

Design for Metal Additive Manufacturing: A Review of Design Strategies and Process Constraints

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Abstract

Metal additive manufacturing (AM) enables components with high geometric complexity and functional integration; however, these advantages are realized only when topology optimization (TO) aligns with AM-specific constraints. This review examines TO strategies for metal AM, with emphasis on laser powder bed fusion (LPBF) as the most established industrial route. It categorizes and assesses density-based methods, level-set approaches, and lattice or architected-material optimization, focusing on how each captures manufacturability (overhang limits, minimum feature size, surface roughness), physics (residual stress, thermal distortion), and AM-induced anisotropy. It further distinguishes algorithms that embed constraints directly into the TO loop from workflows that rely on post-optimization repair. It discusses implications for robustness and transferability across machines and alloys. Experimental and numerical evidence for titanium alloys, aluminum alloys, nickel-based superalloys, and stainless steels is synthesized to relate design decisions and processing conditions to reported gains in stiffness-to-weight ratio, strength, fatigue performance, and buy-to-fly efficiency. Persistent gaps include validation under realistic load spectra, uncertainty quantification, standardized benchmarks, microstructure-informed objectives, and sustainability metrics. Beyond synthesizing existing TO formulations and constraints, this review contributes a criteria-based decision structure linking TO method selection, constraint strategy, and process-physics coupling and identifies four inherent paradoxes defining the field's open challenges.

Keywords: metal additive manufacturing; topology optimization; design for additive manufacturing; laser powder bed fusion; process constraints; lattice structures; process–structure–property relationships



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1. Introduction

Additive manufacturing (AM) has transformed the fabrication of three-dimensional components by enabling layer-by-layer material deposition, facilitating complex geometries, integrated functionalities, and more efficient material utilization—advantages often unattainable with conventional manufacturing methods. Among metal AM techniques, laser powder bed fusion (LPBF) is one of the most well-established and widely adopted processes, particularly in the aerospace, biomedical, and energy sectors. However, effectively leveraging LPBF requires design approaches that explicitly address the process constraints and material characteristics inherent to the technology [1,2].

Designing metal parts for LPBF is essential for both manufacturing feasibility and component quality. Although powder bed techniques do not eliminate all manufacturing limitations, they substantially alter the nature of the constraints that must be addressed during design, compared with conventional manufacturing methods. Design for additive manufacturing (DfAM) aims to optimize part geometry and, where possible, the production process itself, to reduce lead time and cost while enhancing performance, quality, and economic viability [3,4].

Within this context, topology optimization (TO) has emerged as a vital tool for design in metal AM, providing systematic approaches to generate lightweight structures with improved mechanical performance. TO reallocates material within a defined design space to maximize structural efficiency under specified loads, boundary conditions, and constraints. Unlike shape- and size-optimization techniques, TO enables the development of entirely new geometries unconstrained by predefined forms. However, conventional TO methods were largely developed without explicitly accounting for manufacturing constraints, resulting in geometries that may be unsuitable for LPBF fabrication. Constraints such as overhang angles, minimum feature sizes, surface roughness, residual stresses, and anisotropic mechanical behavior are frequently neglected, causing optimized designs to require extensive support structures, suffer distortion during production, or fail to achieve the intended mechanical performance [5–8].

To address these limitations, an increasing number of studies have explored TO formulations tailored to metal AM. These include density-based methods incorporating manufacturability constraints, level-set techniques offering enhanced geometric boundary control, and optimization strategies that exploit lattice structures and architected materials to capitalize on LPBF's layer-by-layer process. Additionally, there is growing interest in process physics-informed optimization methods that explicitly account for thermal effects, residual stresses, and distortions. These approaches differ significantly in how manufacturing constraints are handled—either by integrating them directly into the optimization workflow or by applying geometric corrections after optimization—resulting in trade-offs among robustness, computational cost, and applicability across different machines and material systems [9–12].

Despite these advances, significant challenges persist. Experimental validation typically relies on simplified loading scenarios, limited coverage of real-world service conditions, insufficient uncertainty quantification, and a lack of standardized benchmark protocols. Furthermore, microstructure-informed objectives, formal qualification standards, and sustainability metrics are only partially incorporated into current TO frameworks.

A systematic literature search was conducted using three major academic databases: Web of Science, ScienceDirect, and Google Scholar. The search combined the following keywords: “topology optimization”, “additive manufacturing”, “laser powder bed fusion”, “DfAM”, “design for additive manufacturing”, and “metal AM”. The search was limited to peer-reviewed articles published in English between January 2010 and December 2024, with selected critical advances published up to June 2026 incorporated where relevant to the review's conclusions. Conference proceedings, theses, book chapters, and non-peer-reviewed reports were excluded. Only studies that focused on metallic materials and reported experimental results were considered, excluding purely numerical or simulation-based works without experimental validation.

The initial search returned over 1000 records. A multi-stage screening process was applied: titles and abstracts were first evaluated to remove studies outside the scope of metal AM and design optimization. Subsequently, a full-text analysis was performed to assess methodological rigor, relevance to DfAM principles, and the significance of the reported findings. Studies were selected for their contributions to understanding process constraints,

design strategies, topology optimization workflows, and performance outcomes in metal AM. Inclusion criteria focused on studies that (i) proposed or applied TO methods in metal AM, (ii) addressed manufacturability constraints and/or process physics, and (iii) presented clear methodological or experimental contributions. This process resulted in the inclusion of 86 articles forming the corpus of this review. The selected studies were systematically classified according to: (i) the type of TO formulation (e.g., density-based, level-set, lattice-based); (ii) the approach used to incorporate manufacturing constraints (e.g., constraint integration versus post-processing adjustments); (iii) the consideration of process physics (e.g., thermal effects, residual stresses, distortion); and (iv) the material systems studied (e.g., titanium alloys, aluminum alloys, nickel-based superalloys, stainless steels).

Figure 1 presents the conceptual framework guiding this review, illustrating the logical progression from metal AM process characterization through topology optimization methods, manufacturability-aware design, process physics, and material performance, towards the identification of research gaps and future directions.

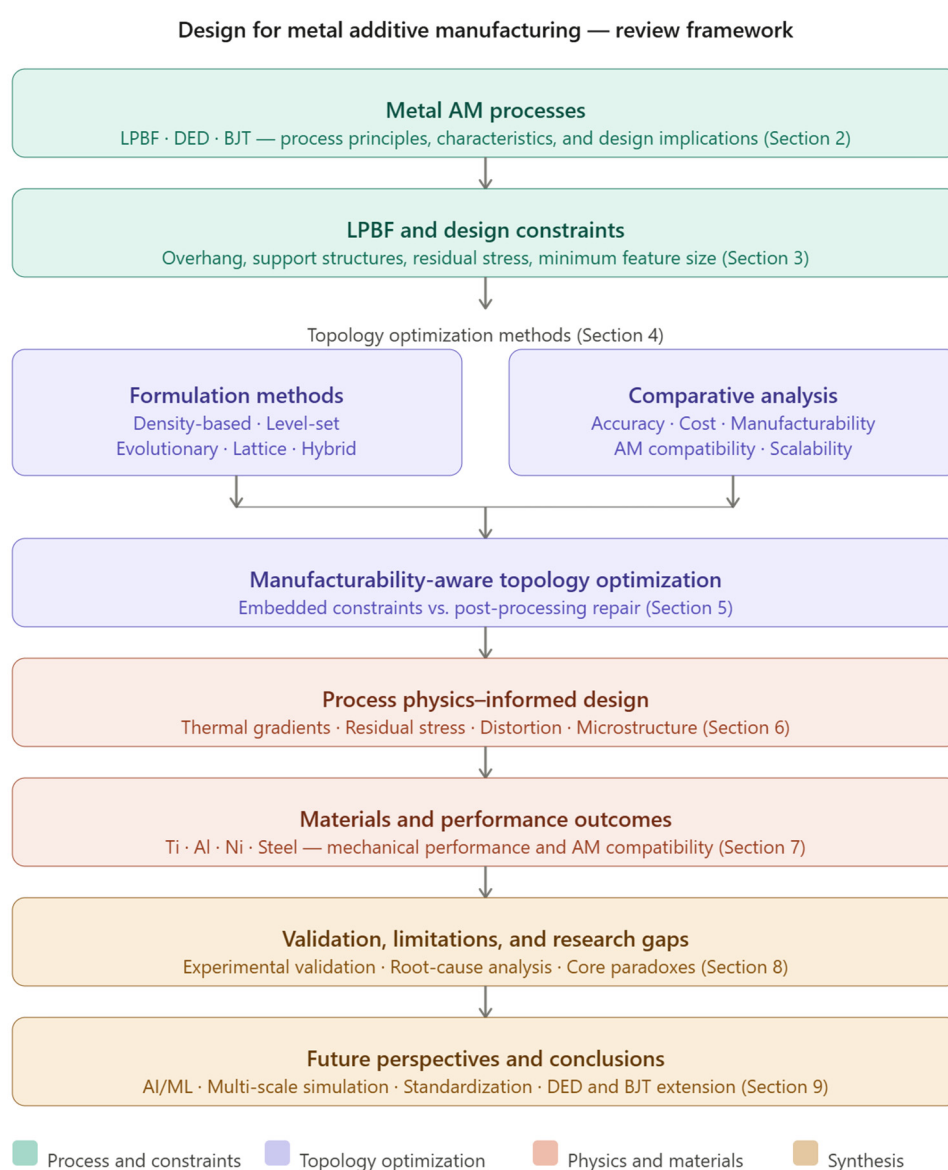


Figure 1. Conceptual framework of the review, illustrating the logical structure and thematic progression from metal AM process characterization and design constraint analysis, through topology optimization methods and process physics-informed design, to materials performance outcomes, validation, and future research directions.

Positioning Relative to Prior DfAM Literature

This work does not propose DfAM as a new concept; rather, its contribution lies in the integration of DfAM principles within a structured decision framework that explicitly links design freedom, manufacturing constraints, material and process selection, post-processing, qualification, sustainability, and industrial implementation for topology-optimized metal AM components.

Several recent contributions have addressed related aspects of DfAM. Chtioui et al. [13] reviewed DfAM rules, guidelines, and design tools, proposing a framework oriented towards early design stage decision-making, but without addressing topology optimization formulations, manufacturability-aware constraint integration, or process physics in any depth. Asapu and Ravi Kumar [14] provided a comprehensive review of DfAM with case study insights, covering support structure optimization, STL conversion errors, and lattice-based lightweighting, but with limited treatment of the mathematical formulations underlying topology optimization and no systematic discussion of process-induced residual stress or distortion. Reinke and dos Santos [15] proposed a systematic, PRISMA-based review and unified DfAM framework, identifying fragmented digital workflows, material anisotropy, and insufficient precision metrology as central barriers to industrial scalability—concerns that closely echo the research gaps identified in Section 8 of this review, but without specific focus on the mathematical and computational distinctions between topology optimization formulations or their differentiated applicability to LPBF, DED, and BJT.

Prior contributions therefore emphasize design rules, guidelines, and optimization tools in a general DfAM context, but comparatively few studies explicitly connect TO formulation selection, manufacturability constraint integration strategy (embedded versus post-processing), process physics coupling, and material-specific design implications within a single, internally consistent analytical structure focused on metal AM. Table 1 positions the present review relative to this recent literature.

This review's distinctive contribution is therefore threefold. First, it provides a comparative, criteria-based analysis of six TO formulations (density-based, level-set, evolutionary, network-based, hybrid, and lattice-based), explicitly linking each formulation to its applicable manufacturability scenarios—a level of methodological granularity not provided in [13–15]. Second, it systematically distinguishes embedded-constraint and post-processing-repair strategies for manufacturability enforcement, providing decision criteria for selecting between them based on constraint type and severity. Third, it identifies, through root-cause analysis, the fundamental barriers underlying current research gaps (Section 8.2) and articulates four inherent paradoxes of the field (Section 8.3)—design freedom versus process constraints, geometric complexity versus structural predictability, multi-objective optimization versus computational tractability, and process-informed design versus process variability—that have not been explicitly framed as such in prior DfAM reviews. This review does not claim to offer a universal DfAM framework; rather, it offers a focused, LPBF-centered synthesis intended to support more rigorous, manufacturability-aware design decisions in metal AM.

Table 1. Positioning of this review relative to recent DfAM literature.

