American Journal of Engineering and Applied Sciences

Review

Additive Manufacturing in the Aerospace Industry

Lidong Wang, Reed Mosher and Patti Duett

Institute for Systems Engineering Research, Mississippi State University, Vicksburg, Mississippi, USA

Article history
Received: 28-03-2024
Revised: 29-04-2024
Accepted: 10-05-2024

Corresponding Author:
Lidong Wang
Institute for Systems Engineering Research,
Mississippi State University,
Vicksburg, Mississippi, USA
Email: lidong@iser.msstate.edu

Abstract: The main advantages of Additive Manufacturing (AM) of metals in the aerospace industry are part consolidation; the reduction of lead time, the construction of complicated structures easily with a great Strength-to-Weight (S:W) ratio; production of parts on-demand with reduced inventory, uncertainty and the costs of supply chains. Ti6Al4V and nickel-based alloys are commonly used AM materials for aerospace parts. Ground-based AM for aerospace has achieved great advances. AM has the potential to develop parts for general aviation, aircraft, missiles and less massive satellite systems. This study introduces AM advantages, the technologies of AM, the materials and applications of AM and research progress in the aerospace industry; deals with the state-of-the-art of AM and its trends for aerospace; and highlights its challenges and future research.

Keywords: Additive Manufacturing (AM), Aerospace, Artificial Intelligence (AI), Direct Energy Deposition (DED), Powder Bed Fusion (PBF), Defect, Residual Stress, Supply Chain

Introduction

AM methods have been employed in aerospace applications and DED and Laser PBF (L-PBF) are popular. DED has been utilized in parts with big build volumes and can be employed to repair existing parts besides producing parts. L-PBF has been commonly employed in aerospace applications, enabling the construction of completely dense components with complicated geometries and small-to-medium build volumes. The applications of AM in the aerospace industry include valves, turbomachinery, propellant tanks, heat exchangers, satellite components, liquid-fuel rocket engines and the sustainment of legacy systems (Blakey-Milner *et al*., 2021). The metal-based AM methods (e.g., PBF and DED) with improved build quality and rate are now feasible to be used in aeronautical applications (Wang *et al*., 2023).

Wire Arc AM (WAAM) is a DED technology appropriate for producing big metal components because of its lower manufacturing costs and higher deposition rate. It has become a prevalent alternative to conventional production processes for materials (e.g., titanium alloys utilized in aerospace) (Li *et al*., 2022). Experiments and investigation on the friction-stir powder AM for Al 6061 powder (aerospace-grade aluminum alloy) and how to find its optimal variables/parameters based on the grey relational analysis were introduced (Chaudhary *et al*., 2022).

Aerospace components, for example, door handles, light housings to power wheels full interior dashboard designs, etc., can be fabricated employing AM (Mohanavel *et al*., 2021). Additional aerospace components include flap lever, rocket engine parts, satellite antenna, turbogenerator casing, RF feed antenna, antenna integrated helix feed and rocket brackets (Balaji *et al*., 2022).

The “buy-to-fly ratio”, also called the BTF ratio, is a weight ratio of a raw material and a component. It is a created parameter or concept in AM applications for the aerospace industry (Debnath *et al*., 2022). Maintenance, Repair and Overhaul (MRO) are crucial for the safety of aircraft and they are thus controlled seriously by national/aeronautical agencies such as the Federal Aviation Administration (FAA) in the US (Ceruti *et al*., 2019).

AM Advantages

AM has been used in the aerospace sector because of the easy construction of complicated structures with a great S: W ratio (Madhavadas *et al*., 2022). The BTF ratio of AM is less compared with traditional manufacturing methods such as machining (subtractive manufacturing). The low BTF ratio and the capability to construct complicated structures have made AM especially attractive in the aerospace industry. Another primary attraction point for AM is the non-existence of cost in tooling (Pasang *et al*., 2023).

The aerospace industry possesses the geometric freedom of AM that allows for making lightweight and high-performance parts. Many parts fabricated using AM have been incorporated into aerospace vehicles and engines (Khorasani *et al*., 2022). AM reduces waste compared with conventional technologies of subtractive manufacturing, which is especially important in the aerospace sector because very expensive and hard-to-manufacture materials (e.g., titanium alloys, nickel-based superalloys, ultra-high temperature ceramics, etc.,) are often utilized in aerospace (Kozhay *et al*., 2022). There are benefits for metal AM applications in aerospace, including novel materials and unique design, multiple components consolidation, reduction in the mass of parts due to lightweight and efficient designs and decrease in the lead-time as well as costs (Blakey-Milner *et al*., 2021).

In aeronautics, AM leads to the following specific benefits: (1) Enhanced efficiency and reduced weight through topological optimization; (2) Decrease in the BTF ratio, reducing the waste of materials and contributing to lower costs in manufacturing; and (3) Reduced costs related to downtime due to the optimal operations of MRO (Montanari *et al*., 2023). Valued spare components/parts with big volumes are required in aircraft sectors because of unpredictable/uncertain demands. AM can make the supply chain regarding aviation spare components/parts more efficient, more effective and simpler. The supply chains of aerospace sectors need to be more efficient and agile through using AM (Debnath *et al*., 2022).

