



Additive Manufacturing Techniques for Lightweight Structural Components in Aerospace

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Abstract

Additive manufacturing (AM) inverts the logic of conventional aerospace fabrication: rather than machining a structure out of a solid billet at buy-to-fly ratios that often exceed 10:1, material is deposited layer by layer only where a component's load path requires it. This article synthesizes the literature on AM for lightweight structural components in aerospace, covering the principal metal AM process families used for flight hardware -- laser and electron beam powder bed fusion, wire-arc and other directed energy deposition variants, and the newer, solid-state cold spray process -- and how each trades build envelope, feature resolution, and deposition rate for the others. We trace the materials science of AM-specific anisotropy, porosity, and fatigue behavior that governs whether a printed part can be trusted with flight loads, and the design methods, principally topology optimization coupled to AM manufacturing constraints, that convert AM's geometric freedom into measured structural mass savings, including case studies reporting a 79% mass reduction on a topology-optimized satellite star tracker bracket, a 40% reduction on a satellite edge insert, and a 62% reduction on a cold-spray-built jet engine bracket. We then examine the qualification and structural-integrity literature that stands between such demonstrations and routine certified use, and close with a discussion of open challenges in cross-process qualification, fatigue design allowables, and design-tool maturity. Read together, the evidence supports additive manufacturing, paired with topology optimization, as a demonstrated and increasingly mature route to substantial aerospace structural mass reduction, with qualification and design-practice maturity, rather than any doubt about the underlying mass-saving potential, as the primary remaining gap.

Keywords: additive manufacturing; aerospace structures; topology optimization; lightweight design; metal powder bed fusion

1. Introduction

Aerospace structures have always been an exercise in subtraction: an engineer starts with a stock billet, and a machine tool removes everything that is not load path. For decades that subtraction has been remarkably effective, but it is also wasteful in a very literal sense — buy-to-fly ratios of 10:1 or higher are routine for machined titanium brackets and fittings, meaning that for every kilogram of aluminum or titanium that ends up on the aircraft, nine or more kilograms are cut away as scrap [1,2]. Additive manufacturing (AM) inverts the logic: material is deposited only where the structure needs it, layer by layer, guided by a digital model rather than a subtractive toolpath. For an industry where every kilogram of structural mass costs recurring fuel burn or payload capacity over an aircraft's or spacecraft's operational life, that inversion is not a curiosity — it is one of the few manufacturing shifts in the last thirty years with a direct, compounding effect on vehicle performance.

The appeal is not simply "less waste." Layer-wise fabrication removes many of the geometric constraints that subtractive and formative processes impose, which means a part can be redesigned around its actual load paths rather than around what a five-axis mill or a forging die can reach [3]. Internal lattices, organically curved ribs, and consolidated assemblies that once required dozens of fasteners and brackets can, in principle, be printed as a single topology-optimized part. This has made additive manufacturing a natural partner to structural topology optimization, and the pairing has moved from academic demonstration to flight hardware over the past decade: satellite brackets, engine components, and airframe fittings redesigned this way have shipped with reported mass reductions in the tens of percent relative to their conventionally manufactured heritage counterparts [4].

This article synthesizes the literature on additive manufacturing for lightweight structural components in aerospace, with a deliberate focus on metal AM processes, since metals — titanium, aluminum, nickel superalloys, and increasingly metal matrix composites — carry the primary structural loads in both airframes and propulsion systems. We organize the discussion around five themes: the metal AM process families actually used for aerospace structures and how they differ in build envelope, resolution, and deposition rate;

the materials and mechanical-property literature that determines whether a printed part can be trusted to carry flight loads; the design methods, principally topology optimization and lattice design, that convert AM's geometric freedom into measurable mass savings; the defect, qualification, and structural-integrity literature that stands between a promising coupon result and a certified flight part; and the emerging applications — from small-satellite structures to cold-spray repair and build — that indicate where the field is heading next. We close with an honest accounting of what remains unresolved.