Reference	Scope	AM Process Focus	Design Focus	Industrial Implementation	Qualification/Validation	Sustainability/Decision Support	Gap Addressed by This Review
Chtioui et al. (2023) [13]	DfAM rules, guidelines, and design tools	General (multi-process)	Early design stage decision-making	Limited discussion	Not addressed	Not addressed	No treatment of TO formulations, manufacturability-aware constraint integration, or process physics
Asapu & Ravi Kumar (2025) [14]	Comprehensive DfAM review with case studies	General (multi-process), case study on bearing bracket	Support structure optimization, STL conversion, lattice lightweighting	Discussed via case study	Briefly discussed (ASTM/ISO standards)	Cost analysis included	Limited treatment of TO mathematical formulations; no systematic process physics or residual stress discussion
Reinke & dos Santos (2026) [15]	Systematic PRISMA-based review and unified DfAM framework	General (multi-process)	Foundational principles and computational strategies	Discussed as barrier to scalability	Identified as a barrier (lack of standardized criteria)	Briefly discussed	No focus on TO formulation selection criteria, embedded vs. post-processing strategies, or LPBF/DED/BJT-specific constraint differentiation
This review	TO methods and manufacturability-aware design for metal AM	LPBF-centered, with explicit extension to DED and BJT	Six TO formulations compared; embedded vs. post-processing constraint strategies; process physics coupling	Discussed throughout (Sections 5, 6 and 9)	Root-cause gap analysis (Section 8.2); qualification barriers explicitly discussed	Sustainability gap identified (Section 8.2); decision criteria provided for TO method and constraint strategy selection	Integrates TO formulation selection, constraint integration strategy, process physics, and material-specific implications within a single decision-oriented structure

This review offers a comprehensive overview of TO methods for metal additive manufacturing, with a particular focus on LPBF. While three mainstream metal AM processes—LPBF, DED, and BJT—are compared in terms of their process characteristics and design implications, LPBF is adopted as the primary research object for several reasons. First, LPBF is currently the most widely used metal AM process for producing complex, high-performance structural components. Consequently, it represents the largest body of literature on TO integration and manufacturability constraints. Second, the high-dimensional accuracy, fine-grained feature resolution, and well-established process parameters of LPBF make it particularly amenable to the geometric complexity generated by TO algorithms. Third, the process physics of LPBF—including steep thermal gradients, rapid solidification, and residual stress accumulation—pose the most extensively studied and design-relevant constraints in the context of DfAM. Where relevant, the applicability and unique challenges of the discussed TO approaches when extended to DED and BJT are also addressed, particularly in Sections 5 and 9. This review categorizes approaches based on the optimization formulation, the extent to which manufacturability and process physics are considered, and the material systems examined—including titanium alloys, aluminum alloys, nickel-based superalloys, and stainless steels. By summarizing known performance improvements and highlighting ongoing research gaps, this work aims to clarify current advancements and propose future directions for developing more robust, qualification-oriented design strategies.

2. Metal AM Methods

Metal AM processes can be broadly classified by their heat source and material supply method. Common heat sources include lasers, electron beams, and electric arcs, while raw materials are supplied as powder, wire, or sheets. The most widely used metal AM processes, powder bed fusion (PBF), directed energy deposition (DED), and binder jetting (BJT), differ significantly in their working principles, and these differences directly influence design constraints and manufacturing capabilities [16–19].

In PBF, a focused energy source selectively melts regions of a powder bed layer by layer [20,21]. LPBF offers high spatial resolution (beam size 30–150 μm) and fine layer thicknesses (50–200 μm), enabling complex geometries with high dimensional accuracy [22]. The recoater blade material has been shown to directly influence the mechanical properties of printed parts, with soft blades accommodating high-aspect-ratio structures and hard blades improving powder distribution consistency [23]. EBPBF, operating in a vacuum environment, allows higher build speeds and thicker layers, but at the cost of surface finish quality and geometric detail [24,25]. Comparative studies between LPBF and EBPBF on Ti-6Al-4V have highlighted significant differences in microstructural texture and mechanical anisotropy, which must be considered at the design stage [25,26]. Repeatability and reproducibility remain key challenges across PBF systems, with process variability directly affecting minimum feature size, surface roughness, and support structure requirements [27].

In DED, energy and feedstock material are simultaneously delivered to the build zone, allowing greater flexibility in part size and multi-material deposition, but with lower resolution compared to PBF [21,24]. In BJT, a liquid binding agent selectively joins powder particles at room temperature, followed by sintering [28,29]. This room-temperature processing avoids the high thermal gradients characteristic of fusion-based processes, significantly reducing residual stress and distortion [28]. As a result, BJT is particularly suitable for complex geometries and overhanging features that would otherwise require extensive support structures [28,30]. However, the sintering step introduces dimensional shrinkage that must be accounted for at the design stage, representing a key process constraint for BJT components [28].

These process characteristics are fundamental to understanding the design strategies and constraints discussed in subsequent sections. Table 2 provides a comparative overview of LPBF, DED, and BJT, summarizing their principal differences in process characteristics, manufacturability constraints, and performance outcomes.

Table 2. Comparative Overview of LPBF, DED, and BJT [4,16,18–20,22,25,27–36].

Category	LPBF	DED	BJT
Process Principle	A laser selectively melts successive layers of metal powder spread across a powder bed inside a closed chamber	Metallic feedstock (powder or wire) is directly delivered into a melt pool generated by a laser, electric arc, or electron beam.	A liquid binder is selectively deposited onto a metal powder bed to form a green part, which is subsequently cured and sintered.
Process Characteristics	High dimensional accuracy and geometric resolution; relatively low build rate due to thin layers and localized laser scanning.	High deposition rate and productivity for large-scale components; lower dimensional accuracy and rougher surface finish.	High throughput with the capability for simultaneous multi-part fabrication; The build speed is high and the overall cycle time is strongly dependent on thermal post-processing.
Energy Source and Consolidation	Full melting of powder by laser; consolidation occurs instantaneously layer by layer.	High thermal energy input via laser, arc, or electron beam; consolidation occurs continuously during material deposition.	No melting during printing; densification is achieved exclusively through post-process sintering.
Typical Materials	Titanium alloys, nickel-based superalloys, stainless steels, aluminum alloys, and high-performance alloys.	Steels, titanium alloys, nickel-based superalloys, and repair materials for structural components.	Stainless steels, nickel-based superalloys, copper alloys, and sinterable metal systems.
Dimensional Accuracy	Very high; fine tolerances and excellent repeatability achievable.	Moderate; post-process machining is frequently required to meet dimensional tolerances.	Moderate; sintering-induced shrinkage introduces dimensional variability that must be compensated at the design stage.
Surface Finish	Best among the three processes; mechanical finishing may still be required for functional surfaces.	Relatively rough Due to the large melt pool size and deposition bead geometry.	Intermediate; generally smoother than DED but inferior to LPBF.

Table 2. Cont.

Category	LPBF	DED	BJT
Geometric Capability	Excellent for complex geometries, lattice structures, and internal channels.	Limited capability for fine features and high geometric complexity; better suited for near-net-shape robust structures.	Good geometric freedom; surrounding powder The bed provides natural support for complex shapes.
Support Structures	Frequently required for overhanging features and thermally stressed regions.	Less critical than in LPBF but still necessary for certain geometries.	Generally not required; the powder The bed acts as a natural support medium.
Manufacturability Constraints	Overhangs below ~45° typically require supports; removal of powder from enclosed channels can be challenging.	Resolution is limited by the melt pool and bead size; small channels and fine features are difficult to fabricate reliably.	Sintering-induced shrinkage and distortion limit dimensional precision in thin-walled and delicate geometries.
Typical Part Size	Limited by build chamber dimensions; generally suited for small-to-medium components.	Well-suited for large-scale components and in-situ repair applications.	Moderate scale; primarily constrained by sintering furnace dimensions.
Process-Induced Anisotropy	Significant; driven by rapid solidification and layer-wise thermal cycling.	Pronounced; characterized by columnar grain growth along the build direction.	Comparatively low; relatively isotropic microstructure obtained after homogeneous sintering.
Mechanical Performance	Excellent mechanical properties; strongly dependent on build orientation and process parameters.	Good structural performance; lower property homogeneity compared to LPBF.	Generally lower mechanical properties than LPBF and DED due to residual porosity after sintering.
Residual Stresses	Very high; generated by steep thermal gradients and rapid solidification.	High; resulting from continuous and concentrated heat input during deposition.	Low during printing; residual stress develop primarily during the sintering stage.
Typical Porosity	Lack of fusion and keyhole porosity associated with laser–powder interaction.	Gas entrapment and the melt pool instability.	Incomplete densification during sintering; porosity The level is strongly dependent on sintering parameters.

Table 2. Cont.

Category	LPBF	DED	BJT
Common Defects	Lack of fusion, warping, keyhole porosity, and thermal cracking.	Excessive dilution, hot cracking, inclusions, and weak inter-track bonding.	Non-uniform shrinkage, delamination, geometric distortion, and residual porosity.
Typical Final Density	Very high (>99%); suitable for structural and safety-critical applications.	High (95–99%); dependent on process parameters and deposition strategy.	Moderate to high (90–98%); dependent on sintering efficiency and powder characteristics.
Post-Processing Requirements	Support removal, stress-relief heat treatment, HIP, and surface machining are commonly required.	Machining and heat treatment are generally essential to achieve dimensional and microstructural targets.	Debinding, depowdering, and sintering are mandatory; metal Infiltration may also be applied to reduce residual porosity.
Main Advantages	Highest dimensional precision, near-full density, and excellent geometric complexity capability.	High deposition rate, suitability for large components, and effective repair and cladding capability.	High throughput, relatively lower equipment and material costs, and no support structure requirement.
Main Disadvantages	High equipment cost, low build rate, and severe residual stress accumulation.	Lower geometric resolution, poor surface finish, and significant post-processing requirements.	Dimensional shrinkage during sintering, lower mechanical performance than fusion-based processes.
Typical Applications	Aerospace structures, biomedical implants, complex tooling, and high-performance components.	Turbine blade repair, cladding, large structural components, and industrial maintenance.	Mass production of complex metal parts, cost-sensitive applications, and sintered structural components.

3. Laser Powder Bed Fusion and Design Constraints

LPBF is one of the most widely used metal AM processes, enabling the fabrication of complex, customized geometries directly from digital designs [20,21]. The process involves CAD modeling, powder spreading, laser scanning, and post-processing operations. In this technique, thin layers of metal powder are selectively melted by a focused laser beam, producing fully dense metallic components layer by layer. Due to its layer-by-layer nature, internal cavities may trap unfused powder, which can compromise component performance if it remains in functional channels, sinters during post-process heat treatment, or is released during operation [31,32].

3.1. LPBF Process Characteristics

The LPBF process begins with the uniform deposition of a thin layer of metal powder onto the build platform. A high-energy laser beam scans the powder bed in the X–Y plane, selectively melting the powder according to the component's sliced geometry. The molten pool rapidly solidifies, forming dense tracks. After each layer is completed, the build platform lowers by a predefined increment, a new powder layer is deposited, and the sequence is repeated until the component is fully fabricated. Upon completion, unmelted powder is recovered for reuse, support structures are removed, and post-processing operations are applied as required [37].

The principal LPBF process parameters—laser power, scan speed, layer thickness, and hatch spacing—collectively govern energy density, melt-pool stability, and the resulting microstructure. Typical layer thicknesses range from 20 to 100 μm , with powder particle sizes of 20 to 50 μm . The process enables near-full density ($\approx 99\text{--}100\%$), yielding mechanical properties superior to those achieved by conventional sintering due to complete particle fusion. LPBF is predominantly applied to monometallic powders, including titanium, aluminum, and steel alloys, as well as high-performance alloys such as cobalt–chromium and nickel-based systems. Support structures are required to mitigate residual stresses and thermal distortions induced by the rapid thermal cycles inherent to the process [33].

Compared with conventional manufacturing, LPBF offers high dimensional accuracy, near-net-shape fabrication, reduced lead times, and the ability to produce geometrically complex, fully functional components. However, the process is energy-intensive, increasing operational costs and the risk of defects, including porosity, lack of fusion, and microcracking. Process parameter optimization and in situ monitoring are therefore essential to ensure stability and part quality [38].

3.2. Geometric and Manufacturability Constraints

In LPBF, not all geometric configurations are equally manufacturable. Inclined surfaces, overhanging features, narrow channels, and thin walls pose specific fabrication challenges that must be addressed at the design stage. When assessing LPBF manufacturability, two fundamental questions arise: first, whether the complete geometry can be successfully built without failure; and second, whether the fabricated part meets dimensional, geometric, and mechanical performance requirements [39].

