Aerospace applications in additive manufacturing

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1 Introduction

Written by Nils FALCOZ-RAVASSE

The aerospace sector is a unique domain, characterized by extreme requirements and significant challenges that go far beyond those encountered in other industries. Its specificities impose technical and economic constraints. Among these particularities are:

- **Extreme conditions:** Temperatures exceeding 3,000°C in engines, high vibrations during takeoff, and space radiation affecting satellites.
- **High certification standards:** Every critical component must follow rigorous testing, given the stakes involving human lives or the high cost of the entire systems.
- **Extended service life:** Aircraft are used intensively for over 25 years, requiring durable parts and rapid maintenance, while space missions can last up to 15 years or more without the possibility of maintenance.
- **Complex supply chain:** Producing and delivering specific components often involve highly variable quantities.

Beyond these technical and economical constraints, environmental challenges are becoming central. Present in the space sector (eco-design, or space debris), this theme is even more crucial in aviation. While achieving flight and safety objectives has long been mastered, minimizing fuel consumption is now a priority, driven by economic factors over the past decade and environmental concerns today[21]. Reducing an aircraft's weight by just a few hundred grams or kilograms can cut CO_2 emissions by several tons over its lifetime, resulting in significant financial savings as well. This pursuit of sustainability is increasingly critical as air traffic continues to grow exponentially, making its control challenging[1].

Évolution période 1973–2019

Trafic	+1 302%
Intensité énergétique	−80%
Intensité carbone	0%
Émissions de CO_2	+184%

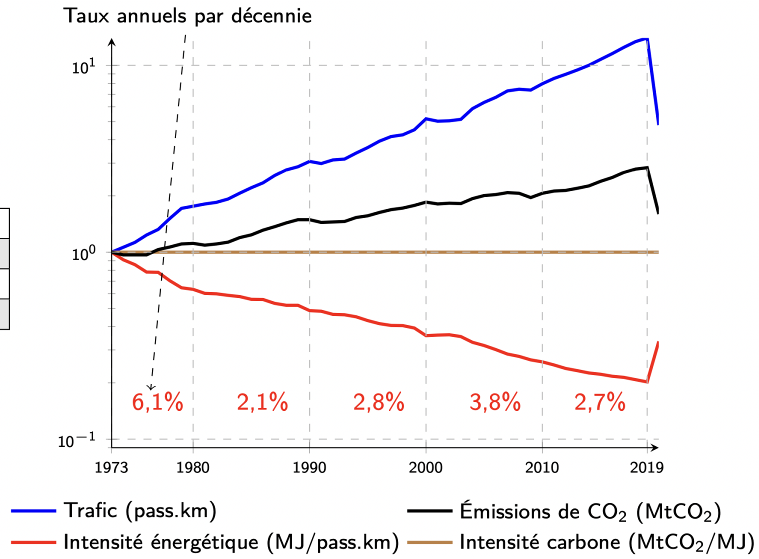


Figure 1.1: Kaya decomposition for aviation [17]

Additive Manufacturing (AM) is emerging as the perfect technology to address these challenges. It enables the design of lightweight, complex parts that were difficult to achieve

[1] Amsterdam Airport unable to close night slots due to external pressure, Rebound effect on flight slots (e.g., flights under 2.5 hours in France), Increasing traffic in developing countries.

a decade ago, while minimizing material waste and associated costs. However, its current expansion in the aerospace industry is the result of a relatively recent widespread adoption.

AM's origins date back to the 1980s-1990s, where it was primarily used for rapid prototyping of non-critical parts. This phase explored the technology's possibilities, but its applications were limited by insufficient precision and unsuitable materials. [3] A significant turning point occurred in the 2010s with advanced processes such as powder bed fusion and laser metal printing improvement. These technological advances paved the way for practical applications, including:

- In aviation, the Leap engine marked a milestone with the first commercial flight using 3D-printed fuel injectors, showcasing optimized and more sustainable production.[36]
- In space, Thales Alenia Space revolutionized satellite manufacturing by printing complex antennas, significantly reducing both production time and component weight.[56]

Today, AM is used on an unprecedented scale. SpaceX and Relativity Space are pushing technological boundaries by printing not only engines but entire rockets. These projects demonstrate that AM, initially a prototyping tool, has become a serial production and disruptive technology capable of transforming value chains and traditional designs. The AM market in aerospace is expected to reach USD 3.187 billion by 2025, with a compound annual growth rate of 20.24%, reflecting its growing adoption in critical applications and its central role in the Industry 4.0 revolution.[12]

This rapid evolution, while full of challenges, underscores the importance of AM in today's and tomorrow's aerospace industry. We will first examine its advantages and limitations before delving into the types of AM, materials, and methods used more in depth. Finally, we will illustrate its role through two representative case studies to better understand its impact on this transforming industry.

2 Advantages of Additive Manufacturing in Aerospace

Written by Nils FALCOZ-RAVASSE

AM has transformed the aerospace sector by offering innovative solutions to technical, economic, and environmental challenges. Its integration into industrial processes occurs at three distinct stages of development and production:

- **Rapid prototyping:** Creating models and prototypes to test designs.
- **Tooling and molds:** Manufacturing custom tools and complex molds.
- **Direct fabrication:** Producing functional components, including final parts.

These three applications demonstrate AM's adaptability throughout the development and production cycle, paving the way for significant gains. The main advantages can be categorized into four interconnected areas: performance optimization, cost and time reduction, logistical revolution, and environmental impact.

2.1 Performance Optimization and Weight Reduction

One of AM's most significant strengths lies in its ability to revolutionize part design. Unlike traditional techniques, AM enables the creation of complex geometries, lightweight structures, and the integration of multiple functions into a single monolithic part. Weight reduction is a strategic advantage in aerospace. As already discussed for aviation applications (gains in both economic and environmental aspects), this advantage becomes even more critical in space, where every gram matters.

Topology optimization and the use of internal structures, made possible by generative design algorithms, achieve these weight reductions. AM also improves performance through adaptive 4D geometries and the integration of features such as cooling channels, which were previously unfeasible[12][19].

2.2 Cost and Time Reduction

Moreover, AM accelerates product development cycles. Rapid prototyping capabilities reduce design, testing, and iteration timelines. AM also significantly reduces time-to-market through accelerating industrialization cycles. For example, Pratt & Whitney achieved a 15-month reduction in stator blade development time compared to traditional methods. AM also redefines costs by minimizing material waste. The "near-net shape" approach reduces material waste by up to 90%, especially for high-value materials like titanium or Inconel. Traditional methods, such as machining, often result in buy-to-fly ratios exceeding 20:1 or even 40:1. In contrast, AM achieves ratios as low as 3:1 with efforts pushing towards 1:1.[2][19]

Cost reductions extend beyond raw materials. By eliminating intermediate steps like assemblies or manual adjustments, AM significantly reduces production times and associated costs. Monolithic parts, which integrate multiple functions, eliminate assembly steps, simplify processes, and enhance reliability, leading to up to a 50% cost reduction for complex parts.[44]

2.3 Logistical Revolution and Production Flexibility

AM disrupts traditional supply chains by enabling decentralized and flexible manufacturing. Previously, spare parts had to be stored in large quantities. Now, on-demand printing offers an efficient and economical alternative. This is particularly relevant for remote bases, aircraft carriers, or space missions, where storage and resources are limited.

This approach reduces storage needs and enables real-time manufacturing. Projects such as drone printing on-site or the production of specific tools in orbit demonstrate the potential of this logistical revolution. AM's flexibility is driven by versatility, allowing a single machine to produce various parts, eliminating centralized production constraints and enhancing supply chain resilience.[2][10][44]

2.4 Environmental Impact and Sustainability

Finally, AM plays a central role in sustainability objectives, a priority in aerospace. Weight reduction decreases fuel consumption, reducing CO_2 emissions over an aircraft's lifecycle. This impact is further enhanced by energy efficiency gains from optimized designs. Additionally, AM's ability to reduce manufacturing waste and stock rare or expensive materials supports a more sustainable use of resources.

2.5 Summary

In summary, AM combines economic, technical, and environmental benefits, positioning itself as a key solution to aerospace challenges. By offering better performance, logistical flexibility, cost savings, and reduced environmental impact. AM redefines industrial paradigms while meeting some of the strict requirements of this demanding sector.

Target Objectives	**Gains vs traditional solution**	**Remarks**
Reduction in material usage	$> 50\%$	For Titanium or Inconel parts
Reduction in manufacturing cost	$> 20\%$	For complex parts
Reduction in industrialization cycle time	$> 50\%$	For complex parts
Reduction in industrialization cost	$> 80\%$	For complex parts
Reduction in part mass through topological optimization	$> 50\%$	Significant "cultural" barrier
Reduction in cost through function integration (including BOM reduction)	$> 80\%$	Includes reduced assembly times

Table 2.1: Summary[50]

3 Limitations and Current Challenges

Written by Nils FALCOZ-RAVASSE

Despite the significant progress made in the field of Additive Manufacturing, this technology is not without its limitations, particularly in a sector as demanding as aerospace. While AM offers numerous opportunities, it also presents technical, regulatory, and economic challenges that continue to slow down its large-scale adoption.

3.1 Technical Challenges and Material Limitations

Although AM revolutionizes design and production, certain technical limitations persist, particularly regarding materials and the properties of produced components. The aerospace sector, with its constant demand for reliability and performance, imposes requirements far beyond standard industrial benchmarks. As a result, the materials used in AM often require specific formulations to withstand the extreme mechanical and thermal constraints of the industry. These materials, however, are not only limited in availability but are also expensive, especially due to the processes required to transform them into powders.