It is worth stating the scope plainly. This is a literature synthesis, not a report of new experiments, and we have been careful to cite only numbers that the underlying sources actually report rather than plausible-sounding figures. Where the literature gives concrete case-study results — and several of the papers synthesized here do, down to the gram — we use those numbers and name their source explicitly. Where the literature is qualitative or the evidence is thinner than the marketing language around additive manufacturing sometimes suggests, we say so rather than smoothing over the gap.

2. Metal Additive Manufacturing Processes for Aerospace Structures

Metal additive manufacturing is not one process but a family of quite different physical mechanisms, and which member of that family gets used for a given aerospace structure depends heavily on part size, required resolution, and how much post-processing the program can tolerate. Frazier's early and still widely cited review lays out the basic taxonomy — powder bed fusion, directed energy deposition, and the sheet- and extrusion-based processes borrowed more from polymer AM — and makes the point, still true a decade later, that for load-bearing metal aerospace structures the field has converged overwhelmingly on powder bed fusion and directed energy deposition variants [1]. Blakey-Milner et al.'s 2021 review, focused specifically on aerospace, surveys how these process families map onto actual flight applications: fuel nozzles and heat exchangers that benefit from powder bed fusion's fine internal channel resolution, large structural spars and ribs better suited to directed energy deposition's higher deposition rates, and the growing use of both process families across engine and airframe programs at Airbus, Boeing, GE, and their suppliers [5].

Table 1: Comparison of metal additive manufacturing process families used for aerospace structural components, with representative build-envelope and deposition characteristics and the specific evidence each cited study reports. [1,8,11,13].

Process	Typical Part Size / Feature Scale	Relative Deposition Rate	Reported Evidence
Laser powder bed fusion (LPBF)	Fine internal features; build chamber typically well under 1 m	Low (fine layers, scan-based)	Fine resolution enables complex internal channels and lattices; process-specific porosity and anisotropy documented across studies [1]
Electron beam melting (EBM)	Similar envelope to LPBF; vacuum chamber	Low-moderate	Distinct, generally coarser porosity than LPBF for the same Ti-6Al-4V alloy, directly affecting fatigue behavior [8]
Wire-arc additive manufacturing (WAAM)	Large; components exceeding 10 kg demonstrated (spars, landing gear, wing ribs)	High (arc/wire-fed)	Used for Ti-6Al-4V spars and landing gear assemblies; requires machining, residual-stress management, and NDT to reach final part [11]
Cold spray additive manufacturing	Bracket- and fitting-scale; solid-state, no melt pool	High (kg/h, exceeds most other AM processes)	62% mass reduction on a topology-optimized jet engine bracket; UTS ~487 MPa, max overhang ~30 deg for tested Ti-TiC composite [13]

Laser and Electron Beam Powder Bed Fusion

Powder bed fusion (PBF) — selectively melting a thin layer of metal powder with a laser or electron beam, then recoating and repeating — is the process most associated with the striking, organic geometries that illustrate additive manufacturing's promise. Gu et al.'s early and detailed treatment of laser additive manufacturing lays out the physical mechanisms governing melt pool behavior, powder consolidation, and the resulting microstructure, work that remains foundational for understanding why PBF parts behave metallurgically differently from cast or wrought material in the first place [6]. Sames et al.'s review of the metallurgy and processing science across metal AM broadens this treatment to compare how different energy sources and scan strategies affect solidification microstructure, and is a useful reference for readers who want the materials-science version of why PBF parts require their own qualification story rather than inheriting one from conventional metallurgy [7].

Electron beam melting (EBM), a powder bed process

that uses an electron beam in a vacuum chamber rather than a laser in an inert-gas atmosphere, produces measurably different defect populations than laser-based PBF. Gong et al.'s direct comparison of selective laser melting and EBM processing of Ti-6Al-4V found that the two processes produce characteristically different porosity — a finding with direct consequences for how each process's parts need to be qualified and inspected, since porosity is one of the primary drivers of scatter in fatigue performance for AM titanium [8]. This process-dependent defect signature is one of the clearest illustrations in the literature that "additive manufacturing" is not a single qualification problem but a family of related ones, each tied to a specific machine, material, and parameter set.

