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Review

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Metal Additive Manufacturing of Engineering Alloys: Process–Material Interactions, Defect Formation, Property Optimization and a Decision-Making Framework

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Abstract: Metal additive manufacturing (MAM) has evolved into a strategic manufacturing route for producing, repairing, and remanufacturing high-value components; however, process selection and optimization remain challenging because manufacturing conditions, alloy behaviour, defect formation, microstructural evolution, and final properties are strongly interdependent. This review provides a critical and comparative assessment of four representative MAM technologies—Laser Powder Bed Fusion (L-PBF), Laser Metal Deposition (LMD), a laser-based variant of Directed Energy Deposition (DED), Wire Arc Additive Manufacturing (WAAM), and Metal Binder Jetting (MBJ)—with particular emphasis on their interactions with titanium alloys, nickel-based superalloys, steels, and aluminium alloys. Rather than comparing these technologies solely in terms of productivity, cost, or geometrical capability, the review examines the physical and metallurgical mechanisms governing thermal history, solidification or densification, phase evolution, defect formation, microstructure, and resulting component performance. Particular attention is given to porosity, lack of fusion, cracking, residual stresses, distortion, anisotropy, and surface integrity, together with process-specific mitigation and post-processing strategies. Based on the relationships identified across the literature, an integrated Process–Material–Defect–Property (PMDP) framework is proposed to connect manufacturing conditions and alloy-specific responses with defect and microstructural evolution, resulting properties, and in-service performance. A complementary PMDP-based decision pathway is introduced to support performance-driven alloy–process selection, risk identification, thermal and parameter optimization, post-processing definition, and final performance validation. The analysis demonstrates that no universally optimal MAM technology exists; instead, process suitability depends on the compatibility between material behaviour, manufacturing physics, component requirements, and the targeted material state. Future progress is expected to rely on transferable process–material maps, additive manufacturing (AM)-specific alloy design, mechanism-informed *in-situ* monitoring, physics-informed data-driven modelling, and adaptive closed-loop control. The proposed framework therefore provides a structured pathway towards material- and performance-driven, state-controlled, and ultimately performance-certified metal additive manufacturing.

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1. Introduction

Metal Additive Manufacturing (MAM) has evolved from a technology predominantly associated with rapid prototyping into an increasingly relevant manufacturing route for the production, repair, and remanufacturing of high-value engineering components. Unlike conventional subtractive manufacturing, in which the final geometry is obtained through material removal, additive manufacturing (AM) produces components through the controlled addition of material, enabling near-net-shape fabrication, increased geometrical freedom, reduced material waste, and the manufacture of complex structures that would be difficult or economically impractical to obtain using conventional routes [1–3]. These characteristics have promoted the growing industrial implementation of MAM, particularly in sectors in which material cost, component complexity, functional performance, and manufacturing flexibility are critical.

However, MAM encompasses several fundamentally different manufacturing technologies rather than a single processing route. Among the most relevant approaches for metallic components are Laser Powder Bed Fusion (L-PBF), Directed Energy Deposition (DED), including Laser Metal Deposition (LMD), Wire Arc Additive Manufacturing (WAAM), and Metal Binder Jetting (MBJ). L-PBF is also referred to as selective laser melting (SLM) in the literature; L-PBF is used consistently in this review. DED denotes the broader process category, whereas LMD denotes its laser-based variant and is used for the laser-deposition route compared here. These processes differ substantially in terms of feedstock, energy source, deposition mechanism, thermal history, dimensional capability, productivity, achievable geometrical complexity, and post-processing requirements [3–7]. WAAM, for example, combines wire feedstock with an electric arc and is particularly attractive for large-scale components because of its high deposition rate and material efficiency [4,8,9]. Conversely, L-PBF enables considerably greater geometrical resolution and the production of intricate geometries and internal features, although at comparatively lower productivity and higher energy intensity [1,10,11]. Laser-based DED provides an intermediate solution with important advantages for local deposition, material addition, repair, and remanufacturing [5,12,13], whereas MBJ separates component shaping from densification and therefore presents distinct opportunities for high-throughput manufacturing [6,7,14–16].

The selection of an AM technology, nevertheless, cannot be based exclusively on productivity, geometrical capability, or economic considerations. The response of the processed material represents an equally important factor. The highly localized energy input, rapid solidification, repeated thermal cycling, and steep thermal gradients associated with fusion-based MAM strongly affect solidification behaviour and consequently determine grain morphology, phase formation, crystallographic texture, residual stresses, and defect generation [17,18]. DebRoy et al. [18] demonstrated that the properties of additively manufactured metallic components result from strongly interconnected relationships between processing conditions, heat transfer, solidification behaviour, microstructure, and defect formation. Consequently, the same AM process may produce substantially different outcomes when applied to different alloy systems. The increasing diversification of AM technologies and feedstock systems has expanded their applicability from conventional metallic alloys to increasingly complex material architectures, including composite materials, further emphasizing the importance of matching manufacturing technology to material characteristics and performance requirements [19]

This issue is particularly relevant for engineering alloys such as titanium alloys, nickel-based superalloys, stainless steels, aluminium alloys, and tool steels. In Ti-6Al-4V, for example, the high cooling rates characteristic of fusion-based AM can promote microstructures significantly different from those obtained through conventional thermomechanical processing, with direct consequences for strength, ductility, anisotropy, and fatigue behaviour [17]. Subsequent thermal treatments can therefore play a decisive role in tailoring the final microstructure and mechanical response, as demonstrated for WAAM-produced Ti-6Al-4V [20]. Similar process-dependent behaviour is observed in other metallic systems, although the dominant metallurgical phenomena and susceptibility to defects vary according to alloy chemistry and processing conditions [18].

Defect formation consequently constitutes one of the principal barriers to the reliable industrial implementation of MAM. Variations in energy input, material delivery, thermal gradients, shielding conditions, and solidification behaviour may promote defects such as lack-of-fusion porosity, keyhole-induced pores, cracking, distortion, residual stresses, surface irregularities, and microstructural anisotropy [17,18,21,22]. These defects are not independent phenomena; rather, they result from the interaction between material properties and

local processing conditions. Wolff et al. [22], for instance, highlighted the importance of linking localized process parameters to the final characteristics of additively manufactured metallic parts. Therefore, understanding the process–material–defect relationship is essential for defining robust processing windows rather than relying exclusively on empirical parameter selection.

The optimization of MAM components must accordingly extend beyond the objective of simply achieving high relative density. Processing parameters need to be selected considering their influence on melt-pool stability, thermal history, solidification behaviour, defect formation, and resulting microstructure. Furthermore, post-processing operations—including heat treatment, Hot Isostatic Pressing (HIP), machining, and surface finishing—can be required to modify microstructures, alleviate residual stresses, eliminate internal porosity, or improve surface integrity. Hybrid additive–subtractive manufacturing has therefore attracted considerable attention as a strategy for combining the geometrical and material-efficiency advantages of AM with the dimensional accuracy and surface quality provided by machining [23,24].

More recently, advanced process monitoring and data-driven methodologies have provided new opportunities for controlling these complex relationships. The integration of sensing, process modelling, and intelligent optimization can support the identification of processing windows capable of simultaneously improving productivity, material performance, and manufacturing efficiency. Mattera et al. [25], for example, demonstrated the use of intelligent data-driven techniques for the optimization of energy efficiency in WAAM processing of Invar 36, illustrating the increasing relevance of Machine Learning (ML) for multi-objective optimization in metal additive manufacturing.

In parallel with these technological and metallurgical requirements, sustainability has become an additional criterion for AM process selection. The potential reduction in material consumption and Buy-to-Fly ratios represents an important advantage of additive manufacturing, particularly when processing energy-intensive and high-value materials [26–28]. Nevertheless, AM is not intrinsically more sustainable than conventional manufacturing. Powder production, electrical energy consumption, shielding gases, post-processing operations, material recycling, and component use-phase performance strongly influence its overall environmental impact [1,3,29,30]. Consequently, the environmental advantages of a given MAM route must be evaluated together with its technological capability, material compatibility, and required component performance rather than as an isolated criterion.

