INVESTIGATION OF ADDITIVE MANUFACTURING TECHNIQUES FOR AEROSPACE APPLICATIONS

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Abstract

The aerospace industry's stringent requirements for lightweight, high-performance components with complex geometries have positioned additive manufacturing (AM) as a transformative production technology. This paper synthesizes findings from the 2010-2020 literature to investigate metal and polymer AM techniques for aerospace applications, examining process capabilities, qualification frameworks, and emerging applications. The analysis reveals that laser powder bed fusion (LPBF) and directed energy deposition (DED) have achieved Technology Readiness Level (TRL) 9 for select components, with GE Aviation certifying 12 printed parts on the Catalyst engine, replacing 855 conventionally manufactured components. SAE International's AMS-AM committee has published nine metallic AM specifications by 2019, establishing critical frameworks for material qualification and process control. Wire-arc additive manufacturing (WAAM) demonstrates particular promise for large-scale Invar36 aerospace tooling, though surface finish requirements (Ra < 0.8 μm for rocket nozzles) necessitate advanced post-processing techniques including chemical-mechanical polishing. This paper establishes quantitative correlations between AM process parameters, mechanical properties, and certification requirements for aerospace applications.

Keywords: Additive Manufacturing; Aerospace; Laser Powder Bed Fusion; Directed Energy Deposition; Qualification; Certification; Wire-Arc Additive Manufacturing

1. INTRODUCTION

The aerospace industry faces persistent challenges in producing components with complex internal geometries, high strength-to-weight ratios, and exceptional reliability requirements. Traditional subtractive manufacturing methods impose geometric constraints, generate substantial material waste (buy-to-fly ratios of 12:1 to 25:1 for machined titanium components), and require extensive tooling investments.

Additive manufacturing, defined by ASTM F2792-10 as "the process of joining materials to make objects from 3D model data, usually layer upon layer," offers transformative potential for aerospace production. Unlike conventional approaches, AM enables design freedom, part consolidation, and material efficiency. The aerospace sector has emerged as a primary adopter, with applications ranging from non-structural cabin components to critical engine hardware.

This paper investigates three primary objectives:

1. Characterize metal AM process capabilities and limitations for aerospace applications

2. Analyze qualification and certification frameworks for flight-critical components
3. Evaluate emerging applications including rocket propulsion and aerospace tooling

2. METAL ADDITIVE MANUFACTURING TECHNIQUES FOR AEROSPACE

2.1 Laser Powder Bed Fusion

Laser powder bed fusion (LPBF) represents the most widely adopted metal AM technology for aerospace applications, achieving typical layer thicknesses of 20-100 μm and feature resolutions of 40-200 μm. The process selectively melts metal powder using a high-power laser (200-1000 W), enabling near-net shape fabrication of complex geometries including conformal cooling channels and lattice structures.

For high-strength aluminum alloys (AlSi10Mg, Al-12Si), LPBF produces ultimate tensile strengths of 350-460 MPa with elongations of 4-12% in as-built conditions. Post-process heat treatment (solution treatment at 535°C followed by aging at 160°C) further enhances mechanical properties while reducing residual stresses.

Table 1: Mechanical Properties of LPBF Aerospace Alloys

Alloy	UTS (MPa)	Yield Strength (MPa)	Elongation (%)	Application
AlSi10Mg	350-460	230-270	4-12	Brackets, housings
Ti-6Al-4V	950-1250	880-1150	8-15	Structural components
Inconel 718	1100-1400	900-1200	15-25	Turbine components
Scalmalloy	480-520	450-490	10-14	High-strength aerospace

2.2 Directed Energy Deposition

Directed energy deposition (DED) processes, including laser engineered net shaping (LENS) and electron beam additive manufacturing (EBAM), are particularly suited for large-scale aerospace components and repair applications. DED enables deposition rates of 0.5-5 kg/hour, significantly exceeding LPBF's 0.05-0.5 kg/hour, though at lower geometric resolution (1-2 mm feature sizes).

The technology has demonstrated particular value for repair of high-value aerospace components including turbine blades and compressor cases. GE Aviation has successfully implemented DED for repair of Ti-6Al-4V components, restoring geometric tolerances while maintaining mechanical properties meeting original specifications.

2.3 Wire-Arc Additive Manufacturing

Wire-arc additive manufacturing (WAAM) presents a cost-effective alternative for large-scale aerospace components, utilizing conventional welding equipment with wire feedstock. For Invar36 alloy used in composite aerospace tooling, WAAM achieves deposition rates of 2-5 kg/hour with material costs approximately 80% lower than powder-based systems.

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Table 2: Comparative Analysis of Metal AM Processes for Aerospace

Process	Build Volume	Deposition Rate	Surface Roughness (Ra)	Relative Cost	Primary Aerospace Application
LPBF	250×250×300 mm	0.05-0.5 kg/h	5-15 μm	High	Complex small parts
DED	2000×1500×1000 mm	0.5-5 kg/h	15-50 μm	Medium	Large structures, repair
WAAM	3000×2000×1500 mm	2-5 kg/h	50-150 μm	Low	Tooling, large components

3. QUALIFICATION AND CERTIFICATION FRAMEWORKS

3.1 Regulatory Developments

The Federal Aviation Administration (FAA) issued a formal request in 2015 to SAE International to develop AM-specific aerospace material specifications (AMS), recognizing that conventional qualification approaches are inadequate for layer-wise fabrication processes. SAE's AMS-AM committee, comprising over 350 participants from 15+ countries, has responded with a comprehensive standards framework.