Kranz, Herzog, and Emmelmann's design guidelines for laser additive manufacturing of TiAl6V4 lightweight structures translate this process-level understanding into practical design rules — minimum wall thickness, achievable overhang angles without support structures, and surface roughness as a function of build orientation — that a structural designer actually needs before drawing a part rather than after it fails to print [9]. Sing and Yeong's more recent perspective on laser powder bed fusion surveys how the process has matured since these earlier foundational works, covering advances in multi-laser systems for larger build volumes and faster throughput, in-process monitoring for defect detection during the build itself, and the expanding materials palette beyond the now-standard titanium, nickel, and aluminum alloys [10].

Directed Energy Deposition, Wire-Arc, and Cold Spray Additive Manufacturing

Powder bed fusion's build chamber, typically well under a cubic meter, is a hard limit on part size, and aerospace structures — wing spars, landing gear components, large engine casings — routinely exceed it. Directed energy deposition (DED) processes, which feed metal wire or powder into a focused energy source (laser, electron beam, or electric arc) mounted on a moving head rather than confining the build to a fixed powder bed, trade some of PBF's fine-feature resolution for much larger achievable part sizes and, in the wire-fed variants, substantially higher deposition rates.

Wire-arc additive manufacturing (WAAM), which adapts conventional arc-welding equipment and wire feedstock to build up large metal components layer by layer, is the

DED variant that has moved furthest toward aerospace production use. Williams et al.'s review of WAAM documents its use in depositing components exceeding 10 kilograms in titanium, aluminum, and steel, including Ti-6Al-4V wing spars, landing gear assemblies, and aluminum wing ribs, and frames the process's central trade-off clearly: WAAM offers high deposition rates and comparatively low material and equipment costs relative to powder-based processes, at the cost of coarser feature resolution and a greater dependence on subsequent machining, residual-stress management, and non-destructive inspection to reach an acceptable final part [11]. Ding et al.'s broader review of wire-feed additive manufacturing situates WAAM within the larger family of wire-based DED technologies, covering the process variants (gas metal arc, gas tungsten arc, plasma arc, and laser- or electron-beam wire feed), their relative deposition rates, and the path-planning and thermal-management research needed to keep large multi-pass builds from developing excessive residual stress and distortion [12].

A newer entrant to this DED family, cold spray additive manufacturing, dispenses with melting altogether: metal particles are accelerated to supersonic velocity and bond to the substrate and to each other through severe plastic deformation on impact, remaining in the solid state throughout. Because there is no melt pool, cold spray avoids much of the residual stress, distortion, and solidification-driven porosity that complicate laser- and arc-based AM, which makes it attractive for repair and for building onto existing structures without disturbing their heat treatment. Lomo et al.'s 2023 design and optimization framework for cold spray additive manufacturing of lightweight aerospace structural components reports that cold spray achieves deposition rates, in kilograms per hour, higher than most other widely used metal AM processes, and demonstrates the approach on a topology-optimized jet engine bracket that achieved a 62% mass reduction relative to the original bracket design while meeting the specified structural loads; the same study reports measured mechanical properties for a titanium-titanium carbide composite build — an ultimate tensile strength of roughly 487 MPa and a Young's modulus near 103 GPa — and identifies a maximum achievable overhang angle of about 30 degrees as a binding design constraint for the process [13].

Table 1 summarizes how these process families compare on the dimensions that matter most for aerospace structural design: achievable part size, relative deposition rate, and the specific evidence each cited study reports about defect behavior, mechanical properties, or achieved mass reduction.

3. Materials and Mechanical Performance of AM Aerospace Alloys

None of this process diversity matters to a structural engineer until the resulting material's mechanical behavior is understood well enough to design against it with confidence. Lewandowski and Seifi's widely cited review of mechanical properties across metal AM processes remains a central reference here, surveying tensile, fatigue, and fracture toughness data across the titanium, nickel, and aluminum alloy systems most relevant to aerospace, and making the point — still one of the most important in the field — that AM material properties are strongly anisotropic, varying with build orientation relative to the part's principal load-bearing direction, in a way that wrought and cast material generally is not [14]. Kok et al.'s critical review of anisotropy and heterogeneity in metal AM microstructure and mechanical properties goes deeper into the mechanistic reasons why: the columnar, epitaxial grain growth characteristic of rapid, directional solidification in both PBF and DED processes produces a crystallographic texture that is itself orientation-dependent, and that texture, combined with process-specific defect populations, is what ultimately produces the anisotropic strength and, especially, anisotropic fatigue behavior reported across the literature [15].