A major challenge remains the anisotropy of mechanical properties in AM components. Performance varies depending on the printing orientation: mechanical properties in the xy-plane are generally superior to those along the z-axis due to the layering inherent in the process. While post-processing techniques, such as thermal treatments, can improve these properties, they lengthen production cycles and increase costs. Additionally, printed parts are often prone to microstructure, a particularly critical issue in applications where safety is paramount. [2][12]

AM also still struggles to integrate multiple materials within a single part, primarily due to delamination at interfaces and disparities in thermal or mechanical properties between the materials. Finally, post-processing remains a costly and complex stage. Whether it involves removing support structures or improving the mechanical and surface properties of parts, these operations add significant time, resource, and cost constraints, reducing AM's competitiveness compared to traditional manufacturing methods. In some cases, processes such as Hot Isostatic Pressing (HIP) are essential to eliminate porosity and enhance durability.[2][10][25]

3.2 Certification and Regulatory Constraints

Technical challenges are further exacerbated by the demanding certification requirements characteristic of the aerospace industry. In this sector, each part must not only meet precise mechanical specifications (with high margin) but also undergo rigorous and often lengthy validation protocols. These processes are particularly complex given the constantly evolving standards specific to AM, such as those established by ASTM and ISO.[12]

This mismatch between the pace of technological advancements and regulatory evolution creates administrative barriers that slow the adoption of new solutions. For example, it can take years to certify an AM component, illustrating the difficulties companies face when trying to introduce innovations within a demanding regulatory framework. The main challenge is demonstrating that we have control over the process and that the observed results are reproducible. A deeper discussion on this topic will be provided in a later section. [10]

While indispensable for ensuring safety and quality, these constraints remain a significant challenge to the rapid and widespread deployment of AM in aerospace.

3.3 Economic and Production Constraints

Beyond technical and regulatory aspects, the high initial costs associated with AM represent a major barrier. The acquisition of advanced machines, often expensive, along with specialized software and the necessary training to fully utilize this technology, constitutes a substantial investment. These financial barriers limit AM adoption primarily to large enterprises, hindering its democratization, particularly for small businesses and start-ups.

Moreover, while AM is particularly well-suited for small series production and complex parts, its profitability remains uncertain for mass production or long printing durations. Traditional methods continue to be more competitive for many standardized components, although AM can complement these methods in intermediate stages, such as mold fabrication.

Finally, the lack of skilled personnel to operate these technologies is another limiting factor. The expertise required to master both digital tools and AM industrial processes remains scarce, slowing the growth of this technology and contributing to its high costs[10].

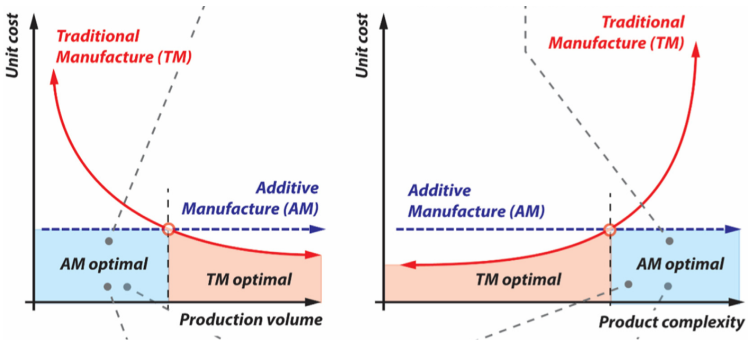


Figure 3.1: AM vs traditional manufacturing[12]

4 Additive Manufacturing Technologies for Aerospace Applications

Written by Léo Digonzelli

4.1 Metal-based additive manufacturing for aerospace

Aerospace field actively uses multiple metal AM processes, which have often different designations and grouping. These AM technologies are categorized either by feedstock, process principles such as energy source, material distribution or state of the metal during fusion according to ISO/ASTM 52900:2015. Metal AM processes are widely used in aerospace for freeform parts manufacturing, coatings, repairs and remanufacturing. Metal AM processes used in aerospace include powder bed fusion processes, directed energy deposition processes or solid-state processes.[43][13][27]

4.1.1 Powder bed fusion processes

(a) Laser Powder Bed Fusion (L-PBF)

Laser Powder Bed Fusion (L-PBF), also referred as Selective Laser Melting (SLM), employs high-power lasers to selectively melt and solidify successive layers of metal powder bed, following a CAD design. The process involves depositing and spreading metal powder across a build platform, where the laser scans and melts the powder in predefined patterns. Parameters such as laser scanning strategy, layer thickness, inert atmosphere, and gas flow must be precisely configured and optimized to suit the specific material and machine setup. L-PBF is the most widely adopted metal AM technology, offering compatibility with a broad range of materials, including nickel and iron-based superalloys, titanium alloys, aluminum alloys, steel alloys, copper alloys, precious metals, and refractory metals. The process is renowned for producing fully dense parts with exceptional precision and a rapid production timeline. These characteristics lead to aerospace applications such as lightweight structural components, heat exchangers, and engine parts. However, the cost of L-PBF remains high, limiting its use to industries requiring high-performance components, such as aerospace, where improved performance justifies the expense. Typically, L-PBF achieves minimum feature sizes of approximately 0.2–0.4 mm and supports maximum part sizes of 300–400 mm. Recent advancements include multi-laser systems, which improve productivity and allow for larger build volumes of up to 500 $\times$ 280 $\times$ 850 mm. While systems with build capacities exceeding 1 meter are under development, they are not yet commercially available or widely accessible.[61][23][13][27][43]

(b) Electron Beam Powder Bed Fusion (EB-PBF)

Electron Beam Powder Bed Fusion (EB-PBF) is an additive manufacturing process that utilizes a high-energy electron beam to selectively melt metal powder layer by layer, producing fully dense solid components. The process operates in a vacuum environment, which is requirement for the electron beam and which also minimizes impurities in oxygen-sensitive materials. Preheating is commonly employed in EB-PBF systems by rapidly scanning the electron beam across the powder bed before melting each layer. This preheating step effectively reduces residual stresses in the fabricated parts. The mechanical properties of EB-PBF-manufactured components are comparable to those of cast materials, underscoring the process's viability as an alternative to traditional manufacturing methods. The maximum build sizes achievable in EB-PBF are similar to those of Laser Powder Bed Fusion (LPBF), with recent systems featuring a build chamber diameter of 350 mm and a height of 380 mm. EB-PBF typically uses larger feedstock powder particles, leading to increased surface roughness. Nevertheless, this process is highly developed, offering relatively short build times due to the electron beam's high power and rapid scanning capabilities.[61][23][13][27][43]

4.1.2 Direct energy deposition (DED) processes

In Directed Energy Deposition (DED) methods, the material is deposited directly into a melt pool, which is generated by an energy source such as a laser, electron beam, or electrical arc. Unlike other additive manufacturing (AM) techniques that rely on powder beds, DED offers greater flexibility in terms of geometric freedom, making it suitable for the production of very large components. This capability makes DED particularly advantageous for the repair of high-value components, such as turbine blades, engine combustion chambers, compressors, airfoils, and blisks. When repairing up to 10% of the component's volume, studies show that there can be a 45% reduction in the carbon footprint and a 36% overall energy savings. However, DED typically has lower resolution compared to powder-bed-based technologies, with minimum feature sizes around 1 mm. As a result, it is primarily used for larger parts or applications where post-processing machining can be performed to achieve the desired finish. [43][48][13][27]

(a) Laser Powder DED (LP-DED) and Laser Wire DED (LW-DED)

Laser Powder Directed Energy Deposition (LP-DED) process employs a laser as the energy source and metal powder as the feedstock. During LP-DED, the powder is directed into a molten pool, where it is deposited in the form of beads. Typically, this process is carried out in an inert atmosphere or with the use of a local purge to prevent contamination during deposition. An alternative of this DED process is Laser Wire DED (LW-DED), which operates on a similar principle but uses wire as the feedstock. The wire can be introduced in either an off-axis or co-axial configuration, offering the advantage of higher material efficiency. However, this method typically results in a lower resolution compared to other DED processes.

(b) Arc Wire Deposition (AW-DED)

Arc Wire Deposition (AW-DED) process, also referred as Wire Arc Additive Manufacturing (WAAM), builds three-dimensional components through the layer-by-layer deposition of a metal wire. The wire feedstock is fed into an electric arc under controlled conditions tailored to the specific material requirements, and is melted to deposit beads with a local purge. AW-DED offers significant advantages over other AM methods, including reduced material usage and comparatively lower equipment and operational costs. It was shown that energy consumption and material waste in AW-DED are significantly lower than those associated with laser or electron beam methods. Despite its benefits, AW-DED has limitations such as material interaction defects and inferior surface finish compared to parts produced through Laser AM processes. However, it is well-suited for producing large-scale structural aerospace components and tooling with minimal complexity and shorter manufacturing times thanks to its high material deposition rates (several kg/h depending on the wire size). Additionally, the microstructure of AW-DED-fabricated components often differs from those created using conventional manufacturing methods, reflecting the unique processing conditions of AW-DED.[18][59][27]

4.1.3 Other metal-based AM processes used in aerospace

Other metal-based AM technologies used in aerospace include Cold Spray Deposition, Binder Jetting, Ultrasonic Additive Manufacturing, Additive Friction Stir Deposition and others.

Cold Spray Deposition process is a solid-state process where material deposition is achieved through the kinetic energy of particles, rather than the thermal energy typically used in other methods. High-temperature compressed gases (mainly nitrogen and helium) are used as a propellant to accelerate the powder feedstock to extreme velocities, which is then directed through a supersonic nozzle into the system. When the critical velocity of the metal particles gets exceeded, it leads to plastic deformation of the particles and powder adherence. This process is mainly used for aerospace applications such as coatings and structural repairs with materials such as aluminum, titanium, and copper alloys, but it has limitations in geometric complexity.[27]

Binder jetting is a widely used technique for efficient and reliable rapid prototyping of metal additive manufacturing (AM) components, such as turbine blades and impellers. It also plays a significant role in rapid tooling, particularly for producing AM sand cores and molds used in the fabrication of large-scale metal parts. Commonly processed materials include aluminum and copper alloys, gray and ductile iron, and magnesium. In the context of sand cores and molds, binder jetting eliminates the necessity for traditional patterns in indirect rapid tooling, thereby streamlining the production process for low-volume manufacturing. For direct rapid tooling, this technology is utilized to create intricate components such as gear cases, fuel tanks, transmission housings, structural hinges, and lightweight engine parts. Binder jetting is particularly effective for fabricating components with draft-free walls and complex geometries, addressing challenges in conventional manufacturing processes while maintaining design flexibility and cost efficiency. [43][48][60]

Ultrasonic additive manufacturing (UAM) is a solid-state process that employs a high-frequency transducer, typically operating at around 20 kHz, to facilitate the bonding of metal foil or tape feedstock through solid-state metallurgical processes. This is achieved under high contact pressure, enabling strong layer-by-layer bonding without melting the materials. Additionally, a standard CNC milling head is utilized between deposited layers to refine the geometry, introduce detailed features, or selectively remove material locally, enhancing the precision and functionality of the fabricated component. [13][27]

