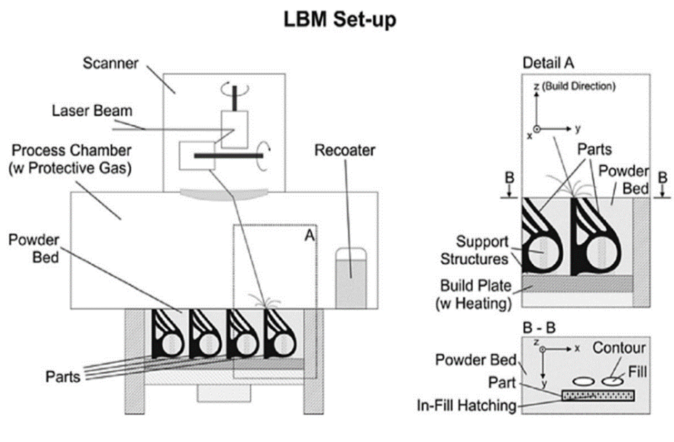

Fig 1: Schematics of LBM system.

1.2 Electron beam melting (EBM)

Additive manufacturing of metal has revolutionised the manner in which we create and manufacture intricate metal parts. One of the metal additive manufacturing techniques gaining attention in recent years is electron beam melting (EBM). [3] EBM is a powder bed fusion technology that employs an electron beam as the heat source to selectively melt metal powder. It operates in a vacuum to avoid interference with the electron beam, and the melting process is precisely controlled by manipulating the electron beam's speed, power, and focus.

One of the unique benefits of EBM technology is the potential to manufacture parts with high accuracy and excellent mechanical properties. [4] The process can produce parts with a density close to theoretical density, thereby reducing the need for post-processing. Additionally, EBM allows the production of parts with intricate geometries, including internal features and overhangs, that are difficult or impossible to achieve using conventional machining techniques. As a result, EBM is used in a wide range of applications, including aerospace, biomedical, and automotive industries, where the components' high complexity and excellent mechanical properties are crucial.

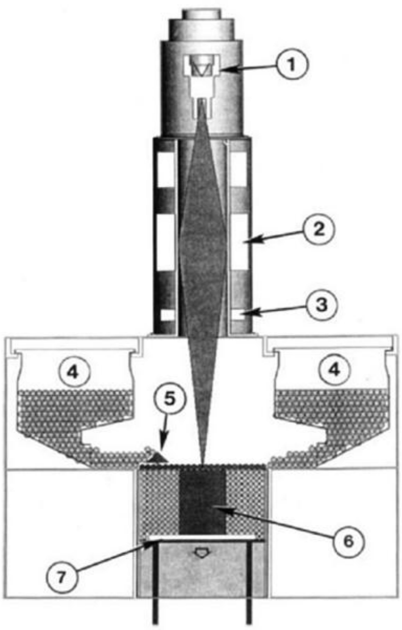

Fig 2: EBM machine schematic

1.3 Laser metal deposition (LMD)

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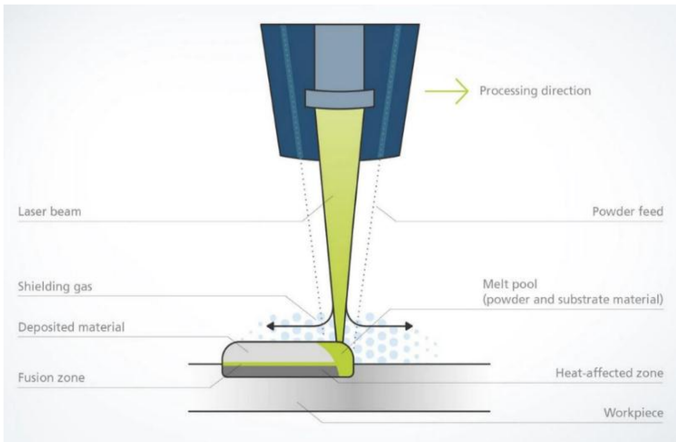

Fig 3: LMD process schematics

2. Feedstock for AM

2.1 Powder Production

Additive manufacturing (AM) is an advanced technique that involves the layer-by-layer addition of materials to produce three-dimensional objects. [5] Metal powders are the most commonly used feedstock material in AM processes. The properties of the powder material determine the quality of the final AM part. Therefore, it is essential to use high-quality powders for AM to achieve optimal results.