Fatigue performance has received particular attention because it is where AM metal's defect population does the most damage to structural confidence. Leuders et al.'s early and detailed study of selective-laser-melted Ti-6Al-4V fatigue resistance and crack growth found that as-built material contains defects that act as crack-initiation sites, substantially degrading fatigue life relative to defect-free wrought material, and that hot isostatic pressing — a post-processing step that closes internal porosity under heat and pressure — measurably improves fatigue performance by removing many of these initiation sites [16]. Sanaei and Fatemi's more recent, comprehensive review of defects in additively manufactured metals and their effect on fatigue

performance synthesizes this line of work across a much broader set of studies and alloys, cataloguing how porosity size, shape, and location interact with applied stress to control fatigue crack initiation, and arguing that defect characterization — not just defect minimization — needs to become a standard part of how AM structural parts are qualified, because even well-controlled processes do not eliminate porosity entirely, only bound its statistics [17].

Beyond the now-standard titanium and nickel alloy systems, functionally graded materials represent a materials-design direction unique to additive manufacturing's layer-by-layer deposition: because composition can, in principle, be varied continuously from layer to layer, a single AM-built part can transition gradually from one alloy to another to place the right material properties exactly where the local loading or thermal environment demands them. Reichardt et al.'s review of additive manufacturing of metal-based functionally graded materials surveys this emerging area, covering both the deposition strategies (primarily DED, since powder or wire feed composition can be varied mid-build far more readily than a fixed powder bed) and the metallurgical challenges — brittle intermetallic phase formation at certain composition transitions being the most persistent one — that stand between the concept and routine aerospace use [18]. Composite lattice architectures represent a related but distinct materials-design direction: Eichenhofer et al.'s work on continuous lattice fabrication of ultra-lightweight composite structures demonstrates a fiber-composite analog to metal AM lattice printing, achieving highly weight-efficient truss-like structures through continuous fiber placement rather than layer-wise metal melting, and is a useful reminder that the lightweighting logic this article traces through metal AM has close cousins in the composites world that aerospace structural designers increasingly draw on together [19].

4. Design for Additive Manufacturing: Topology Optimization and Lattice Structures

If the previous two sections describe what additive manufacturing processes can physically produce, this section describes the design methods that decide what they should produce — and this is where AM's promised mass savings actually get realized or left on the table. Topology optimization is a computational design

method that, given a design space, a set of applied loads, and a target objective (typically minimum mass for a given stiffness or strength constraint), computes a material distribution that satisfies the constraint using as little material as possible, without a human designer first guessing at a shape. Before additive manufacturing, topology optimization's outputs were often organic, strut-like forms that were mathematically optimal but practically unmanufacturable by casting or machining, so the technique's structural-engineering value was limited to inspiring a simplified, buildable reinterpretation of the optimized shape. Additive manufacturing removes much of that manufacturability constraint, which is the primary reason topology optimization and AM are so often discussed together in the aerospace literature.

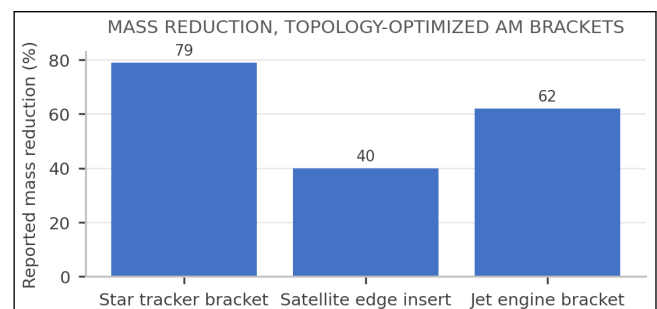


Figure 1: Measured mass reductions reported for three topology-optimized aerospace structural components rebuilt via additive manufacturing, relative to their conventionally manufactured heritage counterparts -- a star tracker camera bracket (425 g to 89 g) and a satellite edge insert, both laser powder bed fusion [4], and a jet engine bracket built by cold spray additive manufacturing [13].

