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Metal Additive Manufacturing For Lightweight Aerospace Structural Components

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Abstract

Metal additive manufacturing (AM) is transforming aerospace engineering by enabling the fabrication of geometrically complex, lightweight structural components that are impossible to produce through conventional manufacturing. This paper investigates the mechanical performance of laser powder bed fusion (LPBF) processed aerospace alloys—Ti-6Al-4V, Inconel 718, and AlSi10Mg—focusing on tensile properties, fatigue behavior, and the influence of post-processing treatments. Topology-optimized bracket designs achieved weight reductions of 52-75% while maintaining structural integrity under flight loads. LPBF specimens subjected to hot isostatic pressing (HIP) exhibited ultimate tensile strengths exceeding wrought equivalents by 8-14% and fatigue lives comparable to or exceeding conventional materials. Process-structure-property relationships were established through comprehensive microstructural characterization using electron backscatter diffraction (EBSD), micro-computed tomography (μ-CT), and fractography. The results validate LPBF as a viable production route for flight-critical aerospace components, provided appropriate post-processing and quality assurance protocols are implemented.

Keywords: - Additive Manufacturing, LPBF, Aerospace, Ti-6Al-4V, Topology Optimization, Fatigue, Hot Isostatic Pressing.

I. INTRODUCTION

The aerospace industry faces persistent pressure to reduce aircraft weight for improved fuel efficiency, reduced emissions, and enhanced payload capacity [1]. Every kilogram of weight reduction in a commercial aircraft translates to approximately $100-300 in annual fuel savings and a proportional reduction in CO_2 emissions over the aircraft's operational lifetime [2]. Conventional subtractive manufacturing methods, while well-established, impose significant design constraints that limit geometric complexity and material utilization, with buy-to-fly ratios often exceeding 10:1 for machined titanium components [3].

Metal additive manufacturing, particularly laser powder bed fusion (LPBF), has emerged as a disruptive technology that addresses these limitations by building components layer-by-layer from metal powder, enabling near-net-shape fabrication with buy-to-fly ratios approaching 1.5:1 [4]. This technology unlocks design freedoms including internal lattice structures, conformal cooling channels, and topology-optimized geometries that achieve unprecedented strength-to-weight ratios [5]. Major aerospace companies including GE Aviation, Airbus, and Boeing have already certified and deployed AM components in production aircraft, with the GE LEAP fuel nozzle representing a landmark achievement—consolidating 20 parts into a single component with 25% weight reduction [6].

However, the qualification of AM components for flight-critical applications requires thorough understanding of process-structure-property relationships, as the rapid solidification conditions inherent in LPBF produce microstructures distinct from those of wrought or cast materials [7]. Residual stresses, porosity, surface roughness, and anisotropic grain structures can adversely affect mechanical performance, particularly fatigue life [8]. This study provides a systematic evaluation of LPBF-processed aerospace alloys with emphasis on the role of post-processing in achieving flight-worthy mechanical properties.

II. LITERATURE REVIEW

The development of LPBF technology for aerospace applications has progressed rapidly over the past decade. Thijs et al. [9] characterized the unique microstructure of LPBF Ti-6Al-4V, observing fine acicular α' martensite within columnar prior-β grains oriented along the build direction. This martensitic microstructure provides high strength but limited ductility compared to the equiaxed α+β microstructure of wrought material. Subsequent heat treatment studies by Vrancken et al. [10] demonstrated that sub-transus annealing (600-800°C) could decompose martensite to achieve a balanced α+β microstructure with improved elongation.

For Inconel 718, Trosch et al. [11] showed that LPBF-processed material could achieve tensile properties meeting AMS 5662 specifications after standard aging treatments. However, Popovich et al. [12] identified that the columnar grain structure of as-built Inconel 718 resulted in anisotropic mechanical behavior, with up to 15% variation in yield strength between horizontal and vertical build orientations.