Overhanging features below a critical angle—typically 45° from the horizontal—require support structures to prevent thermal distortion and collapse during fabrication. The design and placement of support structures significantly influence material consumption, build time, and post-processing effort, and their minimization is a primary objective in DfAM. Minimum feature sizes are constrained by the laser spot diameter and layer thickness, limiting the resolution of fine geometric details such as thin struts, small holes, and sharp edges. Enclosed channels present additional challenges, as trapped powder removal after printing can be difficult or impossible for complex internal geometries [39,40].

From a sustainability perspective, LPBF is most advantageous when it replaces highly subtractive processes: studies indicate that when material removal in CNC machining exceeds 70%, LPBF can offer superior energy and environmental performance [34,41].

However, LPBF itself is energy-intensive—the laser, powder bed heating, and inert gas circulation represent the dominant energy consumers—and metallic powder production by gas atomization carries significant embedded energy (100–150 MJ/kg for aluminum alloys). These considerations underscore the importance of process optimization and powder reuse strategies in sustainable DfAM workflows [40,41].

3.3. Process-Induced Anisotropy and Defects

Due to the layer-by-layer nature of LPBF, manufactured components exhibit anisotropic mechanical properties, typically with reduced strength along the build direction (Z-axis). This anisotropy originates from directional solidification-driven columnar grain growth, the development of preferred crystallographic textures, and variations in interlayer bonding quality arising from rapid thermal cycling [42].

Jeon et al. [43] investigated the influence of microstructure and internal defects on mechanical anisotropy and asymmetry in LPBF-processed 316L stainless steel through tensile and compression tests in multiple orientations, supported by finite element simulations. Their findings demonstrate that pore morphology and melt-pool boundary geometry are the primary factors governing anisotropic and asymmetric mechanical behavior. Pitrmuc et al. [44] further examined the relationship between build orientation, process parameters, and mechanical anisotropy in LPBF 316L, concluding that optimized process conditions yield mechanical properties comparable to those of conventionally manufactured counterparts.

In summary, LPBF-fabricated components exhibit significant mechanical anisotropy driven by columnar grain formation, crystallographic texture, and interlayer bonding variability [26,44]. These microstructural features directly influence fatigue behavior and crack propagation, making build orientation a critical design variable [45]. Pore morphology and melt-pool boundaries play a key role in determining strength asymmetry [43,44], and optimized processing conditions can mitigate—though not eliminate—orientation-dependent performance variations [38,43].

4. Topology Optimization Methods for Metal AM

TO is among the most advanced tools in computational structural and functional design, enabling the automatic identification of optimal material distributions within a predefined domain to maximize structural performance—whether in terms of stiffness, stability, or thermal efficiency—while simultaneously minimizing material consumption [9,46]. Unlike shape or size optimization, TO operates at a conceptual level, generating innovative structural solutions unconstrained by predefined geometries or designer intuition. It has been reported that, in typical design problems, average performance improvements are approximately 5–10% for size optimization, 10–30% for shape optimization, and 40–100% for topology optimization [12,47,48]. This substantial performance advantage, combined with LPBF's capability to fabricate highly complex geometries, makes TO particularly well-suited to metal AM applications.

Several TO formulations have been developed and applied in the context of metal AM. The following subsections review the principal approaches—density-based methods, level-set methods, and lattice-based methods—as well as evolutionary, network-based, and hybrid formulations, and discuss their mathematical foundations, strengths, limitations, and compatibility with AM process constraints.

Figure 2 illustrates the overall topology optimization workflow, incorporating environmental impact assessment, AI-powered distortion and performance prediction, and support/self-support constraints within an iterative loop until convergence.

Recent developments have extended these formulations to multi-material systems, enabling the simultaneous optimization of material distribution and structural topology—a particularly promising direction for metal AM components requiring spatially varying mechanical or thermal properties [49,50].

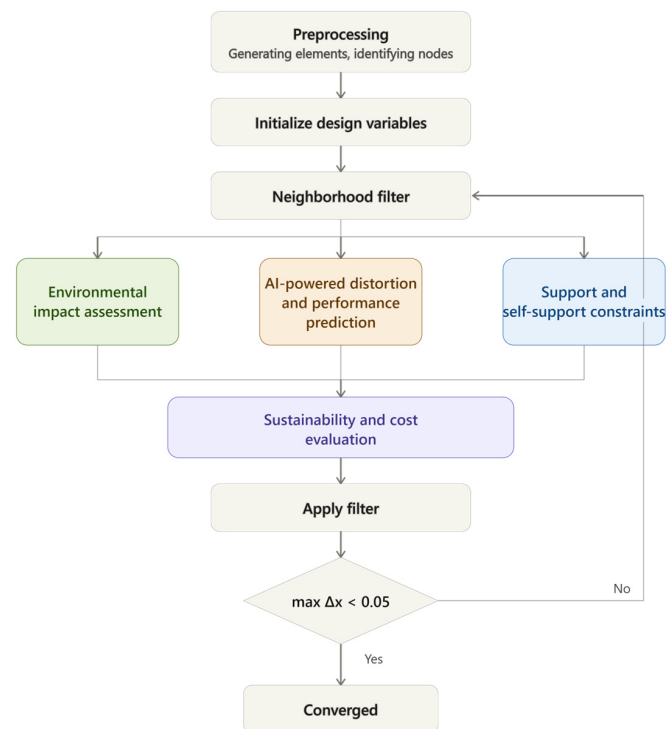


Figure 2. Flowchart illustrating the topology optimization process for Metal Additive Manufacturing. The framework integrates artificial intelligence for distortion and performance prediction with sustainability assessment, including environmental impact and energy cost evaluation. This multi-objective approach enhances structural reliability while reducing support volume and ecological footprint.

4.1. Density-Based Methods

Density-based methods represent the design domain as a mesh of finite elements, each assigned a continuous material density value ranging from 0 (void) to 1 (solid). The optimization process adjusts these density values to minimize or maximize a specific objective function—such as structural compliance or weight—subject to constraints including volume fraction, minimum feature size, and manufacturing requirements [9,51].

The most widely adopted density-based formulation is the Solid Isotropic Material with Penalization (SIMP) method, which interpolates material stiffness as a power-law function of element density, effectively penalizing intermediate densities and driving the solution toward binary solid–void distributions [9]. SIMP is favored for its numerical robustness, computational efficiency, and ease of implementation across a broad range of structural problems.

A key limitation of density-based methods is the presence of gray regions—elements with intermediate density values that do not correspond to any physically realizable material state. These diffuse boundaries complicate the application of interface conditions and can produce non-physical structural responses. Density filtering and projection techniques have been developed to mitigate this issue: regularized Heaviside projection functions enforce minimum length scales in both solid and void phases, while morphological filters integrated into the filtering framework further improve boundary sharpness [51,52]. Despite these advances, gray transition zones remain a characteristic drawback of density-based formulations, particularly in problems requiring precise geometric boundary definition.

4.2. Level-Set Methods

Level-set methods formulate TO by explicitly evolving the structural boundary throughout the optimization process. Rather than using continuous density variables, the interface between solid material and void is represented implicitly by a level-set func-

tion $\varphi(x)$, with the structural domain defined by regions where $\varphi(x) > 0$ and the boundary located at the zero contour $\varphi(x) = 0$ [53,54].

The core principle of level-set TO is to remove material from regions of low stress and add material to regions of high stress, governed by a predefined removal rate, expressed as a fraction of the maximum stress. This rate controls both the velocity of boundary evolution and the nucleation of new holes along closed stress contours. The explicit boundary representation eliminates gray regions, producing sharp, well-defined solid–void interfaces with superior geometric accuracy compared to density-based methods [52,54]. However, level-set methods introduce higher numerical complexity, including reinitialization challenges and sensitivity to the choice of velocity extension schemes, which can compromise convergence stability and increase computational cost.

4.3. Lattice—Based Methods

Lattice structures and architected materials have become central to high-performance DfAM, enabling simultaneous weight reduction and multifunctional properties that are unachievable with homogeneous solid designs [55,56]. Rather than optimizing a simple solid–void distribution, lattice-based TO methods optimize the internal microarchitecture of components—through periodic unit-cell patterns or spatially graded density distributions—to maximize properties such as specific stiffness, energy absorption, and thermal conductivity [56,57].

The most common strut-based unit cells include body-centered cubic (BCC), face-centered cubic (FCC), and their variants incorporating additional struts along the build direction (BCCZ, FCCZ), as well as octet-truss and diamond configurations [58]. The dominant deformation mode governs the mechanical behavior of these architectures. Octet-truss configurations are stretching-dominated and well-suited for supporting loads from multiple directions, offering superior stiffness and strength. Cubic-truss configurations are primarily governed by strut elongation, making them suitable for supporting high loads along a single direction. Open-cell configurations are bending-dominated, which makes them particularly effective for energy-absorption applications [55,59,60].

A key design parameter across all lattice configurations is the volumetric fraction (VF), defined as the ratio of the lattice volume to the total enclosed volume; a VF of 1 corresponds to a fully solid structure. Reducing VF decreases material consumption and component weight while preserving structural integrity, provided that the minimum strut diameter and unit-cell size remain within the printability limits of the selected AM process [57,61]. The integration of graded lattice structures—in which VF varies spatially according to local stress distributions derived from TO—enables further performance improvements over uniform lattice infills, as demonstrated by Panesar et al. [62]. A representative design strategy for end-use parts combines a reticulated octet-truss core at low volume fraction (VF $\approx$ 0.15) with a solid external surface, substantially reducing part weight while preserving functional and mechanical integrity [63,64].

Advances in metal AM, particularly LPBF, have enabled the reliable fabrication of complex lattice geometries with strut diameters as small as 200–300 μm , making lattice-based TO practically viable for aerospace, biomedical, and lightweight structural applications [56,63]. Beyond strut-based architectures, Figure 3 presents additional lattice and lightweight configurations—including simple cubic, fluorite, truncated cube, truncated octahedron, Kelvin cell, IsoTruss, Weaire–Phelan, and triply periodic minimal surface (TPMS) gyroid and diamond designs—broaden the design space available for property tailoring.

Traditionally, lattice and cellular structures were fabricated using casting, press-fitting, or metal wire assembly, approaches that were often complex, costly, and constrained by design limitations that hindered the lightweight potential of such structures. Advances

in metal AM now enable the efficient production of substantially more complex lattice geometries than were previously achievable [59,61,65].

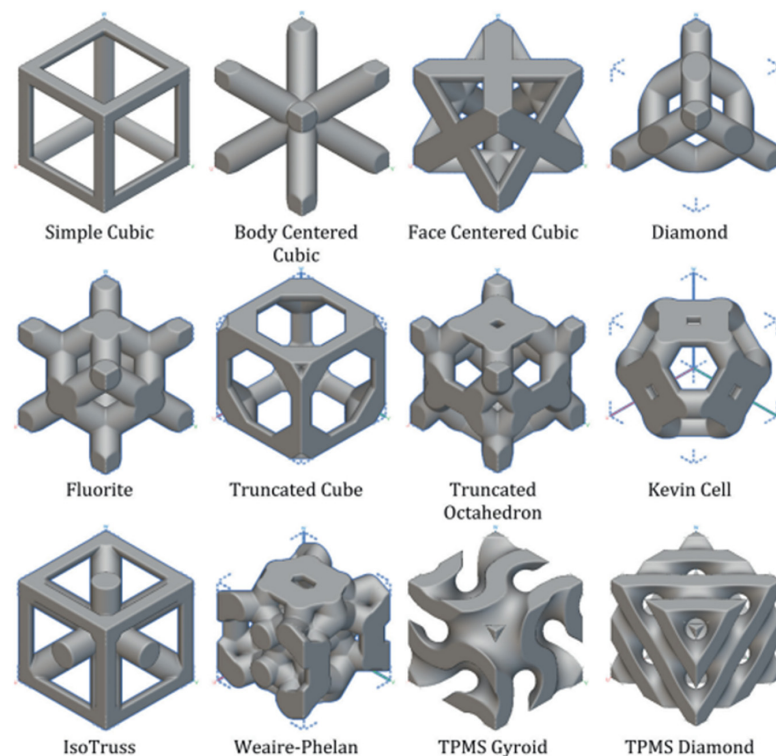


Figure 3. Examples of lattice and lightweight architectures used in metal additive manufacturing: (1) simple cubic, (2) body-centered cubic, (3) face-centered cubic, (4) diamond, (5) fluorite, (6) truncated cube, (7) truncated octahedron, (8) Kelvin cell, (9) IsoTruss, (10) Weaire–Phelan, (11) TPMS gyroid, and (12) TPMS diamond [64].