Despite the extensive body of research on metallic additive manufacturing, the available knowledge remains considerably fragmented. Numerous studies address individual AM processes, specific alloy families, defect mechanisms, mechanical properties, sustainability, or post-processing strategies independently. However, comparatively limited attention has been devoted to integrating these aspects into a unified perspective capable of supporting the selection of the most appropriate manufacturing route for a given alloy and engineering requirement. In particular, a clear understanding is still required of which AM technologies offer the greatest advantages for different alloy families, which defects limit each process–material combination, how processing conditions affect microstructure and properties, and which optimization strategies can be adopted to mitigate these limitations.

Accordingly, this review critically analyses the relationships between the principal metal additive manufacturing technologies and major engineering alloy families. Particular emphasis is placed on the interactions between process characteristics, alloy response, defect formation, microstructural evolution, and final properties, together with the processing and post-processing strategies available for property optimization and defect mitigation. L-PBF, LMD, WAAM, and MBJ are comparatively evaluated to identify their principal advantages and limitations for different metallic materials and application requirements. Finally, an integrated Process–Material–Defect–Property framework is proposed to correlate manufacturing technology, alloy characteristics, critical defects, optimization strategies, resulting properties, and application requirements, providing a structured basis for process selection and future development of metal additive manufacturing.

2. Review Methodology

This study was conducted as a critical literature review aimed at establishing an integrated understanding of the relationships between metal additive manufacturing processes, metallic alloy families, defect formation mechanisms, microstructural evolution, resulting properties, and optimization strategies. Rather than restricting the analysis to individual manufacturing technologies or isolated performance indicators, the review was structured to enable a comparative assessment of the principal process–material combinations reported in the literature.

The literature selection prioritized publications addressing four metal additive manufacturing technologies with significant industrial and scientific relevance: Laser Powder Bed Fusion (L-PBF), Laser Metal Deposition (LMD), Wire Arc Additive Manufacturing (WAAM), and Metal Binder Jetting (MBJ). These technologies were selected because they represent substantially different combinations of energy source, feedstock form, thermal

history, deposition rate, geometrical capability, and post-processing requirements, thereby providing a suitable basis for examining process-dependent material behaviour.

Particular emphasis was placed on publications addressing major engineering alloy families, including titanium alloys, nickel-based superalloys, stainless and other steels, and aluminium alloys. The literature was analysed not only according to the AM technique employed, but also according to the relationships established between processing parameters, thermal and solidification behaviour, microstructure, defect susceptibility, mechanical properties, and post-processing requirements. This approach was adopted to move beyond a purely descriptive comparison of AM technologies and towards a mechanistic interpretation of their suitability for different metallic materials and engineering applications.

Given the rapid development of metal additive manufacturing, priority was assigned to recent literature. The literature set comprises more than 70 references, with emphasis on publications from the 2020–2025 period. Earlier publications were retained when they represented foundational contributions to the understanding of AM process physics, process–structure–property relationships, specific manufacturing technologies, or environmental assessment. This combination of recent and seminal literature was considered necessary to capture both the established scientific foundations of MAM and the latest technological developments.

For the present review, the selected publications were classified according to six principal analytical dimensions: (i) manufacturing technology; (ii) alloy family; (iii) process parameters and thermal/material response; (iv) defect formation mechanisms; (v) microstructural and mechanical properties; and (vi) optimization and post-processing strategies. Sustainability-related indicators, including material utilization, energy consumption, feedstock recyclability, and post-processing requirements, were considered as complementary criteria for process selection rather than as isolated measures of manufacturing performance.

The comparative analysis was subsequently organized through a process–material perspective. For each alloy family, the available evidence was examined to determine which AM processes provide the most favourable combination of manufacturability and resulting properties, which defect mechanisms constitute the principal limitations, and which process-control or post-processing strategies can be employed to mitigate these limitations. Particular attention was given to recurring relationships between energy input, melt-pool behaviour, solidification conditions, microstructure, defect formation, and final material performance.

Based on this analysis, the evidence extracted from the literature was synthesized into an integrated Process–Material–Defect–Property (PMDP) framework. The overall methodological workflow adopted in this review, encompassing literature selection, technology and material classification, scientific analysis, optimization strategies, and the subsequent development of the PMDP framework, is summarized in Figure 1. The framework was conceived to correlate the selected AM technology and alloy characteristics with the expected processing response, dominant defect mechanisms, resulting microstructure and properties, available mitigation strategies, and potential application domains. In this manner, the review seeks not only to summarize the existing literature but also to provide a structured decision-support perspective for selecting and optimizing metal additive manufacturing routes.

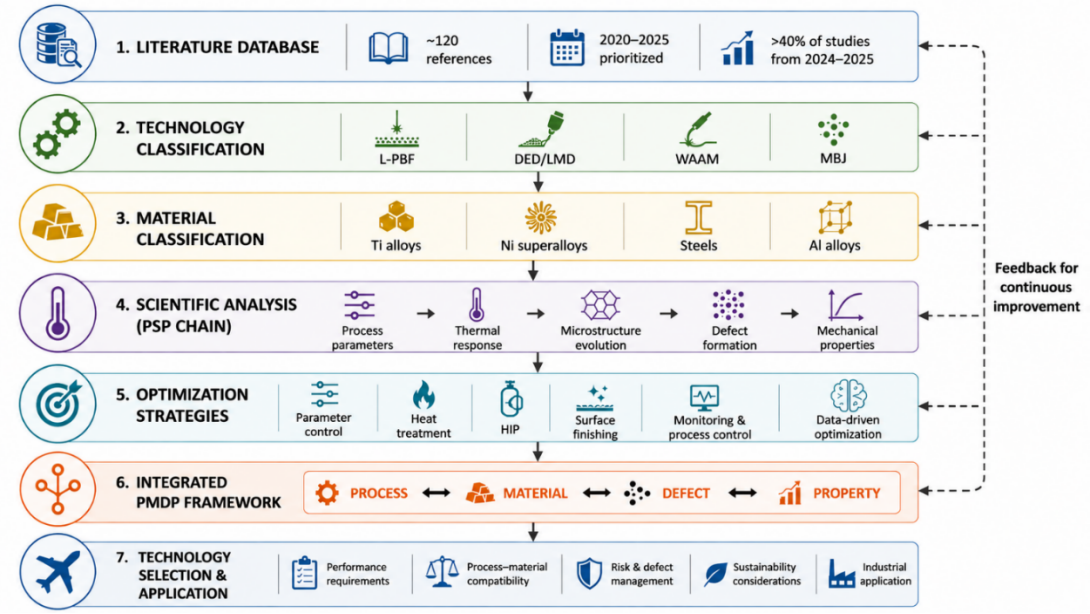


Figure 1. Methodological workflow adopted for the critical literature review, from literature selection and classification to the development of the integrated Process–Material–Defect–Property (PMDP) framework.

3. Fundamentals and Processing Characteristics of Metal Additive Manufacturing Technologies

Metal additive manufacturing technologies differ fundamentally in the manner by which material is supplied, energy is delivered, and consolidation is achieved. These differences determine not only productivity and geometrical capability but also the thermal history imposed on the material, which subsequently controls solidification behaviour, microstructural evolution, defect formation, residual stresses, and final component properties. Consequently, understanding the physical characteristics of each process is essential before assessing its suitability for a particular alloy system.

Among the available technologies, L-PBF, LMD, WAAM, and MBJ represent particularly distinct processing routes. L-PBF, LMD, and WAAM rely on localized thermal energy to produce metallurgical bonding during deposition, whereas MBJ separates geometrical shaping from material consolidation through a subsequent sintering stage. The technologies also span markedly different productivity ranges: reported deposition rates vary from approximately 0.05–0.2 kg/h for L-PBF to 0.2–2.0 kg/h for LMD and 1–10 kg/h for WAAM, while MBJ productivity is primarily governed by build volume and batch configuration [1,31–33]. These differences establish an intrinsic trade-off between geometrical resolution, productivity, thermal exposure, and material response that must be considered when selecting a process.

3.1. Laser Powder Bed Fusion (L-PBF)

Laser Powder Bed Fusion produces metallic components through the selective melting of successive thin layers of powder using a focused high-energy laser beam [10]. The process provides one of the highest levels of geometrical freedom among metallic AM technologies, enabling the manufacture of complex external geometries, lattice structures, and internal channels that are difficult or impossible to obtain through conventional machining or high-deposition-rate AM processes.