AM has the potential to enable on-demand manufacturing, flexibility of design, rapid prototyping, reduction in tooling cost, the mitigation of the dangerous effects of demand volatility and a decrease in excess inventory (therefore dropping the costs in inventory) (Alogla *et al*., 2023). AM can make supply chains simpler, more elastic, more efficient and less risky by putting the production process close to the assembly, utilization and MRO locations. AM helps change the management of aerospace projects by eliminating fabrication and assembling limits, optimizing the design of products and reducing the lead time for aircraft development, production and MRO (Vieira and Romero-Torres., 2016). Table 1 (Nyamekye *et al*., 2023) shows the abilities, benefits and outcomes of the AM of Ti.

Table 1: The AM of Ti

AM abilities	Benefits	Outcomes
Optimized designs	Light weighting, integrated parts, customization	Improved functionality
Near-net shape designs (due to the above ability)	Reduced raw material, space utilization	Reduced cost and embodied energy, compact design
Process without tools and fixtures	Swift and flexible manufacturing with freedom	Efficient manufacturing and process
Localized manufacturing	On-demand manufacturing	Reduced time to market

Technologies of AM

Technologies of AM can be classified. The technologies and related materials, power sources, strengths and downsides are shown in Table 2 (Gao *et al*., 2015). The standard definitions of some technologies according to ASTM (2012) are:

- DED: Focused thermal energy is utilized to fuse materials when they are deposited
- Sheet lamination: The sheets of materials are bonded to produce an item
- Binder jetting: A liquid bonding agent is deposited selectively to bond materials in powder
- Material jetting: The droplets of the build material are deposited selectively
- Vat photopolymer: Liquid photopolymer in a vat is cured selectively by light-activated polymerization
- Material extrusion: The material is dispensed selectively through an orifice or nozzle
- PBF: Thermal energy fuses the zones of a powder bed selectively

Two major types of additive layer manufacturing technologies employed in the aerospace sector are DED and PBF (Kozhay *et al*., 2022). DED is highlighted especially for high-value structural components in the aerospace industry (Pasang *et al*., 2023). An accurate and informative scale model can be developed for material jetting and Stereolithography (SLA). The model can be employed in the aerospace sector for the communication and testing of design (Mohanavel *et al*., 2021).

Material Extrusion AM (MEAM) enables the production of panels with complicated geometries for the aerospace industry in one production step. This helps improve the AM of multi-functional structures for the aerospace industry. MEAM is Fused Filament Fabrication (FFF) (Pierre *et al*., 2023). FFF is a technology for fabricating thermoplastic products through heated extrusion and the layer-by-layer deposition of materials. Multi-material AM of high temperature using FFF for lightweight applications in the aerospace industry was presented (Vakharia *et al*., 2023).

In the EBM technology, powder is gathered in a thin layer before they are pre-heated and melted. LOM is a fast technology with low costs (Mohanavel *et al*., 2021). SLM builds a 3D structure through melting material layers in powder successively. It has gained popularity in aerospace (Chaudhry and Soulaïmani, 2022). Metal AM can be classified as DED, PBF, sheet lamination, material extrusion, material jetting and binder jetting. PBF and DED are the two major technologies among the metal AM technologies (Mu *et al*., 2023). Metal AM technologies have been utilized in the aerospace industry (Guo *et al*., 2022). Among the technologies of metal AM, Direct Metal Deposition (DMD), FDM, SLM and EBM are often used. FDM is a filament-based technology while the others are powder-based as shown in Table 3 (Yakout *et al*., 2017).

Table 2: The classification of AM

Categories	Technologies	Materials	Power Sources	Strengths/Downsides
DED	Electron beam welding, laser engineered net shaping (LENS)	Molten metal powder	Laser beam	Repairment for damaged components, printing of functionally-graded materials; post-processing (machining) required
Sheet lamination	Laminated object manufacturing (LOM)	Metallic sheets, plastic films, ceramic tapes	Laser beam	Good surface finish; low cost of materials, machines, processes; decubing issues
Binder jetting	Indirect inkjet printing	Metal powder, ceramic powder, polymer powder (plaster, resin)	Thermal energy	Wide material selection, full-color object printing; infiltration required in post-processing, many porosities in products
Material jetting	Inkjet printing/Polyjet	Photopolymer, wax	Photocuring/ Thermal energy	Printing of multi-materials, good surface finish; material with inadequate strength
Vat photopoly-merization	SLA	Photopolymer, ceramics (alumina, Zirconia, PZT)	Ultraviolet laser	Good resolution of parts; speedy building; costly materials & supplies, overcuring, scanned line shape
Metal extrusion	Fused deposition modeling (FDM) / Contour crafting	Thermoplastics, ceramic slurries, metal pastes	Thermal energy	Multi-material printing, inexpensive extrusion machines; poor surface finish, limited part resolution
PBF	Selective laser sintering (SLS)	Polyamides/ Polymer	Laser beam with high power	Good accuracy, completely dense products, good stiffness & strength; powder recycling & handling, supporting & anchoring structures
	Direct metal laser sintering (DMLS)	Stainless steel in atomized metal powder, cobalt chromium, Titanium Ti6Al-4V, ceramic powder	Laser beam with high power	
	Selective laser melting (SLM)		Electron beam	
	Electron beam melting (EBM)		Electron beam	

Table 3: The classifications of AM for metals

Shapes of Materials	Feeding Approaches	AM Methods	Cladding or Welding if Applicable	Specific Techniques if Applicable
Filament	Wire fed	FDM		
Powder	Powder bed	SLM, EBM		
	Powder fed (spray)	DMD	3D welding	Shaped metal deposition
			3D cladding	Laser metal deposition Laser consolidation LENS Plasma deposition manufacturing

Laser DED (L-DED) AM technology employs a focused laser beam to melt metallic wires or powders while depositing them (layer by layer) to construct a favorite geometry. L-DED has attracted substantial attention in the industries of aerospace, defense, etc. L-DED is appropriate for fabricating big metal parts/items with greater productivity and lower costs compared with other metal AM technologies, for example, L-PBF and material extrusion (Chen *et al*., 2023).