4.4. Comparative Analysis

The six TO formulations reviewed in Sections 4.1–4.3 and summarized in Table 2 differ fundamentally in their mathematical representation, computational demands, and suitability for metal AM applications. Rather than being mutually exclusive, these methods occupy distinct niches defined by the trade-off between computational efficiency, boundary precision, manufacturability enforcement, and scalability.

Density-based methods, particularly SIMP, remain the most widely adopted formulation due to their low computational cost, straightforward implementation, and robust convergence behavior [49,50]. Their continuous design variables and well-established sensitivity analysis make them well-suited for large-scale structural optimization problems where computational efficiency is paramount. However, the inherent presence of gray regions—elements with intermediate density values that do not correspond to any physically realizable material state—necessitates post-processing filtering and projection techniques to produce binary, manufacturable designs [60]. While minimum member size control and overhang filters have been successfully integrated into density-based frameworks [6,54]. Their ability to enforce sharp geometric boundaries and complex AM-specific constraints remains limited compared to boundary-based methods.

Level-set methods address this limitation by representing structural boundaries as the zero-contour of an implicit function, enabling precise geometric control and smooth boundary definition [66,67]. This makes them particularly well-suited for problems where interface geometry is critical, such as the design of conformal cooling channels, thin-walled aerospace structures, and components with strict surface quality requirements.

However, level-set methods introduce higher numerical complexity, including reinitialization challenges and sensitivity to the choice of velocity extension schemes, which can compromise convergence stability [61]. Their medium-to-high computational cost also limits their applicability to large-scale or multi-physics problems without significant algorithmic acceleration.

Evolutionary methods such as BESO offer an intuitive material addition and removal process that avoids gray regions entirely, producing clear black-and-white designs directly [68]. They have been widely applied to conceptual structural design and compliance minimization benchmarks, including cantilever beam and bridge problems. However, their discrete material evolution process is prone to checkerboarding instabilities and slow convergence, and their moderate compatibility with AM-specific constraints has historically limited their use in manufacturability-aware design workflows. Recent advances have addressed some of these limitations through stress-based multi-material BESO formulations [49] and cross-platform implementations with enhanced computational efficiency [50], extending the applicability of evolutionary methods to more complex and industrially relevant design problems in metal AM.

Network-based and graph-theoretic formulations represent a fundamentally different paradigm, encoding structural connectivity through node and edge parameters rather than continuous density or boundary fields. These methods excel in multi-scale systems and complex interconnected structures, offering efficient representation of load paths and material interfaces. However, their high modeling complexity and limited scalability primarily restrict their current applications to research contexts, and their integration with AM process constraints remains in its early stages.

Hybrid approaches, which combine two or more of the above formulations, consistently achieve the best balance between manufacturability and structural performance, at the cost of significantly higher implementation and computational complexity. By coupling density-based initialization with level-set refinement, or integrating lattice parameterization within a density-based framework, hybrid methods can simultaneously enforce overhang constraints, minimum feature sizes, and stress limitations within a single optimization loop [63,69]. These approaches are increasingly adopted for high-performance AM applications in aerospace and biomedical engineering, where both geometric complexity and process compliance are non-negotiable requirements.

Lattice-based optimization occupies a unique position in this landscape, focusing on the design of periodic or graded microstructures rather than on macroscopic topology. By optimizing unit-cell geometry and spatial grading, lattice-based methods enable the creation of lightweight, multifunctional structures with tailored mechanical, thermal, and acoustic properties [70,71]. Their excellent compatibility with AM—particularly LPBF, which can reliably fabricate strut diameters down to 200–300 μm —makes them the method of choice for metamaterials and energy-absorbing structures. However, their scalability is inherently limited by the computational cost of homogenization-based analyses and the difficulty of transitioning between lattice and solid regions without introducing stress concentrations.

Taken together, the choice of TO formulation should be driven by the specific requirements of the design problem: density-based methods are appropriate for early-stage conceptual design and large-scale problems; level-set methods are preferred when precise boundary control and surface quality are critical; hybrid and lattice-based approaches are best suited for high-performance AM applications where manufacturability and multifunctionality must be simultaneously optimized. No single method currently satisfies all requirements across the full spectrum of metal AM applications, and the development of computationally efficient, constraint-rich hybrid formulations remains one of the central

open challenges in the field. Table 3 summarizes and compares the six TO formulations discussed above across key criteria including representation, manufacturability, computational cost, and typical applications.

4.5. Emerging Hybrid Approaches

Purely density-based TO formulations, despite their numerical robustness and ease of implementation, face well-documented limitations in the context of metal AM: diffuse solid–void boundaries, checkerboarding instabilities, and the generation of thin members that violate minimum feature size constraints [9,51]. These shortcomings have motivated the development of hybrid TO approaches that combine the strengths of multiple formulations to simultaneously address geometric precision, manufacturability enforcement, and structural performance.

The most widely investigated hybrid strategy couples density-based and level-set methods. In this formulation, a level-set function governs the macroscopic boundary geometry—ensuring sharp, well-defined interfaces—while internal material gradation is represented through density variables, enabling concurrent optimization of external shape and internal structure within a single iterative process [72]. This approach eliminates gray regions at the boundary while retaining the computational efficiency of density-based sensitivity analysis in the interior domain, making it particularly well-suited for LPBF components in which both surface quality and internal porosity distribution are design-critical parameters.

A second class of hybrid approaches integrates lattice parameterization within density-based or level-set frameworks, enabling simultaneous optimization of macroscopic topology and microscopic unit-cell geometry. These multi-scale formulations exploit homogenization theory to bridge length scales, allowing the design of graded lattice structures with spatially varying mechanical properties [62]. Panesar et al. demonstrated that functionally graded lattice structures derived through TO exhibit superior stiffness-to-weight ratios compared to uniform lattice infills, highlighting the practical advantage of integrating grading strategies directly into the optimization loop [62].

A third emerging direction involves the incorporation of physics processes, particularly residual stress and thermal distortion models, directly into hybrid TO frameworks. By coupling thermomechanical finite element simulations with TO sensitivity analysis, these approaches constrain not only the geometry but also the process-induced stress state of the optimized design [10,56]. While computationally demanding, such formulations represent the closest current approximation to a truly process-chain-aware TO methodology and are expected to gain traction as simulation efficiency improves.

Despite these advances, hybrid approaches introduce significant implementation complexity and high computational costs that currently limit their application to relatively small design domains or simplified process models. The scalability of hybrid formulations to large-scale, industrially relevant components remains an open challenge, and the lack of standardized software implementations further restricts their adoption beyond specialized research groups. Recent efforts towards cross-platform implementations of enhanced BESO [50] and stress-based multi-material evolutionary formulations [49] represent promising steps towards broader accessibility and industrial adoption of advanced TO methods. Table 4 summarizes the principal manufacturing constraints relevant to topology optimization for metal AM, including their physical origin, impact on the AM process and on TO, and corresponding mitigation strategies. Future developments in parallel computing, surrogate modeling, and AI-assisted optimization are expected to reduce these barriers progressively, positioning hybrid TO as the dominant paradigm for high-performance metal AM design in the coming decade.

Table 3. Comparative Analysis of Topology Optimization Methods for Metal Additive Manufacturing [46,49,50,54,55,57,60,62,64,72–74].

Aspect	Density-Based	Level-Set	Evolutionary	Network-Based	Hybrid	Lattice-Based
Structural Representation	Pseudo-density field distributed over finite elements	Implicit boundary represented by a signed distance function	Material distribution governed by iterative element addition/removal rules	Graph/network encoding structural connectivity through nodes and edges	Combination of two or more formulations	Discrete periodic or graded microstructure defined by unit-cell geometry
Design Variables	Continuous element density (0–1)	Level-set function values at nodes	Element survival/removal criteria	Node and edge parameters	Mixed variables depending on coupled formulations	Geometric parameters of unit cells (strut diameter, cell size, relative density)
Boundary Definition	Diffuse; intermediate densities produce unclear solid–void interfaces	Excellent, sharp and smooth boundaries defined by the zero-contour	Discrete and jagged; staircase effects common	Connectivity-driven; dependent on graph resolution	Improved relative to single-method formulations	Cell-dependent; boundary quality depends on unit-cell type and resolution
Gray Regions	Present; require post-processing projection or filtering	Absent	Absent	Generally absent	Reduced or controlled	Absent
Implementation Complexity	Low	Medium to High	Medium	High	High	High
Computational Cost	Low	Medium to High	Medium	High	High to Very High	High
Manufacturability Enforcement	Moderate	Good	Moderate	Good	Excellent	Excellent
Compatibility with AM	Moderate	High	Moderate	High	Very high	Very high
Scalability	High	Medium	Medium	Medium/Low	Medium	Limited

Table 3. Cont.

Aspect	Density-Based	Level-Set	Evolutionary	Network-Based	Hybrid	Lattice-Based
Typical Applications	General structural optimization; compliance minimization	Geometric boundary control; interface and shape optimization problems	Conceptual structural design; material distribution problems	Multi-scale systems; complex interconnected and load-path structures	High-performance AM components with simultaneous manufacturability and performance requirements	Metamaterials; lightweight and multifunctional structures
Manufacturing Constraints Addressed	Minimum member size; density filtering; overhang angle control	Smooth boundary curvature; minimum wall thickness	Connectivity preservation; minimum feature thickness	Node connectivity; printable link geometry	Overhang angle, minimum feature size, and residual stress; combined constraints	Unit-cell printability; minimum strut diameter; maximum aspect ratio
Key Strengths	Simple implementation; robust and well-established convergence behavior	Sharp boundary definition; precise geometric control; no gray regions	Intuitive material evolution; clear black-and-white designs	Efficient representation of complex structural interactions and multi-scale connectivity	Best balance between structural performance and manufacturability compliance	Excellent specific stiffness; tailorable mechanical, thermal, and acoustic properties
Key Limitations	Gray regions require post-processing; limited geometric precision at boundaries	Numerical instability; reinitialization challenges; higher computational demand	Slow convergence; susceptibility to checkerboarding; limited constraint integration	High modeling complexity; limited scalability to large domains	High implementation and computational complexity; limited software availability	Difficult scalability to large components; high homogenization simulation cost
Typical Validation Approaches	Benchmark compliance optimization (MBB beam, cantilever)	Shape optimization and interface tracking benchmarks	Cantilever and compliance minimization case studies	Multi-scale structural and network optimization problems	AM-oriented structural optimization benchmarks with experimental verification	Experimental AM fabrication and mechanical testing; homogenization analysis

Table 4. Manufacturing constraints in topology optimization for metal additive manufacturing [5,6,10,11,17,19,26,27,35,40,43–45,51,69,71,75,76].

Constraint	Definition	Physical Origin	Impact on AM	Impact on TO	Mitigation Strategies
Overhang Constraint	Geometric limitation associated with inclined surfaces lacking adequate support during fabrication	Gravity, incomplete solidification, and insufficient thermal and mechanical support of the melt pool	Layer collapse, local deformation, and excessive support structure requirements	Restricts free-form geometries and limits lattice member orientation	Angular filtering, directional density constraints, self-supporting geometry optimization
Minimum Feature Size	Lower bound on the thickness of struts, walls, or geometric features	Process resolution limits imposed by laser spot diameter, layer thickness, and melt-pool stability	Fabrication of fragile or non-manufacturable thin members	Prevents checkerboarding and eliminates degenerate members from the optimized design	Density filtering, Heaviside projection, length-scale enforcement
Surface Roughness	Surface irregularities generated during powder fusion and layer deposition	Layer stair-stepping, partially melted powder particles, and build orientation effects	Reduced surface quality and increased stress concentration at functional interfaces	Affects the mechanical performance and contact behavior of optimized surfaces	Post-process finishing, optimized build orientation, geometric boundary refinement
Residual Stress	Internal stresses accumulated during rapid solidification and cooling	High thermal gradients and differential shrinkage across successive layers	Warping, cracking, and structural failure during or after fabrication	May invalidate theoretically optimal geometries if not accounted for during optimization	Thermomechanical simulation, geometric compensation, thermal management strategies
Geometric Distortion	Dimensional deviation between the designed and fabricated geometry	Thermal shrinkage and redistribution of residual stresses after fabrication	Loss of dimensional accuracy and functional misalignment	Reduces the fidelity of optimized solutions relative to as-built performance	Distortion compensation models, optimized support placement, thermal control
Anisotropy	Direction-dependent mechanical properties arising from the build process	Layer-by-layer deposition, directional solidification, and process-induced crystallographic texture	Non-uniform mechanical behavior along different loading directions	Requires anisotropic constitutive modeling to ensure accurate performance prediction	Build orientation optimization, anisotropic homogenization, orientation-aware TO formulations
Fatigue Performance	Progressive mechanical degradation under cyclic loading conditions	Internal defects, surface roughness, residual stress concentration, and microstructural heterogeneity	Reduced service life and premature crack initiation at defect sites	Requires durability-oriented objective functions and fatigue life constraints	Fatigue-aware optimization models, geometric smoothing, TPMS-based lattice structures
Post-processing Requirements	Additional operations required after fabrication to achieve the final dimensional and surface quality	Need for support removal, surface finishing, and heat treatment to relieve residual stresses	Increased production cost, lead time, and manufacturing complexity	Must be integrated into the design stage to minimize post-processing burden	DfAM principles, support structure minimization, accessible internal geometry design

5. Manufacturability-Aware Topology Optimization

While classical TO produces highly efficient mechanical structures, the resulting geometries often cannot be directly fabricated using metal AM processes. Challenges such as support-structure requirements, minimum feature sizes, surface roughness, and thermal distortion require explicit consideration of manufacturability criteria during the optimization process. This has given rise to manufacturability-aware TO, in which process constraints are incorporated from the initial design phase, reducing the gap between computational design and physical fabrication, decreasing the need for post-processing corrections, and increasing the reliability of transferring optimized geometries to manufactured components.