The high spatial concentration of laser energy and relatively small interaction volume result in highly localized melting followed by rapid solidification. Consequently, the thermal history experienced by the material differs substantially from that associated with conventional casting or thermomechanical processing. From a process–structure–property perspective, this characteristic is simultaneously one of the major advantages and limitations of L-PBF: rapid solidification can generate fine microstructures and high mechanical strength, but steep thermal gradients and repeated heating and cooling cycles may also promote residual stresses, distortion, anisotropy, and microstructural heterogeneity [10,18].

Process stability is strongly dependent on the interaction between laser power, scanning velocity, hatch spacing, layer thickness, powder characteristics, and scanning strategy. An insufficient energy input may prevent complete consolidation between neighbouring tracks or layers, favouring lack-of-fusion defects, whereas excessive localized energy may destabilize the melt pool and increase the likelihood of keyhole-type porosity. Therefore, the definition of an appropriate processing window must consider both energy delivery and alloy-dependent thermophysical behaviour rather than relying on an isolated parameter.

Feedstock quality represents another critical factor. L-PBF generally requires highly spherical powders with a relatively narrow particle-size distribution; the original literature reports typical particle sizes of approximately 15–45 μm [34]. Powder morphology and size distribution influence flowability, packing behaviour, layer homogeneity, and ultimately melt-pool stability and defect formation. Powder reuse introduces an additional variable because repeated exposure to the build environment can alter morphology and chemical composition. Studies cited in the original manuscript for MS1 maraging steel and Inconel 718 (IN718) report oxidation and morphological changes associated with repeated recycling [34,35], while oxygen accumulation is particularly critical for reactive alloys such as Ti-6Al-4V [36,37].

The requirement for controlled atmospheres is similarly linked to material quality. Inert gas environments are used to minimize oxidation and contamination during processing, which becomes particularly important for oxygen-sensitive materials. Furthermore, rapid thermal cycles commonly result in residual stresses that may require subsequent stress-relief heat treatments [10]. Thus, although L-PBF offers exceptional geometrical capability and comparatively good as-built dimensional resolution, its successful application depends on stringent control of feedstock quality, atmosphere, energy input, thermal history, and post-processing.

From a material-selection perspective, L-PBF is therefore particularly attractive when geometrical complexity, dimensional resolution, high relative density, and microstructural refinement are dominant requirements. Its principal limitations arise from relatively low productivity, strict powder requirements, high thermal gradients, residual stresses, and susceptibility to process-induced porosity and cracking. These characteristics become particularly important when processing crack-sensitive alloys and will be discussed in relation to specific alloy families in the following sections.

3.2. Laser Metal Deposition (LMD) within Directed Energy Deposition (DED)

Directed Energy Deposition comprises processes in which feedstock material is delivered directly into a localized melt pool generated on the substrate or previously deposited material. In laser-based systems, generally designated Laser Metal Deposition, a focused laser provides the thermal energy while metallic material is supplied in powder or wire form. Compared with L-PBF, LMD typically operates with a larger interaction volume and higher deposition rates, sacrificing geometrical resolution in favour of productivity and greater flexibility in material addition.

One of the most important characteristics of LMD is its ability to deposit material onto existing components rather than being restricted to fabrication from a flat powder bed. This enables localized repair, remanufacturing, surface modification, and the addition of functional features to high-value components. The original manuscript consequently identifies repair capability and multi-material deposition among the principal strengths of LMD, while lower resolution and more complex toolpath planning remain important limitations.

From a metallurgical perspective, LMD remains a fusion-based process and therefore produces repeated melting and solidification cycles. However, its thermal conditions differ considerably from L-PBF because of the larger melt pool, higher material deposition rate, and repeated reheating of previously deposited layers. The resulting microstructure is consequently controlled by the interaction between energy input, material feed rate, travel speed, melt-pool geometry, interlayer temperature, and heat extraction through the substrate and previously deposited material.

These conditions can promote directional solidification and microstructural heterogeneity along the build direction, while excessive heat accumulation may influence grain growth, residual stress development, dilution, and dimensional accuracy. Conversely, inadequate energy delivery or unstable feedstock transfer may promote incomplete bonding and porosity. Consequently, controlling the balance between energy input and material delivery represents one of the principal requirements for obtaining consistent properties in LMD components.

A particularly important advantage is the possibility of using both powder and wire feedstocks. Powder-fed configurations provide greater flexibility for composition control and potentially enable graded or multi-material structures, whereas wire-fed systems can achieve high material utilization and avoid some of the handling and recycling issues associated with fine metallic powders. This versatility makes LMD particularly relevant for repair, remanufacturing, coating, local reinforcement, and functionally graded material applications, rather than exclusively for complete component fabrication.

This capability also provides an important link between technological performance and circular manufacturing. The literature incorporated in the original manuscript identifies LMD as particularly advantageous for extending the service life of high-value components through repair and remanufacturing [13,38]. However, qualification of repaired components, control of the interface between substrate and deposited material, and reproducibility of local properties remain important industrial challenges.

3.3. Wire Arc Additive Manufacturing (WAAM)

Wire Arc Additive Manufacturing combines a metallic wire feedstock with an electric arc heat source to deposit successive beads of molten material. Compared with laser-based powder processes, WAAM is characterized by substantially higher deposition rates, high feedstock utilization, relatively simple material handling, and the capability to manufacture large components without the strict build-volume limitations associated with powder-bed systems. Reported deposition rates typically range between approximately 1 and 10 kg/h, considerably exceeding those commonly achieved by L-PBF and LMD [31,39]

These characteristics make WAAM particularly attractive for large structural components and high-value alloys for which conventional machining from billets or forgings would generate large quantities of waste. Wire feedstock can approach very high material utilization, and the relatively high electrical efficiency of arc-based heat sources contributes to lower specific process energy than laser-based alternatives [31,40,41]. The original manuscript reports specific energy consumption values of approximately 2.5–3.5 kWh/kg for WAAM, compared with 80–150 kWh/kg for L-PBF and 30–60 kWh/kg for LMD [1,31,32].

The same high heat input responsible for high productivity, however, creates significant metallurgical and dimensional challenges. Large melt pools, relatively low cooling rates, repeated thermal cycling, and progressive heat accumulation during fabrication can promote coarse and directionally solidified microstructures, distortion, residual stresses, and anisotropic properties. The original comparative assessment accordingly identifies high heat input, distortion, poor surface finish, and limited geometrical complexity among the principal weaknesses of WAAM.

Process control therefore requires careful coordination of arc power, wire-feed rate, travel speed, deposition strategy, interlayer temperature, shielding conditions, and heat management. Excessive heat accumulation can

modify bead geometry and microstructure as the build height increases, whereas inadequate energy or material transfer may compromise interlayer bonding. Thermal management strategies, including interpass temperature control and optimized deposition sequences, consequently, play an important role in achieving consistent geometrical and metallurgical characteristics.

Another important limitation is surface integrity. The comparatively large, deposited beads and layer dimensions generally result in poorer as-built surface finish than L-PBF, frequently requiring subsequent machining. The original manuscript therefore identifies hybrid WAAM–CNC manufacturing (where CNC denotes computer numerical control) as a particularly promising approach, combining the material efficiency and deposition rate of WAAM with the dimensional accuracy and surface integrity achievable through machining [31].

WAAM is consequently most attractive when component size, deposition rate, material utilization, and manufacturing cost dominate over as-built resolution. Its successful implementation nevertheless depends strongly on controlling heat accumulation and the resulting microstructure, particularly for alloy systems in which thermal history strongly affects phase transformations and mechanical properties.

3.4. Metal Binder Jetting (MBJ)

Metal Binder Jetting differs fundamentally from L-PBF, LMD, and WAAM because component shaping occurs without localized melting. During printing, a liquid binder is selectively deposited onto successive layers of metallic powder to form a geometrically defined but mechanically weak "green" component. Consolidation is subsequently achieved through curing, debinding, and high-temperature sintering. Consequently, the thermal history governing the final properties occurs primarily during post-print densification rather than during layer deposition.

This separation between shaping and consolidation provides several advantages. Because no concentrated thermal energy source is applied during printing, thermal gradients and residual stresses associated with localized melting are substantially reduced. Furthermore, surrounding loose powder provides geometrical support, facilitating the production and stacking of multiple components within the build volume and making MBJ particularly attractive for batch and series production. The original manuscript highlights high throughput, absence of conventional support structures, and the possibility of replacing tooling-dependent manufacturing routes among its principal advantages.