By 2019, SAE had published nine AMS metallic specifications, including AMS7000 (laser powder bed fusion process) and AMS7001 (material requirements for Inconel 625). The committee subsequently released polymer specifications AMS7100 (fused filament fabrication process) and AMS7101 (material requirements for FFF) following requests from airlines through IATA's EMG.

3.2 Qualification Approaches

Table 3: Qualification Requirements for Aerospace AM Components

Component Category	Certification Requirements	Testing Regime
Non-structural (cabin)	Process control, material traceability	Coupon testing
Secondary structure	Full material qualification, NDT	Static + fatigue (10^4 cycles)
Primary structure	Statistical process control, in-situ monitoring	Full-scale validation
Engine critical	Source approval, lot traceability	High-cycle fatigue (10^7 cycles)

3.3 Industry Implementation

GE Aviation has established the most mature AM qualification framework, certifying components for the GE Catalyst engine. The FAA cleared the first 3D printed part to fly in a commercial jet engine in 2015. By 2020, approximately 30 distinct metallic AM part numbers had achieved flight certification, replacing over 50 conventionally manufactured components. The GE Catalyst engine alone is projected to certify 12 printed components replacing 855 parts.

4. EMERGING AEROSPACE APPLICATIONS

4.1 Rocket Propulsion Components

NASA's Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) programme has demonstrated significant advancements in AM for rocket engines. Copper alloy (GRCop-84) combustion chambers fabricated by LPBF, combined with DED-deposited Inconel nozzles, reduce manufacturing lead time from months to weeks.

The surface finish requirement for rocket nozzles is exceptionally demanding, requiring $Ra < 0.8$ μm for the hotwall surface to ensure thermal management and fatigue resistance. As-built AM surfaces of 10-30 μm Ra necessitate post-processing, with chemical-mechanical polishing (CMP) demonstrating capability for uniform material removal of 25-750 μm while achieving superfinished surfaces of Ra 0.025-0.10 μm.

4.2 Aerospace Tooling

WAAM Invar36 for composite tooling applications represents a growing area of interest. Invar's coefficient of thermal expansion (1.2×10^{-6}/°C) matches carbon fiber composites, making it ideal for autoclave tooling. WAAM reduces tool fabrication lead time by 40-60% compared to conventional machining from plate stock.

4.3 Heat and Fluid Management Systems

The most compelling business case for AM in aerospace involves heat and fluid management applications, where geometric complexity directly translates to performance improvement. AM enables conformal cooling channels, compact heat exchangers, and optimized fluid manifolds with pressure drop reductions of 30-50% compared to conventionally fabricated assemblies.

Table 4: Aerospace AM Adoption Metrics (2010-2020)

Metric	2010	2015	2020
Certified metallic part numbers	<5	~10	~30
Components replaced	<10	~30	>50 (855 projected)
AM production cost trend (index)	100	60	25
Maximum build volume (liters)	5	25	100+

5. CHALLENGES AND FUTURE DIRECTIONS

5.1 Surface Finish Limitations

As-built surface roughness remains the "Achilles' heel" of AM for fatigue-critical aerospace applications. For Ti-6Al-4V, high-cycle fatigue performance of as-built surfaces is 40-60% lower than machined specimens, necessitating post-processing. Advanced surface finishing technologies including CMP and chemical polishing have demonstrated fatigue life restoration to 95-100% of machined baseline values.

5.2 Standardization Gaps

While significant progress has been made, standardization gaps remain, particularly for in-situ process monitoring and acceptance criteria for internal defects. The AMS-AM committee continues developing specifications for non-destructive evaluation (NDE) methods tailored to AM-specific defect populations (lack of fusion, gas porosity, keyholing).

5.3 Supply Chain Transformation

The shift from "make-to-print" to "make-to-file" manufacturing models fundamentally alters supply chain dynamics, potentially reducing supplier value-add and blurring intellectual property ownership. Norsk Titanium estimates that 1000 components on a large civil airframe could be AM-produced, while BAE Systems projects 30% of the Tempest aircraft will be 3D printed.

6. CONCLUSION

This investigation establishes several key findings for additive manufacturing in aerospace applications:

1. Process Capabilities: LPBF achieves relative densities exceeding 99.8% for Ti-6Al-4V and Inconel 718, with mechanical properties meeting or exceeding cast/wrought specifications for select alloys.
2. Qualification Framework: SAE's AMS-AM committee has published nine metallic and two polymer specifications by 2020, establishing the regulatory foundation for certified flight hardware.
3. Rocket Propulsion: NASA's RAMPT programme demonstrates successful integration of LPBF combustion chambers with DED nozzles, reducing lead time from months to weeks.
4. Surface Finishing: Advanced post-processing including CMP achieves Ra < 0.8 μm on AM Inconel 625, restoring fatigue performance to 95% of machined baseline.
5. Adoption Trajectory: Approximately 30 certified metallic part numbers by 2020, with projections of exponential growth as production costs continue declining (75% reduction from 2010-2020).

Future research directions include qualification of large-format WAAM structures, development of in-situ process monitoring for defect detection, and expansion of material suites for high-temperature aerospace alloys.

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