Spheroidization and atomization are two commonly used techniques for powder production. [6] Spheroidization involves melting and solidifying a metal in a manner that produces spherical particles of uniform size and shape. This process can be achieved through various methods, including induction plasma spheroidization, which involves melting and atomizing metal using inductively coupled plasma. The resulting powder particles have good flowability and apparent density, making them ideal for AM.

Atomization is another widely used technique for producing metal powders. This process involves the production of small droplets of molten metal, which are rapidly cooled and solidified to form powder particles. Water, gas, or plasma are commonly used as atomization media. Gas atomization is preferred for reactive materials like titanium, where oxidation can be a problem. Gas atomization is achieved by using an inert gas like argon or nitrogen to prevent oxidation during powder production.

Feedstock refers to the raw materials used to produce parts using additive manufacturing (AM) processes. For metals, feedstock typically comes in the form of metal powders, which are used as the starting material to build up the desired part layer by layer. In AM, the quality of the feedstock material plays a crucial role in the final product's quality, strength, and durability.

2.2 Steel

Steel is a widely used material in AM due to its excellent mechanical properties, durability, and affordability. [7] Different types of steel alloys are used in AM, each with distinct characteristics and applications.

One popular type of steel used in AM is stainless steel, which is known for its corrosion resistance, high strength, and durability. Austenitic stainless steels, such as 304L and 316L, are commonly used in AM applications that require high corrosion resistance and good ductility. Another commonly used steel in AM is tool steel, which is used for applications that require high wear resistance, toughness, and hardness. Tool steels, such as H13 and D2, are typically used in the production of moulds, dies, and tooling components. Low carbon steels are also used in AM applications that require high strength and good ductility. Low carbon steels, such as AISI 1020, are commonly used in the production of structural components, automotive parts, and consumer products.

2.3 Aluminium Alloys

One crucial factor that determines the quality and properties of AM parts is the choice of feedstock material. In the case of aluminium alloys, the feedstock material must have certain characteristics, including excellent flowability, high sphericity, and low oxygen content.

Aluminium alloys are widely used in various industries due to their desirable properties such as high strength-to-weight ratio, good corrosion resistance, and excellent thermal conductivity. [8] The choice of aluminium alloy feedstock material for AM processes depends on several factors, including the intended application, the required mechanical properties, and the processing method. Some of the commonly used aluminium alloys for AM include AlSi10Mg, AlSi12, and Al7075.

The AlSi10Mg alloy is a popular choice for AM applications due to its good mechanical properties, such as high tensile strength and good ductility. It is also easy to process and has good corrosion resistance. The AlSi12 alloy, on the other hand, is known for its high thermal conductivity, making it suitable for applications that require good heat dissipation. Al7075, which is a high-strength aluminium alloy, is preferred for applications that require excellent fatigue properties and high strength.

2.4 Titanium and its Alloys

In the case of titanium and its alloys, titanium powders are commonly used as feedstock due to their desirable mechanical properties, such as a high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility.

Titanium powders for AM can be produced using various methods, including gas atomization, plasma atomization, and induction plasma spheroidization. [9] Gas atomization, in particular, is a preferred method for producing high-quality titanium powders with low oxygen content, which is essential for achieving optimum mechanical properties in the final product. Argon or nitrogen gas is used to prevent oxidation during atomization.

Another critical factor in selecting feedstock for AM is the particle size distribution, which influences the microstructure and mechanical properties of the final product. The ideal particle size for titanium powder is in the range of 10-45 micrometres, with a spherical shape, high flowability, and density. This is because the powder's flowability and packing density affect the build quality and mechanical strength of the printed parts.

3. Microstructure of Additively Manufactured Parts

In additive manufacturing, the material undergoes a complex thermal cycle that includes rapid heating above the melting temperature, followed by solidification after the heat source has moved on. This process involves numerous re-heating and re-cooling stages when subsequent layers are deposited, resulting in non-equilibrium compositions and metastable microstructures of the resulting phases. Consequently, additive manufacturing fabricated parts exhibit complex microstructures and composition.

3.1 LBM of Pure Ti

The LBM process involves the selective melting and solidification of successive layers of titanium powder using a high-powered laser. The resulting microstructure is highly dependent on various factors, such as laser power, scanning speed, layer thickness, and powder size distribution. Microstructural analysis of pure titanium produced through LBM has revealed a complex, multi-scale structure characterised by a fine cellular dendritic structure with ultrafine β-grain regions.

