Scilight

Journal of Mechanical Engineering and Manufacturing
https://www.sciltp.com/journals/jmem



Review

Check for updates

Additive Manufacturing for Aerospace and Aeronautical Components Production: Current Status and Future Trends

Rúben D. F. S. Costa [1,2], Ricardo J. Gomes [3], Hedie H. Bernardi [4], Jorge T. Matsushima [4] and Divani B. Gavinier [5,*]

[1] INEGI, LAETA, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[2] DEMec, Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
[3] CIDEM, ISEP, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal
[4] College of Technology São José dos Campos, Professor Jessen Vidal, Centro Paula Souza, Avenida Cesare Mansueto Giulio Lattes, 1350 Distrito Eugênio de Melo, São José dos Campos 12247-014, Brazil
[5] College of Technology Taubaté, Centro Paula Souza, Av. Tomé Portes Del Rei, 525, Vila São José, Taubaté 12070-610, Brazil
* Correspondence: divani.gavinier@cps.sp.gov.br

How To Cite: Costa, R.D.F.S.; Gomes, R.J.; Bernardi, H.H.; et al. Additive Manufacturing for Aerospace and Aeronautical Components Production: Current Status and Future Trends. *Journal of Mechanical Engineering and Manufacturing* **2026**. https://doi.org/10.53941/jmem.2026.100037

Received: 30 April 2026
Revised: 8 September 2026
Accepted: 9 September 2026
Published: 15 October 2026

Abstract: Additive manufacturing (AM), also known globally as three-dimensional (3D) printing, has been gaining traction, since it allows the use of digital models to directly produce components by depositing the required materials one layer at a time. In contrast to conventional subtractive manufacturing processes, the greatest advantage of AM lies in the significant reduction of material waste, while simultaneously enabling much more complex structures, whose topology optimisation may be easily performed, with a wide range of geometric forms. Owing to these outstanding characteristics, AM is now an essential technology in high-value industrial fields, such as aerospace and aeronautics, where performance, weight reduction, and design flexibility are key requirements. Particularly, metal additive manufacturing (MAM) has been growing significantly, with powder bed fusion (PBF) currently being the most widely used process, followed by directed energy deposition (DED) and material extrusion, although the latter is still mostly applied to polymers. The wide range of industrial applications of these technologies includes aircraft ducts, brackets and housings, structurally optimised components, in addition to the repair and manufacture of high-value parts, such as turbine blades and rotor shafts. This review offers a descriptive and updated overview of the state-of-the-art of additive manufacturing technologies applied to the aerospace and aeronautics sectors. It analyses current applications, materials used, and process paths, while critically discussing the key technological and regulatory challenges that continue to limit broader industrial adoption, especially in terms of quality assurance, process repeatability, certification, and compliance with the tight industry standards. Furthermore, emerging trends and future research directions are outlined, providing a forward-looking perspective on this technology's role in shaping next-generation aerospace components. By consolidating dispersed knowledge and synthesising recent scientific and industrial advances, this article's objective is to serve as a foundational reference for both established researchers and newcomers to the field, supporting informed research, technology development, and industrial decision-making in metal additive manufacturing for aerospace applications.

Keywords: additive manufacturing; powder-bed fusion; directed energy deposition; aerospace; aeronautics

Copyright: © 2026 by the authors. This is an open access article under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).
Publisher's Note: Scilight stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Additive manufacturing (AM), generally known as 3D printing, has been rising in the last few decades as one of the most transformative technologies in many sectors, with a special relevance for modern aerospace and aeronautical production systems. Its capability to fabricate complex geometries, reduce material waste, and decrease the overall weight through topological optimisation has positioned it as a key enabler of next-generation design and production paradigms. Over the past decade, AM has transitioned from a prototyping tool to a viable method for the production of flight-critical components, significantly influencing design flexibility, part consolidation, and supply chain efficiency [1,2].

Historically, the conceptual foundation of AM dates back to 1981, when a Japanese researcher, Hideo Kodama, first proposed the idea of a photopolymer-based rapid prototyping system using layer-by-layer deposition. Then, in 1984, the American engineer Chuck Hull developed stereolithography (SLA) technology, one of the first practical 3D printing processes. Two years later, in 1986, Hull had this technology patented and founded the 3D Systems company, selling the first commercial 3D printer, and in the 1990s new techniques started to arise, such as selective laser sintering (SLS) and fused deposition modelling (FDM). Since then, from the beginning of the 21st century, continuous technological advances have expanded AM's reach beyond polymer prototypes into high-performance metallic and composite structures, which have spread to the medical, aeronautics and construction industries [3]. This evolution has allowed aerospace manufacturers to transition from limited experimental components to certified flight hardware.

The aerospace industry, traditionally driven by high performance and strict certification standards, has increasingly integrated AM to meet the dual objectives of lightweighting and cost reduction. Studies indicate that AM allows for the optimisation of structural components, improving fuel efficiency while maintaining mechanical integrity [4,5]. Furthermore, the ability to directly manufacture high-performance polymer and metallic components, using titanium or Inconel, without extensive tooling has drastically shortened production lead times and enabled localized, flexible manufacturing systems [6,7]. Recent research emphasizes that the adoption of AM in aerospace extends beyond part fabrication to encompass a new digital ecosystem [8]. This includes robotic-assisted deposition systems, in-situ monitoring, and data-driven process optimisation that support Industry 4.0 integration [9–11]. Such advancements are crucial for ensuring the repeatability and reliability required for airworthiness certification, a long-standing challenge that continues to define the AM industrialisation [3,12]. Nevertheless, the sector still faces several critical barriers. Issues such as process standardisation, certification of AM parts for flight use, surface finish quality, and the high cost of metal powders remain significant obstacles [13,14]. Moreover, the qualification of AM components for structural applications demands rigorous testing and validation protocols that often offset the potential time savings of digital production [15,16].

Looking ahead, AM's evolution in aerospace manufacturing is expected to be shaped by hybrid processes, automation, and material innovation [17,18]. The integration of artificial intelligence for real-time process control and predictive maintenance will likely enhance production scalability and part reliability [19,20]. As noted by Rossi et al. [12], the synergy between advanced materials, simulation tools, and data analytics will further accelerate the maturity of AM as a cornerstone technology for sustainable and adaptive aerospace manufacturing [21–23]. While additive manufacturing has already proven its value in the aerospace and aeronautical domains, its full industrial realization depends on continued advancements in material science, process certification, and digital integration. The convergence of these elements defines the current state of AM in aerospace and highlights the transformative trends that will shape its future trajectory.

According to the American Society for Testing and Materials (ASTM), AM encompasses a group of seven distinct process categories illustrated in Figure 1: vat photopolymerization, sheet lamination, material jetting, directed energy deposition (DED), powder bed fusion (PBF), material extrusion and binder jetting [13]. Among these, PBF has proven particularly significant for aerospace-grade metal components, as it employs a concentrated heat source—typically a laser or electron beam—to selectively fuse fine metallic powders into dense, near-net-shape parts [1,12]. Every category comprises several different techniques, some more known and used in industry than others, generally grouped by energy source or material family. Due to a lack of agreement in the nomenclature of some techniques, with the same process referred to under several names, and some references only mentioning the most used ones or mixing them, researchers new to this field tend to be lost among a great amount of AM processes, not knowing the differences between them or how to compare them. For this reason, Figure 1 lists every existent AM category and the respective techniques hierarchically organized.

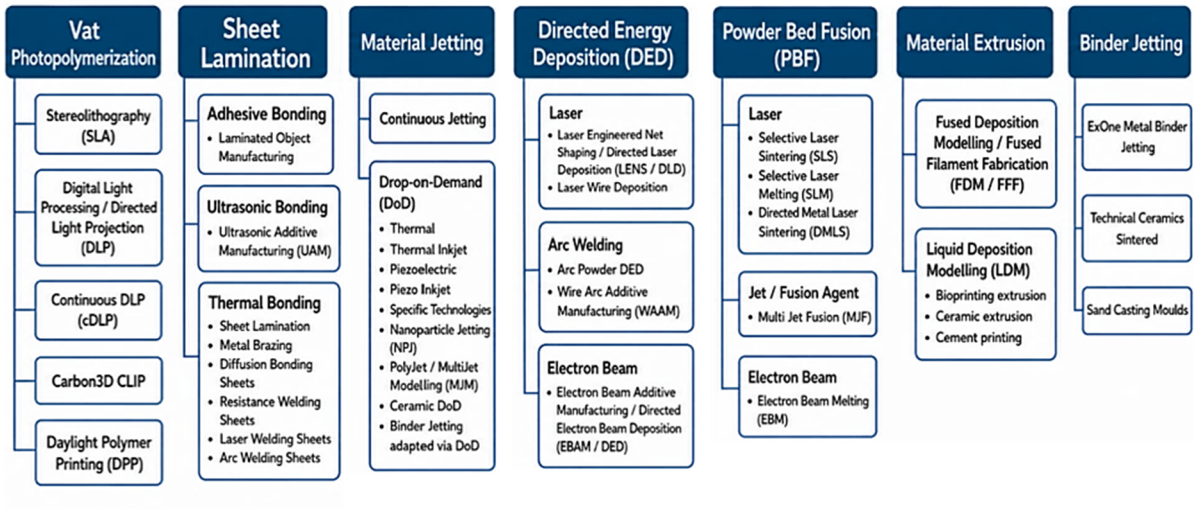


Figure 1. Additive manufacturing different categories and respective techniques.

The vat photopolymerization category's most well-known technique is stereolithography (SLA), which involves a liquid photopolymer thermosetting resin contained in a tank that is processed by selectively delivering energy (a light source, usually ultraviolet (UV) laser or projector) along a specific path to cure specific regions of a part cross-section. On the other hand, digital light processing (DLP), projects a light source to cure an entire layer at once, instead of one path at a time, which is much faster. Other techniques in this category include continuous DLP (cDLP), Carbon3D CLIP and daylight polymer printing (DPP).

Sheet lamination consists of sheets of material deposited layer-by-layer, bonded and cut to shape. Its most common process is laminated object manufacturing (LOM), although ultrasonic additive manufacturing (UAM) and other thermal bonding techniques are also used.

In material jetting, droplets of a photopolymer or wax are jetted layer-by-layer and cured with UV light. It is divided into continuous jetting or several drop-on-demand processes.

In directed energy deposition (DED), a focused energy source is used to melt material at the same time as it is deposited, usually via a nozzle, through a single deposition device. It is usually used to repair components by adding material to an already existing part. Its main techniques, depending on the energy source used, are laser engineered net shaping (LENS), wire arc additive manufacturing (WAAM) and electron beam additive manufacturing (EBAM).

Powder bed fusion (PBF) is currently the most widely adopted method for metal additive manufacturing. This process uses a container filled with powder that is fused selectively using an energy source in an inert gas or vacuum environment to prevent oxidation. Its main techniques are selective laser sintering (SLS), selective laser melting (SLM), multi jet fusion (MJF) and electron beam melting (EBM).

Material extrusion works by passing a melted thermoplastic filament through a heated nozzle and depositing it one layer at a time. This category is divided into fused deposition modelling (FDM) and liquid deposition modelling (LDM), with the latter using materials in the liquid state, such as biomaterials, ceramics and cement.

Finally, in binder jetting, a liquid binding agent, such as metal, sand or ceramic, is selectively deposited onto a powder bed, cured and later sintered or infiltrated to achieve its final properties. Its techniques depend on the used material.

The success of AM in aerospace production depends on the precision of the layer-by-layer deposition. Each layer's dimensional accuracy directly affects part integrity, surface finish, and fatigue performance—parameters that are critical for flight applications [6,7]. Process reliability is maintained through advanced thermal management, in-situ monitoring, and data-driven control strategies that ensure consistency across builds [9]. A wide range of materials—polymers, metals, ceramics, and advanced composites—has been adapted for additive processing; however, challenges remain concerning process optimisation, porosity control, residual stress reduction, and reproducibility [24,25]. The metallurgical quality and microstructural anisotropy of AM-produced alloys continue to be areas of extensive research, as they directly influence mechanical strength and fatigue life [14,15,26]. Furthermore, the qualification and certification of AM parts for flight use demand rigorous non-destructive evaluation and mechanical validation to comply with stringent aerospace standards [4,12,27]. Despite these challenges, the transition from prototyping to full-scale production demonstrates AM's maturing industrial viability. Hybrid systems that integrate AM with traditional machining, together with digital simulation and robotic-assisted manufacturing, are expected to further improve precision and productivity [9,20]. Consequently, AM is increasingly recognised not only

as a manufacturing tool, but also as a strategic enabler of innovation, sustainability, and digital transformation in the aerospace sector [5,21,28].

Figure 2 shows an example of an SLA-printed component, one of the vat photopolymerization processes.

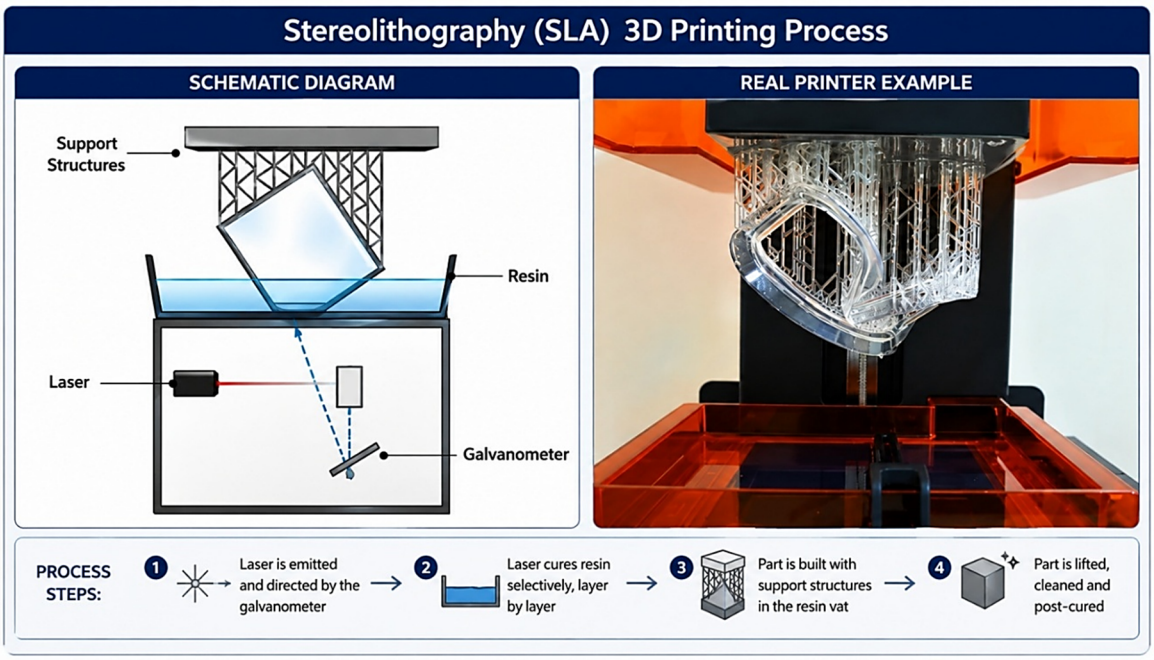


Figure 2. Schematic of the SLA 3D printing process and a print process (adapted from [29]).