PBF has been powerful in the aerospace sector because of good precision and the ability to construct complicated geometry (Alogla *et al*., 2023). It is vital to produce lightweight metal parts in the aerospace sector because reduced weight reduces emissions and oil consumption. The thermal behaviors of L-PBF involve multi-physics phenomena, for example, thermal gradients, heat absorption, etc. The complicated phenomena are sensitive to laser power, beam shape and scan speed. PBF has the best reproducibility and dimensional accuracy among metal AM technologies (Pratap *et al*., 2023).

WAAM is a technique of DED. It has a high BTF ratio and enables the production of parts with full density and reduced porosity. It has been employed to fabricate big metallic parts in the aerospace industry (Mu *et al*., 2023). Powder-Bed AM (PB-AM) is used in aerospace. PB-AM unifies a few powder-based AM technologies: SLS/SLM, EBM and binder jetting (Katz-Demyanetz *et al*., 2019). DMLS and EBM are two common AM methods for printing metals. DMLS has been employed in the industries of aviation and aerospace to produce parts by melting the layers of thin metal powder (e.g., stainless steel, aluminum, titanium) (Prathyusha and Babu, 2022). Hybrid AM uses a secondary process (such as machining) for better surface quality of parts (Khorasani *et al*., 2022).

Materials and Applications of AM

Materials for AM in the aerospace sector include titanium alloys, aluminum alloys, cobalt alloys, copper alloys, refractory alloys, nickel and iron-based superalloys, stainless steel, etc. Most of them are utilized in the form of pre-alloyed powder, regularly made by gas atomization, or in the form of wire depending upon the specific process (Blakey-Milner *et al*., 2021). The most popular materials for AM applications in the aerospace sector are titanium and nickel base alloys because of their outstanding performance at high temperatures. Ti6Al4V alloy has a low thermal coefficient, low density, high strength, high fracture toughness, etc. Therefore, it is commonly utilized in aerospace. Many turbine blades are manufactured using titanium alloy for commercial aircraft (Debnath *et al*., 2022).

Inconel alloys (e.g., Inconel 625 and Inconel 71) and titanium alloys have been extensively utilized for aerospace. Inconel 718 is specifically utilized to produce gas turbines and other high-temperature structural parts (Balaji *et al*., 2022). Titanium is costly, but it can be utilized as AM material without a considerable reduction of waste (Mohanavel *et al*., 2021). Ti6Al4V is one of the most popular titanium alloys in the aerospace sector. The most recommended Ni-based superalloys for aerospace are Inconel 718 and Inconel 625; both are Ni-Cr-based alloys. Inconel 718 has good strength (tensile, rupture, creep and fatigue), corrosion resistance and high working temperature. Inconel 625 has good corrosion resistance, high strength and outstanding manufacturability (including joining) (Katz-Demyanetz *et al*., 2019).

Various materials have been utilized in spacecraft, including stainless steel, plastics, glass, aluminum alloys, Inconel alloys, carbon composites, ceramic matrix composites, etc., (Sacco and Moon, 2019). Carbon fiber is a significant material utilized for aerospace due to its smooth finish and high S:W. FDM is the AM technology for carbon fiber (Madhavadas *et al*., 2022). Applications of AM parts include brackets and structural items, engine components, turbine blades, etc. One of the metal AM applications for aerospace is the antenna (lightweight, made from aluminum) from Robert Hofmann company for communication satellites. This part filters high-frequency radio waves (Khorasani *et al*., 2022). AM products in the aerospace industry include 3D printed communication satellites, Radio Frequency (RF) filters, in communication satellites, satellite brackets (printed with titanium, optimized by topological optimization), rocket engines for spaceships, combustion chambers, 3D printed nozzle (injector heads) (Pant *et al*., 2021). Additional details of AM in the aerospace sector are as follows (Blakey-Milner *et al*., 2021):

- Structures and brackets: Brackets, structures and frames are general application cases of AM and topology optimization in the aerospace sector, for example, aviation structures and brackets, lattice structures and spacecraft structures
- Static and dynamic engine components (e.g., turbomachinery components)
- Thermal devices (e.g., heat exchangers)
- Liquid fuel rocket components (e.g., injector components)

The aerospace sector has been driven strongly by the requirements of large original equipment manufacturers; therefore, the manufacturers of AM equipment have been upgrading their processes as well as systems constantly to fit or follow the requirements. Table 4 shows some aerospace parts, their materials used, AM processes and companies where they are produced (Tepylo *et al*., 2019).