Furthermore, the microstructure of pure titanium produced through LBM is highly dependent on the cooling rate during solidification. [10] Rapid cooling rates lead to the formation of a finer microstructure, while slower cooling rates result in a coarser microstructure with larger β-grains. Understanding the microstructure of pure titanium produced through LBM is critical to optimise the processing parameters and improving the mechanical properties of the final product.

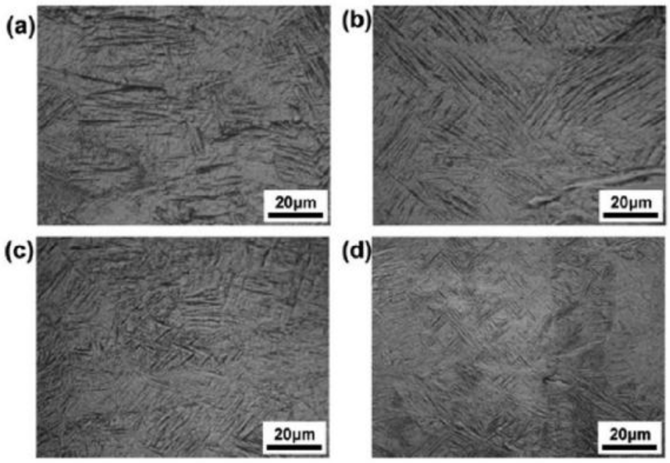

Fig 4: LBM-produced cp-Ti microstructures.

3.2 LBM of Ti-6Al-4V

Ti-6Al-4V is a challenging material to process due to its high melting temperature, thermal conductivity, and reactivity with atmospheric gases. [11] One of the key advantages of LBM for processing Ti-6Al-4V is the ability to achieve a fine and homogeneous microstructure with a refined α/β grain size distribution, which contributes to the high strength, low weight, and superior corrosion resistance properties of the material. Several studies have investigated the effect of LBM processing parameters, such as laser power, scanning speed, and layer thickness, on the microstructure and mechanical properties of Ti-6Al-4V.

Studies have shown that using high laser powers and scanning speeds can result in a refined microstructure with a uniform α/β grain size distribution. In contrast, low laser powers and scanning speeds can lead to coarser α/β grains and an increased presence of β-phase, which can negatively affect the mechanical properties of the material. Layer thickness also plays a critical role in the microstructure of Ti-6Al-4V produced through LBM. [12]Thin layers can result in a more homogenous and refined microstructure, while thicker layers can lead to an increase in porosity and non-uniformity in the microstructure. In addition, parts produced using AM may undergo hot isostatic pressing (HIP) treatment to reduce stresses and minimise remaining porosity. The author discovered that HIP treatment at 850°C for four hours and a pressure of 102 MPa transformed the as-fabricated martensitic microstructure while also reducing porosity.

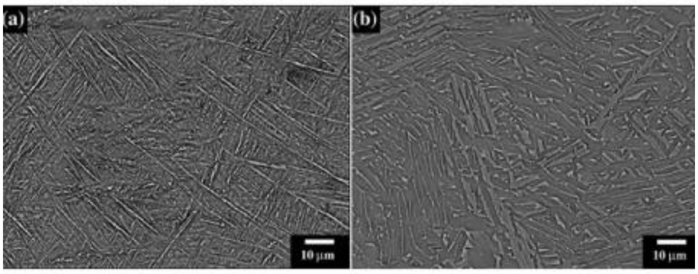

Fig 5: Ti-6Al-4V LBM microstructure.

3.3 EBM of Ti-6Al-4V

This research paper investigates the microstructure of Ti-6Al-4V parts produced using Electron Beam Melting (EBM). The research indicates that the structure on a small scale of the components typically consists of large initial β-grains that change into a finely layered α configuration with a low amount of remaining β. EBM involves the selective melting of successive layers of Ti-6Al-4V powder using a high-energy electron beam in a vacuum environment. The electron beam's energy melts the powder particles, which solidify to form the final part. The microstructure of Ti-6Al-4V produced through EBM is characterised by a columnar α-grain structure with a fine acicular martensitic β-phase distributed within the α-grains.