2. Methodology

The literature review presented in this study concerning the use of Additive Manufacturing (AM) in the aerospace and aeronautics sectors was performed using the scientific database Scopus, by Elsevier, and its advanced search strings within "Article title, Abstract, Keywords", spanning a 17-year period from 2010 to 2026 and considering only papers published in the English language. This database was chosen due to its multidisciplinary coverage of content, as well as quality and curation of its sources. At the time this article was written, the Scopus search string ("Additive Manufacturing" OR "3D Printing") resulted in 161,635 results found, whereas using only ("Additive Manufacturing") resulted in just 94,170 results. When the industries under study are added, for ("Additive Manufacturing" AND "Aerospace" OR "Aeronautics"), in order to search for a more specific topic, the number of papers decreases drastically to 6358 articles.

From the search carried out considering additive manufacturing processes either in aerospace or aeronautics, 133 distinct references were selected to incorporate the body of this review, with the distribution across the considered time period proportional to the number of papers published each year in Scopus. The selection of references was carefully curated around the central themes of the current status, future trends, applications, and material science pertaining to AM in this high-specification industry. Figure 3 shows the evolution of the number of papers per year in Scopus from 2010 to 2026 considering the topic of additive manufacturing in aerospace or aeronautics in total (Figure 3a) and the number of papers used for this review (Figure 3b). It can be seen that the studies comprising aerospace components produced via additive manufacturing started to increase more significantly 10 years ago, from 2016 onwards; however, in this review a higher number of papers was considered only from 2019, in order to keep it as updated as possible. The temporal distribution of the literature reflects the rapid acceleration of research in this domain, confirming its status as a critical and evolving field of study.

As observed through Figure 3a, this concentration, with over 50% of the references published in the last four years, underscores a profound shift in the research paradigm. Initially, the academic focus centred on the fundamental concepts and high-level potential of AM, often exploring its ability to revolutionise the defence and aerospace industries [30] or providing general overviews of challenges and opportunities [13,14]. Regardless, more recently the paradigm has transitioned from conceptual exploration to the stringent technicalities of qualification, performance, and integration [31]. Current research is dominated by detailed, application-specific topics such as the design and qualification of additively manufactured manifolds for aircraft landing gear applications and the assessment of anisotropic effects on topology optimisation [32,33]. These sophisticated studies, which include a design for qualification framework [34], mean that AM has moved beyond novelty to become a core manufacturing

strategy for mission-critical aerospace parts [12]. Consequently, this review places significant emphasis on literature detailing advancements in material properties and validated applications to accurately reflect the current state of industrial adoption and future trends. Figure 4a and Figure 4b show the number of references found by country and by publisher, respectively, using the mentioned keywords. Globally, the USA, China and India lead the research on this topic, with more than double the number of scientific articles than the other countries. Regarding the major editors, Elsevier stands on top, followed by Springer and MDPI.

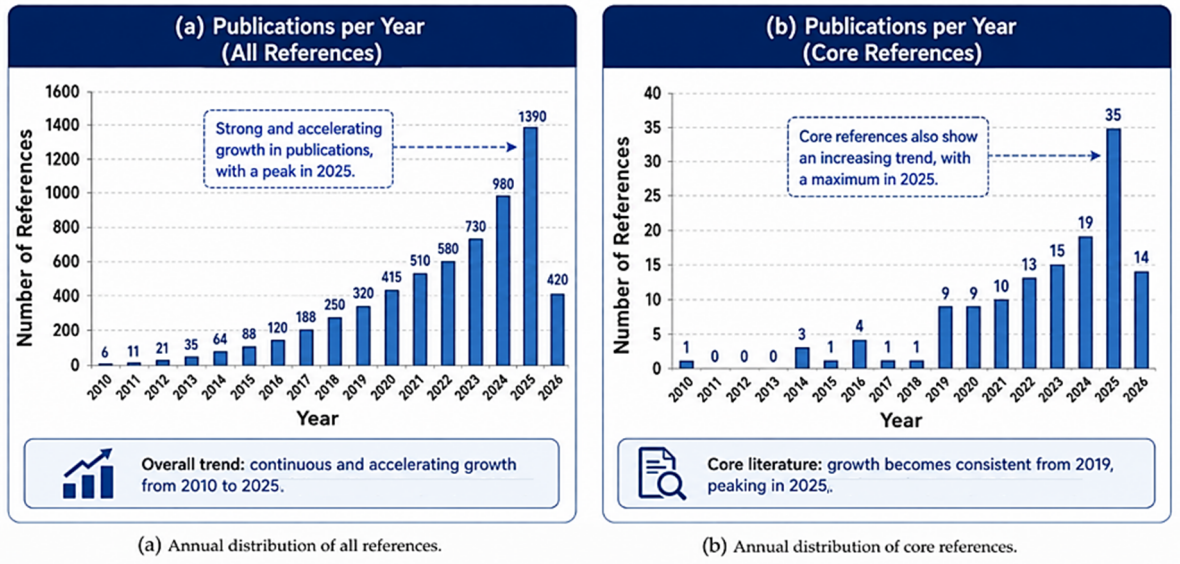


Figure 3. Number of articles on additive manufacturing in aerospace or aeronautics per year in Scopus (**a**) in total and (**b**) used in this study (2010–2026).

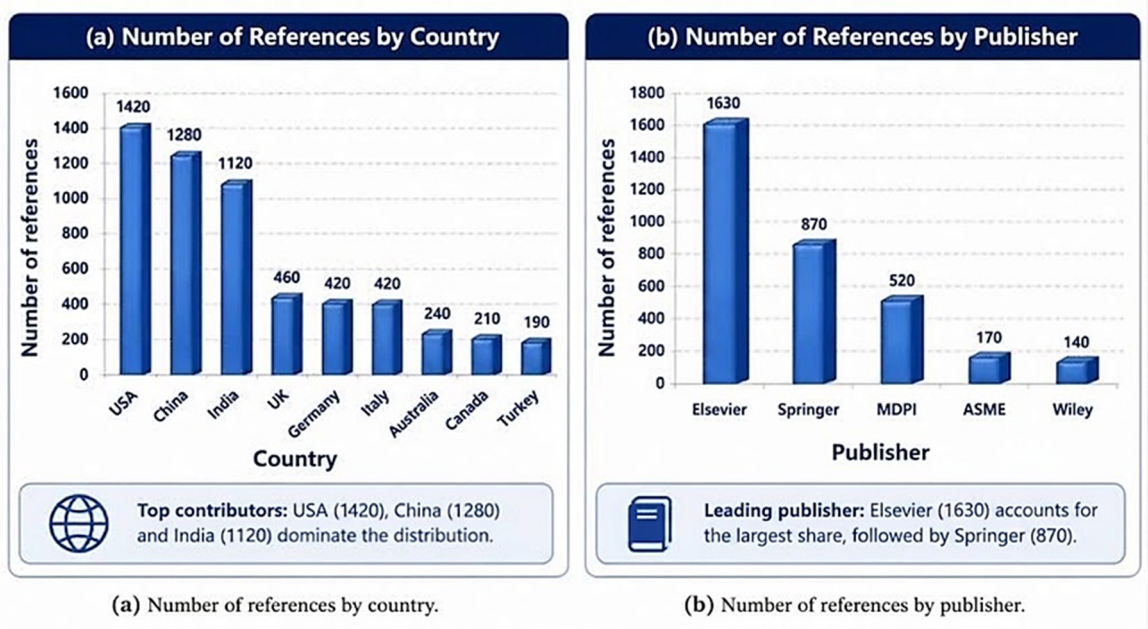


Figure 4. Number of articles on additive manufacturing in aerospace or aeronautics in Scopus (**a**) by country and (**b**) by publisher.

Figure 5's graph represents the number of references found in Scopus featuring the different additive manufacturing main categories applied in aerospace or aeronautics, to highlight the ones which are the subject of more research studies. Among all, PBF is majorly isolated from the remaining ones, leading with 73% of the articles. After it, Material Extrusion and DED complete the podium of additive manufacturing categories used for component production.

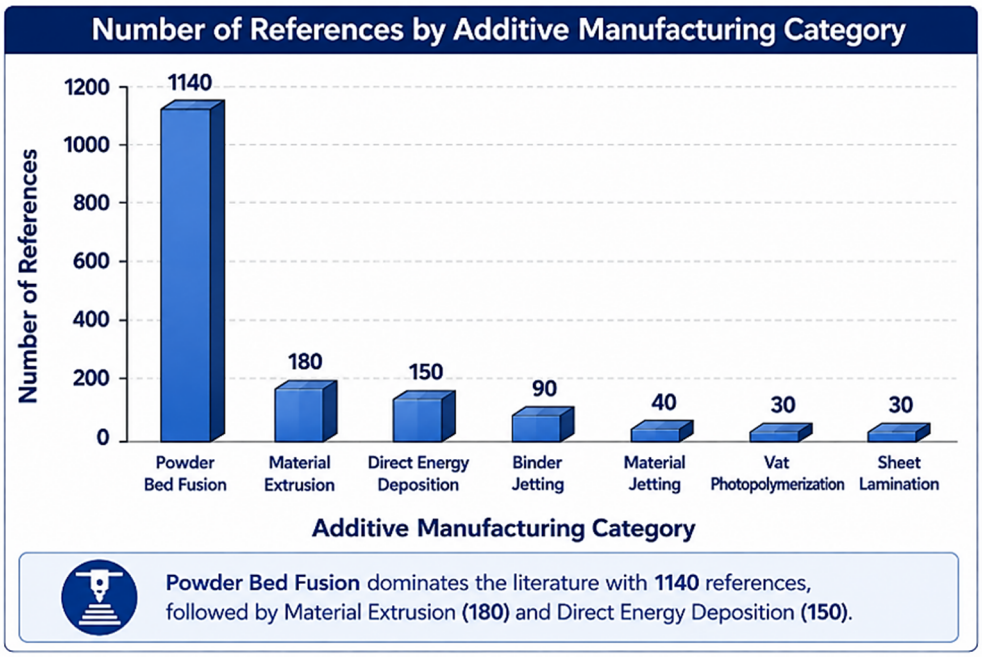


Figure 5. Number of references on additive manufacturing in aerospace or aeronautics in Scopus by category.

3. Additive Manufacturing in Aerospace and Aeronautics

The current status of AM in the aerospace and aeronautics sectors is characterised by a critical transition from rapid prototyping and non-critical applications to the serial production of flight-critical components. This shift introduces substantial technical hurdles, with the most prominent challenges revolving around process standardisation and component qualification. Achieving the stringent mechanical properties and consistent quality demanded by the industry requires robust, real-time quality control techniques [35,36]. Furthermore, the complex process-structure-property relationships inherent to AM make certification a difficult and expensive endeavour, demanding new data-based frameworks for material and process validation [37,38]. Consequently, overcoming issues related to residual stresses, porosity, and anisotropy is critical for reducing potential failure modes and ensuring long-term durability of the components in harsh operating environments [39].

3.1. Industrial Applications

This technology's ability to fabricate complex geometries that are impossible to achieve with conventional subtractive manufacturing has led to diverse applications, ranging from propulsion systems to structural airframe components and specialised electronics. One of the most significant areas of impact is the development of propulsion components where thermal management and fluid dynamics are critical. AM facilitates the creation of intricate internal channels for cooling and weight reduction. Recent advancements have demonstrated the fabrication of high-performance heat exchangers with complex lattice structures that significantly enhance thermal efficiency compared to traditional designs [40,41]. For space exploration, for example, AM is enabling the production of robust alloy components capable of withstanding extreme environments found in next-generation propulsion systems [42–44]. The technology is also being applied to manufacture interior components, as seen in Figure 6.

The drive for lightweighting—reducing mass to improve fuel efficiency and payload capacity—has accelerated the use of AM for structural hardware. Research has successfully validated the design and qualification of additively manufactured manifolds for aircraft landing gears, proving that AM parts can meet the rigorous safety standards required for flight-critical hydraulic systems [45]. There is a growing trend in replacing heavy hydraulic systems with lighter electric alternatives. For instance, lightweight aerospace electric actuators have been designed and manufactured using AM, optimising the balance between weight and mechanical output [46,47]. In the unmanned aerial vehicle (UAV) sector, generative design combined with 3D printing is being utilised to optimise quadcopter drone frames, significantly reducing weight while maintaining structural stiffness [48–50].

AM is increasingly entering the domain of avionics and sensors, enabling the integration of electronic functionality directly into structural components. The fabrication of 3D-printed antennas using advanced materials, such as graphene filaments and copper tape, is emerging as a viable method for producing high-tech air components [51,52]. Methodologies are being developed to implement electronic circuits directly into multifunctional miniaturised thermoplastic enclosures, streamlining the assembly of avionic systems [53].

Additionally, inkjet-printing technologies are being characterised for producing gold films used in airborne equipment under varying temperature conditions [54]. In the satellite sector, AM is being applied to the production of aerospace-grade Carbon Fibre/Silicon Carbide (Cf/SiC) space optics, achieving the transition from complex shaping to mirror-finish quality required for orbital observation [55,56].

The flexibility of AM is extensively leveraged in the production of aircraft interior components, where the primary goals are weight reduction, customisation, and passenger comfort. Unlike critical structural parts, these components often utilise high-performance polymers and complex design strategies [57]. An example of this can be found in Figure 7.