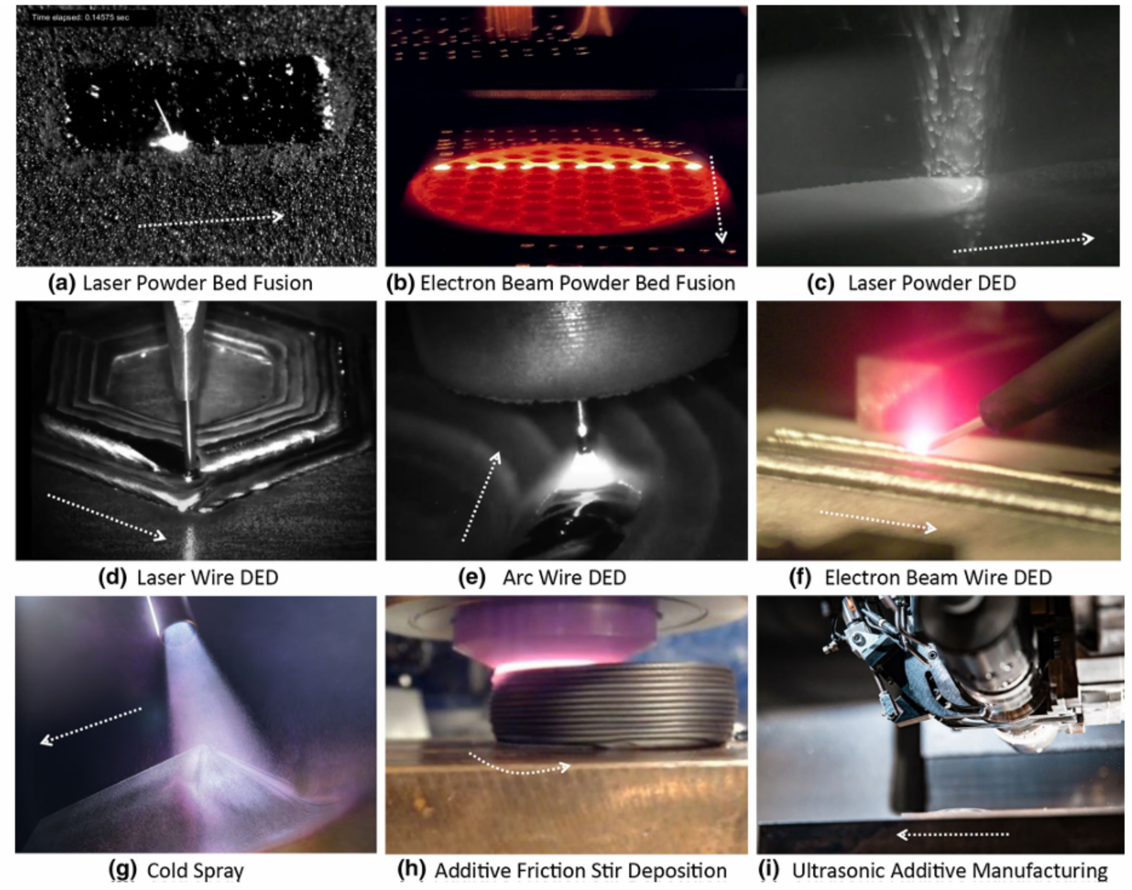


Figure 4.1: Close up images of the various metal AM processes used in aerospace applications (the arrow indicates the deposition/built direction for each process)[27]

4.2 Nonmetallic-based additive manufacturing for aerospace

For nonmetallic components, the additive manufacturing technologies most pertinent to the aerospace sector include selective laser sintering (SLS), stereolithography (SLA), fused deposition modeling (FDM), and PolyJet.

5 Additive Manufacturing Materials for Aerospace Applications

Written by Léo DIGONZELLI

5.1 AM metals and alloys used for aerospace applications

While they are thousands of alloys to choose from for traditional manufacturing, AM lacks the decades of knowledge provided by traditional manufacturing and has only completely matured a limited number of metals and alloys using the various processes. Additionally, aerospace components perform critical functions, are built with few tolerances in challenging conditions (high pressure, corrosive fluids, temperatures ranging from cryogenic to more than 1000°C) and must operate reliably with high duty cycles for thousands of service hours. Therefore, only a limited selection of metallic materials are able to meet these demanding requirements as well as the necessary characteristics to be used with a specific AM process. Distinctive metallic materials for AM in aerospace include Nickel and Iron-based superalloys, Stainless steels, Titanium alloys, Aluminum alloys, Cobalt alloys, Copper alloys and refractive alloys among other.[60][13][27]
Some of the popular commercial aerospace-grade alloys available for additive manufacturing are listed in Table 5.1, and examples of uses of these various alloys for AM aerospace components are depicted in Figure 5.1.

Nickel and Iron-based superalloys are among the most used materials in aerospace applications thanks to their excellent mechanical properties at high temperatures, high pressures and in harsh environment (corrosion and oxidation resistant). Ni and Fe-based superalloys also exhibit high creep resistance, and the combination of their outstanding properties substantially helped to improve the efficiency of modern aircraft engines. These superalloys have become key materials for the manufacturing of many aerospace components such as turbines, casings, combustion chambers, discs and blades in high-pressure turbines for gas turbine engines. They are also used in many other high temperature and cryogenic applications, including valves, turbomachinery, injectors, igniters and manifolds for liquid rocket engines. Popular Nickel-based superalloys accros the AM platforms include Inconel 625 and Inconel 718 among others, which are widely used for many applications listed above. Nickel-based superalloys have become such efficient that they currently represent over 50% of the mass of an advanced aircraft engine. Iron-based superalloys are commonly used in high-pressure hydrogen applications, such as rocket engine, to mitigate risks associated with hydrogen environment embrittlement. NASA HR-1 and JBK-75 are among popular Fe-based superalloys available for AM. [18][13][27]

Titanium alloys have attracted a lot of attention in aerospace applications where strength-to-weight ratio is key. They are substantially used in aircraft due to their high specific strength and high-temperature stability. Titanium alloys also offer excellent corrosion resistance and are electrochemically compatible with polymer-matrix carbon fiber composites widely used in modern aircraft. Additionally, they are of great use for cryogenic applications (rocket propellant tanks) as they exhibit no ductile-to-brittle transition at low temperature. Ti-based alloys have been the subject of much interest for use in AM, such as the Ti-6Al-4V alloy which is commonly used for compressor discs and frames, bearing frames, rotating machinery, landing gears, cryogenic propellant tanks, and more. Ti6242 is used for compressor blades and rotating machinery, and titanium aluminides are used for turbine blades.[13][27]

Aluminum alloys are common aerospace materials choice thanks to their low cost, light weight and good strength-to-weight ratio, despite being weaker than titanium alloys and having poor elevated temperatures capabilities, issues with weld repair and poor stress corrosion cracking resistance for some high-strength Al-based alloys. The production of AM parts includes aluminum alloys from the 1xxx, 2xxx, 4xxx, 6xxx, and 7xxx series (categorized by their alloying elements). Many of these alloys are manufactured using solid-state additive manufacturing techniques. [13][27]

Stainless steels are widely utilized in various aerospace and space components due to their exceptional strength-to-weight ratio, outstanding durability, and robust mechanical properties, even at elevated temperatures. They also have lower cost compared to titanium alloys or super alloys. Different classes of stainless steels, including austenitic, precipitation-hardened (PH), and maraging steels (martensitic and aged), are commonly employed in additive manufacturing (AM). These materials find applications in components such as engine and exhaust systems, hydraulic parts, heat exchangers, landing gear systems, and structural joints. Stainless steels are also known for their excellent resistance to corrosion, oxidation, and wear, which can be tailored based on the specific environmental conditions. This versatility and performance make them integral to aerospace applications where reliability and material longevity are critical. Nevertheless, steel alloys have relatively high density and are not as popular for AM processes than some other alloys as they are prone to cracking. [28][13][27]

Copper and Cobalt alloys are used for high temperature applications. For applications involving elevated temperatures without demand for high thermal conductivity, Cobalt alloys such as Stellite or CoCr can be utilized. On the other hand, copper alloys are extensively used when high thermal conductivity is required. Their elevated thermal conductivity makes them highly suitable for use in heat exchangers, such as for combustion chambers for liquid rocket engines. These environments are subjected to extreme heat flux as well as high pressure, thus requiring alloys with both high conductivity and high strength to properly cool the wall of the chamber with a high pressure propellant or oxidizer (while also meeting material compatibility with the propellant). For this kind of applications, commonly used AM copper alloys that have matured include GRCop-42 and GRCop-84, C18150, C18200 and GlidCop alloys.[26] [13]

Other metal alloys used in aerospace applications with AM processes include refractory alloys (niobium, tantalum, tungsten, molybdenum based alloys). They are used in extreme temperature applications, such as in-space radiatively cooled nozzles (e.g. Nb-based C103 alloy), nuclear thermal propulsion fuel elements, vehicle thermal protection systems, space reactors in-core structures, etc.[27][13]

Development of new alloys and multimetallic materials

Initial applications of additive manufacturing relied on alloys traditionally processed through conventional methods, which were chosen for their traceability rather than their suitability for AM processes. Many of these materials faced challenges such as cracking, porosity, oxidation, and other undesired properties, making them suboptimal for AM. However, AM technology presents a significant opportunity to develop specialized alloys tailored for improved processability and performance in end-use applications. For instance, custom aluminum alloys like 7A77, 6061-RAM2, AlSi10Mg, and Scalmalloy have been developed to achieve high strength and successful AM production, even with alloys prone to cracking under traditional methods (PBF and DED melting processes). NASA has led efforts in this area, creating advanced materials such as GRCop-84 and GRCop-42 copper-based alloys for high-heat flux applications, and the iron-based NASA HR-1 superalloy for high-pressure hydrogen environments. Beyond aluminum and copper, other custom superalloys and refractory metals are also being designed specifically for AM to address the increasing demand for diverse and optimized materials.[13][48]