Table 4: Some aerospace parts produced by AM

Parts	AM processes	Materials used	Companies
Rocket engine combustion chamber	SLM	Copper	NASA
Thrusters on the SuperDraco rocket engines	DMLS	Nickel-based superalloys	SpaceX
Industrial gas turbine blades	SLM	Nickel-based superalloys	Siemens
Ducts on the F/A-18E/F	SLS	Titanium-based	Boeing
Aircraft engine brackets	DMP (direct metal printing)	Titanium-based	3D systems
Front-bearing housing on the XWB-97	EBM	Titanium-based	Rolls Royce
Bleed air leak detectors on the F-35	EBM	Ti6Al4V	Lockheed Martin
F-15 pylon ribs	DED	Ti6Al4V	Multiple companies funded by the DOD in the USA
Nacelle hinge brackets on the A320	DMLS	Ti6Al4V	Airbus
Brackets on the A380	SLM	Ti6Al4V	Laser Zentrum Nord GmbH (representing Airbus)
The rear frame on the Eurofighter typhoon	WAAM	Ti6Al4V	BAE systems
Turbine combustion chamber	DMLS	Inconel 718	EOS
LEAP engine fuel injector nozzles	SLS	Co-Cr	GE and Morris technologies

Multi-material 3D printing has moved to the defense industry. Printing various materials together to fabricate sustainable and cost-effective components has been presented. For example, nickel-based materials are added only in the zones required for wear or corrosion resistance. However, it is still a challenge to join incompatible metals, for example, titanium and aluminum (Machi, 2017). The use of AM has been decided to manufacture rocket engine parts according to NASA' strategy. Unmanned Aerial Vehicles (UAVs) (also known as drones) are very important in the aerospace industry. A complete drone or only a part of the components can be produced using AM (Madhavadas *et al*., 2022).

Research Progress and Trends in AM

Aerospace structures (e.g., aircraft wings) are designed for requirements of strength, stiffness and stability under certain conditions of loading. The AM of continuous carbon fiber composite provides possibilities for the cost-effective and automatic manufacturing of highly loaded structures. Compliant or so-called morphing mechanisms (exploiting the elastic properties of materials to obtain shape changes) show the potential to enhance the flight performance of aerospace structures. The AM of composites combined with utilizing morphing mechanisms has the potential to lower production costs while enhancing the flight performance of the structures (Fasel *et al*., 2020).

Additive (layer) manufacturing of vibration dampers for the aerospace sector was introduced and the spiderweb cellular structure constructed via the AM for aerospace was presented. A lattice structure within the spiderweb absorbs maximal vibration during the high spin of a brushless motor (Bari and Bollenbach, 2022). A design method was developed for the cellular structure to be fabricated using AM. The design method employed the adaptive meshing technique of finite element analysis to design the topology of the cellular structure and then the cross-sectional area of each structure was optimized for the minimal weight subject to compatibility, stress and buckling constraints. The method was demonstrated for an aircraft bracket design (Opgenoord and Willcox, 2019).

An aerospace bracket was redesigned employing Computer-Aided Design (CAD) with topology optimization and manufactured with Ti6Al4V alloy using SLM. SLM is one of the AM methods and a popular deposition technology (layer by layer) for the manufacturing of metallic components. Optimal printing parameters were simulated to minimize the production time with the least residual stress (because of the high thermal gradient in the AM process) (Satya Hanush and Manjaiah, 2022). AM integrated with the topology optimization for the design and manufacturing of lightweight aerospace structures was presented (Prathyusha and Babu, 2022). Topology optimization and the utilization of the lattice structure have the potential to fulfill mass reduction for aerospace applications. The development of new alloys for AM in aerospace applications has been one of the important areas of AM (Blakey-Milner *et al*., 2021).

Generative Design (GD) helps increase the potential of AM. It is based on parametric tools of CAD that enable multiple optimized outputs for a designer to choose. The advantages of synergizing GD with AM in the early development stage of products have been demonstrated (Pilagatti *et al*., 2023). AM defects can be categorized into four types: (1) Pores, (2) Lack of fusion, (3) Irregular surfaces or subsurface defects and (4) Microstructural discontinuities. A formulation of the defect-driven topology optimization for the fatigue design was generalized (Boursier Niutta *et al*., 2022).

Cracks and keyhole pores are damaging defects in alloys produced by L-DED. An in-situ pipeline with acoustic signal-denoising, feature-extraction and sound classification was developed that incorporated convolutional neural networks for the online detection of defects in L-DED. Microscope images were employed to locate the cracks and keyhole pores in a product (Chen *et al*., 2023).

SLM is a metal-based AM technology. Machine Learning (ML) and numerical simulation (based on the finite element model) were combined to study the SLM process. Laser speed, hatch space, layer thickness, Young's modulus and Poisson ratio were considered as input parameters, while output parameters were predicted normal strains in the product. Optimal parameters were found for the SLM process (Chaudhry and Soulaïmani, 2022).

A data model of metal AM products was developed. There are five kinds of data in the model: Parameters of design, parameters of process, signatures of process, parameters of post-processing and the quality of the product. The model is shown in Table 5 (Liu *et al*., 2022).

Table 5: A data model of metal AM products

Data categories	Data sub-categories
Design parameters	Design features
	Build preparation
Process parameters	Parameters of laser/beam and scanning
	Properties of powder materials
	Parameters of powder bed and recoating
	Parameters of the build environment
Process signatures	Melt pool
	By-products
	Single track
	Single layer
	Powder bed
Post-processing parameters	Powder removing
	Heat-treatment
	Post-machining
	Non-standard processes
Product quality	Geometry and dimension
	Quality of the surface
	Physical and mechanical properties

4D printing refers to a printing process with three spatial dimensions, plus material composition as the fourth dimension. Such space and material flexibility in a production process will have valuable applications in the aerospace sector (Katz-Demyanetz *et al*., 2019). The trend of earth or ground-based AM is that metallic 3D printing is employed in big launchers and spacecraft while polymers are utilized in relatively small spacecraft like CubeSats. Substantial efforts are ongoing to combine metallic 3D printing (specifically PBF and laser-based technologies) with the fabrication of launchers for the reduction of complexity and mass (Sacco and Moon, 2019). The main development trends of AM in aerospace are summarized as follows (Katz-Demyanetz *et al*., 2019):