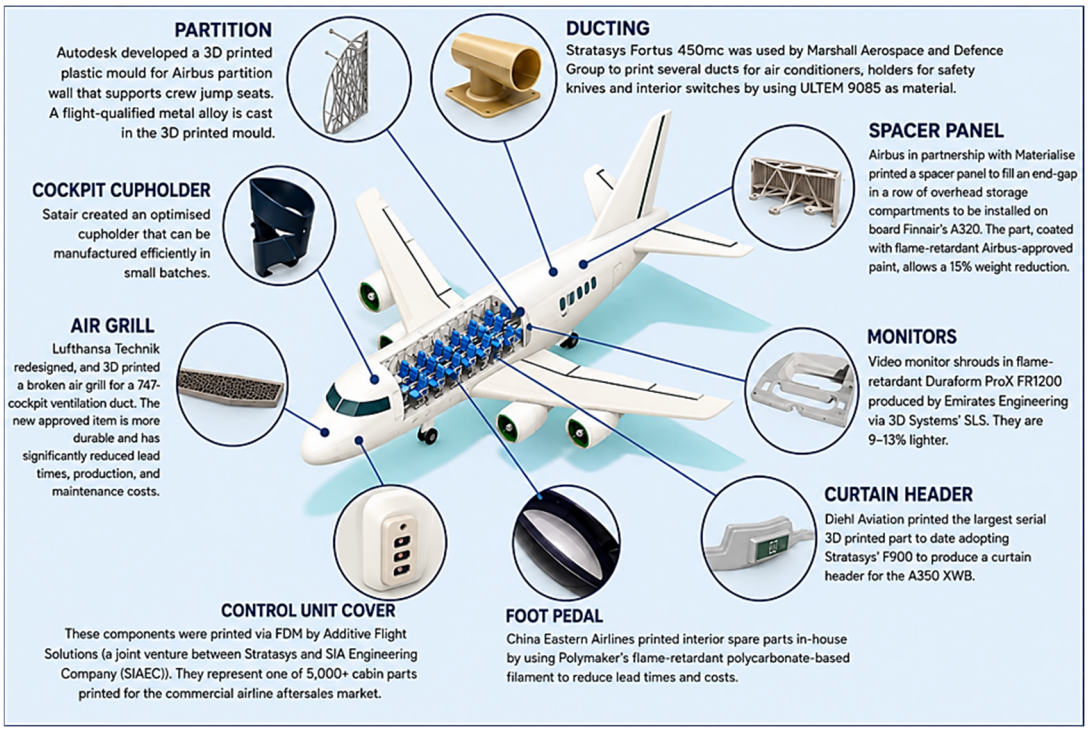


Figure 6. Production of aircraft components using additive manufacturing (adapted from [58]).

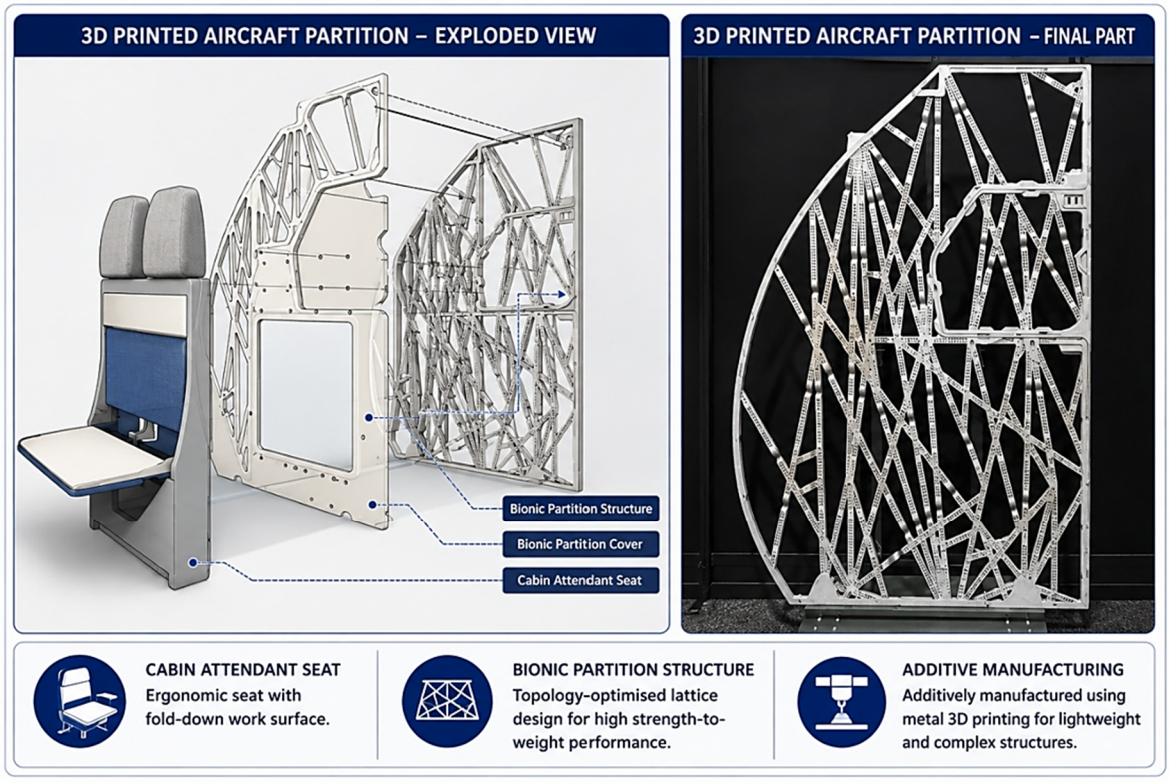


Figure 7. Airbus lattice structure of a partition wall produced by laser PBF (adapted from [59]).

In the Material Extrusion category, FDM and other polymer-based AM technologies are widely employed to manufacture functional interior parts, for example ducts, brackets, and cabin fittings. Research highlights the growing use of high-performance polymers and nanocomposites, which offer the necessary flame retardancy and mechanical strength for aerospace environments [60,61]. Additionally, polymer FDM is being optimised for creating lightweight structural cores, such as honeycomb sandwich composites filled with polyurethane foam, which provide excellent acoustic and thermal insulation properties for cabin panels [62,63]. A key advantage of AM for small parts is the ability to implement lattice structures (intricate, cellular geometries that replace solid components) to drastically reduce weight without compromising stiffness [64,65]. The systematic review by Khan and Riccio [66] on design for AM emphasizes the critical role of these structures in aerospace, where mass reduction is paramount.

Studies have shown that the geometric design of these lattice elements significantly influences the section properties and overall performance of the component [67,68]. Beyond weight saving, these complex designs allow for the consolidation of assemblies. For instance, threaded parts and fasteners, traditionally manufactured separately, can now be integrated directly into larger printed assemblies or optimised for specific loads [44,69]. The fabrication of reticulated mesh arrays and foams using EBM is another emerging application for lattice elements. These porous structures are designed for specific functional requirements, such as vibration damping or impact absorption in small internal components, further illustrating the shift from solid-block design to functionally graded architectures [70].

3.2. Technologies and Materials in Aerospace Additive Manufacturing

Although polymers and composites are important in this sector, to understand the current paradigm of AM in aerospace, it is fundamental to detail the specific technologies utilised for metals. These technologies dominate the production of critical components, such as turbines and engine parts, where structural integrity is paramount [71,72]. The appropriate AM process selection is strictly dictated by the material properties required, size of the component, and specific application within the aircraft or spacecraft [3,73].

Metal laser beam PBF (PBF-LB/M), to which the SLM and DMLS techniques belong, stands as the most extensively investigated technology for high-performance aerospace alloys [72,73]. Its operation occurs within a chamber controlled by inert gas (typically argon or nitrogen) to prevent oxidation during the rapid melting and solidification phases [73,74]. It is particularly dominant in processing nickel-based superalloys (such as Inconel 718) and ultra-high-strength steels [62]. Other advanced materials, such as Scalmalloy, aluminium-lithium-based alloys or oxide dispersion-strengthened alloys are also being processed using this technology, while facing challenges specific to each material's properties [75–77]. Hu et al. [78] wrote a review where the complex cracking mechanisms of CM247LC nickel-based superalloys, as well as the respective crack suppression strategies, are discussed. This process is susceptible to defects, such as warpage and residual stresses, due to the high thermal gradients involved, necessitating careful control of thin-walled structures [74]. The fatigue life of metals processed by this technique is a critical area of study, as process parameters directly influence the density and microstructural integrity of the final part [37].

On the other hand, EBM is a PBF technology that distinguishes itself by using a high-energy electron beam rather than a laser [79]. A key advantage of EBM is its vacuum environment and high-temperature build chamber (typically maintained between 500–800 °C), which acts as an in-situ heat treatment, resulting in significantly lower residual stresses compared to SLM [80,81]. This thermal characteristic makes EBM highly effective for processing crack-prone materials, such as titanium aluminides (TiAl) and pure tungsten [81]. Furthermore, EBM is extensively used to fabricate reticulated, porous mesh arrays and foams, which are essential for lightweighting and specific functional aerospace applications [82]. The vacuum environment provides superior protection against oxidation compared to inert gas atmospheres, which is critical when processing reactive titanium-based alloys (Ti-6Al-4V) for flight-critical hardware [80].

Unlike the two previous PBF techniques, DED covers a category of processes where the material—supplied as either powder or wire—is fused by a focused energy source (Laser, Electron Beam, or Electric Arc) simultaneously as it is deposited [46,83]. A prominent subset of DED, WAAM is gaining traction for the production of large-scale aerospace components due to its high deposition rates and cost-efficiency [32,83]. It is particularly relevant for materials like titanium and aluminium, where reducing the buy-to-fly ratio is essential [84–86]. DED is uniquely suited for the repair of high-value components, such as turbine blades, and for retrofitting legacy parts. It allows for material to be added to existing structures, a capability not easily achieved with PBF systems [32,46,87,88]. This is the case of the study made by Chen et al. [89], which presents a synchronous induction-assisted laser DED method that simultaneously achieves crack suppression and enhanced directional grain growth in M247 nickel-based

superalloy, with significant implications for aeroengine blade repair. Recent advancements in 'digital twin' manufacturing for WAAM are enhancing the precision and predictability of this process for tooling applications [83,90]. Figure 8 contains a SWOT analysis of the SLM, EBM and DED technologies, highlighting their strengths, weaknesses, opportunities and threats when compared to other techniques and each other.

Technology	SLM Selective Laser Melting	EBM Electron Beam Melting	DED Directed Energy Deposition
Strengths (S)	• Dominates the production of complex structural parts, such as turbines; • Ideal for Nickel superalloys and ultra-high-strength steel.	• High-temperature chamber leads to low residual stresses; • Effective for crack-prone (TiAl) and reactive materials; • Excellent for fabricating reticulated mesh arrays and foams.	• High deposition rates allow large component production; • Uniquely capable of adding material to existing/damaged parts; • Reduces buy-to-fly ratio for Ti and Al alloys.
Weaknesses (W)	• High susceptibility to warpage and residual stresses; • Thin-walled structures require careful control to avoid failure; • Fatigue life depends heavily on precise parameter control.	• Requires a strict vacuum environment for operation, increasing the process' complexity and cost; • Relies on high temperatures (≈ 500–800 °C) for process stability.	• Relies on "Digital Twin" technology to ensure predictability; • Tooling applications require advanced precision enhancements.
Opportunities (O)	• Aerospace, energy and luxurious automobile industries may increase the adoption of SLM; • New metal alloys may reduce thermal limitations and improve mechanical properties; • Real time monitoring and artificial intelligence (AI) may reduce SLM defects and improve its reliability.	• High potential in titanium implants and high-performance light components; • Expansion in the use of lattice structures for topological optimization and weight reduction; • Development of new intermetallic and reactive alloys adapted to this process.	• High MRO (maintenance, repair and overhaul) potential in sectors such as aerospace and energy; • Integration with CNC machining to improve precision and finishing; • Expansion in industries such as metallic construction and defence.
Threats (T)	• Competition from other AM technologies, such as the EBM or Binder Jetting, which may result in lower deformations or higher productivity; • SLM equipment and post-processing are still expensive compared to conventional methods; • Parameter sensitivity may compromise critical structural parts.	• Alternative AM processes such as SLM may offer higher resolution and, thus, higher industrial adoption; • Vacuum infrastructure and high energy consumption may limit the EBM use spread; • Its lower material variety and poorer surface finishing may reduce the competitiveness.	• Processes such as SLM and EBM offer higher resolution and surface finishing; • Parameter sensitivity may negatively affect repeatability and quality; • Advanced equipment and control systems may be expensive.

Figure 8. SWOT analysis of the SLM, EBM and DED technologies.

3.3. Critical Materials for Aerospace Additive Manufacturing

The viability of AM in aerospace is intrinsically linked to the availability and qualification of materials capable of withstanding extreme operational environments. The current research landscape focuses heavily on characterizing the microstructural evolution and mechanical properties of these materials when processed via AM to ensure they meet the rigorous certification standards required for flight [44].

Metals constitute the largest proportion of critical AM applications. Research emphasizes the need to control anisotropic properties and defects inherent to the layer-by-layer deposition process to match or exceed the performance of wrought counterparts [72].

- Titanium-based alloys:

Titanium, particularly Ti-6Al-4V, is a focal point due to its high strength-to-weight ratio. Research into WAAM of titanium has shown great promise for producing large structural components, reducing the 'buy-to-fly' ratio [84,86,91]; however, challenges regarding oxidation kinetics during deposition remain a critical concern, as oxygen uptake may embrittle the material [80]. Post-processing techniques, such as Hot Isostatic Pressing (HIP), are often investigated to eliminate porosity and optimise the microstructure of these alloys [40].

- Nickel-based superalloys:

Essential for hot-section engine components, nickel-based superalloys are extensively studied for their ability to maintain mechanical properties at high temperatures. The complex crystallographic texture evolution during the printing process requires precise control to prevent cracking and ensure creep resistance [92]. Additionally, low-expansion alloys, such as the Invar 36, are being investigated for use in composite tooling and precision instruments, where heat input during DED processes must be managed to preserve specific microstructural phases [93].

- Aluminium-based alloys and steels:

High-strength aluminium alloys are increasingly processed via arc additive manufacturing for airframe applications, addressing the historical challenges of porosity in aluminium AM [85]. Concurrently, research on steels, including ultra-high-strength steel and 316L stainless steel, focuses on optimising fatigue life and understanding the behaviour of 'as-built' versus heat-treated states to predict long-term durability [62,94].

- Copper-based alloys:

A renewed interest in copper-based alloys is driving the development of high-efficiency heat exchangers and combustion chamber liners. AM enables the production of complex internal cooling channels in these highly conductive materials, which were previously impossible to manufacture using traditional methods [95].

Despite the widespread use of metals, the paradigm shift toward lightweighting has accelerated the adoption of advanced polymers and composite materials as well, especially for non-critical and semi-structural applications [96].

- High-performance polymers:

Materials such as PEEK and functional nanocomposites are being tailored for aerospace use. These materials must exhibit high thermal stability, chemical resistance, and flame retardancy [97–99].

- Composite structures:

There is a significant trend toward additive manufacturing of composites [100]. Studies on Carbon-Reinforced PEEK and polymer-based sandwich structures, specifically honeycomb cores filled with polyurethane foam, demonstrate substantial potential for energy absorption and acoustic insulation in aircraft interiors [48,61,101]. Furthermore, the integration of metallic particles into polymer matrices is expanding the functional capabilities of FDM-printed parts, allowing for tunable magnetic or thermal properties [60]. The critical review of the material-process-design interplay remains essential for the broader adoption of these aerospace composites [102].