Moreover, AM enables the creation of bimetallic and multimetallic materials, facilitating localized optimization for thermal or structural performance. AM provides a variety of options for bimetallic and multi-alloy joints, including discrete material transitions, transitions involving a thin layer of a third material, or functionally graded materials which provide gradual compositional changes to enhance compatibility and mechanical integrity in complex designs. In this domain, NASA made massive advances for rocket engine optimization. These innovations include the multimetallic additive manufacturing of thrust chambers under RAMPT Project, where GRCop-42 or GRCop-84 copper alloys serve as a base material for the inside of the chamber, usually manufactured via L-PBF, and onto which Inconel 625 or NASA HR-1 can be deposited (via DED processes, cold spray). This technique results in the manufacturing of combustion chambers that exhibits high thermal conductivity thanks to inner GRCop, and extreme strength and heat resistance thanks to the outer superalloy.[26]

Table 5.1: Commonly used aerospace alloys for additive manufacturing [27][13]

Ni-based	**Fe-based**	**Ti-based**	**Al-based**	**Cu-based**	**Co-based**	**Refractory**	**Bimetallic**
Inconel 625	SS15-5 GP1	Ti-6Al-4V	AlSi10Mg	GRCop-84	CoCr	W-based	GRCop-84/IN625
Inconel 718	SS17-4PH	γ-TiAl	A205	GRCop-42	Stellite 6	Mo-based	C18150/IN625
Hastelloy-X	SS304L	Ti-6242	F357	C18150	Stellite 21	Ta-based	
Haynes 214	SS316-L		2024	C18200	Haynes 188	Nb-based	
Haynes 230	SS347		4047	Glidcop		C103	
Haynes 282	SS420		6061	Cu110			
Monel K-500	Invar 36		7050				
C-276	Tool Steel (4140/4340)						
Rene 80	JBK-75						
Waspalloy	NASA HR-1						

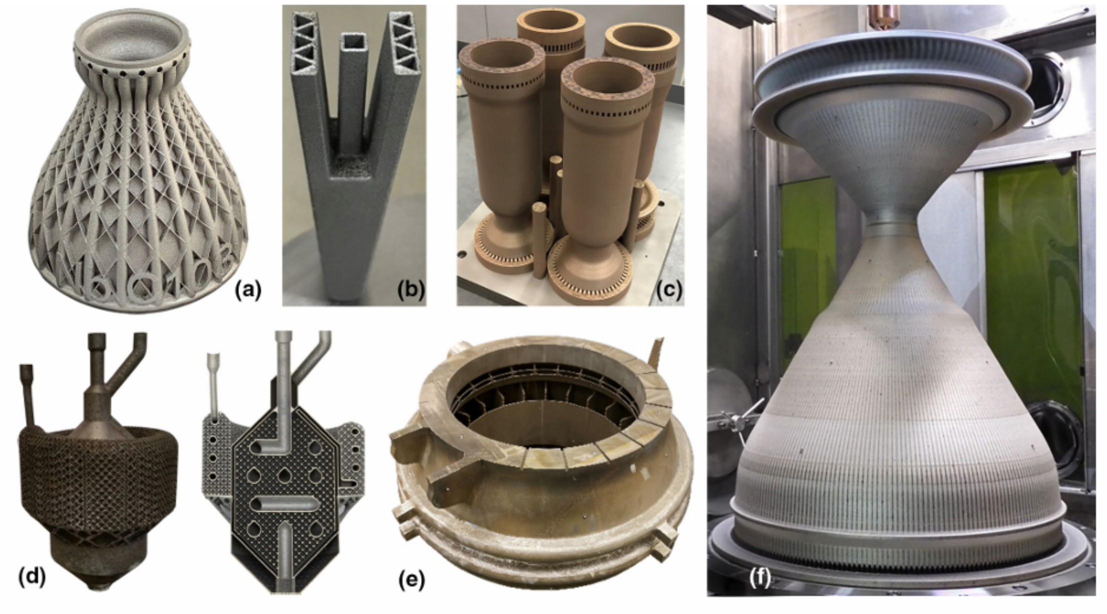


Figure 5.1: Example of complex aerospace components manufactured using various metals and alloys. (a) Actively-cooled thruster using L-PBF C-103 [Courtesy: Castheon], (b) Actively-cooled control surface with L-PBF tungsten, (c) L-PBF GRCop-84 combustion chambers, (d) Mass-optimized AlSi10Mg cryogenic propellant injector along with section to demonstrate internal features, (e) 600 mm diameter L-PBF Inconel 718 integrated heat exchanger, (f) Nuclear Thermal Propulsion Chamber fabricated with NASA HR-1 LP-DED[27]

5.2 AM polymer and composite materials for aerospace applications

PEEK (polyether-ether-ketone) and PEKK (polyether–ketone–ketone) are among the highest performing thermoplastic semi-crystalline polymer and are widely used in the aerospace industry as a suitable metal alloy replacement in numerous structural applications. The advantages that underlie PEEK and PEKK are their high mechanical resistance properties, thermal and chemical resistance as well as electrical insulation. With its density of 1.3 g/cm3, below half that of Aluminum (2.7g/cm3), PEEK is widely used in aircraft components that require high strength-to-weight ratios to increase aircraft efficiency, such as in structural parts, bearings, seals, and electrical connectors. PEKK, which shares similar properties with PEEK but offers improved processing capabilities, is used in aerospace for components that demand enhanced thermal and dimensional stability, such as in engine components and interior fittings. PEEK and PEKK components can hold up to mechanical stress even in chemically aggressive environments without significant loss of mechanical properties and without the presentation of corrosion phenomena. Thanks to their extremely high thermal proper ties and polymorphic crystalline nature, PEKK And PEEK polymers offer clear advantages in powder applications, making them highly suitable with powder bed processes such as SLS. PEEK in particular also allows for extrusion based processes such as FFF or FDM.[24] [55]

These materials can also be reinforced with carbon fibers to produce AM composites with enhanced properties, allowing to substitute metalic components for many applications. These thermoplastic can rather be reinforced with micro or nano carbon fibres and directly be processed with traditional AM techniques such as SLS or FDM, or they can be reinforced with continuous fibers via extrusion processes such as FDM where both the fiber and the melted thermoplastic are extruded at the same time.[16][62]

6 Quality Control and Certifications

Written by Victor CHARTRAIN

6.1 Quality Control

Aerospace applications is a very demanding domain in terms of parts quality and reliability. To ensure that the manufactured parts meet their usage requirements, they need to be inspected by a thorough quality control. A various range of quality control methods exist nowadays for AM: in-situ monitoring, non-destructive testing, material testing, geometric accuracy, mechanical testing, post processing validation. For the specific application covered in this report, the studied control techniques are separated between the printing process and the evaluation process.

6.1.1 Printing process

The most efficient way to ensure part quality is to optimize the relevant printing process parameters, such as the temperature, calibration, pattern, feed rate, etc. Since defects are the most common source of failures in AM, in-situ correction of these flaws has proven to be relatively effective. In fact, one method to do so consists of using real-time monitoring to tune the process parameters to achieve the desired physical and mechanical properties. However, sometimes it is difficult to access to the machine vision system or to integrate an external monitoring devices in it, and for this reason alternative methods are required to control the quality of the part during the printing process. Another less expensive method consists of using benchmark parameters that were proven to yield correct results. If none standard parameter value is found to give the wanted part properties, the value of the printing parameters can be extrapolated from the benchmark values using proposed empirical relationships or even statistical equations for some cases. [35]

As mentioned in the previous section, Direct Metal Deposition (DMD) is widely used for aerospace applications. The main quality issues of this process are related to a heterogeneous melt pool temperature, laser powder density, and material delivery rate. The quality of these parts processed is generally controlled by monitoring the most relevant printing parameters, which are in this case the melt pool temperature, the material delivery rate, and the nozzle tip-substrate distance. [35]

For example, an IR pyrometer was used to measure the melt pool temperature, and this monitored temperature feedback recovered by a close-loop controller, which could then adjust the laser power density in real time to improve the dimensional accuracy of the part being printed. Thanks to this system, the heat accumulation at the melt pool caused by the focusing of the laser was reduced, and therefore the stair-step effects in the final part were reduced, as shown in Figure 6.1. Similar real monitoring systems were also developed to control the powder delivery rate and the melt pool cooling rate. [35]

Another way to analyze the thermal behavior of this process consists is based on analytical models. Indeed, numerical simulations and Finite Element Method (FEM) results were used to predict the effect of key printing parameters (powder feed rate, melt pool temperature, etc.) on the thermal and geometric properties of the printing process. [35]

The deposited layer height is also a parameter than impacts the microstructure of the final part printed. It can be monitored with CCD cameras positioned around the nozzle.

The images taken can then be fed either into a neural network algorithm or into a close-loop controlled, to effectively measure the clad height and even the angle of the liquid/solid interface in real time. With this information, the roughness of the part manufactured can be assessed, which has a direct impact on the product quality. [35]

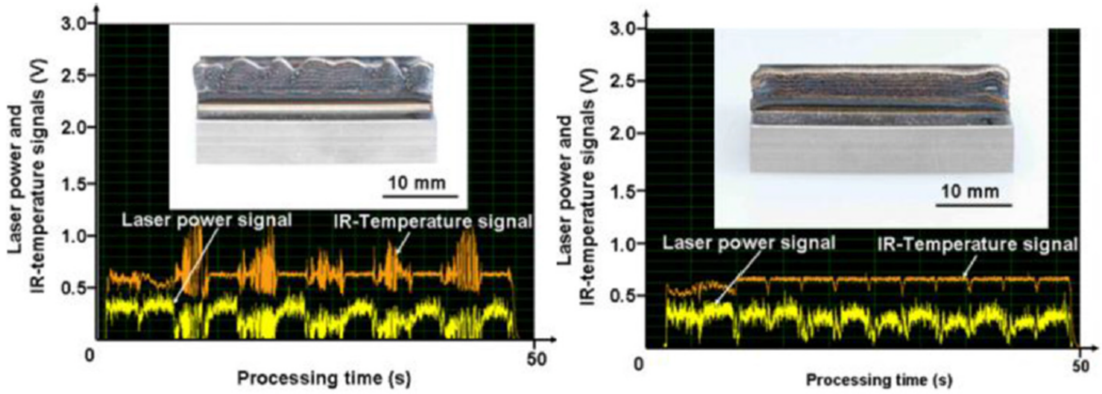


Figure 6.1: Front view of the deposited sample by DMD with the laser power signal (yellow) and IR-temperature signal (orange). The image on the left shows the sample before stabilizing the IR-temperature and the one on the right after stabilizing the IR-temperature signal. [35]