5.1. Overhang, Length-Scale, and Surface Constraints

A primary challenge in LPBF is the management of overhanging features—unsupported regions oriented below a critical angle relative to the horizontal, typically between 30° and 45° —that require support structures to prevent thermal distortion, layer collapse, and surface defects during fabrication. Support structures increase material consumption, extend build time, and demand additional post-processing for removal and surface finishing. Consequently, a significant body of research has focused on incorporating overhang constraints directly into TO formulations to generate self-supporting geometries [6,54].

Two principal strategies have been developed for enforcing overhang constraints. Density-based approaches apply directional filters or anisotropic operators to penalize material placed in non-self-supporting configurations relative to the build direction, discouraging the formation of overhanging members during the optimization loop [54]. Geometric visibility approaches, by contrast, assess the line-of-sight accessibility of each material point from the build platform, identifying and removing non-manufacturable regions from the design domain [6]. Both strategies effectively reduce or eliminate support requirements. However, density-based methods integrate more naturally into gradient-based optimization workflows, while geometric approaches offer greater precision in identifying critical overhang regions.

Minimum feature size constraints are enforced through density filtering and Heaviside projection schemes that prevent the formation of thin members below the printable resolution of the LPBF process [60]. Surface roughness, while not typically incorporated as an explicit TO constraint, is indirectly influenced by build orientation—a key design variable that determines the stair-stepping effect and the extent of partially melted powder adhesion on inclined surfaces. Build orientation optimization can therefore be treated as a complementary design decision within the manufacturability-aware TO workflow [45,77].

5.2. Embedded Constraints vs. Post-Processing Repair

A fundamental decision in manufacturability-aware TO for metal AM concerns whether process constraints should be incorporated directly into the optimization formulation—as embedded constraints—or addressed after optimization via geometric post-processing and repair. These two strategies differ substantially in their computational requirements, design quality, and practical applicability, and their relative merits depend critically on the specific manufacturing constraints under consideration.

Embedded constraint approaches integrate manufacturability requirements directly into the TO sensitivity analysis, ensuring that the optimized geometry is inherently compliant with process limitations from the outset. Overhang angle constraints have been successfully embedded into density-based TO frameworks through directional density filters that penalize unsupported material during the optimization loop [54]. Minimum feature size constraints are enforced via projection schemes and morphological filters applied to the density field [60], while self-support constraints have been formulated as

explicit geometric restrictions within level-set methods [10]. The primary advantage of embedded approaches is that they produce designs that are manufacturable by construction, eliminating the need for costly post-optimization modifications that may compromise structural performance. However, embedded constraints increase the complexity of the optimization problem, can slow convergence, and may overly restrict the design space—particularly when multiple constraints are imposed simultaneously, as is common in real AM process chains.

Post-processing repair approaches perform unconstrained or lightly constrained TO first, then modify the resulting geometry to satisfy manufacturability requirements. Common operations include smoothing and remeshing to improve surface quality, addition of support structures, geometric thickening of thin members below the minimum printable feature size, and reorientation of the build direction to minimize overhang violations. Surface-based representations generated by conventional CAD tools are difficult to convert into editable 3D CAD models, complicating iterative post-processing workflows. Recent advances in isogeometric analysis—employing non-uniform rational B-splines (NURBS) as geometric representations—offer a promising pathway to more seamless integration between TO output and editable CAD geometry, although reliable open-source implementations of full 3D isogeometric conversion remain unavailable [6]. The principal limitation of post-processing repair is that geometric modifications applied after optimization are not guaranteed to preserve the structural performance of the original design; local thickening, smoothing, or the addition of supports can alter load paths and introduce stress concentrations that were not present in the optimized solution.

The nature and severity of the constraints involved should guide the choice between embedded and post-processing approaches. For constraints that are geometrically simple and well-defined—such as global overhang angle limits or minimum wall thickness—embedded formulations are generally preferable, as they enforce compliance without significantly degrading optimization efficiency [6,54]. For constraints that are difficult to formalize mathematically—such as complex support-structure geometries, surface-texture requirements, or post-processing heat-treatment effects—post-processing repair remains the more practical option, provided that structural revalidation is performed after modification. In high-performance applications such as aerospace and biomedical engineering, where both structural integrity and manufacturability are non-negotiable, hybrid workflows that combine embedded geometric constraints with targeted post-processing refinement represent the current best practice [78,79].

While the manufacturability-aware TO approaches discussed in this section have been developed and validated primarily in the context of LPBF, their extension to DED and BJT presents both opportunities and distinct challenges. In DED, the larger melt pool, higher deposition rates, and greater thermal mass lead to distinct residual stress distributions and lower geometric resolution than in LPBF, necessitating adapted constraint formulations that account for path-dependent thermal accumulation and anisotropic mechanical behavior. Furthermore, the multi-axis deposition capability of DED introduces additional degrees of freedom in build orientation that could be exploited within TO frameworks to minimize support requirements and residual distortion. In BJT, the absence of a high-temperature consolidation step during printing means that the primary process constraints relevant to TO are associated with the sintering stage—namely, dimensional shrinkage, residual porosity, and density gradients—rather than with thermal gradients during deposition. Incorporating these sintering-related constraints into TO workflows remains largely unexplored and represents a promising direction for future research.

6. Process Physics-Informed Design

Despite advances in TO and manufacturability-aware approaches, many optimized designs for metal AM still fail to account for the physical phenomena inherent to the fabrication process. In LPBF, extreme thermal cycles, steep temperature gradients, and rapid solidification rates generate residual stresses, geometric distortions, and microstructural variations that can severely compromise the structural performance of components—even when their topology has been formally optimized. Process physics-informed design addresses this limitation by integrating physical models of the manufacturing process directly into the design and optimization cycle, enabling TO to account not only for idealized structural performance but also for the real thermomechanical effects imposed by fabrication.

6.1. Thermal Effects, Residual Stress, and Distortion

In LPBF, the interaction between the focused laser beam and the metallic powder bed generates highly nonlinear, transient thermal fields characterized by steep temperature gradients, localized melting, and extremely rapid cooling rates. These thermal cycles strongly influence the development of residual stresses and geometric distortions, posing significant challenges to the direct translation of topology-optimized designs into functional components [35,80].

During fabrication, each new layer receives thermal energy from the laser, which melts the freshly spread powder and a thin portion of the previously solidified substrate. The newly molten material reaches temperatures significantly higher than those of the underlying layers, generating a localized, transient thermal gradient that moves with the laser scan path [5,6]. As the molten pool solidifies, cooling occurs nonuniformly, while the already solidified material mechanically constrains shrinkage from below. The combined effects of pronounced thermal gradients, rapid cooling rates, material confinement, and non-uniform shrinkage promote the accumulation of residual stresses and geometric distortions throughout the build [75].

Residual stresses and distortions are particularly detrimental in LPBF components, as they may lead to delamination, dimensional deviations, and degraded mechanical performance, ultimately resulting in build failure or part rejection [35]. Levkulich et al. [75] demonstrated that residual stress evolution in LPBF-fabricated Ti-6Al-4V is strongly dependent on process parameters—particularly laser power and scan speed—and that unoptimized parameter combinations can generate stresses approaching the material's yield strength. Le Roux et al. [35] further showed that surface integrity in LPBF Ti-6Al-4V is critically sensitive to process parameter selection, with sub-optimal conditions producing surface defects that act as fatigue crack initiation sites. Effective control of residual stresses and distortions is therefore essential to ensure dimensional accuracy, structural integrity, and process reliability in LPBF.

6.2. Coupling TO with LPBF Process Modeling

The integration of LPBF process models into TO frameworks represents a significant advancement beyond manufacturability-aware approaches, enabling optimization that explicitly accounts for thermomechanical process effects rather than merely geometric constraints. This coupling can be achieved at different levels of fidelity, from simplified analytical distortion models to full thermomechanical finite element simulations [10,81].

At the geometric level, TO strategies that avoid critical overhang angles have been extended to incorporate predicted deformation fields, enabling support structure design that accounts for the actual forces acting on overhanging regions during fabrication rather than relying solely on angular thresholds [10,58]. At the constitutive level, AM-induced mechanical anisotropy—arising from directional solidification and crystallographic texture

development—has been incorporated into TO through anisotropic constitutive models implemented within finite element analyses, allowing the optimization to account for direction-dependent material properties [57,69].

More advanced process-coupled TO formulations directly incorporate residual stress and distortion predictions into the optimization sensitivity analysis, constraining the process-induced stress state of the optimized design in addition to its geometric configuration [10]. Afazov et al. [81] reviewed metal powder bed fusion process chain modeling approaches, demonstrating that multi-scale thermomechanical simulations can predict residual stress distributions and dimensional deviations with sufficient accuracy for integration into design workflows. These process-chain-aware formulations represent the current frontier of process physics-informed design, enabling TO to generate geometries that are simultaneously structurally efficient, geometrically manufacturable, and thermomechanically stable under real fabrication conditions.

The incorporation of post-processing steps—including heat treatment, surface finishing, and inspection—into process-coupled TO frameworks further increases problem complexity due to the greater number of manufacturing constraints involved. TO approaches for multimaterial systems, microstructure control, and graded lattice structures have been identified as promising extensions of process physics-informed design. However, their integration into comprehensive process-chain optimization frameworks remains largely unexplored and presents a significant opportunity for future research.

7. Materials and Performance Outcomes

Material selection is a critical factor in the successful implementation of TO in metal AM, as it directly influences process compatibility, structural performance, and the feasibility of complex geometries such as lattice structures and thin-walled features [78,79].

Titanium alloys, particularly Ti-6Al-4V, are the most widely studied material system in TO for metal AM due to their high strength-to-weight ratio, excellent corrosion resistance, and well-established LPBF processability. Studies have demonstrated that integrating TO with LPBF enables the fabrication of lightweight, high-performance geometries that overcome the limitations of conventional manufacturing [11]. Applications range from porous biomedical scaffolds with controlled geometry and structural properties compatible with bone tissue engineering [82] to optimize aerospace support structures, achieving 50–75% volume reduction relative to the original design [3].

Aluminum alloys such as AlSi10Mg and A205 are attractive for weight-critical structural applications due to their low density and good thermal conductivity. The combination of TO with LPBF has demonstrated significant weight savings in structural components, as illustrated by Costa et al. [83] in the development of a topology-optimized bicycle crank with reduced mass and preserved structural integrity. Gradient lattice structures have shown improvements of up to 22.7% in natural frequency and 130% in damping capacity compared to uniform density designs [84]. However, microstructural heterogeneity, residual stress, and defect formation require careful post-processing management; heat treatment response varies significantly by alloy system, and precise control of temperature and duration is essential to balance strength and ductility [44].

Nickel-based superalloys such as Inconel 718 and IN738LC are employed in high-temperature aerospace applications, where their use in TO-driven designs is primarily motivated by weight reduction in turbine components and critical structural parts [79]. Key design challenges include susceptibility to solidification cracking—driven by high thermal gradients during LPBF—and the development of strong crystallographic texture and columnar grain morphology, leading to pronounced mechanical anisotropy that must be explicitly accounted for at the design stage [81,85].

Stainless steels, particularly 316L and 304, are frequently used as benchmark and validation materials in TO studies due to their process robustness, good ductility, and relatively low cost. LPBF-produced 316L exhibits fatigue resistance comparable to conventionally processed counterparts, making it suitable for cyclically loaded components, provided that process-induced defects such as micropores are minimized through optimized scanning strategies [86]. Mechanical anisotropy and asymmetry in LPBF 316L—governed by pore morphology and melt-pool boundary geometry—must be considered when defining loading conditions and build orientation in TO workflows [43].