In contrast to the two families of materials previously described, ceramics represent the frontier of high-temperature AM applications, offering solutions where metals reach their thermal limits. Ceramic Matrix Composites (CMCs) are being developed for gas turbine engine applications to withstand temperatures exceeding those of metal superalloys [103]. Laser sintering techniques are also being refined to process these difficult-to-manufacture materials for aeronautical applications [104].

In the space sector, specialised applications such as aerospace-grade Cf/SiC are enabling the production of lightweight, high-precision space optics. Recent advancements have demonstrated the ability to transition from complex AM shaping to achieving a mirror-finish quality required for optical instruments [105]. The interrelationship between traditional and additive approaches is the key to advancing ceramics in defence and aerospace contexts [106,107].

3.4. Quality Challenges: Defects and Microstructural Integrity

Despite the geometric freedom offered by Additive Manufacturing, the transition from prototyping to flight-critical hardware is significantly hindered by the quality and reliability of the 'as-built' components. The layer-by-layer consolidation process introduces unique microstructural features and defects that differ fundamentally from those found in wrought or cast materials, serving as the primary obstacles for aerospace certification [3,108].

The thermal history of AM processes, particularly in SLM, involves extreme heating and cooling rates ($\approx 10^3$–10^8 K/s). This rapid solidification results in a non-equilibrium microstructure that dictates mechanical performance [109]. The following bullet points describe key parameters where the AM components' structural integrity influences the appearance of defects:

- Grain structure and texture:

In nickel-based superalloys like Inconel 718, the directional heat flux typically creates strong crystallographic textures characterised by fine, elongated columnar grains growing parallel to the build direction. This heterogeneous structure leads to significant mechanical anisotropy, where properties such as tensile strength and ductility vary depending on the loading orientation relative to the build axis [92,110].

- Phase formation:

The rapid solidification suppresses the formation of equilibrium phases. Instead, the 'as-built' matrix is often characterised by a saturated matrix with the segregation of alloying elements (Nb, Mo, Ti) into interdendritic regions. This segregation promotes the formation of brittle gamma phases and carbides, which are detrimental to ductility and fatigue life unless corrected by subsequent heat treatment [40,92]. Residual stresses are an inherent byproduct of the steep thermal gradients and cyclic thermal expansion and contraction experienced during the SLM process.

- Mechanisms and impact:

As the laser spot moves, the molten pool expands, but its expansion is restricted by the cooler surrounding material. Upon cooling, the material contracts, inducing tensile residual stresses in the solidified layer. These stresses can exceed the yield strength of the material, leading to geometric distortion (warpage), delamination between layers, or even detachment from the build plate [74].

- Fatigue performance:

Residual stresses are particularly critical for aerospace components subject to cyclic loading. Tensile residual stresses near the surface can accelerate crack initiation and propagation, severely reducing the fatigue life of the

component compared to stress-relieved counterparts [37,94]. Research indicates that vertical residual stresses are typically of greater magnitude than horizontal stresses due to the thermal accumulation along the build direction [81].

- Porosity:

Porosity remains a critical defect that compromises the structural integrity of aerospace parts by acting as stress concentrators that facilitate failure [111]. This typically occurs when the energy density is too high. The laser penetrates deeply into the material, causing metal vaporisation that creates a cavity. If the molten pool collapses before the vapour escapes, gas bubbles become trapped, leaving spherical pores [112].

- Lack of fusion (LoF):

Conversely, insufficient energy input or inadequate overlap between scan tracks prevents the powder's complete melting. This results in irregular, sharp-edged voids between layers, which are far more detrimental to mechanical properties than spherical gas pores due to their notch effect [46,113].

- Detection:

Given the internal nature of these defects, non-destructive testing (NDT) methods such as X-ray microtomography are essential for qualifying critical geometries and validating process parameters [114–116]. Not only this technique, but also ultrasounds, eddy currents and thermography are examples of important NDT methods for defect identification in the aerospace field. They allow the observation of internal defects within the AM component's structure which cannot be detected with the naked eye [117].

Solidification cracking (or hot tearing) is a phenomenon driven by the thermal contraction of the metal during the final stages of solidification. If the developing tensile stresses, usually caused by constraints from the surrounding solid material, exceed the mechanical strength of the semi-solid mushy zone, cracks form along grain boundaries [85]. This is a prominent challenge in processing high-strength aluminium-based alloys and certain superalloys, necessitating precise control of the heat input and alloy composition to mitigate defect formation [93].

Figure 9 provides a comprehensive graphical synthesis connecting materials, AM processes, aerospace applications, and engineering requirements.

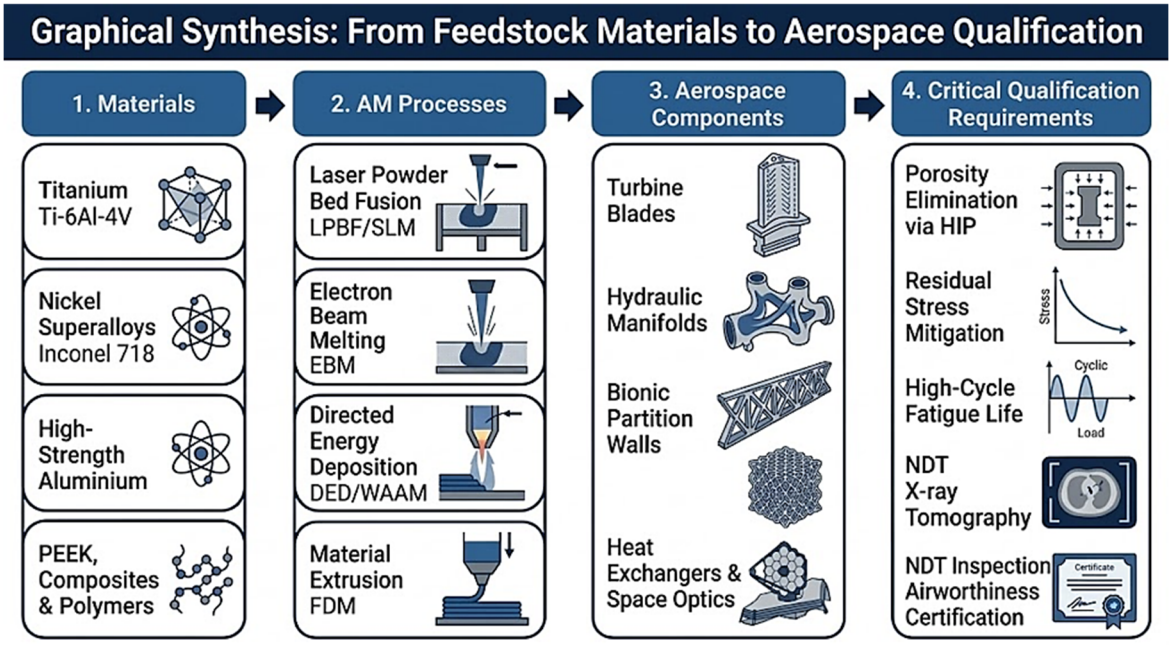


Figure 9. Sequential framework mapping feedstock materials, dominant AM technologies, targeted aerospace components, and critical performance requirements.

3.5. The Critical Role of Post-Processing in Aerospace AM

While the additive manufacturing process defines the geometry, the post-processing phase determines the final performance. In the aerospace sector, 'as-built' components rarely meet the stringent certification requirements for fatigue life, ductility, and surface integrity required by flight-critical applications. Consequently, a robust post-processing chain is essential to transition a printed part from a prototype to functional hardware capable of withstanding demanding operational environments [111].

The extreme heating and cooling rates inherent to processes like SLM result in high residual stresses and metastable microstructures characterised by segregation and undesirable phases. Thermal treatments are indispensable for relieving these stresses and evolving the microstructure to achieve optimal mechanical properties. The primary stage of heat treatment, solution annealing (SA), targets the dissolution of deleterious phases formed during non-equilibrium solidification. In nickel-based superalloys such as Inconel 718, the 'as-built' state often contains brittle gamma phases and carbides segregated in the interdendritic regions, which compromise ductility [92]. Figure 10 shows a heat treatment curve of Inconel 718.

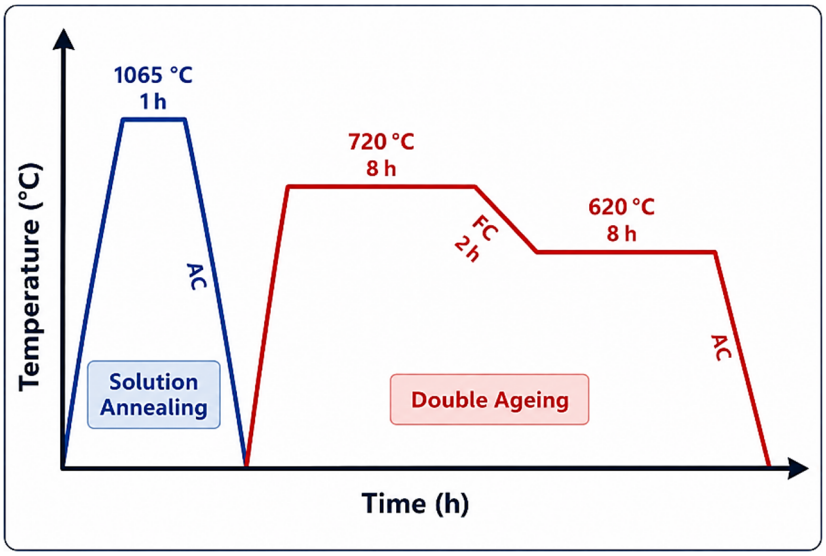


Figure 10. Inconel 718 heat treatment: solution annealing followed by double ageing (adapted from [118]).

The temperature control during Solution Annealing is critical. For alloys like Inconel 718, treating at sufficiently high temperatures (e.g., 1065 °C) is necessary to promote the complete dissolution of these segregated phases back into the matrix, homogenising the material for subsequent hardening steps. Following homogenisation, a two-step ageing process is employed to precipitate the strengthening phases.

This stage drives the formation of fine, coherent precipitates, specifically gamma prime and gamma double-prime. These phases are essential for blocking dislocation movement within the crystal lattice, significantly increasing the material's yield stress and tensile strength to levels required for aerospace structural applications.

For fatigue-critical applications, internal porosity—even at low percentages—acts as a stress concentrator that can lead to premature failure. HIP is the standard industry method for maximising component density and enhancing fatigue performance. By simultaneously applying high temperatures (often above 1150 °C for certain alloys) and high isostatic gas pressure (exceeding 100 MPa), HIP induces plastic deformation and diffusion bonding to collapse internal voids. Research on materials such as Ti-6Al-4V confirms that HIP parameters significantly influence the final microstructure and are essential for eliminating lack-of-fusion defects [40]. The elimination of these internal defects is directly correlated with improved performance. Studies comparing 'as-built' versus HIPed conditions in aerospace alloys demonstrate that HIP significantly extends high-cycle fatigue life, making it a mandatory step for fracture-critical hardware [94]. Figure 11 shows an example of this process applied in canisters with different levels of titanium in their composition. It may be seen that prior to this method, the samples have a long and irregular format, with some heterogeneity, but after the HIP process, they become more compact and uniform, resulting from the densification and collapse of internal voids. The gradual increment in the titanium percentage in the canisters' compositions reveals a lower deformation, which indicates that this addition increases the specimens' structural strength.

The inherent 'stair-stepping' effect caused by layer-wise construction, combined with partially melted powder particles adhered to the surface, results in high roughness values in AM parts. This roughness is detrimental to fluid dynamics and fatigue resistance, requiring surface treatments to reduce it [44]. Techniques such as sanding, abrasive flow machining, and polishing are employed to improve surface texture and remove support structure remnants ('witness marks'). To achieve the tight dimensional tolerances and fits required for aerospace assembly, finish machining or CNC milling is applied to critical interfaces. This hybrid approach leverages the geometric complexity of AM while ensuring the precision of traditional subtractive manufacturing.

While post-processing corrects defects, in-situ process optimisation aims to mitigate them during fabrication. Controlling residual stresses during the build is crucial to prevent geometric distortion (warpage) and cracking

before the part is even removed from the build plate [74,119]. These stresses, which are driven by steep thermal gradients, can be attenuated by optimising the volumetric energy density. Adjusting parameters such as laser power and scanning speed helps manage the heat input and cooling rates. The path the laser takes significantly influences stress accumulation. Research indicates that adopting specific strategies, such as a 'chessboard' pattern—where the layer is divided into small fields scanned in a non-sequential order—is highly effective in breaking up long residual stress vectors, thereby reducing the overall residual stress magnitude and minimising warpage [81].

Figure 12 shows an end-to-end qualification and airworthiness certification pathway for flight-critical metal additive manufacturing components, consolidating the process-structure-property-performance relationship across manufacturing and post-processing stages.

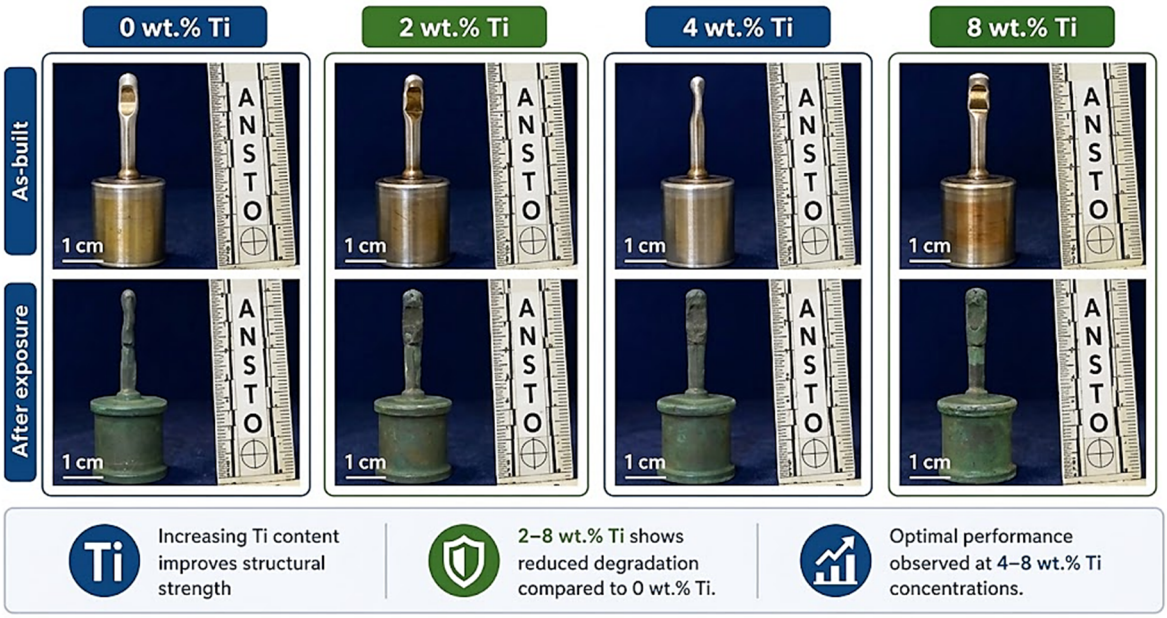


Figure 11. Canisters before (top row) and after (bottom row) HIP process with varying Ti addition (adapted from [120]).