Another AM process used for aerospace applications that was mentioned in the previous section is Powder Bed Fusion (PBF). This family of processes encompasses Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM). The main quality issues for these processes are heterogeneous distribution of powder bed temperature and laser output power. Therefore, quick and dynamic tuning of the printing parameters is also one of the best way to optimize the input variables and therefore enhance part quality. [35]

As an example, let's consider the printing of parts with Ti-6Al-4V (widely used titanium alloy in the aerospace industry) alloy by EBM. The mechanical properties and fatigue performance of this material strongly depend on surface roughness and porosity, which are generally caused by a non-uniform temperature distribution during the printing process. Therefore, the temperature has to be monitored during this printing process, by using either pyrometers or thermocouples. Pyrometers measure the temperature of a body without contact and is based on emitted thermal radiation (photodiodes or digital cameras). On the opposite, thermocouples measure the temperature of a body with contact, and can consequently reduce the freedom of the AM process compared to pyrometers. Due to this key fact, pyrometers are more widely used for monitoring printing process parameters. Indeed, photodiodes and digital cameras can be included inside the laser cladding head in order to enable real time monitoring of the process, and adapt the laser output power to improve the part quality (see Figure 6.2).[11] Using IR thermography is also a solution for real time monitoring of the temperature during EBM and SLM processes. This system can be used to control the melt pool temperature, preheating and hatch heating events, or even porosities caused by thermal phenomena when the laser beam interacts with the powder. Similarly to DMD processes, the thermal properties of the printing process can be predicted with FEM numerical simulations, before printing the part. However, real-time monitoring is still one of the best method to ensure a high quality and reliability in of the parts processed by AM. [35]

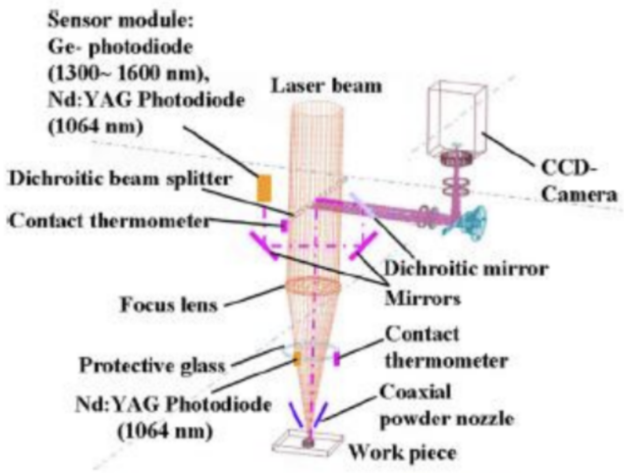


Figure 6.2: Schematic illustration of the laser cladding head incorporating a photodiode and a digital camera [11]

AM processes with polymers can also be used for aerospace applications, even if it is less wide-spreaDMD than printing with metal. The focus here is put on the conventional extrusion based processes such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Sterolithography (SLA).

FDM techniques present non-negligable limitations in surface quality. Indeed, the resolution of the printed part is limited by the filament thickness, which is causes the visual appearance of local variations in the surface height corresponding to the solidified ligament - this is the so-called staircase effect. This generally depends on the rate of material deposition, shrinkage, and residual stresses during solidification. Nevertheless, this effect can be mitigated if the features in plane size of the part to be printed are larger than 1mm on surfaces parallel to the build direction. Similarly, to avoid adjacent features to interact in an unwanted manner during printing, they need to be spaced out at least 1mm away from each other. If such recommendations cannot be respected during the manufacturing of the part, it can still be processed by hot cutter machining or CNC machining to smoothen the surface as desired without altering too much the geometrical dimensions. Additionally thickness deviations of the part can affect their use conditions. For example a reduced-scale prototype for rotor blade can disrupt the flow during wind-tunnel testing due to its non uniform thickness across its surface, as shown in Figure 6.3. [15] However, proper design for manufacture methods can be employed to overcome such inconsistent geometrical deviations.

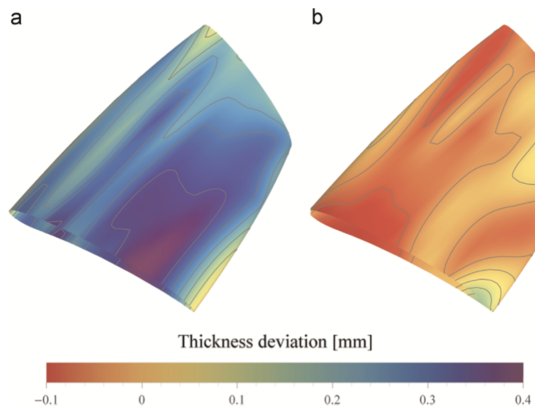


Figure 6.3: 3D mapping of the thickness deviation measurements for the blade. (a) original version, (b) version modified during the design stage [15]

6.1.2 Evaluation process

Once the part has been manufactured, its reliability can be evaluated by various techniques. These includes measuring external and internal characteristics of printed parts, with the aim of checking whether they meet the specific design and mechanical requirements. The external measurement techniques are: checking the overall dimensions of the part with a caliper, investigating the geometry with machine vision, evaluating the surface roughness, etc. The internal measurement techniques are divided into destructive testing and non-destructive testing. As for the printing processes, the evaluation processes could be improved but this is out of the scope of this report.

Non-Destructive Testing (NDT) is strongly prescribed for all critical flight components manufactured by metal AM, for which identifying flaws such as porosity or cracks is crucial before deploying them in service. Many NDT methods exist, but X-ray Computed Tomography (CT) is widely used in this industry, because it fits well the parts complexity of AM and less sensitive to the inherent surface roughness of these parts compared to traditional NDT methods. A first advantage of this technique is that it can inspects the cracks, pores, trapped unmelted metallic powder, deviation from the design geometry, and warping caused by thermal processes, that may be present in the part (see Figure 6.4). [47] A second advantage is that it can provide information on the changes in the part over time with multiple scans at different times, and therefore document many time-related damages, such as crack formation and propagation, the extent of wear, etc. However, this process has a poor resolution for large parts and components with thick walls. Another limitation of this process, is that it does not work well with highly absorbing X-ray metals (tungsten, gold, etc.). [12]

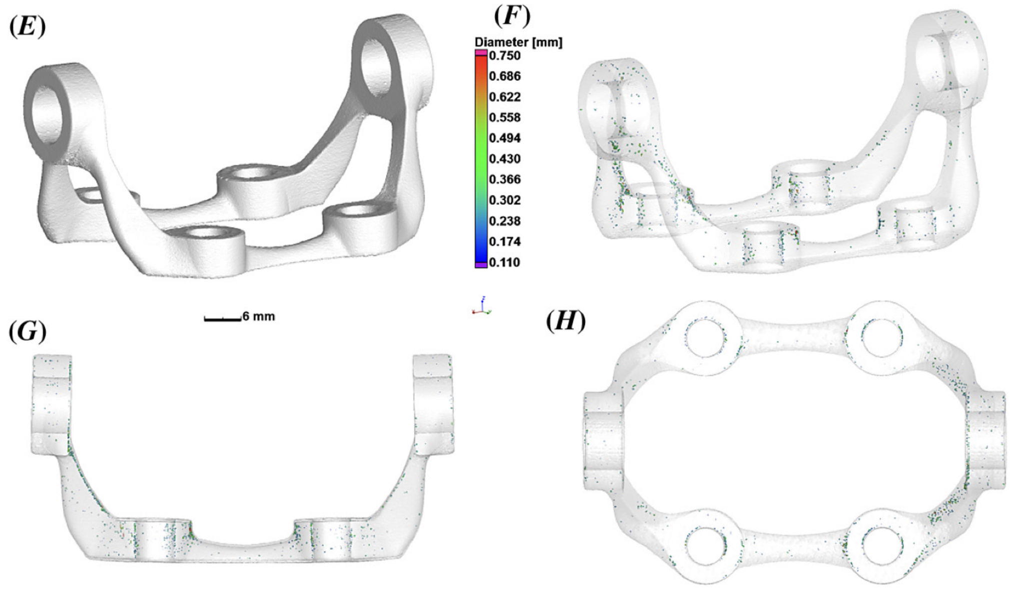


Figure 6.4: Results of X-ray CT scans on a bracket displaying the contour porosity. (E) surface view, (F) transparent angled view, (G) transparent side view, and (H) transparent top view. [47]

6.2 Certifications

The aerospace industry is highly regulated for obvious safety reasons. This represents an extra demand on the quality of the parts manufactured by AM. Therefore, the use and manufacturing of such parts are regulated through strict certifications to ensure that they meet the industry standards. These are developed by the American Society for Testing and Materials (ASTM), the Internal Organization for Standardization (ISO), the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA).

These regulations can concern the machines, the materials, the processes, and even the staff technical training. But most of them generally involve the repeatability of the production processes and the consistency in the quality of the parts manufactured. Therefore, they are crucial for the companies working in the aerospace industry, so that, if a problem occurs with a part, they are able to trace back its origin through all the processes, and make sure it does not continue. To be able to do this in case of a problem, the manufacturers to closely track and record each individual product with a specific system, so that they can know the materials, machinery parameters, personnel involved in the fabrication of each part. This tracking cannot be made for batches of similar products as for conventional manufacturing, because the products made by AM are often customized to the specific customer needs, which can make them very difficult from another and therefore not possible to organize into batches. [33]

Since AM is a relatively novel technology, there are many challenges that arise when developing such certifications, especially the lack of prior knowledge on the subject, complete understanding of the processes, precise property databases, data regarding the failure mechanisms. These, these certifications are difficult to achieve and still limit its use in the aerospace industry. However, this is subjected to change in the future, thanks to the research and the new standards being developed for aerospace the industry. Indeed, as the research advances, the AM processes are being optimized, making them more reliable but also relatively cheap for low series. Nevertheless, it remains very important to be understand very well the standards and to be able to navigate through them, as their highly restrictive nature can often slow down process optimization, especially for aerospace applications. [12]

7 Applications for Space

Written by Jérémie HUSER

7.1 Antennas

Additive Manufacturing can bring significant advantages for space applications, particularly in the production of satellite parts. It enables the creation of highly complex shapes, allowing for the development of intricate RF systems as a single monolithic part instead of relying on the assembly of hundreds of individual components. This approach leads to both mass savings and performance enhancements.