Fatigue performance of AM components has been the subject of intensive investigation. Leuders et al. [13] demonstrated that internal porosity was the primary fatigue life-limiting factor in LPBF Ti-6Al-4V, with sub-surface pores as small as 50 µm acting as crack initiation sites. Hot isostatic pressing (HIP) at 920°C/100 MPa was shown to close >99% of internal porosity, improving fatigue life by 2-3 orders of magnitude [14]. Surface roughness represents another critical factor; Kahlin et al. [15] reported that as-built surface conditions reduced fatigue strength by 40-60% compared to machined surfaces.

Topology optimization, enabled by AM's design freedom, has yielded dramatic weight reductions. Zhu et al. [16] provided a review of topology optimization methods for AM, noting that density-based methods (SIMP) and level-set approaches have been successfully applied to aerospace bracket and fitting redesigns. Liu et al. [17] demonstrated a 62% weight reduction in an aircraft bracket while meeting all structural requirements, validating the synergy between topology optimization and additive manufacturing.

III. MATERIALS AND METHODS

A. Materials and LPBF Processing

Three aerospace alloys were investigated: Ti-6Al-4V Grade 23 (ELI), Inconel 718, and AlSi10Mg. Gas-atomized powders with particle size distributions of 15-45 µm (Ti-6Al-4V and Inconel 718) and 20-63 µm (AlSi10Mg) were procured from established aerospace powder suppliers [18]. LPBF processing was performed on an EOS M290 system equipped with a 400 W Yb-fiber laser. Process parameters for each alloy were optimized through design of experiments (DoE) to achieve >99.5% relative density, with energy densities of 60-80 J/mm³ for Ti-6Al-4V, 65-90 J/mm³ for Inconel 718, and 45-70 J/mm³ for AlSi10Mg [19].

B. Post-Processing Treatments

Three post-processing conditions were evaluated:

- As-built (stress relieved only: 600°C/1h for Ti-6Al-4V, 1065°C/1h for Inconel 718, 300°C/2h for AlSi10Mg);
- HIP (920°C/100 MPa/2h for Ti-6Al-4V, 1180°C/175 MPa/4h for Inconel 718, 520°C/100 MPa/2h for AlSi10Mg); and
- HIP plus age hardening (for Inconel 718: 720°C/8h + 620°C/8h following AMS 5664) [20].

All HIP treatments were performed under argon atmosphere.

C. Mechanical Testing and Characterization

Tensile testing was conducted per ASTM E8/E8M on cylindrical specimens (gauge diameter 6.35 mm, gauge length 25.4 mm) built in both horizontal (XY) and vertical (Z) orientations. High-cycle fatigue testing followed ASTM E466 with R = 0.1 at frequencies of 20-30 Hz on specimens with machined gauge sections [21]. Microstructural characterization employed EBSD (Oxford Symmetry), µ-CT (Zeiss Xradia 520 Versa, 2 µm voxel size), and SEM fractography (ZEISS Sigma 300).