However, the absence of melting during printing transfers the principal metallurgical challenge to the sintering stage. During thermal consolidation, substantial shrinkage occurs as porosity is progressively eliminated. The original comparative analysis identifies shrinkage of approximately 20% and residual porosity as important limitations of MBJ. Consequently, dimensional compensation, homogeneous binder distribution, powder packing density, debinding behaviour, sintering temperature, atmosphere, and thermal cycle become critical parameters.

The sintering process also dominates the energy consumption of MBJ. Although the printing stage itself can require approximately 1 kWh/kg, heating the components to approximately 80–90% of the material melting temperature for several hours increases the overall reported specific energy consumption to approximately 30–50 kWh/kg [33,42]. Thus, the efficiency of MBJ is strongly dependent on batch utilization and furnace loading rather than solely on printing speed.

An additional advantage concerns feedstock reuse. Because unbound powder is not repeatedly exposed to a localized melting source during printing, thermal degradation is reduced compared with fusion-based powder processes. The literature cited in the original manuscript reports repeated reuse of 316L and 17-4PH stainless-steel powders with limited deterioration in flowability and apparent density, with humidity control becoming an important consideration [43].

From a process–material perspective, MBJ is therefore particularly attractive for high-volume production of relatively small and complex components, provided that sinterability, densification, shrinkage, and residual porosity can be adequately controlled. Unlike fusion-based AM, its principal optimization problem is not melt-pool stability but the relationship between powder characteristics, binder distribution, green-part integrity, debinding, and sintering kinetics.

3.5. Comparative Process Perspective

The four technologies therefore occupy distinct regions of the metal additive manufacturing design space rather than representing directly interchangeable alternatives. L-PBF prioritizes geometrical resolution and complexity but imposes strict requirements on powder characteristics and thermal-process control. LMD provides greater deposition flexibility and unique repair and material-addition capabilities. WAAM maximizes deposition rate and material efficiency for large components but introduces significant thermal-management and surface-quality challenges. MBJ provides a fundamentally different route capable of high-throughput batch production but transfers process control from melt-pool dynamics to densification and sintering.

This comparison demonstrates why process selection cannot be performed independently of material behaviour. The same characteristics that represent an advantage for one alloy may become a limitation for another. High cooling rates in L-PBF, high heat accumulation in WAAM, repeated thermal cycling in LMD, and high-temperature sintering in MBJ impose fundamentally different metallurgical conditions. Therefore, the suitability of each technology must ultimately be evaluated according to the response of specific alloy families, including their solidification behaviour, phase transformations, defect susceptibility, and required mechanical performance. These process–material interactions constitute the focus of the following section.

WAAM, classified in the Directed Energy Deposition (DED) category according to ISO/ASTM 52900 (ISO: International Organization for Standardization; ASTM: ASTM International, formerly the American Society for Testing and Materials), uses an electric arc as the thermal source to melt a metal wire feedstock [31]. Unlike powder-based systems, WAAM is characterised by high deposition rates (typically 1–10 kg/h) and virtually unlimited build volumes, limited only by the reach of the robotic arm [40]. From a sustainability perspective, the fundamental advantage of WAAM lies in its feedstock: metal wire is significantly cheaper to produce and easier to handle than gas-atomized powders, and it presents zero health hazards regarding inhalation of micro-particles [41].

A comparative overview of the principal technological characteristics, processing limitations, defect susceptibility, and optimization priorities associated with these four MAM routes is presented in Figure 2.



Figure 2. Comparative technological overview of the main metal additive manufacturing processes, highlighting feedstock, consolidation mechanism, productivity, geometric resolution, thermal characteristics, predominant defect challenges, optimization strategies, and technological strengths.

4. Alloy-Specific Process–Material Relationships

The performance of metal additive manufacturing cannot be evaluated independently of alloy chemistry and metallurgical behaviour. Although the processing characteristics described in Section 3 establish the thermal and geometrical conditions associated with each AM technology, the response to these conditions is strongly material dependent. Melting range, thermal conductivity, absorptivity, oxidation tendency, phase-transformation kinetics, solidification range, and susceptibility to cracking determine whether a particular alloy can be processed within a stable manufacturing window and which microstructures and properties can ultimately be achieved [18].

Accordingly, the selection of AM technology should not be based solely on productivity or geometrical capability. Instead, it should consider the complete relationship between alloy characteristics → process thermal history → solidification or densification mechanisms → microstructure → defect susceptibility → final properties. This section critically examines these relationships for the principal engineering alloy families considered in metal additive manufacturing.

4.1. Titanium Alloys

Titanium alloys represent one of the most technologically important material classes for MAM, particularly in aerospace and other high-performance applications. Among them, Ti-6Al-4V is by far the most extensively investigated alloy because of its high specific strength, corrosion resistance, and established use in structurally demanding applications [17]. The relatively high cost of titanium feedstock and the large Buy-to-Fly ratios associated with conventional machining further increase the attractiveness of near-net-shape additive routes.

However, the response of Ti-6Al-4V to AM is strongly governed by thermal history. Fusion-based processes involve melting above the β-transus followed by cooling under conditions that may differ by several orders of magnitude between L-PBF, LMD, and WAAM. Consequently, the resulting α/β phase balance, morphology, prior-β grain structure, crystallographic texture, and residual stress state can vary considerably between processes [17,18].

4.1.1. Ti-6Al-4V Processed by L-PBF

L-PBF is particularly attractive for Ti-6Al-4V when high geometrical complexity and lightweight design are required. The high cooling rates associated with the small melt pool favour very fine microstructures and can promote the formation of metastable martensitic α′ rather than the equilibrium α+β microstructure [17]. This generally contributes to high strength and hardness in the as-built condition but may be accompanied by reduced ductility and significant residual stresses.

The principal processing challenge is therefore not simply achieving consolidation but controlling the balance between microstructural refinement and residual-stress accumulation. Insufficient energy input can promote lack-of-fusion porosity, whereas excessive energy concentration can destabilize the melt pool and favour keyhole porosity. In addition, titanium's strong affinity for oxygen requires stringent atmosphere and powder-quality control. This is particularly relevant when recycled powder is used, since oxygen accumulation may eventually affect material performance [36,37].

Post-processing consequently becomes an integral component of the L-PBF Ti-6Al-4V processing route. Stress-relief and other heat treatments can modify the as-built microstructure and reduce residual stresses, while surface-finishing treatments are particularly important for fatigue-critical applications. The original literature set already contains recent studies addressing combined heat treatment and surface modification of L-PBF Ti-6Al-4V [44,45].

Therefore, L-PBF is particularly advantageous for Ti-6Al-4V components in which geometrical complexity, lightweighting, and high specific mechanical performance outweigh productivity requirements. Optimization should focus on energy input, scanning strategy, atmosphere/powder quality, residual-stress management, and post-processing.

4.1.2. Ti-6Al-4V Processed by LMD

LMD provides a different processing environment for Ti-6Al-4V. The larger melt pool and lower cooling rates relative to L-PBF reduce the tendency towards extremely fine martensitic structures but increase the influence of directional heat extraction and repeated thermal cycling. These conditions may favour the development of large prior-β grains extending across multiple deposited layers, producing anisotropic microstructures and direction-dependent properties [17,18].

The principal advantage of LMD for titanium is its versatility. Material can be deposited locally onto existing components, making the process particularly attractive for repair, feature addition, and remanufacturing [13]. Moreover, powder- and wire-fed configurations allow different compromises between compositional flexibility, deposition efficiency, and material utilization.

Process optimization requires controlling the relationship between laser energy, travel speed, feed rate, dilution, and interlayer thermal conditions. Excessive energy promotes heat accumulation and microstructural coarsening, whereas insufficient energy may produce incomplete bonding and porosity. The challenge is therefore to maintain stable deposition while limiting excessive thermal exposure [46].

For Ti-6Al-4V, LMD is consequently especially attractive for repair and local material addition, where the capability to process an existing high-value component may outweigh the lower dimensional resolution compared with L-PBF.

4.1.3. Ti-6Al-4V Processed by WAAM

WAAM is particularly attractive for large Ti-6Al-4V structures because it combines high deposition rates with near-complete wire utilization. However, its comparatively high heat input and large melt pool generate a thermal history substantially different from L-PBF. Repeated heating of previously deposited layers and directional

heat extraction can generate coarse columnar prior-β grains and pronounced texture, which may contribute to anisotropic mechanical behaviour [17,20].