Weight reduction is a critical factor in satellite production, as it is directly linked to the overall cost of a mission. Lighter components reduce launch expenses and can also enable the inclusion of additional payloads or functionality.

7.1.1 Swissto12

The Swiss company Swissto12 is specialized in the production of 3D printed RF antennas solutions.

Figure 7.1: Ku-band Antenna (left) and X-band Antenna (right) from Swissto12[9]

Monolithic antenna clusters can contain hundreds of elements, depending on the application. Clusters can improve mechanical performances and weight of the RF system. The production time is much faster than usual antennas.

Patch antennas were also made with the collaboration between Swissto12 and Fleet Space Technologies. In 20221 Swissto12 was selected to deliver the first-ever additively manufactured all-metal patch antennas for Fleet Space's C4 and C5 nanosatellites. [54]

The use of additive manufacturing for producing all-metal patch antennas provides significant advantages over traditional methods, enabling enhanced performance and structural robustness while maintaining a reduced form factor and weight.

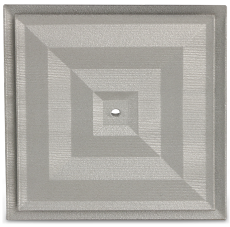


Figure 7.2: RF patch antenna 3D printed

7.1.2 Process used

There exist different process used for RF applications but the most commonly used is Selective laser melting.

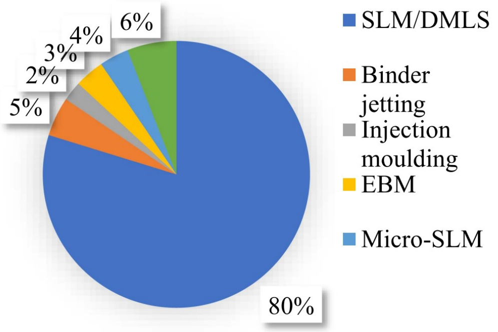


Figure 7.3: Metal-based AM technologies used for RF applications [45]

Selective Laser Melting (SLM) using aluminium is commonly employed for manufacturing RF microwave components due to its ability to produce parts with good RF performance. However, the technique faces challenges with manufacturing tolerances and surface roughness, particularly for higher-frequency applications above 30 GHz. Additionally, SLM production is time-intensive and costly.

Metal Binder Jetting (MBJ) is emerging as an alternative for high-frequency RF parts. It eliminates the need for high-energy sources and support structures, resulting in smoother surfaces and significantly lower costs—up to 10 times cheaper than SLM for small- to medium-scale production. However, the MBJ process involves high-temperature sintering, which can cause shrinkage and affect dimensional accuracy.[45]

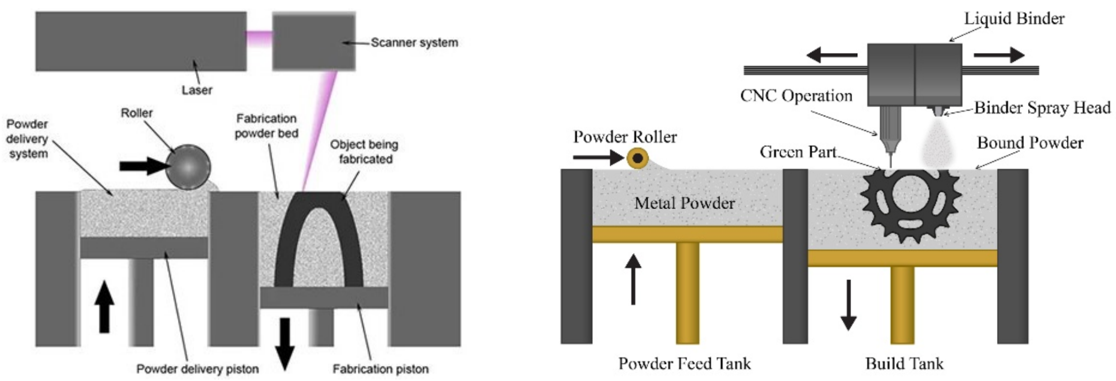


Figure 7.4: SLM process (left)[53] and MBJ process (right)[8]

The table below summarizes the various advantages and disadvantages of the SLM and MBJ processes:

Selective Laser Melting (SLM)	**Metal Binder Jetting (MBJ)**
Advantages • Recyclable base materials (especially metals). • Compatible with many materials. • Enables complex geometries, including overhangs. • Supports stabilize parts and prevent thermal warpage.	**Advantages** • 5–10x faster than SLA. • Cheaper machines and materials. • No support structures needed (self-supporting powder). • Supports metallic and ceramic powders. • Ideal moulds and sand casting cores.
Disadvantages • slower than MBJ • costly	**Disadvantages** • Lower accuracy. • Poor mechanical properties without post-processing.

On the left side of Figure bellow, a non-exhaustive overview of the machines used for the SLM process, and consequently for the metal printing of RF antennas, is presented.

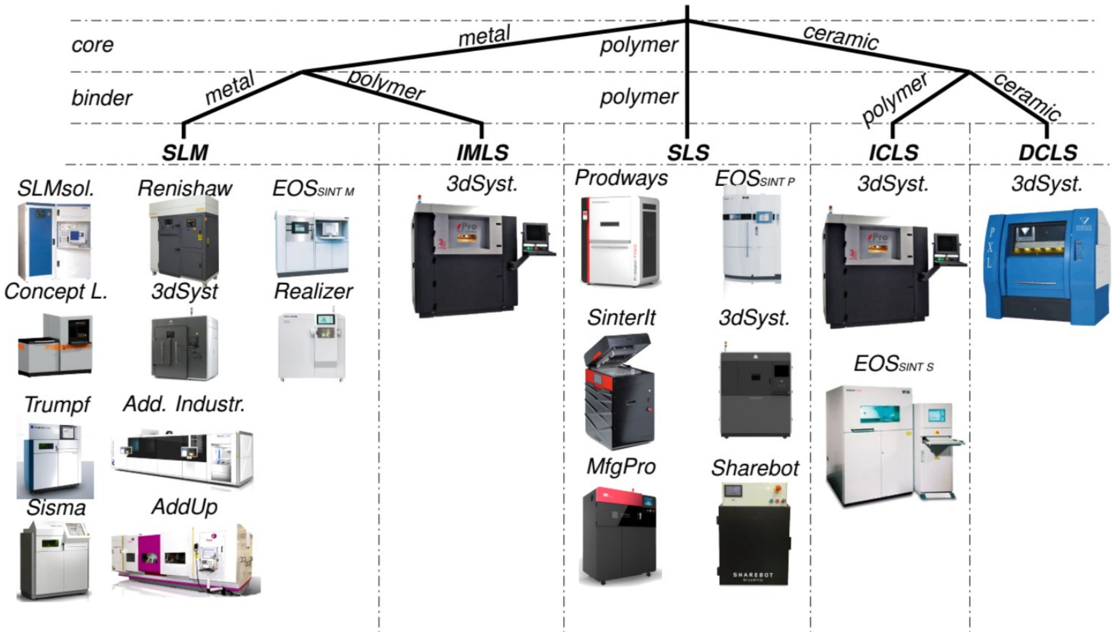


Figure 7.5: Machines used for SLM [14]

7.2 Additive manufacturing in Space

Additive Manufacturing is also very usefull for the production of tools and components in space, addressing the challenges of carrying or resupplying all necessary items during missions, such as those on the International Space Station (ISS). Traditional methods require crews to bring all equipment with them or wait weeks for resupply missions from Earth. The figure below illustrates the evolution of 3D printing in space, showing that these technologies have only been developed relatively recently, starting in 2007.

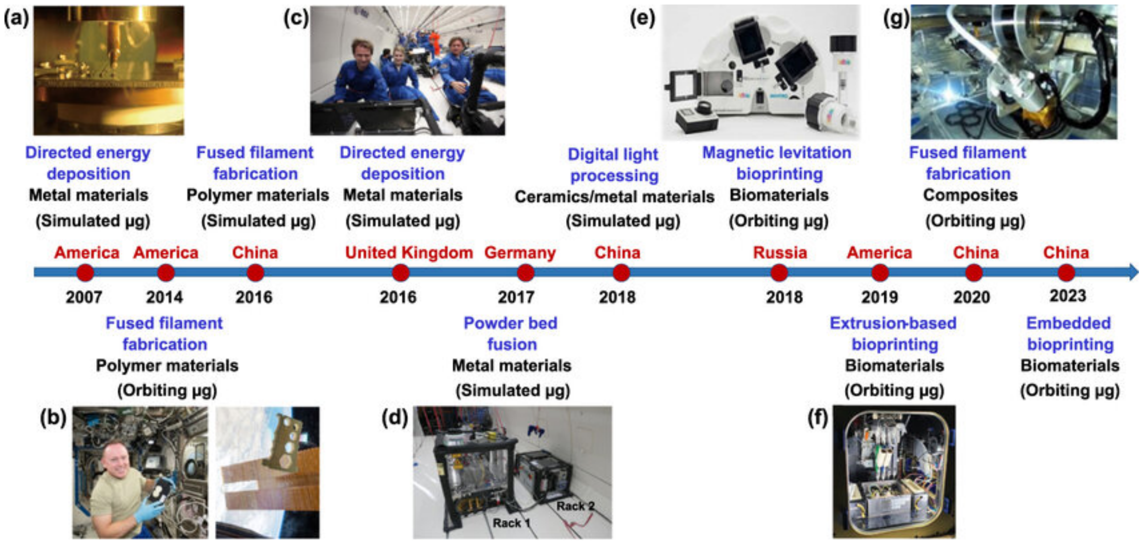


Figure 7.6: Global aerospace industry's exploration of 3D printing in space[31]

Additive manufacturing in space helps reduce costs, enhances mission flexibility, and is essential for long-duration missions and deep-space exploration. It minimizes dependence on Earth for logistical support, a critical factor for future lunar or Martian exploration, for example.