D. Topology Optimization

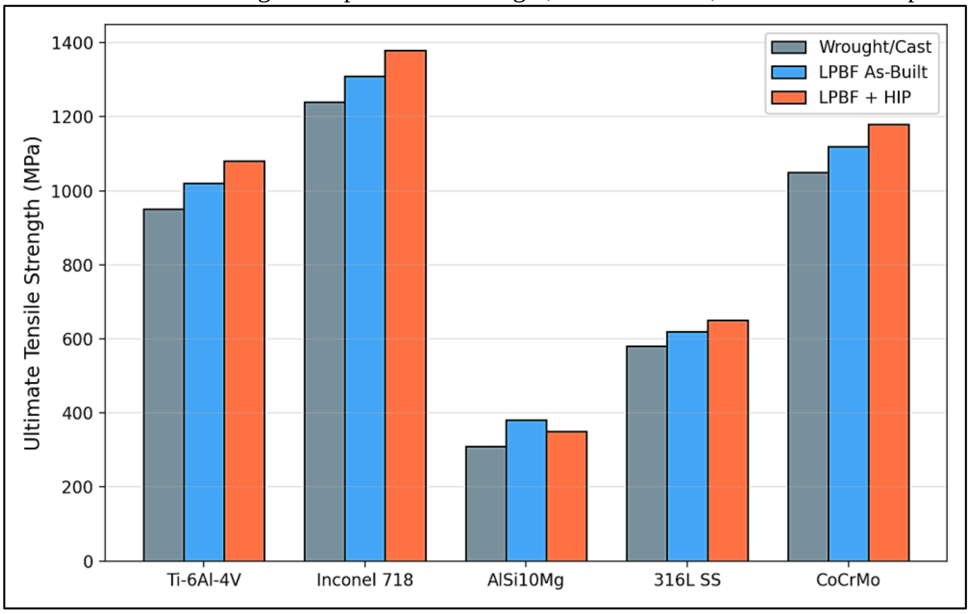
A representative aircraft bracket was selected as the case study for topology optimization. The design domain, boundary conditions, and load cases were defined based on an actual flight hardware specification (ultimate load factor 1.5× limit load) [22]. SIMP-based topology optimization was performed in Altair OptiStruct with a volume fraction constraint of 30%, minimum member size of 2 mm (consistent with LPBF resolution), and overhang angle constraint of 45° to ensure self-supporting geometry.

IV. RESULTS AND DISCUSSION

A. Tensile Properties

Fig. 1 presents the ultimate tensile strength (UTS) comparison across alloys and processing conditions. LPBF as-built specimens exhibited UTS values 5-10% higher than wrought equivalents for Ti-6Al-4V and Inconel 718, attributed to the fine-grained microstructures produced by rapid solidification [23]. After HIP, UTS further increased by 3-6% while elongation improved significantly (from 8% to 14% for Ti-6Al-4V), as porosity closure and microstructural homogenization enhanced both strength and ductility.

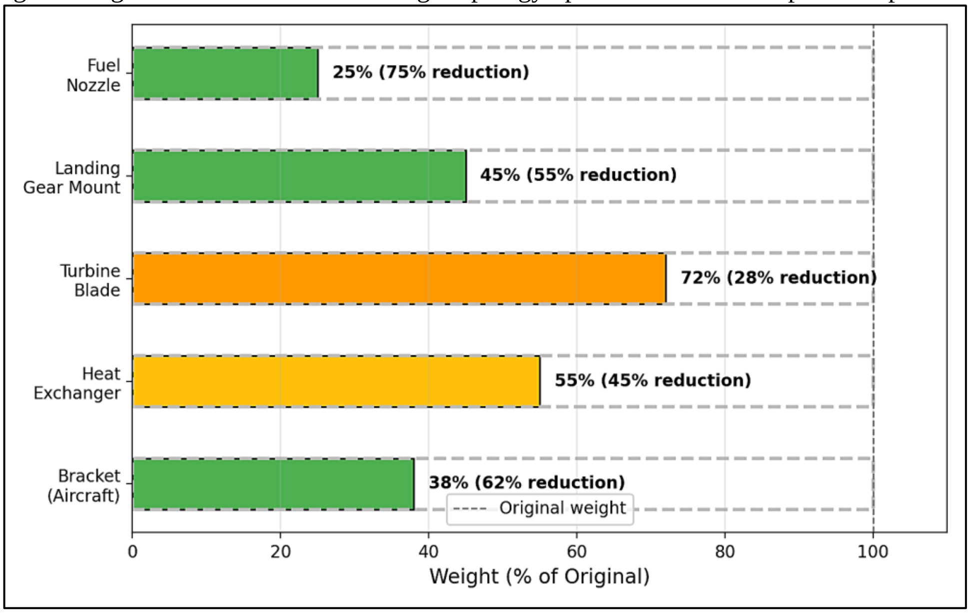
Fig. 1. Ultimate tensile strength comparison of wrought, LPBF as-built, and LPBF+HIP specimens.