The strong dependence of properties on thermal history makes post-processing particularly relevant. Bermingham et al. [20] specifically investigated the optimization of the mechanical properties of WAAM Ti-6Al-4V through post-process heat treatments, demonstrating the importance of controlling the microstructural condition rather than considering the as-deposited state as the final material state. The presence of this reference in the original bibliography is particularly valuable for the process–material framework proposed in this review.

WAAM optimization should therefore focus strongly on heat-input control, interpass temperature, deposition strategy, microstructural refinement, and subsequent heat treatment. Surface machining is also commonly required because the high deposition rate is accompanied by relatively poor as-built surface quality.

Accordingly, WAAM provides its greatest advantage for large-scale titanium structures where deposition rate and material efficiency dominate over geometrical resolution, whereas L-PBF occupies the opposite end of the technological spectrum for complex, smaller, high-resolution Ti-6Al-4V components.

4.2. Nickel-Based Superalloys

Nickel-based superalloys are extensively employed in aerospace, energy, and high-temperature applications because of their ability to retain mechanical strength, oxidation resistance, and creep resistance under severe thermal conditions. IN718 is particularly relevant to MAM and is explicitly represented in the literature considered in this review, including studies addressing powder recycling and surface post-processing [47,48].

Unlike Ti-6Al-4V, where phase transformation and α/β morphology constitute dominant considerations, nickel-based superalloys present important challenges associated with elemental segregation, precipitation behaviour, residual stresses, and susceptibility to cracking during repeated rapid solidification and thermal cycling. Consequently, successful AM processing requires controlling not only density but also the thermal conditions governing solidification and subsequent precipitation.

For L-PBF, the principal advantage is the ability to manufacture geometrically complex high-temperature components, including structures incorporating internal channels. Nevertheless, high thermal gradients may generate residual stresses, while inadequate energy input can promote lack of fusion and excessive energy can produce keyhole porosity. Powder condition also deserves particular attention. The literature considered in the original manuscript identifies morphological and chemical changes during powder recycling, including studies involving IN718 [34–37,48].

LMD is especially relevant to nickel-based superalloys because many components manufactured from these materials—such as turbine-related parts—have high economic value. Local material addition therefore provides an attractive route for repair and remanufacturing rather than complete component replacement. The original bibliography includes both general DED repair literature [13] and work on remanufacturing turbine blades through laser direct deposition [49], providing strong support for this application.

WAAM can potentially provide advantages for larger nickel-alloy components, particularly when deposition rate is important. However, the greater heat input and slower thermal cycles increase the importance of controlling solidification behaviour, segregation, and accumulated thermal exposure. Compared with titanium alloys, alloy-specific weldability therefore becomes an even more important criterion when considering WAAM for nickel-based materials.

Post-processing is particularly significant for precipitation-strengthened superalloys. Heat treatment must be considered as part of the complete manufacturing route because the precipitation state governing high-temperature mechanical performance cannot necessarily be obtained directly from the as-built thermal history.

Overall, L-PBF is particularly advantageous for geometrically complex Ni-superalloy components, while LMD provides exceptional value for repair and remanufacturing of high-value components. The suitability of WAAM becomes more alloy- and geometry-dependent, while MBJ may offer opportunities for series production but requires rigorous control of densification and post-sintering properties.

4.3. Stainless, Duplex and High-Strength Steels

Steels constitute one of the broadest material families processed by AM, encompassing austenitic stainless steels, precipitation-hardening steels, duplex grades, tool steels, and maraging steels. Their comparatively broad industrial application makes them relevant across all four technologies considered in this review.

L-PBF has been extensively applied to steels because many grades exhibit comparatively good laser processability. Nevertheless, powder quality and reuse remain relevant. The original literature includes recent

investigations into recycled MS1 and M300 maraging-steel powders [34,35], reporting changes in powder morphology and oxidation during repeated use.

The rapid solidification associated with L-PBF can produce very fine microstructures, while subsequent heat treatments may be employed to tailor phase constitution, precipitation, hardness, and residual stress state depending on the steel grade. As with other alloy systems, inadequate processing windows may generate lack-of-fusion or keyhole porosity.

LMD offers a particularly attractive route for repair of steel components. The original literature provides a relevant example in the repair of damaged super-duplex stainless-steel components through laser additive manufacturing [38]. This application illustrates an important advantage of LMD: the process can restore material locally while potentially avoiding replacement of an entire high-value component. However, dilution between the deposited material and substrate, local thermal cycling, phase balance, and heat-affected-zone characteristics must be controlled carefully.

WAAM is similarly attractive for large steel structures because of its high productivity and the widespread commercial availability of welding-wire feedstocks. Its metallurgical behaviour is strongly related to conventional welding science, meaning that heat input, interpass temperature, shielding, and deposition sequence strongly influence grain structure, residual stresses, distortion, and mechanical anisotropy.

MBJ is particularly interesting for stainless steels. The original literature specifically includes powder characterization and binder jetting of 316L stainless steel [50], together with reviews of MBJ materials and sintering [7,14,15,50,51]. Moreover, studies incorporated into the manuscript report repeated reuse of 316L and 17-4PH powders with limited degradation in flowability and apparent density.

For MBJ steels, the primary challenge shifts from solidification control to densification control. Powder packing, binder saturation, debinding, sintering temperature and time, shrinkage, and residual porosity determine dimensional accuracy and mechanical performance. Thus, MBJ can be particularly attractive for high-volume production of relatively small steel components, whereas WAAM becomes advantageous for large structures, L-PBF for geometrically complex high-performance parts, and LMD for repair and local modification.

4.4. Aluminium Alloys

Aluminium alloys are particularly attractive for additive manufacturing because their low density makes them important for lightweight structures in aerospace, transportation, and automotive applications. At the same time, they represent a challenging material family for fusion-based AM because high thermal conductivity, laser reflectivity, oxide formation, hydrogen-related porosity, and—in several alloy compositions—solidification cracking can significantly narrow the stable processing window.

Among aluminium alloys, AlSi10Mg represents one of the most extensively investigated compositions for Laser Powder Bed Fusion due to its comparatively favourable processability and suitability for lightweight, geometrically complex components. Nevertheless, its final properties remain strongly dependent on the interaction between processing parameters, powder characteristics, melt-pool stability, and solidification behaviour. Insufficient energy input may promote lack-of-fusion defects, whereas excessive energy concentration can induce keyhole porosity. Furthermore, powder surface chemistry, particularly the presence of oxides, hydroxides, and moisture, can influence gas-related porosity and the reproducibility of the manufacturing process. Recent investigations have demonstrated that processing conditions and defect characteristics significantly affect the mechanical response of L-PBF AlSi10Mg, reinforcing the importance of considering porosity, microstructure, and material performance as interconnected variables rather than independent optimization targets

From a process perspective, L-PBF offers strong potential for lightweight and topologically optimized aluminium components but requires careful control of laser–material interaction and solidification conditions. Process optimization typically aims to simultaneously increase density and suppress solidification-related defects. LMD provides advantages for local deposition and repair but presents challenges associated with oxide formation, melt-pool stability, and thermal management. WAAM is attractive for large aluminium structures because aluminium welding wires are commercially available and high deposition rates can be achieved; nevertheless, porosity, distortion, heat accumulation, and microstructural heterogeneity require careful control. MBJ avoids melt-pool-related cracking during printing but introduces different challenges associated with aluminium powder oxidation and sintering. Achieving sufficient densification is therefore a central issue. The aluminium case particularly demonstrates why the proposed process–material framework is necessary: avoiding fusion during printing may eliminate certain thermal defects but simultaneously introduce new densification limitations, while increasing deposition rate can reduce manufacturing time at the expense of thermal and geometrical control.

4.5. Cross-Alloy Interpretation and Process Selection

The comparison of these alloy families demonstrates that there is no universally optimal MAM technology. Instead, process suitability emerges from the compatibility between the thermal or densification characteristics of the manufacturing route and the metallurgical response of the selected alloy.

For Ti-6Al-4V, the major challenge is controlling phase transformation, texture, anisotropy, and residual stresses while exploiting the high specific properties of the alloy. L-PBF is therefore particularly suited to geometrically complex titanium parts, whereas WAAM offers a compelling route for large structural components and LMD for repair and local deposition [17,20]. For nickel-based superalloys, solidification behaviour, cracking susceptibility, segregation, and precipitation control become more prominent, increasing the importance of thermal management and post-process heat treatment. For steels, the broader range of processable compositions enables application across all four technologies, with process selection strongly dependent on component scale and whether the objective is fabrication, repair, or series production. MBJ becomes particularly attractive for sinterable steel systems and high-volume manufacturing.