7.2.1 Metal 3D printing in Space

The first metal 3D printer for space, developed by Airbus in collaboration with the European Space Agency (ESA), has been launched to the International Space Station (ISS) aboard the Cygnus NG-20 mission on January 30, 2024. This pioneering technology aims to transform in-space manufacturing by enabling the production of metallic components directly in orbit, addressing challenges associated with traditional supply chains and enhancing the autonomy of space missions.[20]

Unlike polymer-based 3D printing, which has been in use on the ISS since 2014, metal 3D printing involves significantly higher temperatures and requires advanced safety measures to protect the crew and station. The system uses a high-power laser to melt stainless steel wire in a microgravity-compatible process. The printer operates within a sealed box, controlling heat and fumes, and relies on nitrogen to prevent oxidation of the hot metal.

On Thursday, May 30, the Metal 3D Printer demonstrator successfully printed four specimens aboard ISS's Columbus laboratory module. These prints will be returned to Earth for detailed analysis to compare their quality and performance to identical prints made on the ground. This experiment will provide valuable insights into how the space environment impacts metal 3D printing.

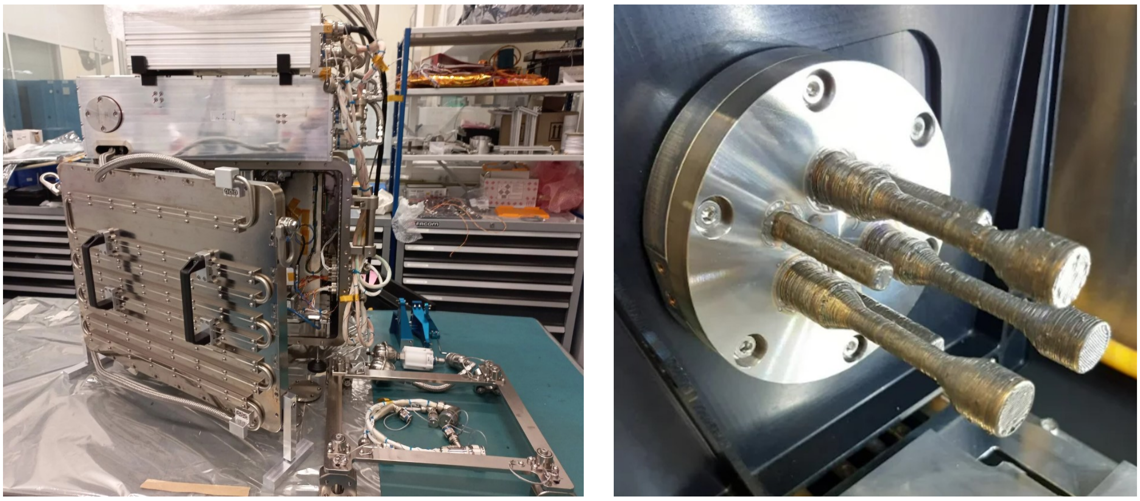


Figure 7.7: The first metal 3D printer for space (left) and four metal 3D specimens to be printed on board the ISS (right)[20]

Parameter	**Details**
Printer size	80 x 70 x 40 cm
Printed part size	9 x 5 cm
Raw material used	Stainless steel wire
Melting temperature of material	Approximately 1400°C
Printing environment	Fully sealed box, nitrogen atmosphere
Time to print a single part	Around 40 hours
Primary use	Tools, mounting interfaces, and mechanical parts
Printing technology	Wire-based metal 3D printing

Table 7.1: Details of the metal 3D printer and printed parts on board the ISS

This demonstration opens the door to exciting future possibilities, like recycling materials from old satellites, building infrastructure directly in orbit, and supporting long-term missions to the Moon and Mars. ESA's goal is to make space exploration more sustainable by focusing on in-situ manufacturing, repairs, and even reusing space structures.

8 Engine and Aeroplanes Manufacturing

Written by Guillaume VULLIOUD

8.1 Airbus and Engine Manufacturers

Airbus, one of the biggest names in aerospace, designs and builds everything from commercial planes to helicopters and military transporters. Founded in 1970, it now stands with Boeing, as one of the top two aircraft manufacturers in the world. The A320 and A350 are some of its famous models, and since the early 2010s, Airbus has been using AM to create lighter and more efficient parts, like cabin interiors and structural components. By 2022, Airbus had integrated over 1,000 3D-printed parts into its A350 XWB, cutting down on both weight and material waste, while still meeting strict safety standards. This push towards AM is a key part of Airbus' goal to make aviation more sustainable by lowering fuel use and emissions.

On the engine side, companies like GE Aerospace, Rolls-Royce, and Pratt & Whitney have also embraced AM to revolutionize their designs. By 2023, they had 3D-printed over 100,000 of these and other parts, saving both time and money. Rolls-Royce has used AM for turbine blades that handle extreme heat, while Pratt & Whitney focuses on cooling ducts and combustion chambers to streamline engine complexity and improve thermal performance.

Altogether, these companies are investing hundreds of millions annually in AM, recognizing its ability to create designs that were once impossible, simplify production, and significantly cut costs. More importantly, AM is helping to address environmental challenges by making aircraft lighter and more fuel-efficient—an essential step in a world increasingly focused on sustainability.

8.2 Airbus

8.2.1 Collaboration with universities

Airbus has partnered with the Massachusetts Institute of Technology (MIT) to explore digital manufacturing in aircraft construction.

The focus is on creating new composite structures that can be assembled from modular, snap-together components instead of being manufactured as large, single-piece parts. This innovative approach aims to reduce aircraft weight, lower production costs, and enhance sustainability.

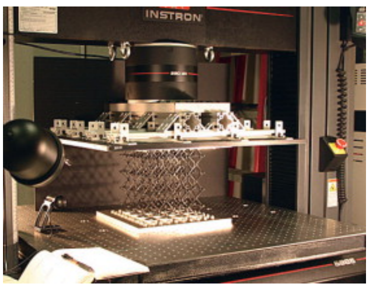


Figure 8.1: A sample of the cellular composite material being prepared for strength testing at MIT

The technology being developed involves MIT's cellular composite materials, which combine fibre composites, cellular materials, and AM, such as 3D printing. This enables the creation of lightweight, durable parts with mechanical interlocking connections, making them stronger and easier to repair than traditional composites. Furthermore, the use of AM allows for the development of morphing structures, like aircraft wings that adjust shape in response to aerodynamic forces, offering new design possibilities.

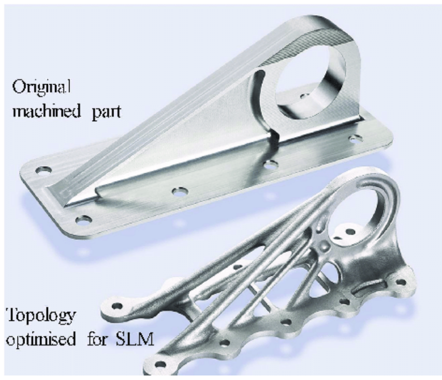
By integrating AM into aircraft construction, Airbus hopes to achieve significant reductions in weight, fuel consumption, and operating costs, while improving the overall repairability and efficiency of aircraft structures. Airbus will work with MIT's Center for Bits and Atoms (CBA), which has been developing new methods for manufacturing structures out of carbon fibre reinforced plastic (CFRP)[7].

8.2.2 Processes used

Airbus is extensively using Powder Bed Fusion (PBF) for their processes. The two methods leading the way of these processes are Selective Laser Melting (SLM) and Electron Beam Direct Melting (EBDM). As explain before in Section 4, those processes use high-energy beam to melt and fuse fine layers of metal powder, building pars layer by layer.

In our example, Airbus has used SLM to produce titanium brackets for the A350 XWB since 2017. We can easily see on the Figure 8.2b, the previous piece and the new one made with SLM. The first thing that is easily seeable, is the weight saving.

(a) Airbus A350 XWB



(b) Titanium Brackets

Figure 8.2: A350 XWB Example

Where traditional methods involve machining from a solid block, SLM uses only slightly more material than the part itself requires. This piece reduces component's waist by up to 50%. Moreover, the geometry achieved for this piece couldn't be done with traditional machining. It achieves tolerances as fine as $\pm 0.05\ mm$, ensuring the components meet strict aviation safety and performance standards.

SLM is superior to other AM techniques for aerospace applications due to its ability to produce fully dense metal parts with great mechanical properties, intricate geometries, and lightweight designs. SLM supports aerospace-grade metals like titanium and nickel alloys, enabling high-performance components capable of withstanding extreme temperatures and stresses. Compared to techniques like Electron Beam Melting (EBM), and polymer-based methods like FDM or SLA, SLM offers unmatched precision, better surface quality, and broader material compatibility.

Airbus uses various machines such as the TRUMPF TruPrint 5000 (cf. Figure 8.3a), the Concept Laser M2 (cf. Figure 8.3b) or the RenAm 500Q (cf. Figure 8.3c). This equipment uses LPBF (SLM) in order to produce, for example, the brackets used in the A350 XWB.

(a) TruPrint 5000 [58] (b) Concept Laser M2 [49] (c) RenAm 500Q [46]

Figure 8.3: Machines used by Airbus for SLM

	Details		
Specifications	**TRUMPF TruPrint 5000**	**Concept Laser M2 Serie 5**	**RenAM 500Q**
Build Volume (Cylinder)	Diameter: 300 mm, Height: 400 mm	245 mm × 245 mm × 350 mm	250 mm × 250 mm × 350 mm
Processable Materials	Metals (e.g., stainless steels, tool steels, Aluminium, nickel-based alloys, titanium alloys)	Metals (e.g., aluminium alloys, titanium alloys, nickel-based alloys, steels, cobalt-chromium alloys)	Wide range of metals including nickel alloys, tool steel, titanium alloys, aluminium alloys
Maximum Laser Power (TRUMPF Fibre Laser)	500 W	Dual fibre lasers, up to 400 W each	500 W (quad laser system)
Beam Diameter	80 µm	70–500 µm (adjustable)	70–100 µm
Layer Thickness	30–150 µm	20–80 µm	20–100 µm
Build Rate	5–180 cm^3/h (depending on parameters)	Up to 35 cm^3/h per laser	Up to 194 cm^3/h
Shielding Gas	Nitrogen, Argon	Nitrogen, Argon	Argon
Machine Weight	7085 kg	2500 kg	2040 kg
Machine Dimensions (W × D × H)	4616 mm × 1645 mm × 2038 mm	2695 mm × 1818 mm × 2185 mm	2165 mm × 1236 mm × 2130 mm
Estimated Cost	$750,000–$1,000,000	$500,000–$700,000	$750,000–$1,000,000

Table 8.1: Key Specifications of the TRUMPF TruPrint 5000, Concept Laser M2 Cusing, and RenAM 500Q

While many manufacturers focus on structural components, Airbus extends AM applications to interior cabin parts such as air nozzles, seat frames and decorative panels using polymer-based Fused Deposition Modelling (FDM) to create lightweight and customized features for enhanced passenger comfort and operational efficiency. FDM is easier to use and is ideal for non-critical interiors applications. High performance thermoplastic are often used, such as ULTEM 9085. One of Airbus' notable achievements with FDM is the production of 3D-printed jigs and fixtures for the assembly of its BelugaXL aircraft. These tools, essential for manufacturing efficiency, showcase how AM can support both the production and maintenance phases of aerospace operations.