Several factors can influence the microstructure of Ti-6Al-4V produced through EBM, including the beam energy, beam current, scan speed, layer thickness, and powder size distribution. For instance, higher beam energy and current result in a higher melting rate and faster cooling rate, which lead to a finer microstructure. Studies have shown that the microstructure of Ti-6Al-4V produced through EBM is highly anisotropic, with a directional dependence on mechanical properties.

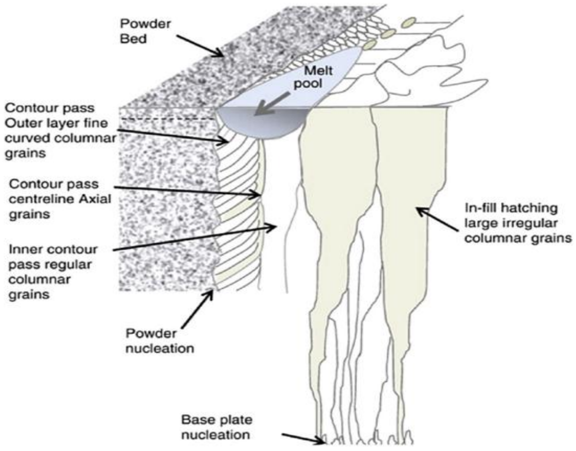

Fig 6: Ti-6Al-4V EBM microstructure.

4. Tensile Properties of AM Fabricated Titanium and Titanium Alloys

Tensile testing is a standard method for characterising the mechanical properties of materials, including the tensile strength, yield strength, and elongation. Several studies have investigated the tensile properties of AM-fabricated titanium using various AM processes. For instance, Murr et al. (2012) investigated the tensile properties of SLM-fabricated Ti-6Al-4V alloy and compared them with conventionally produced Ti-6Al-4V alloy. [13] The study found that the SLM-fabricated alloy exhibited similar or slightly higher yield strength, tensile strength, and elongation compared to the conventionally produced alloy.

Similarly, Zhao et al. (2018) investigated the tensile properties of EBM-fabricated Ti-6Al-4V and pure titanium. The study found that the EBM-fabricated Ti-6Al-4V alloy exhibited similar yield strength and tensile strength compared to the conventional Ti-6Al-4V alloy, but with lower elongation. The EBM-fabricated pure titanium showed a higher yield strength and lower elongation compared to the conventional material. In addition to pure titanium, several studies have investigated the tensile properties of AM-fabricated titanium alloys. For instance, Gong et al. (2016) investigated the tensile properties of SLM-fabricated Ti-6Al-4V and Ti-5Al-2.5Fe alloys. The study found that both alloys exhibited similar or slightly higher yield strength and tensile strength compared to the conventionally produced alloys, but with lower elongation.

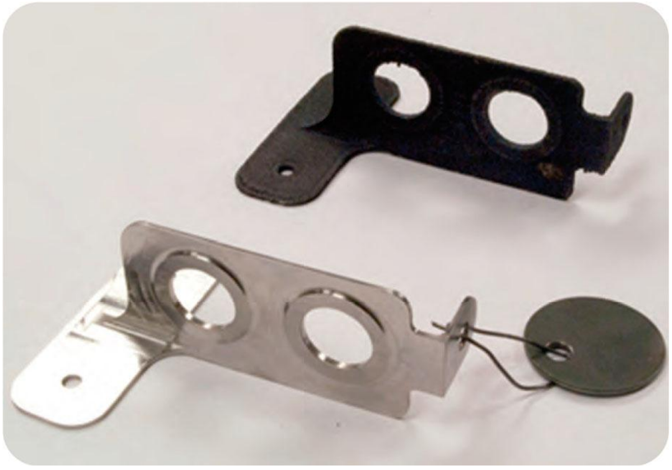

Fig.9: Post-HIP Ti 6Al–4V brackets, before and after machining

5. Post-processing and Defect Management

Post-processing and defect management are critical aspects of metal additive manufacturing (AM) that affect the quality, reliability, and performance of the final product. In this section, we will discuss the common post-processing techniques used in metal AM, as well as the various types of defects that can arise during the process and their corresponding management strategies.

5.1 Support, Powder & Substrate removal

Support, powder, and substrate removal are important aspects of metal additive manufacturing (AM) that affect the surface finish and dimensional accuracy of the final product. In this section, we will discuss the common techniques used for support, powder, and substrate removal in metal AM.