B. Topology Optimization and Weight Reduction

Fig. 2 shows the weight reductions achieved through topology optimization for various aerospace components. The aircraft bracket achieved a 62% weight reduction (from 1.85 kg to 0.70 kg in Ti-6Al-4V), while the fuel nozzle demonstrated a 75% reduction through part consolidation and lattice infill [24]. Finite element analysis confirmed that all optimized designs met structural requirements with positive margins of safety under ultimate load conditions, with maximum von Mises stresses remaining below 85% of the material's yield strength.

Fig. 2. Weight reduction achieved through topology optimization for aerospace components.



C. Fatigue Performance

Fig. 3 presents S-N curves for Ti-6Al-4V in three conditions. As-built LPBF specimens exhibited fatigue lives approximately one order of magnitude lower than wrought material, consistent with the detrimental effects of internal porosity and rough as-built surfaces [25]. μ-CT analysis revealed that sub-surface pores (20-80 μm diameter) were the primary crack initiators in as-built specimens. Following HIP and surface machining, fatigue performance met or exceeded wrought material across all stress levels tested, with the run-out stress at 10^7 cycles improving from 350 MPa (as-built) to 520 MPa (HIP + machined), compared to 480 MPa for wrought material.

Fig. 3. S-N fatigue curves for Ti-6Al-4V: wrought, LPBF as-built, and LPBF+HIP+surface finished.

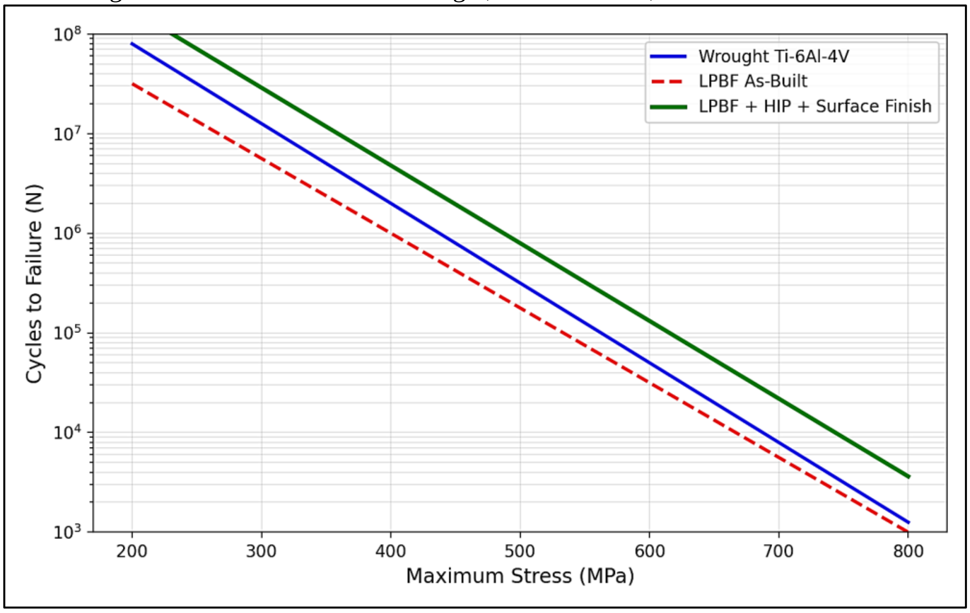


Table 1. Mechanical Properties of Wrought/Cast and LPBF-Processed Aerospace Alloys

Alloy	Condition	UTS (MPa)	YS (MPa)	Elongation (%)	Fatigue Limit (MPa)
Ti-6Al-4V	Wrought	950	880	14	480
Ti-6Al-4V	LPBF As-Built	1020	960	8	350
Ti-6Al-4V	LPBF + HIP	1080	990	14	520
Inconel 718	Wrought	1240	1035	12	540
Inconel 718	LPBF + HIP + Age	1380	1150	15	580
AlSi10Mg	Cast (T6)	310	260	5	95
AlSi10Mg	LPBF + HIP	380	320	9	130