This comparison also demonstrates that defect mitigation and property optimization must be alloy-specific. Increasing energy input may eliminate lack-of-fusion porosity but simultaneously increase keyhole formation, residual stresses, dilution, or thermal accumulation. Similarly, decreasing cooling rate may reduce residual stresses while promoting microstructural coarsening. Optimization must therefore be treated as a multi-objective problem in which density, microstructure, defect population, residual stress, surface condition, productivity, and final mechanical performance are considered simultaneously.

This behaviour is consistent with the broader process–structure–property framework established in the AM literature [18,22], in which local processing conditions govern thermal history and microstructure and ultimately determine final component performance. The central implication is that process selection and material selection cannot be treated as independent decisions. The comparison of these alloy families demonstrates that there is no universally optimal MAM technology. Instead, process suitability emerges from the compatibility between the thermal or densification characteristics of the manufacturing route and the metallurgical response of the selected alloy. Figure 3 summarizes these process–alloy relationships by comparatively mapping the relative suitability of L-PBF, LMD, WAAM, and MBJ for the principal alloy families considered in this review, together with the main technological advantage and dominant limitation associated with each combination [52].



Figure 3. Process–alloy compatibility map for the main metal additive manufacturing technologies, highlighting their relative suitability, principal technological advantages, and dominant processing limitations for titanium alloys, nickel-based superalloys, steels, and aluminium alloys. The star ratings represent relative suitability trends

derived from the reviewed literature and should not be interpreted as absolute rankings. Actual process suitability depends on the specific alloy grade, component geometry, processing conditions, post-processing route, and intended application.

As illustrated in Figure 3, process suitability is strongly dependent on the intended manufacturing objective. L-PBF provides its greatest advantage when geometrical complexity and high resolution are required, particularly for titanium alloys and nickel-based superalloys, although residual stresses, cracking susceptibility, and process-induced porosity remain important limitations. LMD is particularly attractive for repair, remanufacturing, and local material addition, especially for high-value titanium- and nickel-based components. Conversely, WAAM becomes increasingly advantageous when component size, deposition rate, and material utilization dominate the selection criteria, while its comparatively high thermal input requires careful management of heat accumulation, distortion, anisotropy, and microstructural coarsening. MBJ occupies a distinct technological domain, with particular potential for high-throughput production of steel components, although shrinkage and residual porosity during sintering remain critical limitations. Importantly, the suitability ratings presented in Figure 3 should not be interpreted as absolute process rankings. Actual performance depends on the specific alloy grade, component geometry, processing parameters, required properties, and post-processing route. Rather, the map provides a comparative representation of the dominant trends identified in the literature and reinforces the central premise of this review: process selection and material selection must be treated as coupled engineering decisions.

5. Defect Formation Mechanisms and Mitigation Strategies in Metal Additive Manufacturing

Defect formation remains one of the principal barriers to the reproducibility, qualification, and widespread industrial adoption of metal additive manufacturing. Unlike conventional manufacturing processes, defects in MAM frequently originate from highly localized and transient interactions between energy input, feedstock delivery, melt-pool dynamics, heat transfer, solidification, and repeated thermal cycling. Consequently, defects should not be considered isolated imperfections but rather manifestations of an unstable or suboptimal process–material interaction [18,21,22].

The mechanisms governing defect formation vary considerably among MAM technologies. In fusion-based processes such as L-PBF, LMD, and WAAM, defect generation is predominantly governed by melt-pool stability, energy–material balance, solidification behaviour, thermal gradients, and shielding conditions. Conversely, MBJ does not involve melting during printing; its dominant defects originate from powder packing, binder deposition, debinding, shrinkage, and incomplete densification during sintering [7,14,15,50,51].

Understanding these mechanisms is therefore essential for establishing processing windows that simultaneously minimize defects and optimize microstructure and mechanical performance.

5.1. Porosity and Lack-of-Fusion Defects

Porosity is among the most frequently reported defects in metal additive manufacturing and can originate from fundamentally different physical mechanisms. In fusion-based processes, pores may result from insufficient melting, unstable melt-pool behaviour, entrapped gases, feedstock contamination, or excessive energy input. Their morphology, distribution, and origin are therefore directly related to processing conditions and material characteristics [18,21].

Lack-of-fusion (LOF) porosity occurs when the supplied energy is insufficient to produce adequate melting and metallurgical bonding between adjacent tracks or successive layers. In L-PBF, this may result from an unfavourable combination of laser power, scanning velocity, hatch spacing, and layer thickness. In LMD and WAAM, inadequate energy relative to material feed rate or unstable deposition can similarly compromise interlayer bonding. LOF defects are generally irregular in morphology and particularly detrimental under cyclic loading because their sharp geometrical features promote local stress concentration.

Increasing energy input can reduce LOF formation, but this does not imply that continuously increasing energy density improves material quality. Beyond a stable conduction-mode processing window, excessive localized energy may generate deep and unstable vapour depressions within the melt pool, promoting keyhole-type porosity. Thus, LOF and keyhole porosity can be regarded as opposite manifestations of an inappropriate energy–material balance: insufficient energy favours incomplete fusion, whereas excessive energy promotes melt-pool instability [18,22].

Gas-related porosity represents an additional mechanism. Gas may originate from the feedstock, surface contamination, shielding conditions, or gases trapped during rapid solidification. Feedstock condition therefore becomes an important control variable. The original literature set shows that repeated powder reuse can promote

oxidation and morphological changes, including satellite formation and spatter fusion [34,35], while oxygen accumulation is particularly critical for reactive materials such as Ti-6Al-4V [36,37].

In MBJ, porosity has a fundamentally different origin. Since particles are not melted during printing, the green part initially contains substantial interparticle void space. Final density is developed during sintering, and insufficient densification leaves residual porosity that directly influences mechanical performance. Powder size distribution, packing density, binder saturation, debinding conditions, sintering temperature, time, and atmosphere therefore become the principal variables controlling final porosity [7,14–16,50,51]. The extensive MBJ literature already included in the manuscript provides a strong basis for this distinction.

Mitigation of porosity consequently requires mechanism-specific strategies. For fusion-based MAM, optimization must establish an energy window that ensures adequate fusion without inducing keyhole instability, together with appropriate control of feedstock and atmosphere. For MBJ, optimization instead focuses on powder packing and sintering kinetics to maximize densification while maintaining dimensional control.

5.2. Cracking and Solidification-Related Defects [53]

Cracking represents a more severe limitation because even relatively small cracks can compromise structural integrity and may render a component unacceptable regardless of its overall density. Crack susceptibility is strongly alloy-dependent and therefore illustrates particularly well the need to couple process and material selection.

The experimentally observed morphologies of representative L-PBF defects are compared in Figure 4. Gas porosity typically exhibits a relatively spherical morphology associated with gas entrapment during rapid solidification, whereas keyhole porosity develops under excessive localized energy input and unstable vapour-depression conditions. In contrast, lack-of-fusion defects exhibit irregular geometries and may contain incompletely melted powder as a consequence of insufficient fusion between adjacent tracks or layers. Thermal cracking represents a fundamentally different failure mechanism, arising from the interaction between severe thermal gradients, constrained shrinkage, solidification behaviour, and alloy-specific cracking susceptibility. These morphological distinctions are important because defect severity cannot be assessed solely from total porosity or relative density; defect geometry, location, and formation mechanism also govern stress concentration and ultimately component performance.