Support structures are used in metal AM to provide support for overhanging features during printing. After printing, the support structures must be removed carefully to avoid damaging the printed part. Powder removal is necessary in metal AM to remove excess powder that has not been fused during printing. Excess powder can affect the surface finish and dimensional accuracy of the printed part. Substrate removal is necessary in metal AM to separate the printed part from the build platform. [14] Substrate removal can be challenging, especially when the printed part has complex geometries or features that are difficult to access.

5.2 Post-processing

Post-processing is an essential step in additive manufacturing (AM) to improve the mechanical properties, surface finish, and dimensional accuracy of the final product. [15] Ti6Al4V is a popular titanium alloy used in AM due to its excellent mechanical properties, corrosion resistance, and biocompatibility. In this section, we will discuss the various post-processing techniques used in Ti6Al4V AM and their impact on the final product's properties.

Heat treatment is a commonly used post-processing technique in Ti6Al4V AM to improve the alloy's mechanical properties. The most common heat treatment process used is the solution treatment, which involves heating the printed part to a specific temperature (typically between 900-950°C) for a set period, followed by quenching in water or oil. The solution treatment improves the alloy's mechanical properties by dissolving the alpha phase, resulting in a more homogeneous microstructure. [16]

Treatment	Ti–6Al–4V
Stress relief	2 hours, 700–730°C[197]
Hot isostatic pressing (HIP)	2 hours, 900°C, 900 MPa[197] 180 ± 60 min, 895–955°C, >100 MPa[192]
Solution treat (ST)	Not typical
Aging	Not typical

Fig.7: Heat treatment for Ti-6Al-4V .

5.3 Stress relief

To alleviate stress in materials, elevated temperatures accelerate atomic diffusion, causing atoms to migrate from high-stress areas to low-stress regions, which leads to the release of internal strain energy. [17] Prior to the removal of SLM and DED parts from the substrate, annealing is typically performed to eliminate any residual stress (as illustrated in Figure 8). Stress-relief treatments should be performed at a temperature that permits atomic mobility, but for a duration that prevents grain recrystallization and growth (unless intentionally desired), as this often results in reduced strength. In metal AM processes, recrystallization can be advantageous to facilitate the formation of equiaxed microstructures instead of columnar microstructures. In iron, thermal residual stress is thought to be the driving force behind recrystallization, although this occurs without cold working. Similarly, similar phenomena have been observed in wire-fed DED.

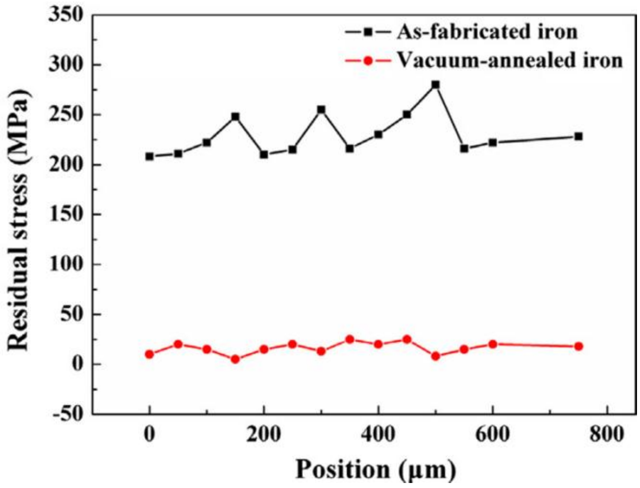

Fig.8: Stress relief through vacuum

5.4 Surface finishing

Surface finishing is another important post-processing technique in Ti6Al4V AM that can improve the surface texture and reduce surface roughness. Surface finishing techniques include mechanical polishing, chemical polishing, and electropolishing. Mechanical polishing involves using abrasive media to remove surface defects and roughness. Chemical polishing involves immersing the printed part in an acid solution to remove surface roughness. Electropolishing involves applying an electric current to the printed part while immersed in an electrolyte solution to remove surface defects and improve the surface finish. Parts intended for use in service are usually subjected to post-processing heat treatment, which can cause surface oxidation of the metal. Figure 9 shows examples of post-HIP items before and after surface machining. [18] For thin-wall EBM samples with open pores, oxidation can penetrate into the interior of the part, as shown in Figure 10.