Across all material systems, anisotropic mechanical behavior, residual stress, and defect formation are recurring design-relevant concerns that must be integrated into the TO workflow to ensure that optimized geometries are both manufacturable and structurally reliable under real service conditions.

8. Validation, Limitations, and Research Gaps

8.1. Current State of Experimental Validation

The studies reviewed generally demonstrate a consistent progression in the integration of TO with metal AM, with complementary experimental and numerical methods increasingly employed to validate optimized designs. Mechanical testing, microstructural characterization, and finite element analysis are the most commonly combined validation approaches, collectively strengthening the reliability of reported findings [78]. However, most studies rely on small sample sizes, single material systems, and simplified loading conditions that do not capture the complexity of real industrial applications. Furthermore, the diversity of TO formulations, process parameters, and validation metrics across studies severely limits direct comparability, making it difficult to establish consensus on the relative performance of competing approaches [9,78]. The absence of standardized benchmark problems—analogue to those established in purely structural TO, such as the Messerschmitt–Bölkow–Blohm (MBB) beam or the cantilever problem—represents a significant barrier to systematic progress in manufacturability-aware TO for metal AM [62].

8.2. Research Gaps and Root-Cause Analysis

Several critical research gaps persist in the field, each rooted in identifiable fundamental barriers:

Gap 1: Insufficient integration of process physics into TO frameworks. While thermal and mechanical process models for LPBF are well-established [80,81]. Their coupling with TO sensitivity analysis remains computationally prohibitive for industrially relevant part sizes. The root cause is the disparity in length and time scales between process-level phenomena—microstructure evolution, melt pool dynamics—and component-level structural optimization, which prevents direct integration without significant model simplification or surrogate approximation [10,81].

Gap 2: Lack of formal qualification and certification frameworks for topology-optimized AM components. Safety-critical applications in aerospace and biomedical engineering require rigorous qualification processes that current TO workflows do not support [79]. The root cause lies in the inherent variability of AM processes—including batch-to-batch powder variability, machine drift, and environmental factors—which produces scatter in mechanical properties that deterministic TO formulations cannot account for [27,30]. Probabilistic or reliability-based TO approaches exist but remain computationally expensive and poorly integrated with AM-specific sources of uncertainty.

Gap 3: Limited consideration of sustainability and lifecycle performance. Material efficiency, energy consumption, and end-of-life recyclability are increasingly important design objectives, yet they are only minimally integrated into current TO frameworks [46,47]. The

root cause is the absence of validated lifecycle assessment models that can be coupled with TO in a computationally tractable manner, and the lack of regulatory incentives to drive industrial adoption of sustainability-aware design tools.

Gap 4: Poor scalability of advanced TO methods to large-scale components. Hybrid, lattice-based, and process-physics-informed TO formulations have demonstrated strong performance on small benchmark geometries but fail to scale to large, multi-feature components due to prohibitive computational costs [78]. The root cause is the combinatorial explosion of design variables and constraints as part complexity increases, compounded by the high cost of repeated finite element evaluations required by gradient-based optimization algorithms [62,69].

Gap 5: Absence of long-term experimental data on fatigue, creep, and environmental degradation. Most validation studies report quasi-static mechanical properties under idealized conditions, leaving the long-term structural reliability of topology-optimized AM components largely uncharacterized [86]. The root cause is the high cost and time requirements of long-term experimental campaigns, combined with the novelty of the field and the rapid pace of process and material development, which render historical datasets quickly obsolete.

8.3. Core Challenges and Inherent Paradoxes

Beyond the specific research gaps identified above, the field of TO for metal AM is characterized by several fundamental contradictions that resist straightforward resolution and define the deepest intellectual challenges facing researchers and practitioners:

Paradox 1: Design freedom vs. process constraints. Metal AM is celebrated for enabling unprecedented geometric freedom, yet the imposition of AM-specific constraints—overhang angles, minimum feature sizes, support requirements, residual stress limits—progressively restricts the design space that TO is intended to explore [5,54]. The more rigorously manufacturability constraints are enforced, the closer the optimized design approaches what could have been achieved by conventional manufacturing. Resolving this paradox requires not merely adding more constraints, but developing fundamentally new constraint formulations that distinguish between genuinely AM-specific opportunities and limitations imposed by current, improvable process parameters.

Paradox 2: Geometric complexity vs. structural predictability. TO generates geometrically complex designs that exploit the full capability of AM, yet this complexity makes experimental validation, fatigue life prediction, and failure mode identification significantly more difficult [70,78]. The more structurally efficient the topology-optimized design, the harder it becomes to certify its reliability under real operating conditions—creating a fundamental tension between performance optimization and qualification tractability.

Paradox 3: Multi-objective optimization vs. computational tractability. Industrial AM components must simultaneously satisfy structural, thermal, dynamic, manufacturability, sustainability, and cost objectives. While multi-objective TO formulations exist, the simultaneous treatment of all relevant objectives and constraints rapidly becomes computationally intractable for real part geometries [78]. Current practice typically reduces this to a single-objective problem with constraint satisfaction, inevitably sacrificing optimality for the neglected objectives. No general solution to this dimensionality challenge currently exists.

Paradox 4: Process-informed design vs. process variability. Incorporating process physics into TO assumes that the AM process behaves deterministically and predictably—yet AM processes are inherently stochastic, with residual stress distributions, microstructural textures, and defect populations varying between builds, machines, and even locations within a single part [27,30,81]. Designing for a deterministic process model that does not

reflect real process variability may produce designs that are theoretically optimal but practically unreliable, particularly under fatigue loading, where defect sensitivity is high [86].

These paradoxes are not merely technical challenges amenable to incremental improvement—they reflect deeper tensions between the goals of design optimization, manufacturing physics, and engineering qualification that will require conceptually new frameworks to resolve. Acknowledging and explicitly addressing these contradictions is essential for the field to progress beyond incremental advances toward genuinely transformative design methodologies for metal AM.

9. Future Perspectives and Conclusions

This review has provided a comprehensive analysis of design strategies and process constraints for metal additive manufacturing, with particular emphasis on laser powder bed fusion. Distinct from prior DfAM reviews [13–15], the present synthesis explicitly integrates TO formulation selection, manufacturability constraint integration strategy, and process-physics coupling within a single decision-oriented structure centered on LPBF, with extension to DED and BJT. The following key findings emerge from the literature:

Metal AM processes—particularly LPBF, DED, and BJT—differ substantially in their energy input mechanisms, material consolidation principles, and post-processing requirements, each imposing distinct constraints on design freedom, dimensional accuracy, and mechanical performance [20,21,37]. Understanding these process-specific characteristics is a prerequisite for effective DfAM implementation.

Topology optimization has established itself as a powerful tool for exploiting the geometric freedom afforded by metal AM, enabling significant weight reductions and performance improvements across aerospace, biomedical, and industrial applications [9,78]. However, the effective integration of TO with AM requires manufacturability-aware formulations that explicitly incorporate process constraints such as overhang angles, minimum feature sizes, residual stress, and support structure requirements directly into the optimization workflow [5,6,10,54].

Process physics—including thermal gradients, rapid solidification, and layer-by-layer deposition—governs microstructural evolution, mechanical anisotropy, and defect formation in LPBF-fabricated components [77,80]. These phenomena must be accounted for at the design stage to ensure that topology-optimized geometries are both manufacturable and structurally reliable. Material selection further conditions these outcomes, with titanium alloys, aluminum alloys, nickel-based superalloys, and stainless steels each presenting distinct advantages and challenges in the context of TO for metal AM [78,79].

Despite significant progress, the systematic integration of constraints spanning the full AM process chain—from design and process parameters to post-processing and final performance—remains an open challenge [81]. To the best of the authors' knowledge, this represents one of the most significant gaps in the current literature, and future research should prioritize large-scale experimental validation, standardized benchmarking methodologies, and the development of coupled design-process optimization frameworks.

Beyond these conceptual contributions, this review enables design and process engineers to move beyond generic DfAM guidance towards criteria-based decision-making at three concrete points in the design workflow: (i) selecting a TO formulation appropriate to the geometric and computational requirements of the problem at hand, rather than defaulting to density-based SIMP by convention (Section 4.4); (ii) choosing between embedded-constraint and post-processing-repair strategies based on the mathematical tractability of the governing constraint, rather than on tool availability alone (Section 5.2); and (iii) anticipating, through the root-cause and paradox analysis in Section 8, which manufacturability or qualification barriers are addressable through current methods and

which require fundamentally new formulations. Existing DfAM frameworks [13–15] provide valuable guidance on design rules and general best practice but do not offer this level of formulation-specific, constraint-strategy-specific decision support for metal AM. This distinction—between general DfAM guidance and TO-method-specific, constraint-strategy-specific decision criteria—constitutes the practical novelty of the present work.

In conclusion, the convergence of topology optimization, process-informed design, and metal additive manufacturing holds considerable promise for the next generation of high-performance structural components. Realizing this potential requires continued interdisciplinary research that bridges computational design, materials science, and manufacturing engineering.

9.1. Emerging Trends and Critical Advances (2024–2025)

The period between 2024 and 2025 has witnessed significant advances in several areas directly relevant to the topics covered in this review, reinforcing and in some cases extending the conclusions drawn from the core literature (2010–2024).

9.1.1. Manufacturability-Aware Topology Optimization with Residual Stress and Distortion Constraints

One of the most significant recent developments concerns the explicit incorporation of residual stress and distortion constraints into TO formulations. Recent work has proposed TO methods with constraints related to residual stress for self-supporting LPBF-fabricated parts, coupled with laser scan path optimization to minimize residual deformation, and support structure design that simultaneously accounts for multiple LPBF process constraints [10,58]. These advances represent a meaningful step beyond conventional geometric constraints, such as overhang angle limitations, towards a more holistic, process-informed design approach. In LPBF-processed Ti-6Al-4V, residual dimensional deviation has been reported to fall within 0.1–0.8% when geometric compensation, preheating, and optimized support strategies are implemented, whereas uncompensated shrinkage can reach 1.2–2.0%, particularly in thin-walled or thermally constrained geometries [77,80]. These quantitative insights underscore the importance of integrating distortion prediction directly into the TO workflow rather than treating it as a post-processing correction.

The extension of these residual stress and distortion-aware TO formulations to DED and BJT remains largely unexplored. For DED, path-dependent thermal accumulation and the larger process zone require fundamentally different constraint models. For BJT, the relevant constraints shift from thermal gradients during printing to shrinkage and porosity evolution during sintering—a domain where TO-integrated approaches are virtually absent from the current literature [28,31].

9.1.2. Multi-Scale Process Simulation Across the Full AM Process Chain

Multi-scale modeling strategies for metal AM have gained considerable traction, with thermomechanical simulations increasingly employed to predict residual stress and distortion across the full process chain—from printing and heat treatment to final post-processing [81]. Finite element-based simulation tools capable of emulating the complete LPBF process chain, including pre-deformation compensation and machine-specific file export, have recently been demonstrated and experimentally validated [48]. These frameworks are emerging as essential tools for predicting and mitigating process-induced defects before fabrication, thereby reducing costly trial-and-error iterations. Future research should focus on coupling these simulation frameworks with TO algorithms to enable truly process-chain-aware design optimization.

9.1.3. Integration of Artificial Intelligence and Machine Learning in DfAM

The integration of artificial intelligence (AI) and machine learning (ML) into DfAM workflows has emerged as one of the most actively investigated research directions in recent years [53]. Recent systematic reviews highlight the growing role of AI and ML in topology optimization, generative design, defect prediction, and process parameter selection, with increasing emphasis on practical industrial implementation [78]. Deep learning-enabled DfAM frameworks have been proposed to optimize geometries through iterative simulation loops, incorporating manufacturability constraints and predictions of material behavior. This convergence of data-driven methods with physics-based design optimization holds considerable promise for reducing design iteration cycles, improving manufacturability predictions, and enabling real-time process feedback. However, the lack of large, standardized experimental datasets remains a significant barrier to the broader adoption of ML-based DfAM tools in industrial settings [30].

9.1.4. Standardization and Benchmarking in DfAM

Despite the maturity of individual TO methods and AM processes, the absence of standardized benchmarking methodologies and unified digital design workflows continues to limit the systematic comparison and industrial scalability of DfAM approaches [1,78]. Recent reviews have identified fragmented digital workflows and insufficient precision metrology standards as critical barriers to reproducibility and industrial adoption [43,80]. Future efforts should prioritize developing shared experimental datasets, reproducibility protocols, and certification frameworks to enable rigorous comparison of TO strategies across AM platforms, material systems, and application domains. The establishment of such standards would also facilitate the validation of AI-assisted design tools and multi-scale simulation frameworks, accelerating their transition from research to industrial practice.