- Expanding the range of precursor materials, i.e., metallic alloys (high entropy alloys and bulk metallic glasses), lightweight structures and compositionally and functionally graded materials, metallic and ceramic matrix composites, as well as composite-like materials
- Increasing the application trials of different PB-AM technologies for aerospace, focusing on AM of crucial aerospace parts
- The regulations standardization of AM for aerospace

AM Challenges and Future Research

There are challenges for AM in the aerospace sector. All the challenges can be future research. Table 6 lists the challenges according to the used materials (Frazier, 2014; Zhan and Li, 2021). Other challenges in the aerospace area lie in (1) Problems in measuring porosity and residual stresses accurately; (2) No suitable certifications or standards for a product manufactured using AM; (3) Size constraints in some AM processes; (4) Not easy to analyze surface roughness when using certain AM technologies; (5) Limitations in build consistency, resolution and build quality for AM technologies; (6) Impossible to make big structures utilizing some AM parts; (7) A challenge when employing topological optimization for AM; (8) Not easy to qualify materials used for AM because of inconsistencies, thus expensive to complete a good quality testing; (9) A problem in having the perfect microstructure and composition for a component although ceramics can be used in AM with a high S:W; and (10) With disadvantages (e.g., residual stresses, poor microstructure control and less choices of materials) when metallic glasses used (Madhavadas *et al*., 2022).

Despite many benefits, AM has inherent issues in aerospace applications, including imperfection in materials, size limitation, lack of process repeatability and predictability, uncertainty in long-term performance, high infrastructure and running costs etc., (Tepylo *et al*., 2019).

Table 6: Challenges of AM with various materials in the aerospace industry

Materials	Challenges
Polymers and composites	Few choices Weak mechanical properties
Metal and metal alloys	Few choices in alloys Not ideal surface finish Inadequate dimensional accuracy Post-processing needed
Ceramics	Few choices Not ideal surface finish Inadequate dimensional accuracy Need for post-processing

AM parts can have defects/stress risers, for example, powder particles stuck on surfaces, partially melted powder, voids from imperfection or gas pores and lack of adhesion or pre-existing cracks/fractures formed between subsequent printing layers. Hot Isostatic Pressing (HIP) and heat treatment help decrease residual stress and voids. HIP enables material joining improvement, porosity elimination, powder compaction and fatigue damage refinement (Yakout *et al*., 2017).

Composite structures are widely applied in aerospace because of their high strength/stiffness. However, defects in materials can evolve into local cracks/fractures easily under extreme or cyclic loading. Failures of composites often result from very few cracks and defects formed during the AM process. It is significant to monitor the AM process, detect defects in real time and eliminate the defects in composite structures (Lu *et al*., 2023).

AM drawbacks lie in cracks, porosity, surface roughness, material anisotropy, unique microstructures and residual stress (inducing crack extension and structural deformation). Post-processing is sometimes required with thermomechanical treatment, surface polishing, or final machining. Major defects in Al parts produced using AM include anisotropy, residual stresses, poor surface quality (great surface roughness), porosity and hot cracking. One drawback of Al alloys is oxidation (causing porosity in the product). In addition, parts made of Al alloys using AM often exhibit porosity that is associated with both process parameters and material composition, which is shown in Table 7 (Montanari *et al*., 2023).

The aerospace sector substantially relies on available spare components/parts to sustain the reliability and safety of aircraft. Volatility (variability or unpredictability of customer demands) can happen because of incidents or accidents, maintenance requirements, changes in aircraft design and shifts in economic conditions and customer demands. Thus, managing inventory and supply chain risk effectively is a challenging task because of unpredictable demands, parts with a high value and long lead time related to production and delivery (Alogla *et al*., 2023). The influences of AM on the bullwhip effect in the spare components/parts of the aerospace sector can be an important future research topic (Debnath *et al*., 2022).

Table 7: The reasons for porosity in Al alloy parts produced using AM

Reasons	Details
Process parameters	Laser power
	Scanning strategy
	Scanning speed
	Building direction
	Thickness of the powder layer
	Preheating temperature
	Atmosphere of building room
Material composition	Impurities
	Al wettability
	Low absorption of laser energy
	Evaporation of alloying elements

The aerospace sector runs many kinds of business, such as general aviation, military or commercial aircraft, satellites, missiles, space launches and in-space systems. Manufacturing in the aerospace sector depends on many interactional, technological and economic goals. The goals and related issues can be described as follows (Blakey-Milner *et al*., 2021):

- Delivery of a safety-critical component in a small manufacturing volume with a relatively inflexible schedule of delivery
- Lightweighting is related to the technological as well as economic situations of aerospace structures
- A critical issue of metal AM products in the aerospace sector is the problem of certifications
- An aerospace structure is usually complicated with a low volume; therefore, issues related to sustainment are important. Sustainment involves repair or remanufacture, part availability for aging aircraft, as well as re-certification of existing aircraft for alternative use

Discussion

AM applications in aerospace lie in prototyping, tooling, production, etc. AM will continue transforming the industry. Some AM materials can be recycled and reused in the aerospace industry, which demonstrates the benefits of AM in preserving natural resources and maintaining the sustainability of materials. Design for AM offers more opportunities due to design freedom compared with traditional manufacturing, which enhances innovations and drives the aerospace industry toward unprecedented heights of creativity. AM can fulfill the on-demand fabrication of components, reduce inventory uncertainty, streamline assembly processes and reshape the supply chain in the aerospace sector. It is valuable to research the influences of AM on the bullwhip effect in the spare components/parts of the aerospace sector.