However, surface machining may not be sufficient to remove defects, which must be avoided. Tool path selection, tool orientation, and tool geometry have all been extensively studied in relation to CNC machining of freeform surfaces. AM and CNC have been investigated in combination, resulting in "hybrid manufacturing" or "hybrid AM." Hybrid systems often involve a dead process with CNC, with the CNC tools mounted in the same location as the dead process. This hybrid approach is currently used to repair compressor blades and other complex service parts in aerospace components. Figure 11 depicts the restoration of turbine blades using this method. In Japan, Matsuura has developed LUMEX, a hybrid technology that combines SLM and CNC, which cuts specific features after each layer. Unlike part repair, the LUMEX technique has found applications in tool and die fabrication.

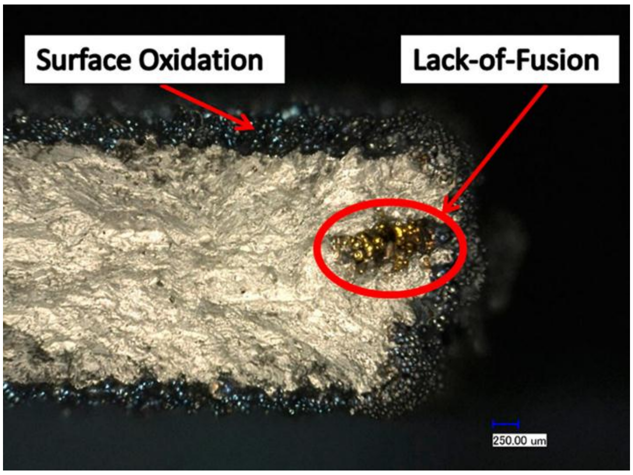

Fig.10: EBM fracture of Inconel 718 with surface oxidation.

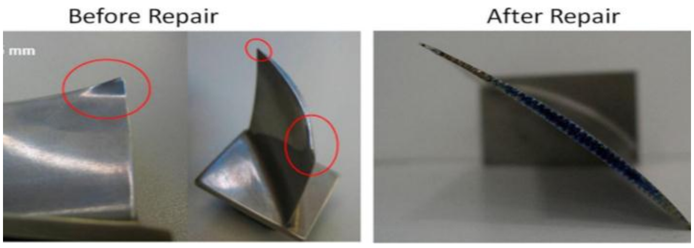

Fig.11: CNC and AM used to repair turbine blades.

6. Applications of Additive Manufacturing

6.1 Topological optimization

The process of topology optimization involves identifying the optimal structural configuration that satisfies a set of objectives, constraints, loads, and boundary conditions within a defined design space. The primary aim of topological optimization is to reduce the weight or volume of a component while ensuring that it meets the operational requirements without failure or yielding.

In this research paper, we present an example of topology optimization applied to an aircraft hinge product. [19] The hinge's topology was altered to align with the current structural performance standards and optimised to minimise its overall weight. The resulting design was then manufactured using an AM laser powder bed technique, as illustrated in the accompanying photos. By changing the part's topology, the hinge's weight was significantly reduced, while ensuring it met the specified operational constraints.

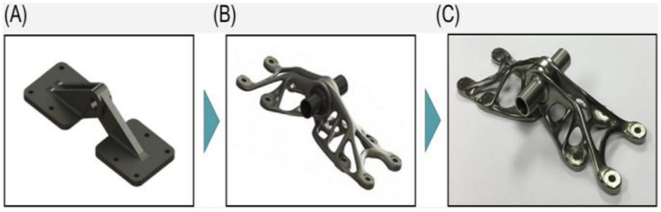

Fig.12: Topologically optimised hinge for AM

This research paper explores how topology optimization can effectively utilise additive manufacturing to produce parts that were previously impossible to manufacture using traditional manufacturing methods. A prime example of this is illustrated in the hinge case study presented above. Furthermore, the industry has coined the phrase "Complexity is free" to emphasise the minimal cost difference in producing complex topologically optimised parts compared to their original counterparts.

The process of optimization is a joint endeavour between finite element software packages and topology optimization. This algorithm uses information from the FE model, which includes displacement, contact force, stress, and strain, to adjust a part's topology in an iterative manner until the desired goal is met within the application's limits. The current study examines topology optimization, its interaction with FE software packages, and its possibilities in additive manufacturing.