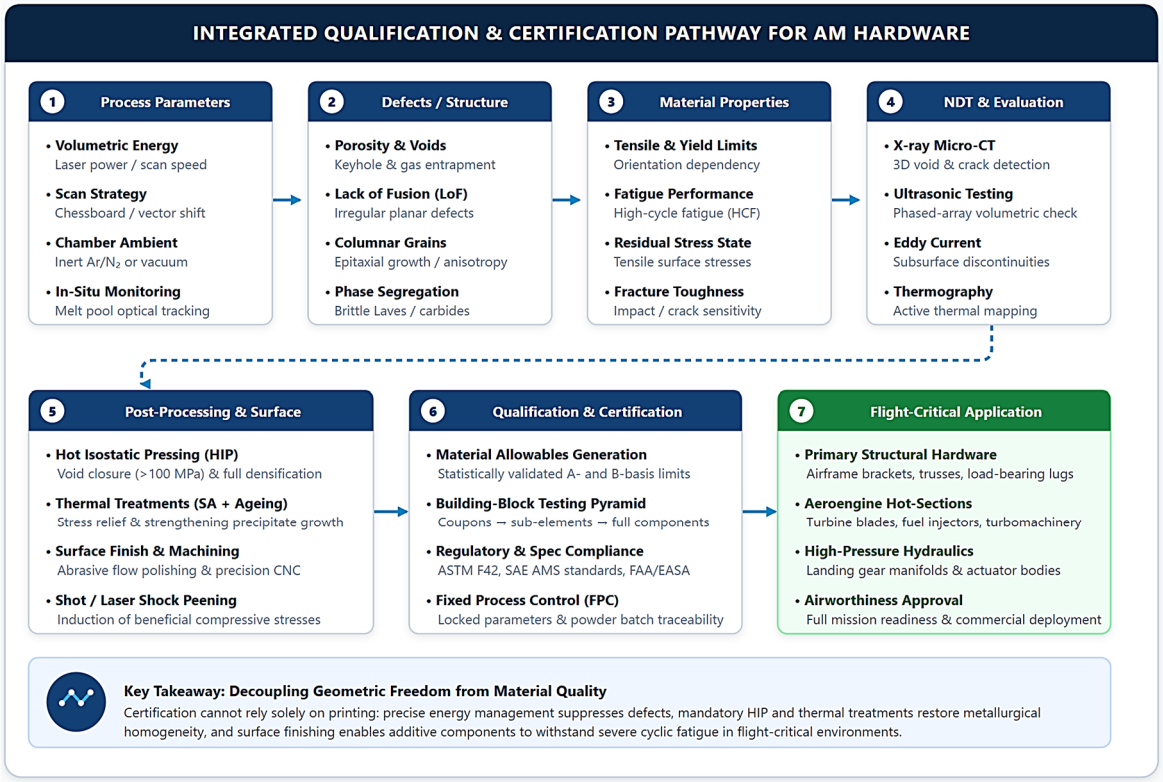


Figure 12. Qualification pathway for flight-critical metal additive manufacturing components.

4. Discussion: Future Trends and Innovation in Aerospace AM

The preceding sections have highlighted that while AM offers unprecedented geometric freedom for aerospace applications [3,73], achieving the necessary quality levels for flight-critical hardware remains contingent on rigorous process control and extensive post-processing [111]. The discussion now turns to the horizon of AM integration. The future paradigm of aerospace manufacturing is not just about the printing process itself, but the synergistic integration of secondary processes and the continued evolution of material science to address current limitations. This section explores emerging research domains—specifically robot-assisted hybrid manufacturing and advanced materials engineering—that are poised to drive the next wave of industrial adoption.

4.1. The Rise of Robot-Assisted Machining in Hybrid Workflows

As AM technologies, particularly DED, scale up to produce larger structural components in lightweight materials like aluminium-based and titanium-based alloys, as well as Carbon Fibre Reinforced Polymers (CFRP), the integration of subtractive post-processing becomes unavoidable to meet dimensional tolerance and surface finish requirements. Traditional large-gantry CNC machines are often too inflexible or prohibitively expensive for very large, complex AM parts. In this context, robot-assisted machining emerges as an economically viable and flexible alternative for hybrid manufacturing cells [30,121].

Nevertheless, the primary barrier to widespread adoption is the inherent lack of structural rigidity in articulated robot arms compared to conventional machine tools. This limitation leads to deflection during cutting forces, resulting in geometric inaccuracies that are unacceptable in aerospace applications. Consequently, current research is intensely focused on overcoming these limitations through intelligent compensation strategies rather than just mechanical stiffening. The integration of multi-sensor measurement systems allows for real-time 6 degrees of freedom (6-DOF) positional tracking of the robot end-effector. Furthermore, advanced techniques utilising binocular vision algorithms for precise positioning relative to the AM part, coupled with online trajectory compensation methods, have demonstrated the capability to reduce machining deviations by up to 90% [30,122]. The ultimate research objective in this domain is to consistently achieve geometric accuracy below 100 μm, a threshold necessary for many aerospace assembly interfaces, thereby validating robotics as a cornerstone of future hybrid AM factories.

4.2. Advanced Computational Modelling for Residual Stress Prediction

The management of residual stresses and associated geometric distortion remains a primary challenge in metal PBF, often requiring costly and time-consuming iterative trial-and-error builds to optimise support structures and scan strategies [74]. The development of faster, more reliable computational models to predict thermal history and stress evolution is paramount. While traditional finite element method (FEM) simulations provide high-fidelity insights into temperature fields during processes like selective EBM (SEBM), they are often too computationally expensive for routine industrial use on complex part geometries. Future research should prioritise the development of reduced-order models and accelerated simulation techniques that can quickly provide reasonably accurate approximations of residual stress fields. These predictive tools are essential for enabling ‘first-time-right’ production by allowing engineers to optimise orientation and process parameters virtually before actual fabrication [123]. Machine learning tools are starting to be adopted in the literature to improve quality control in additively manufactured components as well, with the purpose of reducing costs and preventing functional problems [124]. This approach is becoming widespread throughout all of the manufacturing processes, as engineers are understanding the positive impact and several advantages of these tools, especially for defect prediction, but also to improve productivity using fewer experimental campaigns, thereby saving time and resources [125].

4.3. Optimisation of Advanced Materials and Surfaces

Finally, the expansion of AM applications continues to depend on the broadening of the available material palette and the enhancement of surface properties. Research must persist in investigating the process-structure-property relationships for emerging high-performance materials tailored for extreme environments [44,112]. This includes not only novel metal alloys, but also the advancement of complex shaping capabilities for aerospace-grade ceramics and composites, pushing the boundaries of achieving mirror-finish quality directly through advanced processing and finishing techniques for applications such as space optics [55,105].

Other examples of advanced materials include functionally graded materials, metal-polymer hybrid structures and dissimilar materials in general. Multi-material and hybrid material systems are one of the fastest-growing research areas in additive manufacturing, due to the advantages brought by combining the properties of two distinct materials into a single high-performance structure. Their deposition poses additional complexity, since the AM

technology needs to alternately deposit each part in a hybrid approach. The outcome usually shows interfacial problems, generated by the lack of adhesion between the different materials. Nasir and Röttger [126] identified crucial challenges in fabricating metal-based functionally graded materials (FGMs), namely thermal mismatch, phase segregation, and cracking, but whose mechanical properties could be optimised through the integration of multi-axis deposition strategies, real-time process monitoring, and hybrid processing techniques. On the other hand, Ghanavati et al. [127] reviewed DED and PBF technologies for multi-material production, establishing clear manufacturing guidelines for high-demand industries through pathway designs which mitigate brittle intermetallic phase formation and severe dilution issues. Furthermore, Tian et al. [128] used ultrasonic vibration during the additive manufacturing process as a way of refining the dendritic grain structure and, thus, producing a crack-free metallurgical bond between IN738 and CuCrZr, two highly dissimilar and difficult-to-weld alloys.

4.4. Frontiers in Advanced Materials Engineering

The advancement of AM processes must occur concurrently with deeper research into materials and their properties. Despite the maturity of alloys like Inconel 718 in the aerospace sector, its application via high-thermal-gradient AM processes introduces complexities which require further investigation.

A critical ongoing challenge is the significant variability in mechanical properties induced by differing process parameters, scan strategies, and build orientations [92,129]. The anisotropic nature of the 'as-built' microstructure, characterised by columnar grains and segregated brittle phases, means that standard wrought heat treatments are often suboptimal for maximising performance [40,92]. Future research efforts must prioritise the development of novel, AM-specific thermal treatment cycles. The goal is to move beyond simple stress relief or standard homogenisation and develop tailored treatments that can precisely balance conflicting mechanical properties—specifically, maximising strength and yield limits without compromising ductility and fatigue resistance [94]. This requires a multi-scale understanding of how post-processing affects microstructural evolution at a fundamental level [44].

4.5. Innovation in Tooling for Difficult-To-Cut Materials

The efficacy of the post-processing chain is also heavily dependent on the tooling used for finish machining. Aerospace alloys, particularly nickel-based superalloys and titanium-based alloys processed by AM, are notoriously 'difficult-to-cut' due to their high strength, low thermal conductivity, and work-hardening tendencies, leading to rapid tool wear and increased production costs.

Currently, titanium aluminium nitride (TiAlN) coatings produced by the physical vapour deposition (PVD) process are widely used due to their reasonably high thermal stability and wear resistance. Nevertheless, to improve efficiency in serial AM production, the trend is moving towards the development of next-generation nanostructured coatings. Research is increasingly focusing on nanolayered and nanocomposite coating architectures that exhibit 'super-hardness' (exceeding 40 GPa). These advanced coatings are designed to drastically improve resistance to abrasive wear and inhibit crack propagation during the machining of highly abrasive AM surfaces, thereby extending tool life and ensuring consistent final part quality across large production runs. Figure 13 shows a SWOT analysis of the trends that are emerging in the additive manufacturing process applied to aerospace components, namely in hybrid manufacturing and advanced materials [30,92,94,130].

Regarding the strengths of aerospace AM emerging trends, the intelligent compensation in robotics refers to the integration of multi-sensor measurement systems and online trajectory compensation methods, which have demonstrated the capability to reduce robotic machining deviations by up to 90%. As for the baseline coating technology, current physical vapour deposition (PVD) coatings based on TiAlN provide reasonably high thermal stability and wear resistance for machining AM alloys. The weaknesses are robotic rigidity limitations and 'as-built' material variability. In the first one, articulated robot arms have an inherent lack of structural rigidity compared to conventional machine tools, leading to deflection during cutting forces and geometric inaccuracies. As for the second, the anisotropic nature of 'as-built' microstructures in alloys like Inconel 718 results in significant variability in mechanical properties, making standard wrought heat treatments suboptimal for maximising performance.

Nevertheless, several opportunities arise in this field, such as flexible hybrid workflows, AM-specific thermal treatments and next-generation tool coatings. Robot-assisted machining emerges as an economically viable and flexible alternative for hybrid manufacturing cells producing large, complex AM parts. Furthermore, research is prioritising the development of novel, tailored thermal treatment cycles to precisely balance conflicting properties, such as maximising strength without compromising ductility. In addition, the development of nanostructured coatings exhibiting 'super-hardness' (>40 GPa) aims to drastically improve resistance to abrasive wear during the

finish machining of AM surfaces. In spite of this, this technology's stringent precision requirements and 'difficult-to-cut' materials are still strong threats to its further development. Achieving the necessary geometric accuracy below 100 µm for aerospace assembly interfaces remains a critical challenge for widespread robotic adoption, and the high strength and work-hardening tendencies of aerospace alloys processed by AM lead to rapid tool wear and increased production costs during necessary subtractive post-processing.

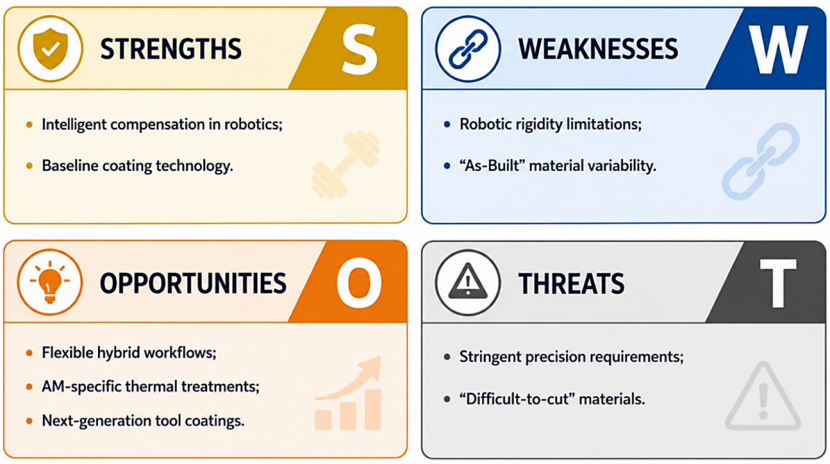


Figure 13. SWOT analysis of emerging trends in aerospace AM.

4.6. Circular Economy of Additively Manufactured Components

Besides the range of applications and advantages of the additive manufacturing technologies already discussed, it is of the utmost importance to study the environmental impact of these novel components. This may be evaluated through the energy consumption in the manufacturing stage, as well as their life cycle assessment (LCA) and life cycle costing (LCC) study, for example through recycling [131]. Uralde et al. [132] compare the life cycle assessment of additive manufacturing of two design approaches for the WAAM process, namely the topology optimisation and the design for additive manufacturing. They also tested three WAAM arc variants, and the findings compare the different environmental impacts by analysing thermal efficiency, deposition rates and post processing. Beyond new production, AM is revolutionising the Maintenance, Repair, and Overhaul (MRO) sector by enabling digital warehousing and on-demand manufacturing. AM mitigates inventory costs and lead times by facilitating the decentralized production of spare parts directly at the point of need [110,133]. The technology allows for the retrofitting of legacy aerospace components. Through topology optimisation, obsolete or worn parts can be redesigned and manufactured with improved performance metrics compared to the originals [134,135]. The synergy between AM and Augmented Reality is redefining maintenance procedures, providing technicians with advanced tools for repairing aeronautical components [81]. Figure 14 presents a roadmap containing the future trends in aerospace AM across digital control, hybrid robotics, advanced material systems, and circular lifecycle engineering.