Liu et al.'s survey of current and future trends in topology optimization for additive manufacturing catalogues how the optimization formulations themselves have evolved to account for AM-specific manufacturing constraints — minimum feature size, maximum unsupported overhang angle, and anisotropic material behavior — rather than treating AM as an unconstrained fabrication method that can produce literally any computed shape [20]. Liu and To's more specific work on deposition-path-planning-integrated topology optimization goes a step further, coupling the structural optimization directly to the AM build process itself — specifically the self-supporting constraint that determines whether a given overhang angle can be printed without auxiliary support material — so that the optimizer never proposes a geometry the printer cannot actually build without extensive supports that would themselves need to be machined away afterward [21]. This coupling matters in practice: a topology-optimized

part that looks elegant in simulation but requires dense internal support structures to print correctly loses much of its manufacturing and mass advantage once those supports are accounted for.

The clearest evidence for what this design methodology actually delivers on real aerospace hardware comes from Orme et al.'s case studies of topology optimization applied to flight components. Their star tracker camera bracket, redesigned from a heritage titanium part through topology optimization and built in aluminum via laser powder bed fusion, achieved a final mass of 89 grams compared with 425 grams for the heritage design — a 79% mass reduction — while meeting the same structural loading requirements, with the full design-to-testing cycle completed in roughly eight weeks [4]. A second case study in the same paper, an edge insert component developed with Surrey Satellite Technology Ltd., achieved a 40% mass reduction over its heritage solid counterpart through the same topology-optimization-plus-AM approach [4]. These figures are not projections or simulation outputs; they are measured masses of built and tested flight hardware, and they are among the most concrete, verifiable evidence in this literature that the combination of topology optimization and additive manufacturing delivers real, not merely theoretical, structural mass savings. Lomo et al.'s cold-spray bracket case study, discussed above, adds a third data point along the same lines — a 62% mass reduction on a topology-optimized jet engine bracket — obtained through a different AM process family entirely, which strengthens the case that the mass savings are attributable to the design methodology and the layer-wise fabrication freedom it exploits, not to any single process's idiosyncrasies [13]. Figure 1 presents these three reported mass-reduction figures alongside one another.

Lattice and cellular infill structures are topology optimization's natural extension at a finer length scale: rather than optimizing only the part's outer envelope, the interior can be filled with an engineered lattice — strut-based, sheet-based, or otherwise periodic — that provides most of a solid section's stiffness at a fraction of its mass. Thompson et al.'s broad survey of design for additive manufacturing situates lattice design within the wider set of AM-enabled design freedoms, alongside part consolidation (replacing multi-part assemblies with a single printed component) and internal channel

routing, and argues that realizing AM's structural benefits requires design tools and designer training that most engineering programs and most commercial CAD software, as of that survey, had not yet caught up to [3]. Kumke, Watschke, and Vietor's methodological framework for design for additive manufacturing addresses this gap directly, proposing a structured process for guiding designers through AM-specific opportunities and constraints — including lattice and topology design — rather than leaving them to rediscover AM's rules through trial and error on real hardware [22].

5. Defects, Qualification, and Structural Integrity

Every advantage described so far comes with a cost that the aerospace industry, more than almost any other, cannot simply wave away: certifying that a printed part will perform reliably over its service life. Seifi et al.'s overview of materials qualification needs for metal AM lays out why this is harder than qualifying a conventionally manufactured part: AM's mechanical properties depend on a much larger set of interacting process parameters — laser or beam power, scan speed, layer thickness, powder chemistry and morphology, build orientation, and post-processing — than casting or forging does, and a qualification approach built around testing a fixed set of coupons from a fixed process no longer transfers cleanly when any of those parameters change, even slightly, between builds or machines [23]. This is the crux of what makes AM qualification an open, actively worked problem rather than a solved one: the industry is, in effect, being asked to qualify not a material but a process-material-machine system, and to demonstrate that system stays within its qualified envelope build after build.