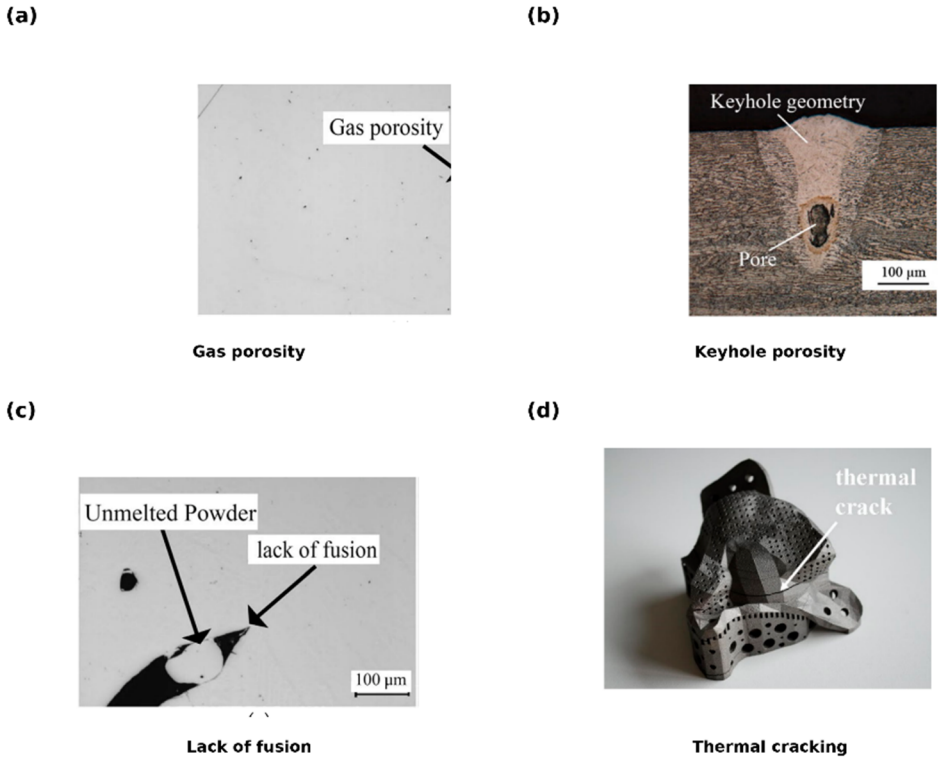


Figure 4. Representative experimentally observed defects in laser powder bed fusion (L-PBF): (**a**) gas porosity, characterized by a relatively spherical morphology associated with gas entrapment; (**b**) keyhole porosity, resulting from excessive localized energy input and instability of the vapour depression; (**c**) lack-of-fusion defect, exhibiting irregular morphology and incompletely melted powder associated with insufficient fusion; and (**d**) thermal cracking. Adapted from [54] under the Creative Commons Attribution License.

In fusion-based MAM, steep thermal gradients and rapid solidification generate localized thermal and mechanical stresses while the material passes through temperature ranges in which ductility may be limited. Depending on alloy chemistry and thermal history, cracking can be associated with solidification behaviour, segregation, liquation phenomena, phase transformations, or accumulated residual stresses [18].

Nickel-based superalloys and several aluminium compositions require particular attention because their solidification behaviour can restrict the available processing window. Similarly, repeated thermal cycling in LMD and WAAM may alter local microstructures and produce heat-affected regions that differ significantly from the newly deposited material. The transport phenomena and thermal conditions governing LMD are therefore fundamental to understanding defect formation [21].

The most direct mitigation strategy is control of the thermal cycle. Reducing excessive thermal gradients, modifying energy input, controlling interpass temperature, and selecting appropriate scanning or deposition sequences can reduce local stress accumulation. Feedstock preheating provides another route for reducing the thermal shock associated with material entering the melt pool. Hot-wire laser DED, for example, has been investigated using resistive preheating of the wire feedstock [55].

Nevertheless, process optimization alone cannot eliminate cracking susceptibility in every alloy. This is an important point for the review: processability is partly an intrinsic material characteristic. In highly crack-sensitive compositions, alloy modification, substrate preheating, alternative deposition technologies, or post-processing may ultimately be required. This reinforces the process–alloy compatibility concept established in Section 4.

5.3. Residual Stresses and Distortion

Residual stresses originate primarily from non-uniform heating and cooling during additive manufacturing. Localized energy input produces steep temperature gradients between the melt pool, surrounding solid material, previously deposited layers, and substrate. During cooling, differential thermal contraction is mechanically constrained by neighbouring material, generating residual stresses that accumulate throughout the build [18,22].

The magnitude and spatial distribution of residual stress depend on process characteristics. L-PBF combines very high thermal gradients with rapid cooling, making residual-stress control particularly important. The original manuscript already notes that stress-relief heat treatment is commonly required for L-PBF components because of stresses induced by rapid thermal cycling [10].

LMD and WAAM operate with larger melt pools and generally lower cooling rates, but this does not eliminate residual-stress problems. Their higher heat input and larger deposited volumes can instead produce substantial heat accumulation and macroscopic distortion. WAAM is particularly sensitive because the repeated deposition of relatively large beads introduces considerable thermal energy into the component and substrate.

Residual stresses may influence dimensional accuracy, promote cracking, modify fatigue behaviour, and cause component deformation during removal from the build plate or subsequent machining. Their mitigation therefore requires a combination of thermal management during deposition and stress redistribution after fabrication.

Strategies include substrate or feedstock preheating, interpass-temperature control, optimized scanning/deposition sequences, reduced local heat accumulation, and stress-relief heat treatments. In large-scale deposition processes, path planning can become an important thermal-management tool because the sequence in which material is deposited controls the spatial and temporal distribution of heat.

Thus, residual stress should not be considered exclusively a post-processing problem. Ideally, it should be controlled throughout the complete process chain, from deposition strategy to final heat treatment.

5.4. Microstructural Anisotropy and Heterogeneity

Not all MAM limitations are conventional defects such as pores or cracks. The layer-wise nature of additive manufacturing and directional heat extraction can generate pronounced microstructural anisotropy even in components with very low porosity.

Directional solidification frequently promotes elongated or columnar grains aligned with the dominant thermal gradient. Repeated deposition and reheating may further generate spatial variations in grain size, phase constitution, precipitation state, and texture. Consequently, mechanical properties measured parallel to the build direction may differ from those measured perpendicular to it [17,18].

This phenomenon is particularly relevant in Ti-6Al-4V. The AM literature represented in the original reference set emphasizes the strong dependence of titanium microstructure and properties on the processing route [17], while post-process heat treatments have been specifically investigated as a means of optimizing the properties of WAAM-produced Ti-6Al-4V [20].

In WAAM and LMD, the relatively large melt pool and directional heat flow may favour columnar grain growth across multiple layers. In L-PBF, the substantially higher cooling rate produces finer microstructures, but texture and directional solidification can still generate anisotropic behaviour.

Mitigation strategies therefore extend beyond simply reducing porosity. Scan rotation, deposition-path modification, thermal management, controlled reheating, heat treatment, and other microstructural engineering approaches may be required to disrupt persistent directional growth or modify the as-built phase structure.

The critical point is that a fully dense component is not necessarily an isotropic or optimized component. Process qualification should consequently consider microstructure and direction-dependent properties together with defect population.

5.5. Surface Integrity and Geometrical Defects

Surface integrity represents another important limitation because the as-built surface directly influences dimensional accuracy, friction, corrosion, and particularly fatigue performance. Surface condition varies considerably between MAM technologies due to differences in feedstock size, layer thickness, melt-pool dimensions, and consolidation mechanisms.

L-PBF generally provides better as-built resolution than LMD and WAAM, but surface roughness remains sufficient to require finishing for many high-performance applications. The original manuscript reports typical L-PBF roughness values of approximately and identifies sandblasting and electrolytic polishing among commonly employed post-processing routes [10,44,47]. Recent work contained in the reference set also specifically investigates post-processing of IN718 and plasma electrolytic polishing of titanium alloys [44,47].

WAAM presents a more pronounced geometrical challenge because large deposited beads and high deposition rates generate comparatively rough surfaces and limited dimensional accuracy. Consequently, machining is frequently required to achieve the final tolerance and surface condition. This creates a strong rationale for hybrid additive–subtractive manufacturing, which is already represented in the original bibliography [23,24].

In powder-based fusion processes, additional surface-related phenomena may include partially fused particles and spatter attachment, while unstable melt tracks can contribute to irregular surface formation. In LMD and WAAM, bead geometry and layer-height stability become critical for dimensional consistency.

MBJ again presents a different mechanism. Since geometrical dimensions change substantially during sintering, shrinkage and dimensional compensation become central design considerations. The MBJ literature included in the manuscript identifies sintering as a defining stage governing final part characteristics [7,15,50,51].

Surface and geometrical optimization therefore requires technology-specific solutions, ranging from melt-track stabilization and powder control in L-PBF to bead-geometry control and machining in WAAM and shrinkage compensation in MBJ [56].