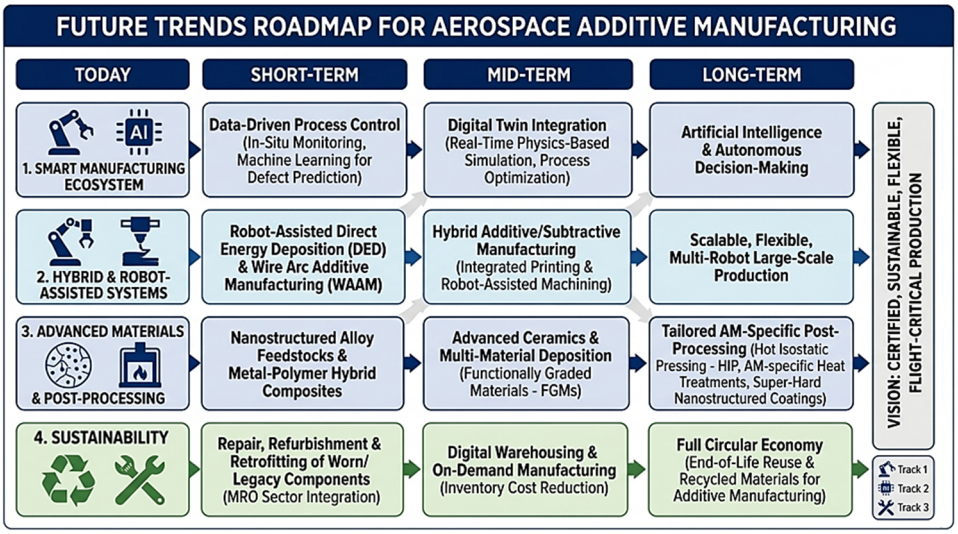


Figure 14. Technological roadmap synthesising future trajectories in aerospace AM.

5. Conclusions

This review has thoroughly examined the current status of AM in the aerospace and aeronautics sectors, evidencing its profound transition from a rapid prototyping tool to a pivotal enabling technology for the production of flight-critical hardware. The capacity of AM technologies, particularly SLM, EBM, and DED, to fabricate components with unprecedented geometric complexity has fundamentally reshaped prevailing design paradigms. It allows the consolidation of assemblies, the integration of intricate internal features like cooling channels, and significant structural lightweighting, which are foundational goals in aerospace engineering [3,72,73].

Despite this, the central thesis emerging from this analysis is that the geometric freedom of AM cannot be decoupled from the stringent demands of material quality. The reliable application of AM in high-specification aerospace environments is intrinsically linked to the rigorous control of the entire manufacturing value chain, starting with the inherent challenges of the 'as-built' state [111]. The extreme thermal histories characteristic of metal AM processes result in non-equilibrium microstructures, crystallographic anisotropy, and segregation phenomena that compromise mechanical performance, particularly ductility and fatigue resistance [92,109]. Furthermore, process-induced defects, such as keyhole porosity, caused by excessive energy density and lack-of-fusion voids resulting from insufficient overlap, act as critical stress concentrators, threatening the components' structural integrity [46,112].

Therefore, the realization of AM's full potential in aerospace is contingent upon a robust and validated post-processing strategy. This review underscores that post-processing is not merely a corrective step, but a mandatory phase for certification. Tailored thermal treatments, such as solution annealing and multi-step ageing, are essential to homogenise the microstructure and precipitate strengthening phases in superalloys such as Inconel 718 [92]. Concurrently, HIP remains the industry standard for eliminating internal porosity and densifying components, thereby significantly enhancing fatigue life for fracture-critical applications [40,94]. Ultimately, achieving confidence in additively manufactured flight hardware requires a holistic approach that integrates precise process parameter control with optimised thermal and mechanical post-processing to ensure consistent, certifiable material properties comparable to or superior to those of traditional wrought counterparts [136].

While significant progress has been made in industrialising AM for aerospace, several technological and scientific frontiers require concerted research efforts to address current limitations in scalability, efficiency, and predictability. The future trajectory of AM in this sector will be driven by demonstrable advances in hybrid manufacturing strategies, physics-based and data-driven computational modelling, and alloy and feedstock engineering, as detailed in the Discussion section. By critically consolidating materials science, process physics, and certification-driven constraints, this review provides a structured knowledge framework to support both research development and industrial decision-making in aerospace additive manufacturing.

Author Contributions

R.J.G.: conceptualization; R.J.G., R.D.F.S.C.: methodology; R.D.F.S.C.: data curation, visualization; R.J.G., R.D.F.S.C.: writing—original draft preparation; R.J.G.: investigation, supervision; H.H.B., J.T.M., D.B.G.: validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by FCT—Fundação para a Ciência e Tecnologia, I.P. by project reference 2024.05867.BDANA and DOI identifier https://doi.org/10.54499/2024.05867.BDANA.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Gemini Pro to improve the English language and figures. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

1. Kalender, M.; Bozkurt, Y.; Ersoy, S.; et al. Product Development with Additive Manufacturing and 3D Printer Technology in Aerospace Industry. *J. Aeronaut. Space Technol.* **2020**, *13*, 129–138.
2. Gao, G.; Wang, Y.; Wang, Y.; et al. Development on Shape and Performance Control of Aeronautical Parts in Additive Manufacturing. *J. Manuf. Process.* **2025**, *141*, 351–374. https://doi.org/10.1016/j.jmapro.2025.03.015.
3. Gupta, A. Advantages and Challenges of Additive Manufacturing: A Breakthrough in Aerospace Manufacturing. *Int. J. Res. Aeronaut. Mech. Eng.* **2024**, *12*, 1–14. https://doi.org/10.5281/zenodo.10847767.
4. Roucoules, L.; Paredes, M.; Eynard, B.; et al. Advances on Mechanics, Design Engineering and Manufacturing III. In Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing, Online, 2–4 June 2020. https://doi.org/10.1007/978-3-030-70566-4.
5. Radhika, C.; Shanmugam, R.; Ramoni, M.; et al. A Review on Additive Manufacturing for Aerospace Application. *Mater. Res. Express* **2024**, *11*, 022001. https://doi.org/10.1088/2053-1591/ad21ad.
6. Abdulhameed, O.; Al-Ahmari, A.; Ameen, W.; et al. Additive Manufacturing: Challenges, Trends, and Applications. *Adv. Mech. Eng.* **2019**, *11*, 1687814018822880. https://doi.org/10.1177/1687814018822880.
7. Sherekar, R.; Gaddamwar, S. Advanced Applications of Additive Manufacturing in the Design and Fabrication of High-Performance Aerospace Heat Exchangers. *Int. J. Sci. Res. Eng. Manag.* **2025**, *9*, 1–9. https://doi.org/10.55041/ijsrem51777.
8. Prater, T.; Tilson, W.; Vickers, J.; et al. Breakthrough Materials for Space Applications Workshop. In Proceedings of the Workshop at Jackson Center, Huntsville, AL, USA, 23–24 April 2019.
9. Mohanavel, V.; Ashraff Ali, K.S.; Ranganathan, K.; et al. The Roles and Applications of Additive Manufacturing in the Aerospace and Automobile Sector. *Mater. Today Proc.* **2021**, *47*, 405–409. https://doi.org/10.1016/j.matpr.2021.04.596.
10. Dordlofva, C. A Design for Qualification Framework for the Development of Additive Manufacturing Components—A Case Study from the Space Industry. *Aerospace* **2020**, *7*, 25. https://doi.org/10.3390/aerospace7030025.
11. Ceruti, A.; Marzocca, P.; Liverani, A.; et al. Maintenance in Aeronautics in an Industry 4.0 Context: The Role of Augmented Reality and Additive Manufacturing. *J. Comput. Des. Eng.* **2019**, *6*, 516–526. https://doi.org/10.1016/j.jcde.2019.02.001.
12. Rossi, S.; Hernandez, M.; Hassan, B. Additive Manufacturing (3D Printing): Applications in Healthcare, Aerospace, and Consumer Products. 2024. Available online: https://www.researchgate.net/publication/384326285 (accessed on 30 April 2026).
13. Scalia, T.; Bonventre, L.; Vecchiarelli, P.; et al. Additive Manufacturing: Scientific & Patent Trends in the Space Sector. In Proceedings of the 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25–29 October 2021.
14. Khorasani, A.; Ghasemi, A.; Rolfe, B.; et al. Additive Manufacturing a Powerful Tool for the Aerospace Industry. *Rapid Prototyp. J.* **2022**, *28*, 87–100. https://doi.org/10.1108/rpj-01-2021-0009.
15. Rietter, L.; Freitas, R.; Carneiro, F.; et al. Study for Implementation of Electronic Circuits into Multifunctional Miniaturized Thermoplastic Enclosures. In Proceedings of the 2023 15th International Congress Mechatronic Integration Discourse (MID), Amberg, Germany, 21–22 June 2023; pp. 1–5. https://doi.org/10.1109/mid59615.2023.10461320.
16. Vlaeyen, M.; Sinico, M.; Witvrouw, A.; et al. End-to-End Additive Manufacturing for a Structural Aerospace Component. In Proceedings of the 23rd International Conference of the European Society for Precision Engineering and Nanotechnology, Copenhagen, Denmark, 12–16 June 2023; pp. 103–106.
17. Getachew, M.T.; Shiferaw, M.Z.; Ayele, B.S. Recent Advances of Additive Manufacturing for Aerospace Industries: Methods, Materials, Challenges, and Future Outlooks. In *Sustainable Development Research in Manufacturing, Process Engineering, Green Infrastructure, and Water Resources*; Springer Nature Switzerland: Cham, Switzerland, 2025; pp. 47–82. https://doi.org/10.1007/978-3-031-77339-6_4.
18. Heikkinen, T.; Stolt, R.; Elgh, F. Incorporating Design for Additive Manufacturing in Multidisciplinary Design Automation—Challenges Identified. *Comput. Aided Des. Appl.* **2020**, *17*, 936–947. https://doi.org/10.14733/cadaps.2020.936-947.
19. Nguyen, D.S. Design of Lattice Structure for Additive Manufacturing in CAD Environment. *J. Adv. Mech. Des. Syst. Manuf.* **2019**, *13*, JAMDSM0057. https://doi.org/10.1299/jamdsm.2019jamdsm0057.
20. Zhu, J.H.; Zhang, W.H.; Xia, L. Topology Optimization in Aircraft and Aerospace Structures Design. *Arch. Comput. Methods Eng.* **2016**, *23*, 595–622. https://doi.org/10.1007/s11831-015-9151-2.
21. Crespo-Sánchez, J.; Solek, C.; Fuentes del Toro, S.; et al. Retrofitting of a High-Performance Aerospace Component via Topology Optimization and Additive Manufacturing. *Machines* **2025**, *13*, 700. https://doi.org/10.3390/machines13080700.

22. Ferreira, B.T.; Monteiro, J.; Borille, A.; et al. Reuse Powder Impacts in Additive Manufacturing for Aeronautical Parts. *Int. J. Adv. Manuf. Technol.* **2025**, *141*, 2027–2062. https://doi.org/10.1007/s00170-025-16619-z.
23. Doğru, A.; Seydibeyoğlu, M.Ö. Sustainable Materials Used by Additive Manufacturing for Aerospace Industry. In *Research Developments in Sustainable Aviation*; Springer International Publishing: Cham, Switzerland, 2021; pp. 99–107.
24. Olabisi, S.A.; Madueke, C.I.; Adediran, A.A.; et al. A Mini Review on Additive Manufacturing in Aerospace: Challenges and Opportunities. *NIPES J. Sci. Technol. Res.* **2025**, *7*, 126–138. https://doi.org/10.37933/nipes/7.4.2025.si16.
25. Getachew, M.T.; Shiferaw, M.Z.; Ayele, B.S. The Current State of the Art and Advancements, Challenges, and Future of Additive Manufacturing in Aerospace Applications. *Adv. Mater. Sci. Eng.* **2023**, *2023*, 8817006. https://doi.org/10.1155/2023/8817006.
26. Bozkurt, Y.; Avşar, A.; Korgancı, M.; et al. A Comprehensive Review on Friction Stir Additive Manufacturing of Various Structural Alloys for Aerospace Applications. *Prog. Addit. Manuf.* **2025**, *10*, 7365–7390. https://doi.org/10.1007/s40964-025-01160-y.
27. Saracyakupoglu, T. The Qualification of the Additively Manufactured Parts in the Aviation Industry. *Am. J. Aerosp. Eng.* **2019**, *6*, 1–10. https://doi.org/10.11648/j.ajae.20190601.11.
28. Rahman, M.M.; Ramzan, A. Additive Manufacturing and 3D Printing for Aerospace and Automotive Industries. *Spectr. Eng. Sci.* **2025**, *3*, 1241–1259. https://doi.org/10.5281/zenodo.16477032.
29. Zhou, L.; Miller, J.; Vezza, J.; et al. Additive Manufacturing: A Comprehensive Review. *Sensors* **2024**, *24*, 2668. https://doi.org/10.3390/s24092668.
30. Wang, T.; Li, N.; Yu, N.; et al. Robot-Assisted Additive Manufacturing for Aerospace Applications: Recent Trends and Its Future Possibilities. *Int. J. Comput. Integr. Manuf.* **2026**, *39*, 204–244. https://doi.org/10.1080/0951192x.2025.2478007.
31. Franco, G.; Candura, F. Production Technology and Use of Composite Materials in the Aeronautics Industry, Risks and Pathology in the Manufacturing Workers. *G. Ital. Med. Lav.* **1985**, *7*, 45–57.
32. Pant, H.; Arora, A.; Gopakumar, G.S.; et al. Applications of Wire Arc Additive Manufacturing (WAAM) for Aerospace Component Manufacturing. *Int. J. Adv. Manuf. Technol.* **2023**, *127*, 4995–5011. https://doi.org/10.1007/s00170-023-11623-7.
33. Tyan, M.; Min, D.; Maw, A. Topology Optimization in Additive Manufacturing for Lightweight Aerospace Components. *Int. Innov. Res. J. Eng. Technol.* **2025**, *11*, 44–53. https://doi.org/10.32595/iirjet.org/v11i1.2025.231.
34. Ferreira, C.M.; Reis, L.; Carmezim, M.J.; et al. Additive Manufacturing of Aluminium Alloys in the Aeronautical Sector—A Bibliometric Analysis. *Procedia Struct. Integr.* **2024**, *53*, 254–263. https://doi.org/10.1016/j.prostr.2024.01.031.
35. Gradl, P.; Mireles, O.R.; Katsarelis, C.; et al. Advancement of Extreme Environment Additively Manufactured Alloys for next Generation Space Propulsion Applications. *Acta Astronaut.* **2023**, *211*, 483–497. https://doi.org/10.1016/j.actaastro.2023.06.035.
36. Waller, J.M.; Burke, E.R.; Wells, D.N.; et al. NDE-Based Quality Assurance of Metal Additively Manufactured Aerospace Parts at NASA, JAXA, and ESA. In Proceedings of the ASTM Special Technical Publication, STP 1620, West Conshohocken, PA, USA, 6–8 November 2018. https://doi.org/10.1520/stp162020180106.
37. Afkhami, S.; Piili, H.; Salminen, A.; et al. Effective Parameters on the Fatigue Life of Metals Processed by Powder Bed Fusion Technique: A Short Review. *Procedia Manuf.* **2019**, *36*, 3–10. https://doi.org/10.1016/j.promfg.2019.08.002.
38. Neumann, G.; Schwarz, H.; Groh, W.; et al. A Data-Based Certification Approach for Additively Manufactured Metal Aircraft Components. *Prog. Addit. Manuf.* **2025**, *10*, 4061–4071. https://doi.org/10.1007/s40964-025-01107-3.
39. Blachowicz, T.; Ehrmann, G.; Ehrmann, A. Metal Additive Manufacturing for Satellites and Rockets. *Appl. Sci.* **2021**, *11*, 12036. https://doi.org/10.3390/app112412036.
40. Stelling, O.; Maywald, K. Influence of Processing Parameters during Hot Isostatic Pressing on Properties and Microstructure of Additive Manufactured TiAl6V4. *HTM J. Heat Treat. Mater.* **2020**, *75*, 35–47. https://doi.org/10.3139/105.110403.
41. Di Caprio, F.; Acanfora, V.; Franchitti, S.; et al. Hybrid Metal/Composite Lattice Structures: Design for Additive Manufacturing. *Aerospace* **2019**, *6*, 71. https://doi.org/10.3390/aerospace6060071.
42. Chiapperi, J.D.; Bron, J.A.; Gregory, D.C.; et al. An Integrative Course in Turbomachine Design, Manufacturing, and Measurement. In Proceedings of the ASME Turbo Expo 2025: Turbomachinery Technical Conference and Exposition, Memphis, TN, USA, 16–20 June 2025. https://doi.org/10.1115/gt2025-152137.
43. Subeshan, B.; Ali, Z.; Asmatulu, E. Metal Additive Manufacturing in Space and Aerospace Exploration: Current Processes, Material Selection and Challenges. *J. Eng. Appl. Sci.* **2024**, *11*, 35. https://doi.org/10.5455/jeas.2024021104.
44. Marketyn, S.; Ellis, B.; Rajab, H. Material Selection Criteria for Additive Manufacturing in Aerospace. 2025. Available online: https://www.researchgate.net/publication/389819194 (accessed on 25 April 2026).
45. Arena, M.; Ambrogiani, P.; Raiola, V.; et al. Design and Qualification of an Additively Manufactured Manifold for Aircraft Landing Gears Applications. *Aerospace* **2023**, *10*, 69. https://doi.org/10.3390/aerospace10010069.
46. Valentin, M.; Arnaud, C.; Kling, R. Additive Manufacturing by Wire Based Laser Metal Deposition. In Proceedings of the Laser 3D Manufacturing VI, San Francisco, CA, USA, 5–7 February 2019. https://doi.org/10.1117/12.2510074.