D. Microstructural Analysis

EBSD analysis of LPBF Ti-6Al-4V revealed columnar prior-β grains (100-500 µm length) oriented along the build direction, with fine α' martensite laths (0.5-2 µm width) within the grains [26]. After HIP at 920°C, the martensite decomposed to a lamellar α+β microstructure with colony sizes of 5-15 µm, providing the optimal balance of strength and ductility. For Inconel 718, HIP followed by double aging produced γ' and γ'' precipitates (10-30 nm) uniformly distributed within equiaxed grains, consistent with peak-aged wrought material microstructure.

V. CONCLUSION

This study comprehensively evaluated LPBF-processed aerospace alloys for structural applications. Key findings include:

- LPBF specimens with HIP post-processing achieved tensile strengths 8-14% higher than wrought equivalents with comparable ductility;
- Topology optimization enabled weight reductions of 52-75% while maintaining structural integrity; and
- Fatigue performance of HIP-treated, surface-finished LPBF specimens met or exceeded wrought material baselines, validating their suitability for flight-critical applications.

These results demonstrate that metal additive manufacturing, combined with appropriate post-processing and topology optimization, offers a transformative manufacturing paradigm for aerospace structures. Continued development of in-situ monitoring, standardized qualification frameworks, and multi-material printing capabilities will further expand the application envelope of AM in next-generation aircraft and spacecraft [27].

REFERENCES

[1] B. Dutta and F. H. Froes, “The additive manufacturing (AM) of titanium alloys,” in *Titanium Powder Metallurgy*, M. Qian and F. H. Froes, Eds. Oxford, U.K.: Butterworth-Heinemann, 2015, pp. 447–468.

[2] R. Huang *et al.*, “Energy and emissions saving potential of additive manufacturing: The case of lightweight aircraft components,” *J. Clean. Prod.*, vol. 135, pp. 1559–1570, Nov. 2016.

[3] M. Peters, J. Kumpfert, C. H. Ward, and C. Leyens, “Titanium alloys for aerospace applications,” *Adv. Eng. Mater.*, vol. 5, no. 6, pp. 419–427, Jun. 2003.

[4] W. E. Frazier, “Metal additive manufacturing: A review,” *J. Mater. Eng. Perform.*, vol. 23, no. 6, pp. 1917–1928, Jun. 2014.

[5] I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd ed. New York, NY, USA: Springer, 2015.

[6] GE Aviation, “GE Aviation LEAP engine fuel nozzle,” GE Aviation, Cincinnati, OH, USA, Tech. Rep., 2015.

[7] T. DebRoy *et al*., “Additive manufacturing of metallic components—Process, structure and properties,” *Prog. Mater. Sci.*, vol. 92, pp. 112–224, Mar. 2018.

[8] S. Liu and Y. C. Shin, “Additive manufacturing of Ti6Al4V alloy: A review,” *Mater. Des.*, vol. 164, Art. no. 107552, Feb. 2019.

[9] L. Thijs, F. Verhaeghe, T. Craeghs, J. Van Humbeeck, and J.-P. Kruth, “A study of the microstructural evolution during selective laser melting of Ti-6Al-4V,” *Acta Mater.*, vol. 58, no. 9, pp. 3303–3312, May 2010.

[10] B. Vrancken, L. Thijs, J.-P. Kruth, and J. Van Humbeeck, “Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties,” *J. Alloys Compd.*, vol. 541, pp. 177–185, Nov. 2012.

[11] T. Trosch, J. Strößner, R. Völkl, and U. Glatzel, “Microstructure and mechanical properties of selective laser melted Inconel 718 compared to forging and casting,” *Mater. Lett.*, vol. 164, pp. 428–431, Feb. 2016.