6.2 Part Consolidation

The principle of consolidating parts involves decreasing the number of components in an assembly or structure composed of multiple parts into a redesigned part with the same operational capacity but fewer overall components. In this approach, additive manufacturing (AM) is used to simplify the assembly process by producing a single redesigned part. There are several advantages to using part consolidation in AM, including component simplification, possible performance improvement, and reduced tooling and fabrication time. Manufacturers can considerably decrease overhead costs associated with labour, tooling, part traceability, and inventory for that assembly by reducing the number of components. Furthermore, simplifying the components can make the product easier to operate and maintain from the user's standpoint.

Fig13: AM component consolidation of a jet engine cowl latch.

6.3 Micro-Trusses

The unique capabilities of AM, such as the ability to produce complex geometries, have made it possible to design and fabricate micro-trusses with high strength-to-weight ratios, excellent energy absorption properties, and optimal stress distribution. These microtrusses can be used in various aerospace applications, such as aircraft wings, fuselage, and engine components, to improve performance, fuel efficiency, and reduce emissions. Furthermore, the use of AM microtrusses allows for customization and optimization of the design for specific performance requirements, making it an attractive option for the aerospace industry. However, challenges remain in the design and optimization of micro-trusses, such as understanding the effect of different microstructure parameters on the mechanical properties and the development of reliable simulation models. Therefore, further research is required to fully realise the potential of A micro-trusses in the aerospace industry. [20]

6.4 Circuits

The University of Texas has developed multifunctional components that incorporate integrated circuitry. [21] To combine conductive inks with structural components, they employed additive manufacturing techniques like fused deposition modelling and stereolithography. As shown in Fig. 14, they have created working prototypes of various components using this approach. This research places a high emphasis on incorporating electronics with other features, such as heat management, radiation shielding, strength enhancement, and control systems. The method's potential uses for space applications, particularly in CubeSat systems, are currently under investigation.

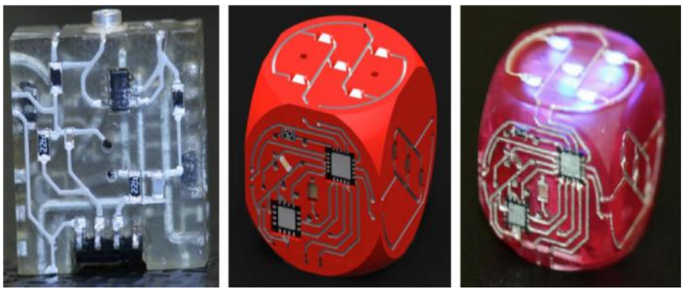

Fig.14: Structural element with integrated circuitry

6.5 Static and dynamic engine components

Static and dynamic engine components are crucial in the aerospace industry as they play a critical role in ensuring the safety and reliability of the aircraft. [22] Static components refer to the parts that remain stationary during engine operation, such as the engine casing, exhaust system, and inlet duct. These components must be designed to withstand extreme temperatures and pressures, as well as resist corrosion and wear. On the other hand, dynamic components refer to parts that move during engine operation, such as the turbine blades, compressor rotor, and bearings. These components must be designed to withstand high speeds, vibrations, and forces while maintaining precise tolerances and durability. The development of advanced materials and manufacturing techniques has led to significant improvements in the performance and durability of static and dynamic engine components, contributing to the increased safety and efficiency of modern aircraft in the aerospace industry.

One of the aerospace industry's most well-known AM applications is the LEAP engine fuel injector. The production of over 30,000 injectors began in 2015 and continued through 2018, with production still ongoing. The fuel injector, shown in Fig. 16, was fabricated using L-PBF and is currently used in multiple engines employed in commercial aircraft.

Fig.15: GE LEAP Fuel Nozzle

6.6 In Situ Fabrication and Assembly

The use of additive manufacturing technology in space flight presents an intriguing possibility for the on-site production of very large structures through robotics. Various design approaches can be utilised to construct kilometre-sized structures, which can be made with low strength since they will not be subjected to launch or gravity loads. This will considerably decrease the amount of raw material that needs to be transported into orbit. However, to fully realise the potential of these structures, they must be built and erected autonomously. [23] For example, an antenna could be additively printed in space using this approach.

Previous research has been conducted on the 3D printing of plastic components on the International Space Station to examine how microgravity impacts additive manufacturing processes.