9.2. Summary

Taken together, these emerging trends point towards a future in which TO, process physics, AI-driven design, and full-process-chain simulation are deeply integrated into a unified DfAM framework. Realizing this vision will require sustained interdisciplinary collaboration between computational designers, materials scientists, process engineers, and standardization bodies, and represents the most promising direction for advancing the field beyond the current state of the art reviewed in this manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

AM	Additive Manufacturing
BJT	Binder Jetting

CAD	Computer-Aided Design
CNC	Computer Numerical Control
DED	Directed Energy Deposition
DfAM	Design for Additive Manufacturing
EBPBF	Electron beam PBF
FEA	Finite Element Analysis
FEM	Finite Element Method
HIP	Hot Isostatic Pressing
LPBF	Laser Powder Bed Fusion
SEM	Scanning Electron Microscopy
SIMP	Solid Isotropic Material with Penalization
TO	Topology Optimization
STL	Stereolithography

References

1. Bracken, J.; Pomorski, T.; Armstrong, C.; Prabhu, R.; Simpson, T.W.; Jablowski, K.; Cleary, W.; Meisel, N.A. Design for metal powder bed fusion: The geometry for additive part selection (GAPS) worksheet. *Addit. Manuf.* **2020**, *35*, 101163. [\[CrossRef\]](#)
2. Zinovieva, O.; Romanova, V.; Dymnich, E.; Zinoviev, A.; Balokhonov, R. A Review of Computational Approaches to the Microstructure-Informed Mechanical Modelling of Metals Produced by Powder Bed Fusion Additive Manufacturing. *Materials* **2023**, *16*, 6459. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Jain, R.; Singh, S.K.; Upadhyay, R.K.; Agrawal, B.N. Design and development of topology-optimized aircraft bracket using additive manufacturing. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2025**, *19*, 1051–1059. [\[CrossRef\]](#)
4. Costa, J.M. From Technology to Strategy: A Gated Decision Framework for Integrating Metal Additive Manufacturing into Sustainable Industrial Systems. *Metals* **2026**, *16*, 537. [\[CrossRef\]](#)
5. Mhapsekar, K.; McConaha, M.; Anand, S. Additive Manufacturing Constraints in Topology Optimization for Improved Manufacturability. *J. Manuf. Sci. Eng.* **2018**, *140*, 051017. [\[CrossRef\]](#)
6. Langelaar, M. An additive manufacturing filter for topology optimization of print-ready designs. *Struct. Multidiscip. Optim.* **2017**, *55*, 871–883. [\[CrossRef\]](#)
7. Dalpadulo, E.; Pini, F.; Leali, F. Assessment of Computer-Aided Design Tools for Topology Optimization of Additively Manufactured Automotive Components. *Appl. Sci.* **2021**, *11*, 10980. [\[CrossRef\]](#)
8. Ranjan, R.; Samant, R.; Anand, S. Integration of Design for Manufacturing Methods with Topology Optimization in Additive Manufacturing. *J. Manuf. Sci. Eng.* **2017**, *139*, 061007. [\[CrossRef\]](#)
9. Zhu, J.; Zhou, H.; Wang, C.; Zhou, L.; Yuan, S.; Zhang, W. A review of topology optimization for additive manufacturing: Status and challenges. *Chin. J. Aeronaut.* **2021**, *34*, 91–110. [\[CrossRef\]](#)
10. Miki, T. Self-support topology optimization considering distortion for metal additive manufacturing. *Comput. Methods Appl. Mech. Eng.* **2023**, *404*, 115821. [\[CrossRef\]](#)
11. Xu, Y.; Zhang, D.; Zhou, Y.; Wang, W.; Cao, X. Study on Topology Optimization Design, Manufacturability, and Performance Evaluation of Ti-6Al-4V Porous Structures Fabricated by Selective Laser Melting (SLM). *Materials* **2017**, *10*, 1048. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Nirish, M.; Rajendra, R. Suitability of metal additive manufacturing processes for part topology optimization—A comparative study. *Mater. Today Proc.* **2020**, *27*, 1601–1607.
13. Chtioui, N.; Gaha, R.; Benamara, A. Design for additive manufacturing: Review and framework proposal. *Sustain. Eng. Innov.* **2023**, *5*, 73–84. [\[CrossRef\]](#)
14. Asapu, S.; Kumar, Y.R. Design for Additive Manufacturing (DfAM): A Comprehensive Review with Case Study Insights. *JOM* **2025**, *77*, 3931–3951. [\[CrossRef\]](#)
15. Reinke, G.; dos Santos, A.C. A systematic review and unified framework for design for additive manufacturing (DfAM). *Int. J. Adv. Manuf. Technol.* **2026**, *143*, 4507–4535. [\[CrossRef\]](#)
16. Gu, D.D.; Meiners, W.; Wissenbach, K.; Poprawe, R. Laser additive manufacturing of metallic components: Materials, processes and mechanisms. *Int. Mater. Rev.* **2012**, *57*, 133–164. [\[CrossRef\]](#)
17. Raghavan, N.; Babu, S.S.; Dehoff, R.; Pannala, S.; Simunovic, S.; Kirka, M.; Turner, J.; Carlson, N. Numerical modeling of heat-transfer and the influence of process parameters on tailoring the grain morphology of IN718 in electron beam additive manufacturing. *Acta Mater.* **2016**, *112*, 303–314. Corrigendum in *Acta Mater.* **2017**, *140*, 472. <https://doi.org/10.1016/j.actamat.2017.08.067>. [\[CrossRef\]](#)

18. Cunningham, C.; Flynn, J.; Shokrani, A.; Dhokia, V.; Newman, S. Invited review article: Strategies and processes for high quality wire arc additive manufacturing. *Addit. Manuf.* **2018**, *22*, 672–686. [\[CrossRef\]](#)
19. Lewandowski, J.J.; Seifi, M. Metal Additive Manufacturing: A Review of Mechanical Properties. *Annu. Rev. Mater. Res.* **2016**, *46*, 151–186. [\[CrossRef\]](#)
20. Yap, C.; Chua, C.; Dong, Z.; Liu, Z.; Zhang, D.; Loh, L.; Sing, S. Review of selective laser melting: Materials and applications. *Appl. Phys. Rev.* **2015**, *2*, 041101. [\[CrossRef\]](#)
21. Patel, S.; Liu, Y.; Siddique, Z.; Ghamarian, I. Metal additive manufacturing: Principles and applications. *J. Manuf. Process.* **2024**, *131*, 1179–1201. [\[CrossRef\]](#)
22. Yadroitsev, I.; Yadroitsava, I.; Du Plessis, A. Basics of laser powder bed fusion. In *Fundamentals of Laser Powder Bed Fusion of Metals*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 15–38. [\[CrossRef\]](#)
23. Fox, H.; Kamaraj, A.B.; Drake, D. Investigating the effect of powder recoater blade material on the mechanical properties of parts manufactured using a powder-bed fusion process. *Manuf. Lett.* **2022**, *33*, 561–568. [\[CrossRef\]](#)
24. Murr, L.E.; Gaytan, S.M.; Ramirez, D.A.; Martinez, E.; Hernandez, J.; Amato, K.N.; Shindo, P.W.; Medina, F.R.; Wicker, R.B. Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies. *J. Mater. Sci. Technol.* **2012**, *28*, 1–14. [\[CrossRef\]](#)
25. Rafi, H.K.; Karthik, N.V.; Gong, H.; Starr, T.L.; Stucker, B.E. Microstructures and Mechanical Properties of Ti6Al4V Parts Fabricated by Selective Laser Melting and Electron Beam Melting. *J. Mater. Eng. Perform.* **2013**, *22*, 3872–3883. [\[CrossRef\]](#)
26. Al-Bermani, S.S.; Blackmore, M.L.; Zhang, W.; Todd, I. The Origin of Microstructural Diversity, Texture, and Mechanical Properties in Electron Beam Melted Ti-6Al-4V. *Metall. Mater. Trans. A-Phys. Metall. Mater. Sci.* **2010**, *41*, 3422–3434. [\[CrossRef\]](#)
27. Dowling, L.; Kennedy, J.; O'Shaughnessy, S.; Trimble, D. A review of critical repeatability and reproducibility issues in powder bed fusion. *Mater. Des.* **2020**, *186*, 108346. [\[CrossRef\]](#)
28. Mostafaei, A.; Elliott, A.M.; Barnes, J.E.; Li, F.; Tan, W.; Cramer, C.L.; Nandwana, P.; Chmielus, M. Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Prog. Mater. Sci.* **2021**, *119*, 100707. [\[CrossRef\]](#)
29. Utela, B.; Storti, D.; Anderson, R.; Ganter, M. A review of process development steps for new material systems in three dimensional printing (3DP). *J. Manuf. Process.* **2008**, *10*, 96–104. [\[CrossRef\]](#)
30. Malgave, S.; Shanthappa, P.; Polidas, C.; Nagaraja, A. Evaluation of Binder Jet 3D Printed (BJT) M2 Tool Steel against the Wrought M2, Powder Metallurgy (PM) M2 and Laser Powder Bed Fusion (LPBF) Maraging Steel for Mould Application. *J. Jpn. Soc. Powder Powder Metall.* **2025**, *72*, S395–S401. [\[CrossRef\]](#)
31. Liu, F.Q.; Wei, L.; Shi, S.Q.; Wei, H.L. On the varieties of build features during multi-layer laser directed energy deposition. *Addit. Manuf.* **2020**, *36*, 101491. [\[CrossRef\]](#)
32. Herzog, D.; Seyda, V.; Wycisk, E.; Emmelmann, C. Additive manufacturing of metals. *Acta Mater.* **2016**, *117*, 371–392. [\[CrossRef\]](#)
33. Herzog, D.; Asami, K.; Scholl, C.; Ohle, C.; Emmelmann, C.; Sharma, A.; Markovic, N.; Harris, A. Design guidelines for laser powder bed fusion in Inconel 718. *J. Laser Appl.* **2022**, *34*, 012015. [\[CrossRef\]](#)
34. Attar, H.; Ehtemam-Haghighi, S.; Kent, D.; Wu, X.; Dargusch, M.S. Comparative study of commercially pure titanium produced by laser engineered net shaping, selective laser melting and casting processes. *Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process.* **2017**, *705*, 385–393. [\[CrossRef\]](#)
35. Le Roux, S.; Salem, M.; Shabbar, M.; Vicharapu, B.; Muthu, N.; Moussaoui, K.; Hor, A.; Velay, V. Effect of process parameters on surface integrity in laser powder bed fusion of Ti-6Al-4V alloy. *Sci. Rep.* **2025**, *15*, 43786. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Widomski, P.; Kaszuba, M.; Dobras, D.; Terefinko, D.; Kołodziński, M. Comparative Study of Different Additive Manufacturing Methods for H13 Tool Steel. *Materials* **2025**, *18*, 5299. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Contuzzi, N.; Campanelli, S.L.; Caiazzo, F.; Alfieri, V. Design and Fabrication of Random Metal Foam Structures for Laser Powder Bed Fusion. *Materials* **2019**, *12*, 1301. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Haase, F.; Siemers, C.; Rösler, J. Laser powder bed fusion (LPBF) of commercially pure titanium and alloy development for the LPBF process. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1260925. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Ceccanti, F.; Giorgetti, A.; Arcidiacono, G.; Citti, P. Laser Powder Bed Fusion: A Review on the Design Constraints. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1038*, 012023. [\[CrossRef\]](#)
40. Zhang, Y.; Yang, S.; Zhao, Y.F. Manufacturability analysis of metal laser-based powder bed fusion additive manufacturing—A survey. *Int. J. Adv. Manuf. Technol.* **2020**, *110*, 57–78. [\[CrossRef\]](#)
41. Giorgetti, A.; Ceccanti, F.; Baldi, N.; Kemble, S.; Arcidiacono, G.; Citti, P. Axiomatic Design of a Test Artifact for PBF-LM Machine Capability Monitoring. *Machines* **2024**, *12*, 199. [\[CrossRef\]](#)
42. Faludi, J.; Baumers, M.; Maskery, I.; Hague, R. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, or Power Dominate? *J. Ind. Ecol.* **2017**, *21*, S144–S156. [\[CrossRef\]](#)
43. Jeon, J.M.; Park, J.M.; Yu, J.-H.; Kim, J.G.; Seong, Y.; Park, S.H.; Kim, H.S. Effects of microstructure and internal defects on mechanical anisotropy and asymmetry of selective laser-melted 316L austenitic stainless steel. *Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process.* **2019**, *763*, 138152. [\[CrossRef\]](#)