Aerospace products need to adhere to rigorous certifications and standards to ensure safety. However, the development of rigorous procedures and standards for certifying the AM processes and materials of various AM methods or technologies is still a challenge. Furthermore, AM challenges in this study were summarized based on the literature; there are possibly more challenges in the actual production processes of various AM techniques. There is an increasing trend towards manufacturing larger or more complex parts using AM. Advanced robotics and automation help to improve the efficiency and productivity of large-scale AM. Artificial Intelligence (AI) can be used to optimize the geometry of AM parts and AM process parameters (Pratap *et al*., 2022).

Conclusion

Advantages of AM for an aerospace lie in (1) The easy construction of complicated structures with a great S:W ratio; (2) The consolidation of multiple components and mass reduction of products; (3) A decrease in the BTF ratio; (4) The optimization of MRO to reduce costs associated with downtime. AM also enables the on-demand production of parts and helps reduce transportation, inventory, uncertainty and overall supply chain costs. DED and PBF processes are commonly used AM for aerospace. The most common materials of aerospace components made using AM are nickel-based alloys (used for aero-engines) and Ti6Al4V (used for aerostructures and aero-engines). Major challenges of AM for aerospace include making large structures using some AM parts, joining incompatible metals, poor microstructure control (when metallic glasses are used), possible cracks, porosity, part's intrinsic anisotropy, surface roughness, residual stress due to the high thermal gradient and a lack of resilience of the spare part logistics. All the challenges discussed in this study can be future research.

Acknowledgment

The support from Mississippi State University is appreciated.

Funding Information

The authors have not received any financial support or funding to report.

Author's Contributions

All authors equally contributed to this study.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and that no ethical issues are involved.

References

Alogla, A. A., Alzahrani, A., & Alghamdi, A. (2023). The Role of Additive Manufacturing in Reducing Demand Volatility in Aerospace: A Conceptual Framework. *Aerospace*, *10*(4), 381. https://doi.org/10.3390/aerospace10040381

ASTM. (2012). Committee F42 on Additive Manufacturing Technologies and Subcommittee F42. 91 on Terminology. Standard terminology for additive manufacturing technologies. *ASTM International*. https://doi.org/10.1520/f2792-09

Balaji, D., Ranga, J., Bhuvaneswari, V., Arulmurugan, B., Rajeshkumar, L., Manimohan, M. P., Devi, G. R., Ramya, G., & Masi, C. (2022). Additive Manufacturing for Aerospace from Inception to Certification. *Journal of Nanomaterials*, *2022*, 7226852. https://doi.org/10.1155/2022/7226852

Bari, K., & Bollenbach, L. (2022). Spiderweb Cellular Structures Manufactured via Additive Layer Manufacturing for Aerospace Application. *Journal of Composites Science*, *6*(5), 133. https://doi.org/10.3390/jcs6050133

Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F., & Du Plessis, A. (2021). Metal Additive Manufacturing in Aerospace: A Review. *Materials and Design*, *209*, 110008. https://doi.org/10.1016/j.matdes.2021.110008

Boursier Niutta, C., Tridello, A., Barletta, G., Gallo, N., Baroni, A., Berto, F., & Paolino, D. S. (2022). Defect-Driven Topology Optimization for Fatigue Design of Additive Manufacturing structures: Application on a real Industrial Aerospace Component. *Engineering Failure Analysis*, *142*, 106737. https://doi.org/10.1016/j.engfailanal.2022.106737

Ceruti, A., Marzocca, P., Liverani, A., & Bil, C. (2019). Maintenance in Aeronautics in an Industry 4.0 Context: The Role of Augmented Reality and Additive Manufacturing. *Journal of Computational Design and Engineering*, *6*(4), 516-526. https://doi.org/10.1016/j.jcde.2019.02.001

Chaudhary, B., Jain, N. K., & Murugesan, J. (2022). Experimental Investigation and Parametric Optimization of Friction Stir Powder Additive Manufacturing Process for Aerospace-Grade Al Alloy. *The International Journal of Advanced Manufacturing Technology*, *123*, 603-625. https://doi.org/10.1007/s00170-022-10211-5

Chaudhry, S., & Soulaïmani, A. (2022). A Comparative Study of Machine Learning Methods for Computational Modeling of the Selective Laser Melting Additive Manufacturing Process. *Applied Sciences*, *12*(5), 2324. https://doi.org/10.3390/app12052324

Chen, L., Yao, X., Tan, C., He, W., Su, J., Weng, F., Chew, Y., Ng, N. P. H., & Moon, S. K. (2023). In-Situ Crack and Keyhole Pore Detection in Laser Directed Energy Deposition Through Acoustic Signal and Deep Learning. *Additive Manufacturing*, *69*, 103547. https://doi.org/10.1016/j.addma.2023.103547

Debnath, B., Shakur, M. S., Tanjum, F., Rahman, M. A., & Adnan, Z. H. (2022). Impact of Additive Manufacturing on the Supply Chain of Aerospace Spare Parts Industry-A Review. *Logistics*, *6*(2), 28. https://doi.org/10.3390/logistics6020028