DebRoy et al.'s comprehensive review of metallic-component additive manufacturing ties this qualification challenge back to process physics, tracing how melt pool thermal history determines the resulting grain structure, residual stress state, and defect population, and arguing that predictive process models — capable of forecasting a build's resulting microstructure and defects from its process parameters before the part is even printed — are an essential complement to purely empirical qualification testing, because empirical testing alone cannot practically cover the full parameter space that governs AM part quality [24]. Sanaei and Fatemi's fatigue-focused review,

discussed above, makes a closely related qualification point from the fatigue-design side: because porosity in AM metal cannot currently be eliminated entirely, only statistically bounded and controlled, structural design allowables for AM parts increasingly need to account explicitly for a realistic defect population rather than assuming the pristine, defect-free material behavior that conventional design allowables implicitly assume [17].

Non-destructive evaluation and in-process monitoring are the practical tools the industry is developing to close this qualification gap without inspecting every part destructively. Williams et al.'s WAAM review explicitly discusses the role of online monitoring and non-destructive testing as part of the process's path toward aerospace production use, alongside residual-stress management and in-situ machining to correct geometry mid-build [11]. Gradl et al.'s review of robust metal AM process selection and development for aerospace components takes perhaps the most systems-level view of the qualification challenge in this literature, examining how geometric constraints, material properties, cost, post-processing requirements, and — critically — supply chain and inspection maturity all factor into which AM process a program should select for a given aerospace component, rather than treating AM process selection as a purely mechanical-properties decision [25]. Their treatment is a useful corrective to any framing of this literature that presents AM process selection as simply picking whichever process achieves the best coupon properties: in a qualification-driven industry, a process's inspectability and production repeatability can matter as much as its peak reported strength.

Najmon, Raeisi, and Tovar's review chapter on additive manufacturing technologies and applications in the aerospace industry situates all of this qualification effort within the broader adoption story, surveying how different AM processes and applications — from polymer tooling to flight-critical metal structures — sit at different points along the qualification and certification maturity curve, with fully flight-critical structural applications generally representing the most qualification-intensive end of that spectrum [26]. Huang, Leu, Mazumder, and Donmez's earlier roadmap-style review of additive manufacturing's current state, future potential, gaps, and needs made a similar point at an earlier stage of the field's

development, identifying qualification and certification, process repeatability, and standardized design and testing methods as among the primary gaps standing between AM's demonstrated potential and its routine industrial use — an assessment that later work in this synthesis largely confirms is still, a decade on, only partially closed [27].

6. Emerging Applications and Process Selection

The most recent literature reflects a field moving from proving that additive manufacturing can produce a lightweight aerospace structure to working out, program by program, which process and design approach fits a given application best. Small-satellite structures are a particularly active area for this reason: CubeSat- and PocketQube-class spacecraft combine an extreme mass sensitivity, since launch cost scales directly with mass, with production volumes and budgets that cannot support the qualification programs used for large, crewed, or high-value aerospace hardware. Valencia et al.'s 2026 systematic review of additive manufacturing for PocketQube-class satellite structural components surveys how materials selection, process choice, and qualification pathways — including compliance with European Cooperation for Space Standardization (ECSS) requirements — are being adapted specifically for this small-satellite context, where the qualification rigor of a crewed aircraft program is neither achievable nor, arguably, necessary, but where some structured qualification pathway is still required for mission success [28]. This work is a useful signal of where the field's qualification conversation is heading: not toward a single universal AM qualification standard, but toward risk- and application-appropriate qualification frameworks that scale with what a given aerospace program actually needs.

Gradl et al.'s process-selection framework, discussed above, points in a related direction from the propulsion side, where NASA and its industry partners have accumulated substantial flight and ground-test experience with AM combustion chambers, injectors, and turbopump components, and where the process-selection question has correspondingly matured from "can this be printed" to "which of several qualified AM processes is the right one for this specific component's loads, geometry, and production volume" [25]. Cold spray's emergence, per Lomo et al., as a viable structural AM process for brackets and similar fittings —

alongside its more established use for coating and repair — is a third signal of the same trend: the aerospace AM toolkit is diversifying beyond laser powder bed fusion's early dominance, with each process family finding the application niche where its particular trade-off of resolution, deposition rate, residual stress, and achievable part size fits best [13].