There isn't only piece production that use AM, but also repairing parts. Direct Metal Deposition (DMD), has been integrated by Airbus into its maintenance processes, where it proves invaluable for extending the life of expensive engine and airframe parts. By repairing worn components layer by layer, DMD avoids the need for complete replacement, saving time and resources.

Features / Techniques	SLM	FDM	DMD
Material Type	Metals (e.g., titanium, aluminium, superalloys)	Polymers and composites	Metals, often for large parts
Material Density	Nearly 100% dense, suitable for aerospace-grade metals	Not dense (polymer layers)	Moderate density, requires post-processing
Precision and Surface Quality	High precision, layer thickness **20-50 µm**, surface roughness **5-20 µm**	Low precision, layer thickness **100-250 µm**, surface roughness **50-200 µm**	Moderate precision, layer thickness **100-300 µm**, surface roughness **20-100 µm**
Complex Geometry	Excellent for intricate, lightweight designs	Limited by layer resolution and polymer properties	Limited; suited for simpler geometries
Thermal and Mechanical Performance	Exceptional (can withstand high stresses and temperatures)	Low (unsuitable for high-temperature aerospace applications)	Good but dependent on material and process control
Applications in Aerospace	Lightweight structures, turbine blades, fuel injectors	Prototypes, non-critical parts, interior cabin components	Repair and manufacture of large, simpler parts

Table 8.2: Comparison of SLM, FDM, and DMD in Aerospace Applications

8.3 Rolls-Royce

Rolls-Royce has been pioneering the integration of AM to enhance the efficiency and sustainability of aerospace engines. A notable milestone was the creation of one of the largest 3D-printed aerospace parts for the Trent XWB-97 engine, which is used on Airbus A350 XWB aircraft. This titanium structure, manufactured with electron beam melting (EBM) technology, measures 1.5 meters in diameter and demonstrates the scalability of AM for large, complex components.

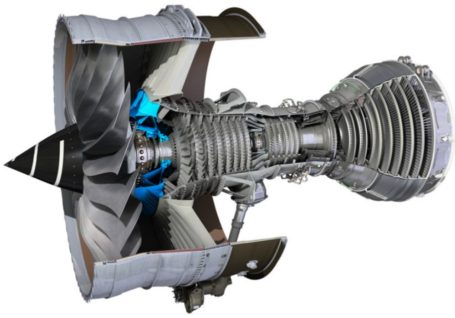


Figure 8.4: XWB-97 engine by Rolls-Royce

The technology enables Rolls-Royce to consolidate multiple parts into single components, improving strength, reducing assembly time, and minimizing material wastage. For example, the Advance3 engine project incorporates both AM and ceramic matrix composites (CMCs) to achieve a 25% improvement in fuel efficiency over earlier engine models. This is critical as it reduces operating costs and emissions—a priority in aerospace innovation. Rolls-Royce's UltraFan demonstrator engine also leverages 3D printing extensively, aiming for similar breakthroughs in weight reduction and efficiency.

Additionally, the use of AM allows Rolls-Royce to implement innovative designs that are impractical with traditional manufacturing, such as intricate cooling channels and lattice structures. These designs help optimize airflow and heat management within engines. The reliability and performance of these components have been validated through rigorous testing under extreme conditions, highlighting the transformative potential of 3D printing in aerospace engineering.

8.4 Pratt & Whitney

Pratt & Whitney are well known in the aerospace industry. They apply AM in the production of several key components such as fuel nozzles, cooling ducts, and turbine parts for its Geared Turbofan (cf. FIGURE 8.5) engines.

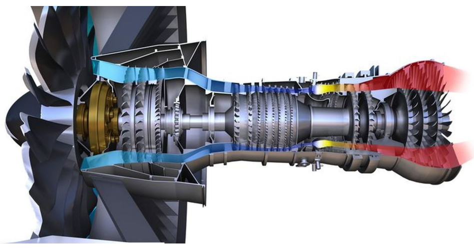
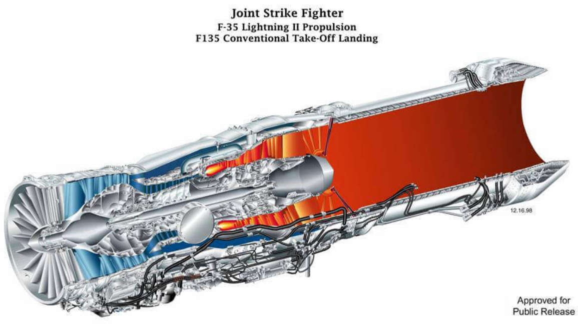


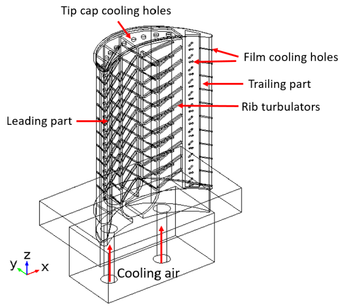
Figure 8.5: Pratt & Whitney PW1000G

The fuel nozzles, implemented in the PW1000G, are manufactured using Laser Powder Bed Fusion (LPBF). The new AM design and this process, achieve a 30 % reduced weight of this key part. Combined with other pieces made with the manufacturing technique, Pratt & Whitney have, with Airbus, achieved a fuel efficiency 16 % better on the A320neo than the previous-generation engines.

Apart from the civil application, Pratt & Whitney are powering the F-35 Lightning II fighter aircraft with their F135 engine. In this case, the motivation was costs saving. They principally manufactured the Turbine Exhaust Case Trailing Edge (TE) box, used for directing the flow of exhaust gazes.



(a) F135 engine by Pratt & Whitney



(b) Turbine Exhaust Case Trailing Edge[57]

Figure 8.6: F135 Additive Manufactured

The TE box has been produced with an process called hydroforming, where a high-pressure fluid bends metal plates into precise shapes that can withstand the forces of jet propulsion. With the changes made, Pratt & Whitney have not only simplified the supply chain, but estimate a $ 1 billion saving on castings and mouldings.

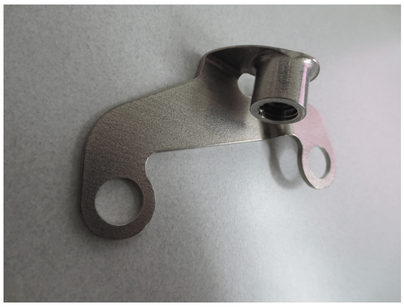
Another example of changes made in the military domain are the brackets made for the TF33 engine that equips the B-52H.

The engine of this aircraft have been built over 8000 times between 1960 and 1985. Since it is still operating maintenance and reparations are mandatory. The suppliers of these piece do not produce them any more, therefore Pratt & Whitney designed a newer version of these, in AM.

Figure 8.7: U.S. Air Force B-52H Stratofortress aircraft

This is a huge breakthrough, especially in this field so specific as the military one. Broken parts of aircraft could be produce on the field, the only need would be the AM equipment. Which is far easier than producing the part in the manufacture, then shipping it to the field.

(a) Conventional



(b) Additive Manufacturing

Figure 8.8: Brackets by Pratt & Whitney[30]

Techniques / Features	**LPBF (SLM)**	**EBM**	**CMCs (Ceramic Matrix Composites)**
Material Type	Metals (e.g., titanium, aluminium, nickel alloys)	Metals (e.g., titanium, cobalt-chrome)	Ceramic matrix with embedded fibres (e.g., SiC-SiC)
Material Density	Nearly 100% dense, with high structural integrity	High but slightly less dense than LPBF	Porosity depends on the manufacturing process; designed for lightweight and high-temperature stability
Precision and Surface Quality	High precision, layer thickness **20-50 µm**, surface roughness **5-20 µm**	Moderate precision, layer thickness **50-100 µm**, surface roughness **20-50 µm**	Low precision, depends on manufacturing; roughness **50-200 µm**
Complex Geometry	Excellent for intricate, lightweight designs	Limited by beam size and heat zones	Limited by moulding or layering techniques; not suited for highly intricate designs
Thermal and Mechanical Performance	Exceptional mechanical strength, good thermal resistance	Strong, but lower precision impacts small-scale mechanical properties	Outstanding high-temperature resistance and low thermal expansion
Applications in Aerospace	Lightweight structures, turbine blades, fuel injectors	Structural parts requiring moderate complexity, such as medical implants or jet engine parts	Heat shields, turbine components, and structures exposed to extreme temperatures

Table 8.3: Comparison of LPBF (SLM), EBM, and CMCs in Aerospace Applications

9 Conclusion

AM has highly reshaped the aerospace industry, driving innovation and addressing critical challenges. Its ability to produce complex geometries, reduce weight, minimize waste, and optimize performance highlights its potential. By enhancing efficiency in production, improving material utilization, and enabling the creation of lightweight, highly customized parts, AM aligns with the industry's goals of sustainability and cost-effectiveness.

While the technology offers numerous advantages, it also faces challenges, including material limitations, technical constraints, high initial costs, and rigorous certification requirements. However, these are steadily being mitigated through advancements in technology and industry regulations. Finally, AM's role in aerospace applications, from satellite components to jet engines, shows its importance in enabling the next generation of aerospace innovation.

Looking ahead, the integration of AM into aerospace manufacturing processes promises continued breakthroughs in design and production. As the industry evolves, the adoption of AM will play an essential role in meeting both technical demands and environmental objectives, which are crucial in modern aerospace engineering.

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