44. Pitrmuc, Z.; Šimota, J.; Beránek, L.; Mikeš, P.; Andronov, V.; Sommer, J.; Holešovský, F. Mechanical and Microstructural Anisotropy of Laser Powder Bed Fusion 316L Stainless Steel. *Materials* **2022**, *15*, 551. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Zhang, H.; Chan, C.-W.; Li, Y.; Chu, F.; Wu, X.; Cao, Z.; Li, L.; Yi, Y.; Wang, X.; Cao, S. Anisotropic microstructure and tensile property of laser powder bed fusion fabricated Al-Mn-Mg-Sc-Zr alloy built at different layer thickness. *J. Mater. Res. Technol.* **2024**, *33*, 845–860. [\[CrossRef\]](#)
46. Deaton, J.D.; Grandhi, R.V. A survey of structural and multidisciplinary continuum topology optimization: Post 2000. *Struct. Multidiscip. Optim.* **2014**, *49*, 1–38. [\[CrossRef\]](#)
47. Cunha, B.R.; Guimarães, B.M.; Figueiredo, D.; Vieira, M.F.; Costa, J.M. Development of a Workflow for Topological Optimization of Cutting Tool Milling Bodies. *Metals* **2026**, *16*, 116. [\[CrossRef\]](#)
48. Ercolini, E.; Calignano, F.; Galati, M.; Viccica, M.; Iuliano, L. Redesigning a flexural joint for metal-based additive manufacturing. *Procedia CIRP* **2021**, *100*, 469–475. [\[CrossRef\]](#)
49. Han, Y. Stress-based bi-directional evolutionary topology optimization for structures with multiple materials. *Eng. Comput.* **2024**, *40*, 2905–2923. [\[CrossRef\]](#)
50. Liu, W.; Huang, G.; Xie, W. An efficient cross-platform multi-material topology optimization approach occupying enhanced BESO method. *Meccanica* **2025**, *60*, 173–193. [\[CrossRef\]](#)
51. Gu, X.; Yu, Q.; Dong, Y.; He, S.; Qu, J. Structural topology optimization for additive manufacturing with free choice of self-supporting and infill-supporting structures. *Comput. Methods Appl. Mech. Eng.* **2024**, *421*, 116788. [\[CrossRef\]](#)
52. Makhija, D.; Maute, K. Numerical instabilities in level set topology optimization with the extended finite element method. *Struct. Multidiscip. Optim.* **2014**, *49*, 185–197. [\[CrossRef\]](#)
53. Moussa, A.; Melancon, D.; El Elmi, A.; Pasini, D. Topology optimization of imperfect lattice materials built with process-induced defects via Powder Bed Fusion. *Addit. Manuf.* **2021**, *37*, 101608. [\[CrossRef\]](#)
54. Yamada, T.; Izui, K.; Nishiwaki, S.; Takezawa, A. A topology optimization method based on the level set method incorporating a fictitious interface energy. *Comput. Methods Appl. Mech. Eng.* **2010**, *199*, 2876–2891. [\[CrossRef\]](#)
55. Maconachie, T.; Leary, M.; Lozanovski, B.; Zhang, X.; Qian, M.; Faruque, O.; Brandt, M. SLM lattice structures: Properties, performance, applications and challenges. *Mater. Des.* **2019**, *183*, 108137. [\[CrossRef\]](#)
56. Wang, R.; Shi, H.; Gu, J.; He, X.; Zhang, P.; Yu, Z.; Yan, H.; Lu, Q. Additive manufacturing of metal lattice structures: A comprehensive review of technologies, mechanical properties, applications, and future trends. *Mater. Today Phys.* **2025**, *59*, 101933. [\[CrossRef\]](#)
57. Yavari, S.A.; Ahmadi, S.; Wauthle, R.; Pouran, B.; Schrooten, J.; Weinans, H.; Zadpoor, A. Relationship between unit cell type and porosity and the fatigue behavior of selective laser melted meta-biomaterials. *J. Mech. Behav. Biomed. Mater.* **2015**, *43*, 91–100. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Jiwane, V.; Tiwari, G.; Goel, M.D.; Andraskar, N.; Sirdesai, N.; Venkateswaran, K.P. Crashworthiness of Ultrathin Aluminum Honeycomb Structure. *Mech. Solids* **2024**, *59*, 1588–1602. [\[CrossRef\]](#)
59. Dong, L.; Deshpande, V.; Wadley, H. Mechanical response of Ti-6Al-4V octet-truss lattice structures. *Int. J. Solids Struct.* **2015**, *60–61*, 107–124. [\[CrossRef\]](#)
60. Bernard, A.R.; Elsayed, M.S.A. Crashworthiness of 3D Lattice Topologies under Dynamic Loading: A Comprehensive Study. *Materials* **2024**, *17*, 1597. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Mun, J.; Yun, B.-G.; Ju, J.; Chang, B.-M. Indirect additive manufacturing based casting of a periodic 3D cellular metal—Flow simulation of molten aluminum alloy. *J. Manuf. Process.* **2015**, *17*, 28–40. [\[CrossRef\]](#)
62. Panesar, A.; Abdi, M.; Hickman, D.; Ashcroft, I. Strategies for functionally graded lattice structures derived using topology optimisation for Additive Manufacturing. *Addit. Manuf.* **2018**, *19*, 81–94. [\[CrossRef\]](#)
63. Vaneker, T. The role of Design for Additive Manufacturing in the successful economical introduction of AM. *Procedia CIRP* **2017**, *60*, 181–186. [\[CrossRef\]](#)
64. Costa, J.M.; Sequeiros, E.W.; Figueiredo, D.; Reis, A.R.; Vieira, M.F. Optimizing Metal AM Potential through DfAM: Design, Performance, and Industrial Impact. In *Additive Manufacturing—Present and Sustainable Future, Materials and Applications*; Montealegre-Meléndez, I., Ed.; IntechOpen: Rijeka, Croatia, 2024.
65. Queheillalt, D.T.; Wadley, H.N. Cellular metal lattices with hollow trusses. *Acta Mater.* **2005**, *53*, 303–313. [\[CrossRef\]](#)
66. Feppon, F.; Michailidis, G.; Sidebottom, M.A.; Allaire, G.; Krick, B.A.; Vermaak, N. Introducing a level-set based shape and topology optimization method for the wear of composite materials with geometric constraints. *Struct. Multidiscip. Optim.* **2017**, *55*, 547–568. [\[CrossRef\]](#)
67. Allaire, G.; Jouve, F.; Toader, A.-M. Structural optimization using sensitivity analysis and a level-set method. *J. Comput. Phys.* **2004**, *194*, 363–393. [\[CrossRef\]](#)
68. Tang, T.; Wang, L.; Zhu, M.; Zhang, H.; Dong, J.; Yue, W.; Xia, H. Topology Optimization: A Review for Structural Designs Under Statics Problems. *Materials* **2024**, *17*, 5970. [\[CrossRef\]](#) [\[PubMed\]](#)

69. Afazov, S.; Roberts, A.; Wright, L.; Jadhav, P.; Holloway, A.; Basalto, H.; Milne, K.; Brierley, N. Metal powder bed fusion process chains: An overview of modelling techniques. *Prog. Addit. Manuf.* **2022**, *7*, 289–314. [\[CrossRef\]](#)
70. Trovato, M.; Cicconi, P. A Decision Tree approach for an early evaluation of 3D models in Design for Additive Manufacturing. *Procedia CIRP* **2024**, *128*, 96–101. [\[CrossRef\]](#)
71. Sigmund, O. Morphology-based black and white filters for topology optimization. *Struct. Multidiscip. Optim.* **2007**, *33*, 401–424. [\[CrossRef\]](#)
72. Jansen, M.; Pierard, O. A hybrid density/level set formulation for topology optimization of functionally graded lattice structures. *Comput. Struct.* **2020**, *231*, 106205. [\[CrossRef\]](#)
73. Geyer, S.; Hözl, C. Comparison of CAD Software for Designing Cellular Structures for Additive Manufacturing. *Appl. Sci.* **2024**, *14*, 3306. [\[CrossRef\]](#)
74. Cheng, L.; Liang, X.; Bai, J.; Chen, Q.; Lemon, J.; To, A. On utilizing topology optimization to design support structure to prevent residual stress induced build failure in laser powder bed metal additive manufacturing. *Addit. Manuf.* **2019**, *27*, 290–304. [\[CrossRef\]](#)
75. Levkulich, N.; Semiatin, S.; Gockel, J.; Middendorf, J.; DeWald, A.; Klingbeil, N. The effect of process parameters on residual stress evolution and distortion in the laser powder bed fusion of Ti-6Al-4V. *Addit. Manuf.* **2019**, *28*, 475–484. [\[CrossRef\]](#)
76. Xin, H.; Tang, D.; Dang, L.; Gao, L.; Yang, Z.; Wu, B.; He, X.; Zhan, Z. Fatigue failure mechanisms and life prediction of additive manufactured metallic lattices: A comprehensive review. *Virtual Phys. Prototyp.* **2025**, *20*, e2451124. [\[CrossRef\]](#)
77. Li, W.; Chen, X.; Yan, L.; Zhang, J.; Zhang, X.; Liou, F. Additive manufacturing of a new Fe-Cr-Ni alloy with gradually changing compositions with elemental powder mixes and thermodynamic calculation. *Int. J. Adv. Manuf. Technol.* **2018**, *95*, 1013–1023. [\[CrossRef\]](#)
78. Ibadode, O.; Zhang, Z.; Sixt, J.; Nsiempba, K.M.; Orakwe, J.; Martinez-Marchese, A.; Ero, O.; Shahabad, S.I.; Bonakdar, A.; Toyserkani, E. Topology optimization for metal additive manufacturing: Current trends, challenges, and future outlook. *Virtual Phys. Prototyp.* **2023**, *18*, e2181192. [\[CrossRef\]](#)
79. Akula, S.B.; Sastry, C.; Seshagirirao, D.V.; Suryakumar, S.; Rahman, A.H.; Reddy, N.S. Metallic lattice structures via additive manufacturing: Applications, challenges and opportunities in aerospace and defence. *J. Manuf. Process.* **2026**, *157*, 1308–1336. [\[CrossRef\]](#)
80. Costa, J.M.; Sequeiros, E.W.; Santos, R.F.; Vieira, M.F. Benchmarking L-PBF Systems for Die Production: Powder, Dimensional, Surface, Microstructural and Mechanical Characterisation. *Metals* **2024**, *14*, 520. [\[CrossRef\]](#)
81. Bryndza, G.; Tchuindjang, J.T.; Chen, F.; Habraken, A.M.; Sepúlveda, H.; Tuninetti, V.; Mertens, A.; Duchêne, L. Review of the Microstructural Impact on Creep Mechanisms and Performance for Laser Powder Bed Fusion Inconel 718. *Materials* **2025**, *18*, 276. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Xiao, D.-M.; Yang, Y.-Q.; Su, X.-B.; Wang, D.; Luo, Z.-Y. Topology optimization of microstructure and selective laser melting fabrication for metallic biomaterial scaffolds. *Trans. Nonferrous Met. Soc. China* **2012**, *22*, 2554–2561. [\[CrossRef\]](#)
83. Costa, J.M.; Maia, M.C.; Fernandes, A.P.; Oliveira, E.C.; Vieira, M.F.; Sequeiros, E.W. Topology optimization of an aluminum bicycle pedal crank using laser powder bed fusion. *Mater. Sci. Addit. Manuf.* **2025**, *4*, 025040003. [\[CrossRef\]](#)
84. Celik, B.B.; Mirzaei, A.H.; Razavi, N.; Van Hooreweder, B. Mode shape-informed design of lightweight metal lattice structures produced by laser powder bed fusion for enhanced dynamic properties. *Addit. Manuf. Lett.* **2025**, *15*, 100347. [\[CrossRef\]](#)
85. Villanueva, C.H.; Maute, K. Density and level set-XFEM schemes for topology optimization of 3-D structures. *Comput. Mech.* **2014**, *54*, 133–150. [\[CrossRef\]](#)
86. Tian, X.; Li, Q.; Zhao, G.; Qu, Z.; Ai, S. Fatigue behavior of selective laser melted 316L stainless steel: Experiments and modeling. *Eng. Fract. Mech.* **2024**, *298*, 109942. [\[CrossRef\]](#)

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