Fasel, U., Keidel, D., Baumann, L., Cavolina, G., Eichenhofer, M., & Ermanni, P. (2020). Composite Additive Manufacturing of Morphing Aerospace Structures. *Manufacturing Letters*, *23*, 85-88. https://doi.org/10.1016/j.mfglet.2019.12.004

Frazier, W. E. (2014). Metal Additive Manufacturing: A Review. *Journal of Materials Engineering and Performance*, *23*, 1917-1928. https://doi.org/10.1007/s11665-014-0958-z

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S., & Zavattieri, P. D. (2015). The Status, Challenges and Future of Additive Manufacturing in Engineering. *Computer-Aided Design*, *69*, 65-89. https://doi.org/10.1016/j.cad.2015.04.001

Guo, S., Agarwal, M., Cooper, C., Tian, Q., Gao, R. X., Guo Grace, W., & Guo, Y. B. (2022). Machine Learning for Metal Additive Manufacturing: Towards a Physics-Informed Data-Driven Paradigm. *Journal of Manufacturing Systems*, *62*, 145-163. https://doi.org/10.1016/j.jmsy.2021.11.003

Katz-Demyanetz, A., Popov, V. V., Kovalevsky, A., Safranchik, D., & Koptyug, A. (2019). Powder-Bed Additive Manufacturing for Aerospace Application: Techniques, Metallic and Metal/Ceramic Composite Materials and Trends. *Manufacturing Review*, *6*, 5. https://doi.org/10.1051/mfreview/2019003

Khorasani, M., Ghasemi, A., Rolfe, B., & Gibson, I. (2022). Additive Manufacturing a Powerful Tool for the Aerospace Industry. *Rapid Prototyping Journal*, *28*(1), 87-100. https://doi.org/10.1108/RPJ-01-2021-0009

Kozhay, K., Turarbek, S., Ali, M. H., & Shehab, E. (2022). Challenges of Developing Digital Twin for Additive Layer Manufacturing in the Aerospace Industry. *IEEE Xplore*, 1-6. https://doi.org/10.1109/iceccme55909.2022.9987941

Liu, C., Le Roux, L., Körner, C., Tabaste, O., Lacan, F., & Bigot, S. (2022). Digital Twin-Enabled Collaborative Data Management for Metal Additive Manufacturing Systems. *Journal of Manufacturing Systems*, *62*, 857-874. https://doi.org/10.1016/j.jmsy.2020.05.010

Li, Y., Mu, H., Polden, J., Li, H., Wang, L., Xia, C., & Pan, Z. (2022). Towards Intelligent Monitoring System in Wire Arc Additive Manufacturing: A Surface Anomaly Detector on a Small Dataset. *The International Journal of Advanced Manufacturing Technology*, *120*(7), 5225-5242. https://doi.org/10.1007/s00170-022-09076-5

Lu, L., Hou, J., Yuan, S., Yao, X., Li, Y., & Zhu, J. (2023). Deep Learning-Assisted Real-Time Defect Detection and Closed-Loop Adjustment for Additive Manufacturing of Continuous Fiber-Reinforced Polymer Composites. *Robotics and Computer-Integrated Manufacturing*, *79*, 102431. https://doi.org/10.1016/j.rcim.2022.102431

Machi, V. (2017). Defense Industry Moves Toward Multi-Material 3D Printing. *National Defense*, *102*(768), 21-22. https://www.jstor.org/stable/27022002

Madhavadas, V., Srivastava, D., Chadha, U., Aravind Raj, S., Sultan, M. T. H., Shahar, F. S., & Shah, A. U. M. (2022). A Review on Metal Additive Manufacturing for Intricately Shaped Aerospace Components. *CIRP Journal of Manufacturing Science and Technology*, *39*, 18-36. https://doi.org/10.1016/j.cirpj.2022.07.005

Mohanavel, V., Ashraff Ali, K. S., Ranganathan, K., Allen Jeffrey, J., Ravikumar, M. M., & Rajkumar, S. (2021). The Roles and Applications of Additive Manufacturing in the Aerospace and Automobile Sector. *Materials Today: Proceedings*, *47*, 405-409. https://doi.org/10.1016/j.matpr.2021.04.596

Montanari, R., Palombi, A., Richetta, M., & Varone, A. (2023). Additive Manufacturing of Aluminum Alloys for Aeronautic Applications: Advantages and Problems. *Metals*, *13*(4), 716. https://doi.org/10.3390/met13040716

Mu, H., He, F., Yuan, L., Commins, P., Wang, H., & Pan, Z. (2023). Toward a Smart Wire Arc Additive Manufacturing System: A Review on Current Developments and a Framework of Digital Twin. *Journal of Manufacturing Systems*, *67*, 174-189. https://doi.org/10.1016/j.jmsy.2023.01.012

Nyamekye, P., Rahimpour Golroudbary, S., Piili, H., Luukka, P., & Kraslawski, A. (2023). Impact of Additive Manufacturing on Titanium Supply Chain: Case of Titanium Alloys in Automotive and Aerospace Industries. *Advances in Industrial and Manufacturing Engineering*, *6*, 100112. https://doi.org/10.1016/j.aime.2023.100112

Opgenoord, M. M. J., & Willcox, K. E. (2019). Design for Additive Manufacturing: Cellular Structures in Early-Stage Aerospace Design. *Structural and Multidisciplinary Optimization*, *60*, 411-428. https://doi.org/10.1007/s00158-019-02305-8