47. Lizarribar Carrillo, B.; Prieto, B.; Martínez-Iturralde, M.; et al. Design and Additive Manufacturing of a Lightweight Aerospace Electric Actuator. *Open Res. Eur.* **2024**, *4*, 121. https://doi.org/10.12688/openreseurope.17752.1.
48. Kumar, S.A.; Ahmad, N. Microstructure Analysis of Carbon-Reinforced PEEK in Additive Manufacturing for Aerospace Applications. **2024**. https://doi.org/10.13140/rg.2.2.21023.37288.
49. Bagassi, S.; Lucchi, F.; de Crescenzio, F.; et al. Generative Design: Advanced Design Optimization Processes for Aeronautical Applications. In Proceedings of the 30th Congress of the International Council of the Aeronautical Sciences (ICAS 2016), Daejeon, South Korea, 25–30 September 2016.
50. Andries, V.; Zaharia, S.M. Generative Design, Simulation, and 3D Printing of the Quadcopter Drone Frame. *Appl. Sci.* **2025**, *15*, 9647. https://doi.org/10.3390/app15179647.
51. Khajavi, S.H.; Partanen, J.; Holmström, J. Additive Manufacturing in the Spare Parts Supply Chain. *Comput. Ind.* **2014**, *65*, 50–63. https://doi.org/10.1016/j.compind.2013.07.008.
52. Avşar Aydın, E.; Biçer, M.B.; Mert, M.E.; et al. 3D-Printed Antenna Design Using Graphene Filament and Copper Tape for High-Tech Air Components. *SAE Int. J. Aerosp.* **2022**, *16*, 131–140. https://doi.org/10.4271/01-16-02-0008.
53. Gradl, P.; Tinker, D.C.; Park, A.; et al. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. *J. Mater. Eng. Perform.* **2022**, *31*, 6013–6044. https://doi.org/10.1007/s11665-022-06850-0.
54. Acosta, C.; Flynn, W.P.; Santillan, L.; et al. The Performance Characterization of a Drop-on-Demand Inkjet-Printed Gold Film Under the Temperature Conditions for Airborne Equipment. *J. Compos. Sci.* **2025**, *9*, 231. https://doi.org/10.3390/jcs9050231.
55. León-Becerra, J.; Hidalgo-Salazar, M.Á.; González-Estrada, O.A. Progressive Damage Analysis of Carbon Fiber-Reinforced Additive Manufacturing Composites. *Int. J. Adv. Manuf. Technol.* **2023**, *126*, 2617–2631. https://doi.org/10.1007/s00170-023-11256-w.
56. Arévalo, C.M.; Perez-Soriano, E.M.; Ariza, E.; et al. Optimizing Titanium-Boron Carbide Composites for Aerospace Manufacturing via Plasma Metal Deposition. *Mater. Sci. Forum* **2025**, *1146*, 49–56. https://doi.org/10.4028/p-4t23q8.
57. Danylenko, V.; Lipovskyi, V. Review of Polymer Fused Deposition Material Additive Manufacturing Technology for Aerospace Application. *J. Rocket. Space Technol.* **2025**, *34*, 21–30. https://doi.org/10.15421/452502.
58. Aliberti, F.; Longo, R.; Raimondo, M.; et al. Additive manufacturing of polymers and composites for applications in aerospace and aeronautics. *Mater. Horiz.* **2025**, *13*, 532–588. https://doi.org/10.1039/d5mh01403d.
59. Montanari, R.; Palombi, A.; Richetta, M.; et al. Additive Manufacturing of Aluminum Alloys for Aeronautic Applications: Advantages and Problems. *Metals* **2023**, *13*, 716. https://doi.org/10.3390/met13040716.
60. Palmero, E.M.; Casaleiz, D.; de Vicente, J.; et al. Composites Based on Metallic Particles and Tuned Filling Factor for 3D-Printing by Fused Deposition Modeling. *Compos. Part A Appl. Sci. Manuf.* **2019**, *124*, 105497. https://doi.org/10.1016/j.compositesa.2019.105497.
61. Kafalı, H.; Tunca, E. Investigation of the Mechanical Properties of Polyurethane Foam-Filled FDM-Printed Honeycomb Core Sandwich Composites for Aircraft. *Aeronaut. J.* **2024**, *128*, 577–597. https://doi.org/10.1017/aer.2023.85.
62. Wei, S.; Cai, Y.; Wang, Q.; et al. Research Progress and Prospect of Laser Additive Manufacturing of Ultra-High-Strength Steel. *J. Mater. Eng. Perform.* **2026**, *35*, 14285–14316. https://doi.org/10.1007/s11665-025-12334-8.
63. Galib, G.; Silva, F.J.G.; Pedroso, A.F.V.; et al. A Comprehensive Review of Additive Manufacturing Technologies for Composite Materials. *J. Mech. Eng. Manuf.* **2025**, *1*, 2. https://doi.org/10.53941/jmem.2025.100002.
64. Rastegarzadeh, S.; Wang, J.; Huang, J. High-Performance Aerospace Components Design with Architected Cellular Materials. *Integr. Mater. Manuf. Innov.* **2025**, *14*, 606–619. https://doi.org/10.1007/s40192-025-00424-3.
65. Sargent, J.F.; Schwartz, R.X. 3D Printing: Overview, Impacts, and the Federal Role. In *Key Congressional Reports for August 2019: Part VII*; Nova Science Publishers, Inc.: Hauppauge, NY, USA, 2020.
66. Khan, N.; Riccio, A. A Systematic Review of Design for Additive Manufacturing of Aerospace Lattice Structures: Current Trends and Future Directions. *Prog. Aerosp. Sci.* **2024**, *149*, 101021. https://doi.org/10.1016/j.paerosci.2024.101021.
67. Ellis, B.; Marketyn, S.; Alex, C.; et al. The Role of Metal Additive Manufacturing in Modern Aerospace Exploration. 2025. Available online: https://www.researchgate.net/publication/389819643 (accessed on 20 April 2026).
68. Almalki, A.; Downing, D.; Noronha, J.; et al. The Effect of Geometric Design and Materials on Section Properties of Additively Manufactured Lattice Elements. *Int. J. Adv. Manuf. Technol.* **2023**, *126*, 3555–3577. https://doi.org/10.1007/s00170-023-11251-1.
69. Shetty, K.; Murthy, H.R. Additive Manufacturing of Threaded Parts for Aerospace Applications. In Proceedings of the AeroCON 2022, Bangalore, India, 2 June 2022. https://doi.org/10.4271/2022-26-0030.
70. Tilvaldyev, S.A.; Caldiño Herrera, U.; Dávalos Ramírez, J.O.; et al. The Importance of Additive Technology and Manufacturing Processes for Laboratory Experiments in Aeronautics. *Ing. Investig. y Desarro.* **2023**, *23*, 56–64. https://doi.org/10.19053/1900771x.v23.n2.2023.16703.
71. Wang, L.; Mosher, R.; Duett, P. Additive Manufacturing in the Aerospace Industry. *Am. J. Eng. Appl. Sci.* **2024**, *17*, 116–125. https://doi.org/10.3844/ajeassp.2024.116.125.

72. Blakey-Milner, B.; Gradl, P.; Snedden, G.; et al. Metal Additive Manufacturing in Aerospace: A Review. *Mater. Des.* **2021**, *209*, 110008. https://doi.org/10.1016/j.matdes.2021.110008.
73. Venkatesan, S.; S, V. Review on Additive Manufacturing Process in Aircraft Industries. *Acceleron Aerosp. J.* **2024**, *2*, 204–208. https://doi.org/10.61359/11.2106-2412.
74. Lu, X.; Chiumenti, M.; Cervera, M.; et al. Warpage Analysis and Control of Thin-Walled Structures Manufactured by Laser Powder Bed Fusion. *Metals* **2021**, *11*, 686. https://doi.org/10.3390/met11050686.
75. Tabares, I.; Andral, U.; Escudero, M.; et al. Surface Smoothing and Periodic Microstructuring of Additively Manufactured Scalmalloy® by Sequential Continuous-Wave Polishing and Direct Laser Interference Patterning. *Surf. Coat. Technol.* **2026**, *531*, 133560. https://doi.org/10.1016/j.surfcoat.2026.133560.
76. Chen, H.; Li, M.; Yin, H.; et al. A Novel Low-Density and High-Strength Al-Mg-Li Based Multicomponent Alloys Manufactured by Laser Powder Bed Fusion. *Mater. Charact.* **2026**, *236*, 116444. https://doi.org/10.1016/j.matchar.2026.116444.
77. Yan, Y.; Zhang, C.; Liu, Y.; et al. Laser-Directed Energy Deposition of Y_2O_3 Nanoparticle-Reinforced GH5188 Superalloy with Enhanced Strength. *J. Alloys Compd.* **2026**, *1080*, 190339. https://doi.org/10.1016/j.jallcom.2026.190339.
78. Hu, Z.; Song, R.; Liu, X.; et al. A Review on Additive Manufacturing of CM247LC Nickel-Based Superalloy: Cracking Mechanisms, Suppression Strategies, and Microstructure-Property Control. *J. Alloys Compd.* **2026**, *1061*, 187453. https://doi.org/10.1016/j.jallcom.2026.187453.
79. Li, M.X.; Qu, W.Q. Electron Beam Additive Manufacturing and Its Applications in Aerospace Field. *Mater. Sci. Forum* **2014**, *789*, 377–383. https://doi.org/10.4028/www.scientific.net/msf.789.377.
80. Estupiñán-López, F.; Orquiz-Muela, C.; Gaona-Tiburcio, C.; et al. Oxidation Kinetics of Ti-6Al-4V Alloys by Conventional and Electron Beam Additive Manufacturing. *Materials* **2023**, *16*, 1187. https://doi.org/10.3390/ma16031187.
81. Jiang, J.; An, N.; Yang, G.; et al. Finite Element Simulation of Temperature Field during SEBM Process of Pure Tungsten. *Chin. J. Lasers* **2022**, *49*, 0802006. https://doi.org/10.3788/cjl202249.0802006.
82. Gaytan, S.M.; Murr, L.E.; Medina, F.; et al. Fabrication and Characterization of Reticulated, Porous Mesh Arrays and Foams for Aerospace Applications by Additive Manufacturing Using Electron Beam Melting. In Proceedings of the TMS Annual Meeting, Seattle, WA, USA, 14–18 February 2010.
83. Yıldız, A.; Yilmaz, O.; Yamaner, Y.; et al. Digital Twin Manufacturing of Aerospace Tooling in Wire Arc Additive Manufacturing. In Proceedings of the 34th CIRP Design Conference, Cranfield, UK, 3–5 June 2024.
84. Lin, Z.; Song, K.; Yu, X. A Review on Wire and Arc Additive Manufacturing of Titanium Alloy. *J. Manuf. Process.* **2021**, *70*, 24–45. https://doi.org/10.1016/j.jmapro.2021.08.018.
85. Guan, S.; Wang, H. Current Status of High-Strength Aluminum Alloy Arc Additive Manufacturing Technology. *Acad. J. Sci. Technol.* **2025**, *17*, 13–23. https://doi.org/10.54097/s0k94887.
86. Chakraborty, D.; Tirumala, T.; Chitral, S.; et al. The State of the Art for Wire Arc Additive Manufacturing Process of Titanium Alloys for Aerospace Applications. *J. Mater. Eng. Perform.* **2022**, *31*, 6149–6182. https://doi.org/10.1007/s11665-022-07128-1.
87. Pedroso, A.F.V.; Durão, L.M.; Martinho, R.P.; et al. Recent Advances and Future Trends in Extending the Service Life of Injection Moulding Tools: A Comprehensive Review. *J. Mech. Eng. Manuf.* **2026**, *2*, 12. https://doi.org/10.53941/jmem.2026.100012.
88. Bester, D. Applying Design for Additive Manufacturing to Existing Aerospace Parts. *MATEC Web Conf.* **2023**, *388*, 05002. https://doi.org/10.1051/matecconf/202338805002.
89. Chen, M.; Wang, W.; Dong, K.; et al. Crack Suppression and Directional Grain Growth in M247 Nickel-Based Superalloy via Synchronous Induction-Assisted Laser Directed Energy Deposition. *Mater. Des.* **2026**, *266*, 116172. https://doi.org/10.1016/j.matdes.2026.116172.
90. Stehr, C. Accelerating Adoption of Large-Format Additive Manufacturing in Aerospace Tooling. Master's Thesis, Massachusetts Institute of Technology, 2022.
91. Sebbe, N.P.V.; Silva, F.J.G.; Pinto, A.; et al. Exploring Post-Processing Operations of Ti Alloys Using Hybrid Manufacturing Systems. *J. Mech. Eng. Manuf.* **2026**, *2*, 9. https://doi.org/10.53941/jmem.2026.100009.
92. Jack, W.; Sofiyan, U. Microstructure and Crystallographic Texture Evolution in Additive Manufacturing of Nickel-Based Superalloys for Aerospace Applications. *ResearchGate* **2024**. https://doi.org/10.13140/rg.2.2.28573.12008.
93. Veiga, F.; Suárez, A.; Artaza, T.; et al. Effect of the Heat Input on Wire-Arc Additive Manufacturing of Invar 36 Alloy: Microstructure and Mechanical Properties. *Weld. World* **2022**, *66*, 1081–1091. https://doi.org/10.1007/s40194-022-01295-4.
94. Aghayar, Y.; Behvar, A.; Antu, M.N.R.; et al. Ambient and High-Temperature Rotating Bending Fatigue of as-Built and Hot Isostatic Pressed Additively Manufactured 316L Stainless Steel. *Int. J. Fatigue* **2026**, *204*, 109365. https://doi.org/10.1016/j.ijfatigue.2025.109365.