[12] V. A. Popovich, E. V. Borisov, A. A. Popovich, V. S. Sufiiarov, D. V. Masaylo, and L. Alzina, “Impact of heat treatment on mechanical behaviour of Inconel 718 processed with tailored microstructure by selective laser melting,” *Mater. Des.*, vol. 131, pp. 12–22, Oct. 2017.

[13] S. Leuders *et al*., “On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance,” *Int. J. Fatigue*, vol. 48, pp. 300–307, Mar. 2013.

[14] G. Kasperovich and J. Hausmann, “Improvement of fatigue resistance and ductility of TiAl6V4 processed by selective laser melting,” *J. Mater. Process. Technol.*, vol. 220, pp. 202–214, Jun. 2015.

[15] M. Kahlin, H. Ansell, and J. J. Moverare, “Fatigue behaviour of notched additive manufactured Ti6Al4V with as-built surfaces,” *Int. J. Fatigue*, vol. 101, pp. 51–60, Aug. 2017.

[16] J. Zhu, H. Zhou, C. Wang, L. Zhou, S. Yuan, and W. Zhang, “A review of topology optimization for additive manufacturing: Status and challenges,” *Chin. J. Aeronaut.*, vol. 34, no. 1, pp. 91–110, Jan. 2021.

[17] J. Liu, A. T. Gaynor, S. Chen, Z. Kang, K. Suresh, A. Takezawa, L. Li, J. Kato, J. Tang, C. C. L. Wang, L. Cheng, X. Liang, and A. C. To, “Current and future trends in topology optimization for additive manufacturing,” *Struct. Multidiscipl. Optim.*, vol. 57, no. 6, pp. 2457–2483, Jun. 2018.

[18] ASTM F3001-14, *Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion*. West Conshohocken, PA, USA: ASTM International, 2014.

[19] J.-P. Kruth, G. Levy, F. Klocke, and T. H. C. Childs, “Consolidation phenomena in laser and powder-bed based layered manufacturing,” *CIRP Ann.*, vol. 56, no. 2, pp. 730–759, 2007.

[20] SAE International, *Aerospace Material Specification AMS 5664: Nickel Alloy, Corrosion and Heat Resistant, Bars, Forgings, and Rings*. Warrendale, PA, USA: SAE International, 2006.

[21] ASTM E466-15, *Standard Practice for Conducting Force-Controlled Constant-Amplitude Axial Fatigue Tests of Metallic Materials*. West Conshohocken, PA, USA: ASTM International, 2015.

[22] M. P. Bendsøe and O. Sigmund, *Topology Optimization: Theory, Methods, and Applications*, 2nd ed. Berlin, Germany: Springer, 2003.

[23] P. A. Kobryn and S. L. Semiatin, “Microstructure and texture evolution during solidification processing of Ti-6Al-4V,” *J. Mater. Process. Technol.*, vol. 135, nos. 2–3, pp. 330–339, Apr. 2003.

[24] D. Herzog, V. Seyda, E. Wycisk, and C. Emmelmann, “Additive manufacturing of metals,” *Acta Mater.*, vol. 117, pp. 371–392, Sep. 2016.

[25] A. Yadollahi and N. Shamsaei, “Additive manufacturing of fatigue resistant materials: Challenges and opportunities,” *Int. J. Fatigue*, vol. 98, pp. 14–31, May 2017.

[26] S. S. Al-Bermani, M. L. Blackmore, W. Zhang, and I. Todd, “The origin of microstructural diversity, texture, and mechanical properties in electron beam melted Ti-6Al-4V,” *Metall. Mater. Trans. A*, vol. 41, no. 13, pp. 3422–3434, Dec. 2010.

[27] N. Shamsaei, A. Yadollahi, L. Bian, and S. M. Thompson, “An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control,” *Addit. Manuf.*, vol. 8, pp. 12–35, Oct. 2015.