Pant, M., Pidge, P., Nagdeve, L., & Kumar, H. (2021). A Review of Additive Manufacturing in Aerospace Application. *Journal of Composite and Advanced Materials*, *31*(2), 109-115. https://doi.org/10.18280/rcma.310206

Pasang, T., Budiman, A. S., Wang, J. C., Jiang, C. P., Boyer, R., Williams, J., & Misiolek, W. Z. (2023). Additive Manufacturing of Titanium Alloys-Enabling Re-Manufacturing of Aerospace and Biomedical Components. *Microelectronic Engineering*, *270*, 111935. https://doi.org/10.1016/j.mee.2022.111935

Pierre, J., Iervolino, F., Farahani, R. D., Piccirelli, N., Lévesque, M., & Therriault, D. (2023). Material Extrusion Additive Manufacturing of Multifunctional Sandwich Panels with Load-Bearing and Acoustic Capabilities for Aerospace Applications. *Additive Manufacturing*, *61*, 103344. https://doi.org/10.1016/j.addma.2022.103344

Pilagatti, A. N., Atzeni, E., & Salmi, A. (2023). Exploiting the Generative Design Potential to Select the Best Conceptual Design of an Aerospace Component to be Produced by Additive Manufacturing. *The International Journal of Advanced Manufacturing Technology*, *126*(11), 5597-5612. https://doi.org/10.1007/s00170-023-11259-7

Pratap, A., Sardana, N., Utomo, S., Ayeelyan, J., Karthikeyan, P., & Hsiung, P.-A. (2022). A Synergic Approach of Deep Learning towards Digital Additive Manufacturing: A Review. *Algorithms*, *15*(12), 466. https://doi.org/10.3390/a15120466

Pratap, A., Sardana, N., Utomo, S., John, A., Karthikeyan, P., & Hsiung, P.-A. (2023). Analysis of Defect Associated with Powder Bed Fusion with Deep Learning and Explainable AI. *In 2023 15th International Conference on Knowledge and Smart Technology (KST)*, 1–6. https://doi.org/10.1109/kst57286.2023.10086905

Prathyusha, A., & Babu, G. R. (2022). 3D Printing Integration with Topology Optimization for Innovative Design and Fabrication of Light Weight Aerospace Structures. In 2022 International Conference on Recent Trends in Microelectronics, Automation, Computing and Communications Systems (ICMACC), 1–6. https://doi.org/10.1109/icmacc54824.2022.10093386

Sacco, E., & Moon, S. K. (2019). Additive Manufacturing for Space: Status and Promises. *The International Journal of Advanced Manufacturing Technology*, *105*, 4123-4146. https://doi.org/10.1007/s00170-019-03786-z

Satya Hanush, S., & Manjaiah, M. (2022). Topology Optimization of Aerospace Part to Enhance the Performance by Additive Manufacturing Process. *Materials Today: Proceedings*, *62*, 7373-7378. https://doi.org/10.1016/j.matpr.2022.02.074

Tepylo, N., Huang, X., & Patnaik, P. C. (2019). Laser-Based Additive Manufacturing Technologies for Aerospace Applications. *Advanced Engineering Materials*, *21*(11), 1900617. https://doi.org/10.1002/adem.201900617

Vakharia, V. S., Leonard, H., Singh, M., & Halbig, M. C. (2023). Multi-Material Additive Manufacturing of High Temperature Polyetherimide (PEI)-Based Polymer Systems for Lightweight Aerospace Applications. *Polymers*, *15*(3), 561. https://doi.org/10.3390/polym15030561

Vieira, D. R., & Romero-Torres, M. A. (2016). Is 3D Printing Transforming the Project Management Function in the Aerospace Industry?. *The Journal of Modern Project Management*, *4*(1), 187. https://doi.org/10.3963/JMPM.V4I1.187

Wang, C., Chandra, S., Huang, S., Tor, S. B., & Tan, X. (2023). Unraveling Process-Microstructure-Property Correlations in Powder-Bed Fusion Additive Manufacturing Through Information-Rich Surface Features with Deep Learning. *Journal of Materials Processing Technology*, *311*, 117804. https://doi.org/10.1016/j.jmatprotec.2022.117804

Yakout, M., Cadamuro, A., Elbestawi, M. A., & Veldhuis, S. C. (2017). The Selection of Process Parameters in Additive Manufacturing for Aerospace Alloys. *The International Journal of Advanced Manufacturing Technology*, *92*, 2081-2098. https://doi.org/10.1007/s00170-017-0280-7

Zhan, Z., & Li, H. (2021). A Novel Approach Based on the Elastoplastic Fatigue Damage and Machine Learning Models for Life Prediction of Aerospace Alloy Parts Fabricated by Additive Manufacturing. *International Journal of Fatigue*, *145*, 106089. https://doi.org/10.1016/j.ijfatigue.2020.106089

Appendix

Table A1: Acronyms

DED	Direct Energy Deposition
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
FAA	Federal Aviation Administration
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
GD	Generative Design
L-DED	Laser Direct Energy Deposition
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
MEAM	Material Extrusion Additive Manufacturing
ML	Machine Learning
MRO	Maintenance, Repair and Overhaul
PB-AM	Powder-Bed Additive Manufacturing
PBF	Powder Bed Fusion
RF	Radio Frequency
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
UAVs	Unmanned Aerial Vehicles
WAAM	Wire Arc Additive Manufacturing