95. Morshed-Behbahani, K.; Aliyu, A.; Bishop, D.P.; et al. Additive Manufacturing of Copper-Based Alloys for High-Temperature Aerospace Applications: A Review. *Mater. Today Commun.* **2024**, *38*, 108395. https://doi.org/10.1016/j.mtcomm.2024.108395.
96. Doğru, Ö.; Seydibeyoğlu, M.; Doğru, A.; et al. Polymer Composite Based Additive Manufacturing for Aerospace Applications. In *Havacilik Teknolojisi ve Uygulamalari Kitab*i; Ege University: İzmir, Turkey, 2022.
97. Rai, R.S. Applications of Additively Manufactured Functional Polymers and Nanocomposites in Aerospace and Aviation Industry. In *Additive Manufacturing of Functional Polymers and Nanocomposites: Recent Progress, Applications, Challenges and Future Opportunities*; Woodhead Publishing: Cambridge, MA, USA, 2025; pp. 385–438. https://doi.org/10.1016/b978-0-443-26516-7.00014-6.
98. Boado-Cuartero, B.; Pérez-Álvarez, J.; Roibás-Millán, E. Material Characterization of High-Performance Polymers for Additive Manufacturing (AM) in Aerospace Mechanical Design. *Aerospace* **2024**, *11*, 748. https://doi.org/10.3390/aerospace11090748.
99. Guimarães, A.; Messias, S.; Lopes, J.; et al. Development of a Polymer Filament Extruder: Recycling 3D Printer Waste. *J. Mech. Eng. Manuf.* **2026**, *2*, 1. https://doi.org/10.53941/jmem.2026.100001.
100. Palmero, E.M.; Bollero, A. 3D and 4D Printing of Functional and Smart Composite Materials. In *Encyclopedia of Materials: Composites*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 2. https://doi.org/10.1016/b978-0-12-819724-0.00008-2.
101. Acanfora, V.; Sellitto, A.; Russo, A.; et al. Experimental Investigation on 3D Printed Lightweight Sandwich Structures for Energy Absorption Aerospace Applications. *Aerosp. Sci. Technol.* **2023**, *137*, 108276. https://doi.org/10.1016/j.ast.2023.108276.
102. Shen, C.; Guo, Y.; Shen, Z.; et al. Additive Manufacturing of Aerospace Composites: A Critical Review of the Material-Process-Design Interplay and Prospects for Application. *Materials* **2025**, *18*, 4280. https://doi.org/10.3390/ma18184280.
103. Singh, M.; Halbig, M.C.; Grady, J.E. Additive Manufacturing of Light Weight Ceramic Matrix Composites for Gas Turbine Engine Applications. In Proceedings of the Advanced Processing and Manufacturing Technologies for Nanostructured and Multifunctional Materials, Daytona Beach, FL, USA, 25–30 January 2015. https://doi.org/10.1002/9781119211662.ch16.
104. Goulas, A.; Friel, R.J. Laser Sintering of Ceramic Materials for Aeronautical and Astronautical Applications. In *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*; Elsevier Inc.: Amsterdam, The Netherlands, 2017; pp. 373–398.
105. Zhang, B.; Wang, L.; Chen, X.; et al. From Complex Shaping to Mirror Finish: Additive Manufacturing of Aerospace-Grade Cf/SiC Space Optics. *Adv. Sci.* **2026**, *13*, e17980. https://doi.org/10.1002/advs.202517980.
106. Shvydyuk, K.O.; Lanceros-Mendez, S.; Silva, A.P. Advanced Ceramics in Aerospace and Defense: The Interrelationship between Traditional and Additive Manufacturing Approaches. *Adv. Mater. Technol.* **2026**, *11*, e01012. https://doi.org/10.1002/admt.202501012.
107. Tadjdeh, Y. 3D Printing Promises to Revolutionize Defense, Aerospace Industries. *Natl. Def.* **2014**, *98*, 20–23.
108. Balaji, D.; Ranga, J.; Bhuvaneswari, V.; et al. Additive Manufacturing for Aerospace from Inception to Certification. *J. Nanomater.* **2022**, *2022*, 7226852. https://doi.org/10.1155/2022/7226852.
109. Chen, Z.K.; Li, X.Y. Numerical Simulations for Microstructure Evolution during Metal Additive Manufacturing. *Adv. Mech.* **2022**, *52*, 397–409. https://doi.org/10.6052/1000-0992-22-021.
110. Totuk, O.H.; Özkara, M.; Akar, S. Anisotropic Effects on Topology Optimization for Additive Manufacturing in Aerospace Applications. *Kocaeli J. Sci. Eng.* **2025**, *8*, 30–37. https://doi.org/10.34088/kojose.1565969.
111. Onafide, M.; Al Turk, A. Additive Manufacturing Techniques for Reducing Failure Modes and Enhancing Durability in Aerospace Components. *J. Manag. Eng. Integr.* **2025**, *18*, 42–52. https://doi.org/10.62704/10057/30204.
112. Özsoy, K.; Duman, B.; Gültekin, D.İ. Metal Part Production with Additive Manufacturing for Aerospace and Defense Industry. *Int. J. Technol. Sci.* **2020**, *11*, 201–210.
113. Monteiro, H.; Carmona-Aparicio, G.; Lei, I.; et al. Energy and Material Efficiency Strategies Enabled by Metal Additive Manufacturing—A Review for the Aeronautic and Aerospace Sectors. *Energy Rep.* **2022**, *8*, 298–305. https://doi.org/10.1016/j.egyr.2022.01.035.
114. Lesseur, J.; Tranchand, B.; Mancier, T.; et al. On the Use of X-Ray Microtomography to Control Artificial Defect Geometries Produced by Metal Additive Manufacturing. *Nondestruct. Test. Eval.* **2022**, *37*, 611–630. https://doi.org/10.1080/10589759.2022.2085701.
115. Seifert, D.; Grzona, P.; Raval, K.; et al. Quality Control Techniques in Additive Manufacturing: Current Trends and Their Prototypical Implementation. *Procedia Comput. Sci.* **2025**, *253*, 1206–1215. https://doi.org/10.1016/j.procs.2025.01.182.
116. Kiefel, D.; Scius-Bertrand, M.; Stößel, R. Computed Tomography Inspection of Additive Manufactured Components in Aeronautic Industry. In Proceedings of the 8th Conference on Industrial Computed Tomography, Wels, Austria, 6–9 February 2018.

117. Siddiqui, M.M.U.Z.; Tabassum, A. Condition-Based Monitoring Techniques and Algorithms in 3d Printing and Additive Manufacturing: A State-of-the-Art Review. *Prog. Addit. Manuf.* **2025**, *10*, 4257–4304. https://doi.org/10.1007/s40964-024-00816-5.
118. Barros, R.; Silva, F.J.G.; Gouveia, R.M.; et al. Laser Powder Bed Fusion of Inconel 718: Residual Stress Analysis before and after Heat Treatment. *Metals* **2019**, *9*, 1290. https://doi.org/10.3390/met9121290.
119. Omede, B.; Festa, S.; Tirelli, M.; et al. Design for Additive Manufacturing: Integrating Structural Optimization and Printability Analysis for Aerospace Components. In Proceedings of the European Rotorcraft Forum 2025, Venice, Italy, 9–12 September 2025.
120. Farzana, R.; Dayal, P.; Peristyy, A.; et al. Effect of Ti-Metal Addition on Hot-Isostatically Pressed (HIPed) Synroc-C. *J. Am. Ceram. Soc.* **2023**, *106*, 6971–6986. https://doi.org/10.1111/jace.19313.
121. Sebbe, N.; Lafuente, J.L.; Aibar, C.; et al. Posture Optimization Techniques for Enhanced Robotic Machining Performance: A Review. *J. Mech. Eng. Manuf.* **2026**, *2*, 13. https://doi.org/10.53941/jmem.2026.100013.
122. Tian, Z. Adaptive Slicing Algorithm and Path Planning for Additive Manufacturing of Aerospace Parts. *Appl. Comput. Eng.* **2025**, *186*, 78–86. https://doi.org/10.54254/2755-2721/2025.gl27145.
123. Acanfora, V.; Garofano, A.; Battaglia, M.; et al. On the Effect of Printing Orientation on the Surface Roughness of an Additive Manufactured Composite Vertical Tail. *Int. J. Adv. Manuf. Technol.* **2024**, *130*, 4543–4564. https://doi.org/10.1007/s00170-024-12999-w.
124. Hu, Z.; Huang, C.; Xie, L.; et al. Machine Learning Assisted Quality Control in Metal Additive Manufacturing: A Review. *Adv. Powder Mater.* **2025**, *4*, 100342. https://doi.org/10.1016/j.apmate.2025.100342.
125. Ekengwu, I.; Jude, D.; Ilechukwu, A.; et al. Machine Learning for Process Optimization and Defect Detection in Metal Additive Manufacturing: A Critical Review of Algorithms, In-Situ Monitoring Strategies, and Quality Assurance Frameworks. *J. Mech. Eng. Manuf.* **2026**. https://doi.org/10.53941/jmem.2026.100022.
126. Nasir, N.; Röttger, A. Additive Manufacturing of Functionally Graded Materials: Advances, Challenges, and Strategies for Processing and Performance Optimization. *Next Mater.* **2026**, *12*, 102285. https://doi.org/10.1016/j.nxmate.2026.102285.
127. Ghanavati, R.; Mosallanejad, M.H.; Behjat, A.; et al. Multi-Material Processing of Metallic Components by Direct Additive Manufacturing Methods: Technologies, Scientific Insights, and Industrial Applications. *Int. J. Extrem. Manuf.* **2026**, *8*, 042004. https://doi.org/10.1088/2631-7990/ae5295.
128. Tian, Z.; Zheng, Y.; Liu, Y.; et al. Ultrasonic-Assisted Additive Manufacturing of Crack-Free IN738/CuCrZr Dissimilar Components: Interfacial Evolution and Gradient Microstructure Formation. *J. Mater. Process. Technol.* **2026**, *355*, 119401. https://doi.org/10.1016/j.jmatprotec.2026.119401.
129. Crispo, L.; Kim, I.Y. Combined Topology and Build Orientation Optimization for Support Structure Minimization in Additive Manufacturing. *Struct. Multidiscip. Optim.* **2025**, *68*, 216. https://doi.org/10.1007/s00158-025-04124-6.
130. Achyut, T.; Patel, M.; Prakash, A.; et al. A Critical Review of Smart Materials in Additive Manufacturing for Sustainable Future. *Int. J. Innov. Sci. Res. Technol.* **2025**, *10*, 2066–2071. https://doi.org/10.38124/ijisrt/25jul1381.
131. Pacheco, F.; Sebbe, N.P.V.; Silva, F.J.G.; et al. Challenges and Frontiers in the Circularity of Polymer Additive Manufacturing: A Systematic Review of Recycling Pathways and Material Degradation. *J. Mech. Eng. Manuf.* **2026**, *2*, 19. https://doi.org/10.53941/jmem.2026.100019.
132. Uralde, V.; Veiga, F.; Cervera, A.; et al. Comparative Assessment of Design Approaches and Wire Arc Additive Manufacturing Variants Using Life Cycle Assessment: Gas Metal Arc Welding, Gas Tungsten Arc Welding, and Plasma Arc Welding. *Results Eng.* **2026**, *29*, 109688. https://doi.org/10.1016/j.rineng.2026.109688.
133. Marudhappan, R.; Chandrasekhar, U. Additive Manufacturing in India Aerospace Manufacturing and MRO Industry: Challenges and Opportunities. *J. Inst. Eng. India Ser. C* **2022**, *103*, 1013–1030. https://doi.org/10.1007/s40032-022-00812-0.
134. Rodrigues, J.; Barter, S.; Das, R. Additive Manufacturing towards Sustainable Aerospace Structures. In *Sustainable Materials and Manufacturing Techniques in Aviation*; Springer: Cham, Switzerland, 2024; pp. 55–71.
135. Satya Hanush, S.; Manjaiah, M. Topology Optimization of Aerospace Part to Enhance the Performance by Additive Manufacturing Process. *Mater. Today Proc.* **2022**, *62*, 7373–7378. https://doi.org/10.1016/j.matpr.2022.02.074.
136. Lasagni, F.; Vilanova, J.; Periñán, A.; et al. Getting Confidence for Flying Additive Manufactured Hardware. *Prog. Addit. Manuf.* **2016**, *1*, 129–139. https://doi.org/10.1007/s40964-016-0014-7.