6.7 In Situ Resource Construction

In situ resource construction is an emerging concept in additive manufacturing that has the potential to revolutionise the aerospace industry. The idea is to use AM technology to build structures and systems directly from materials that are available at the destination site, such as on a planetary surface or in space. This approach can greatly reduce the cost and complexity of space missions by eliminating the need to transport large amounts of material from Earth. It also has the potential to enable new capabilities, such as the construction of large-scale structures in space. Several research efforts are underway to develop in situ resource construction for the aerospace industry, including the advancement of AM systems that can work in low-gravity environments and the exploration of new materials that can be used in space. While there are still many technical challenges to be addressed, in situ resource construction represents a promising approach for enabling new frontiers in space exploration and development.

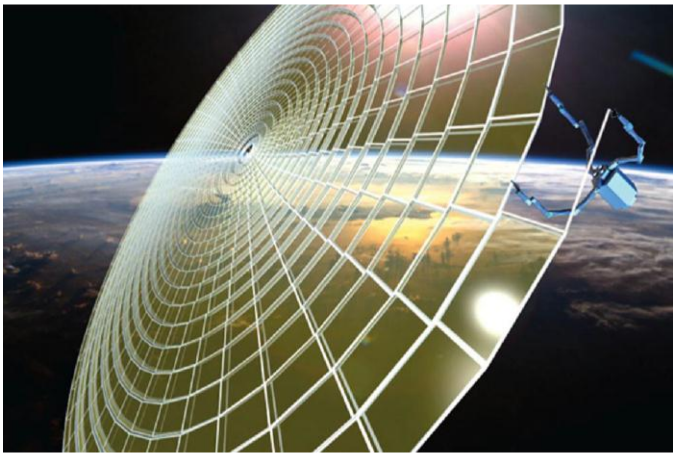

Fig.16: A robot fabricating an antenna in space; image courtesy of NASA.

7. Future modelling and simulations

7.1 Uncertainty quantification and optimization

The authors emphasise the increasing significance of comprehending and computing the error propagation rate during AM simulations. [24] It is important to conduct comprehensive uncertainty quantification (UQ) of diverse physical and processing characteristics to comprehend the fundamental factors that influence the quality of parts and accurately forecast their properties. This project is essential in optimising AM processes through in-silico approaches by reducing the number of trial-and-error experiments required to find optimal process parameters and conditions. This facilitates improvement in part qualities and cost reduction.

7.2 Upscaling methods

As the aerospace industry continues to adopt additive manufacturing (AM) for the production of complex components, there is a growing need to upscale the process for high-volume production. [25] To achieve this, new methods are being developed to increase production rates and reduce costs while maintaining the high quality and reliability standards required by the industry. One promising approach is the use of multi-laser systems that can print multiple parts simultaneously, resulting in a significant increase in productivity. [26] Additionally, advancements in material science are enabling the use of higher strength and temperature-resistant materials that can withstand the harsh environments encountered in aerospace applications. Another area of research involves the integration of AM with traditional manufacturing methods, such as casting and forging, to produce hybrid components with the benefits of both processes. [27] As the demand for AM in aerospace continues to grow, the development of these future upscaling methods will play a crucial role in enabling the industry to meet its production needs while maintaining the high standards of quality and performance required.

8. Conclusion

This research paper presents an analysis of various critical domains of additive manufacturing, highlighting its potential to revolutionise the manufacturing industry. Additive manufacturing, however, comes with various difficulties, including distinct quality control demands, inadequate high-volume production speeds, restricted material accessibility, complications in post-processing, potential impairment of fatigue characteristics, high machinery expenses, and a requirement for specialised knowledge to fabricate functional components.

To establish additive manufacturing as a dominant player in the manufacturing industry, several improvements are necessary in the following areas:

1. Enhancing production rates.
2. Reducing costs.
3. Developing new alloys suitable for additive manufacturing and aerospace applications.
4. Implementing in situ monitoring and accurate flaw identification.
5. Using built simulation to identify risks.
6. Exploring additive manufacturing for in-space and non-terrestrial applications.

7. Widening the use of architected cellular structures (lattices).

8. enabling the development of multifunctional components such as integrated electronics and sensors in additive manufacturing processes.

Addressing these challenges can significantly improve the adoption of additive manufacturing and pave the way for its integration in various industrial applications.

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