7. Open Challenges

Several gaps recur across this literature and are worth stating plainly rather than leaving implicit. First, qualification remains the field's central unresolved problem, not a solved formality: Seifi et al.'s characterization of AM qualification as a process-material-machine system qualification problem, rather than a materials qualification problem, still describes the state of the art, and DebRoy et al.'s call for predictive process models as a qualification complement to empirical testing remains, in our reading of the more recent literature synthesized here, only partially realized [23,24]. Second, fatigue design allowables that explicitly account for realistic, process-specific defect populations — rather than either assuming defect-free material or applying a single conservative knockdown factor across very different processes and alloys — are still more the subject of active research, as in Sanaei and Fatemi's review, than of settled industry practice [17].

Third, the process-selection literature, while maturing quickly per Gradl et al., is still fragmented across process families that have historically been studied by largely separate research communities — the powder bed fusion metallurgy community, the WAAM and wire-feed DED welding-adjacent community, and the newer cold spray solid-state community — and genuinely comparative, apples-to-apples studies across process families on the same component and load case remain rarer than single-process case studies like Orme et al.'s and Lomo et al.'s [25,4,13]. Fourth, design tools and designer training have not fully caught up to AM's geometric freedom, a gap Thompson et al. identified some years ago and that Kumke et al.'s methodological framework was an explicit attempt to close, but which, based on how much of the more recent literature still frames "design for AM" as a distinct competency rather than a default part of structural design practice, does not yet read as closed [3,22].

Fifth, functionally graded materials and advanced lattice

architectures remain, per Reichardt et al., constrained by metallurgical challenges at certain composition or geometry transitions that are not yet fully solved at a fundamental materials-science level, which limits how aggressively these more exotic design freedoms can currently be exploited on qualified flight hardware relative to their demonstrated laboratory potential [18]. We do not read any of these gaps as evidence against the underlying technology — the measured, verified mass-reduction case studies synthesized here are real, not aspirational — but an honest synthesis of this literature should name where the evidence is genuinely settled (that topology-optimized AM parts can and do achieve large, measured mass reductions on flight hardware) and where it is still accumulating (comprehensive, cross-process qualification and design-allowable frameworks).

8. Conclusion

The literature reviewed here supports a fairly specific claim: additive manufacturing, paired with topology optimization and lattice design, is a demonstrated and increasingly mature route to substantial structural mass reduction in aerospace components, with measured case-study results — a 79% mass reduction on a topology-optimized star tracker bracket, a 40% reduction on a satellite edge insert, and a 62% reduction on a cold-spray-built jet engine bracket — providing concrete, verifiable evidence rather than aspirational projections [4,13]. This mass-reduction capability rests on a genuinely diverse set of underlying processes, from laser and electron beam powder bed fusion's fine-feature resolution to wire-arc and cold spray's much larger achievable part sizes and higher deposition rates, each suited to a different point in the aerospace structural design space [1,5,11,13].

Realizing this potential at production scale, rather than only in case studies and demonstration hardware, depends on treating the materials, design, and qualification literatures surveyed here as inseparable from one another. Understanding AM's characteristic anisotropy and defect populations [14,15,8] is what makes it possible to design against them rather than be surprised by them; coupling topology optimization directly to AM's manufacturing constraints [20,21] is what keeps optimized designs actually buildable; and confronting qualification as a process-material-machine system problem, not a conventional materials

qualification problem, [23,24,17] is what stands between promising case studies and routine certified use. The consistent recurrence, across independent research groups and independent AM process families, of large and directly measured mass reductions on real aerospace and space hardware is, in our reading, the strongest available evidence that additive manufacturing for lightweight aerospace structures is not a narrow technique but a durable structural design paradigm — one whose remaining open problems are engineering and qualification problems to be worked through, not open questions about whether the underlying approach works.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this article.

Data Availability Statement

This article is a literature synthesis and did not generate new experimental data; all figures reported are drawn directly from the cited sources, which readers should consult for full underlying data and methods.

Ethical Approval

Not applicable. This study did not involve human participants, animal subjects, or primary data collection, and so ethical approval was not required.

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