5.6. Integrated Defect Mitigation and Property Optimization Strategies

The preceding analysis demonstrates that defect mitigation cannot be reduced to the optimization of a single processing parameter. Most defects emerge from coupled thermal, fluid-flow, metallurgical, and geometrical phenomena. Furthermore, strategies that suppress one defect may increase susceptibility to another. Increasing energy input, for example, can eliminate LOF defects while simultaneously increasing the risk of keyhole instability or heat accumulation.

A more robust approach therefore requires optimization across the complete manufacturing chain. At the feedstock level, powder morphology, particle-size distribution, chemical composition, oxygen content, wire quality, and binder characteristics must be controlled. Powder reuse must also be monitored because repeated recycling can modify morphology and chemistry [34–37].

At the processing level, energy input must be balanced with material delivery and heat dissipation. Laser power, arc parameters, scanning or travel speed, hatch spacing, layer thickness, wire/powder feed rate, interpass temperature, and deposition strategy should therefore be optimized as interacting variables rather than independently. Wolff et al. [22] specifically proposed linking localized process parameters with final AM part properties, providing a conceptual foundation for this multi-variable approach.

At the thermal-management level, preheating, interpass-temperature control, scan/deposition sequencing, and controlled cooling can be employed to modify thermal gradients and reduce residual stress, distortion, cracking susceptibility, and excessive microstructural heterogeneity.

At the post-processing level, heat treatment, Hot Isostatic Pressing (HIP), machining, polishing, and other surface treatments can be used to modify microstructure, relieve residual stresses, reduce internal defect populations, and improve surface integrity. The references already incorporated in the manuscript demonstrate the

relevance of heat treatment for WAAM Ti-6Al-4V [20] and surface post-processing for L-PBF IN718 and titanium alloys [44,45,47].

Finally, *in-situ* monitoring and closed-loop control provide an increasingly important route towards defect prevention rather than defect correction. Monitoring melt-pool behaviour, thermal signatures, layer quality, or deposition stability can potentially identify deviations before they propagate through the build. The original reference set already includes work addressing measurement requirements for real-time powder bed fusion (PBF) control [57] and a recent control-system approach for L-PBF [11].

The resulting optimization philosophy can therefore be expressed as a closed relationship:

Process parameters → physical/thermal response → defect mechanism → microstructure → properties → monitoring and corrective action.

Rather than relying primarily on post-process inspection, future MAM systems should increasingly aim to identify and suppress defect-generating conditions during fabrication. Such an approach transforms quality control from a predominantly reactive strategy into a predictive and adaptive manufacturing methodology. The relationships between the principal processing conditions, defect formation mechanisms, property consequences, and corresponding mitigation strategies discussed throughout this section are summarized in Figure 5. The map emphasizes that apparently similar defects may originate from fundamentally different physical mechanisms and therefore require different corrective actions. In fusion-based processes, the dominant mechanisms are primarily associated with energy–material imbalance, melt-pool instability, thermal gradients, solidification behaviour, and feedstock or atmosphere conditions, whereas MBJ is predominantly governed by powder packing, debinding, densification, and sintering phenomena.

As illustrated in Figure 5, defect mitigation should therefore follow a cause–mechanism–consequence–mitigation approach rather than relying exclusively on empirical parameter adjustment. For example, insufficient energy input may produce lack-of-fusion defects and require increased energy delivery or improved track overlap, whereas excessive energy input may generate keyhole instability and require the opposite intervention. Similarly, residual porosity in MBJ cannot be addressed through melt-pool control but instead requires optimization of powder packing, debinding, and sintering conditions. This distinction reinforces the need for process-specific and material-specific optimization strategies.

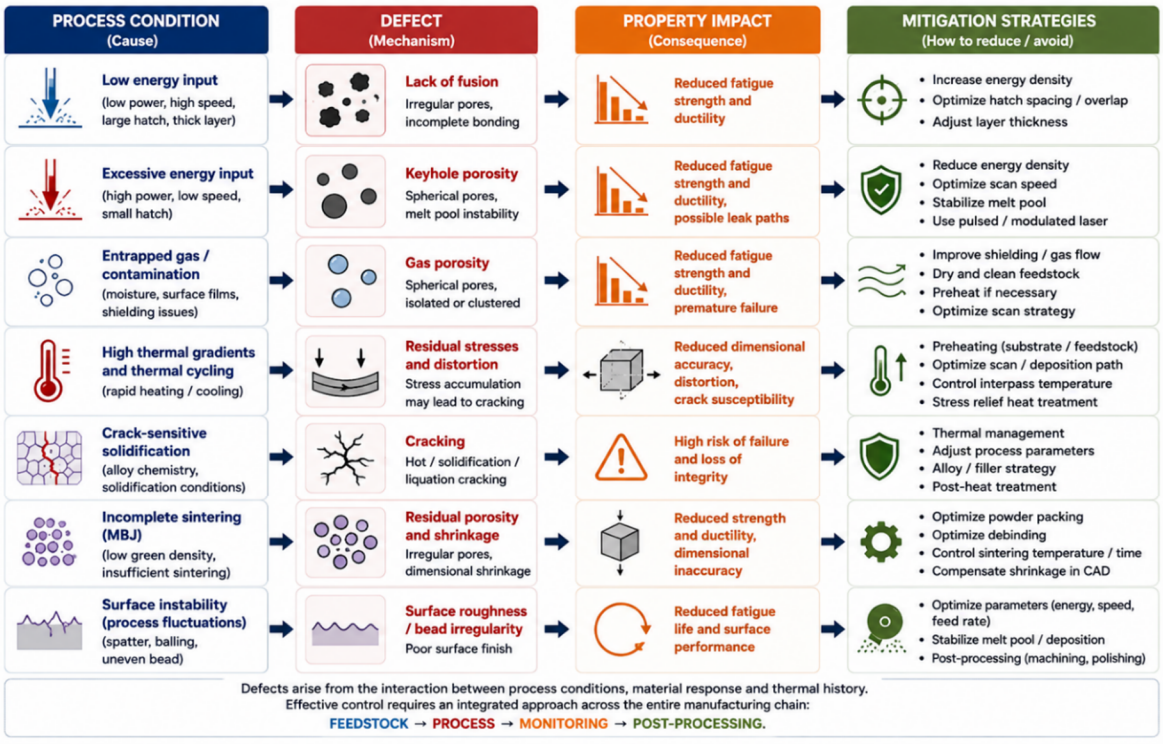


Figure 5. Integrated defect formation and mitigation map for metal additive manufacturing, correlating processing conditions with dominant defect mechanisms, their consequences on component properties, and the corresponding mitigation strategies.

5.7. From Defect Control to Process–Material Optimization

A critical outcome of the literature analysis is that the same defect may arise through different mechanisms depending on the selected process and material. Porosity in L-PBF may originate from lack of fusion, keyhole instability, or gas entrapment, whereas residual porosity in MBJ is predominantly associated with incomplete sintering and densification. Similarly, distortion in WAAM is closely associated with high heat input and accumulated thermal history, while dimensional deviations in MBJ are strongly influenced by sintering shrinkage.

Consequently, defect terminology alone is insufficient for process optimization. The physical mechanism responsible for the defect must first be identified, after which an appropriate mitigation strategy can be selected. This distinction is central to the framework proposed in this review.

The process–material relationships discussed in Section 4 and the defect mechanisms analysed in the present section therefore establish three interconnected levels of decision-making: process selection determines the imposed physical conditions; material characteristics determine the response to those conditions; and their interaction determines the dominant defect mechanisms and achievable properties. This mechanistic interpretation provides the foundation for the integrated Process–Material–Defect–Property framework developed in the subsequent sections.

6. Process–Structure–Property Relationships and Performance Optimization

The functional performance of additively manufactured metallic components cannot be predicted solely from nominal alloy composition or relative density. Unlike conventional processing routes, metal additive manufacturing generates highly localized and spatially variable thermal histories that continuously evolve during fabrication. Energy input, material delivery, melt-pool geometry, heat extraction, cooling rate, repeated reheating, and solidification conditions collectively determine the microstructural state of the deposited material and, consequently, its mechanical and functional properties [18,22].

The fundamental relationship can therefore be expressed as:

Process parameters → Thermal history → Solidification/densification → Microstructure → Defects → Properties → Functional performance

This sequence is not strictly unidirectional. Geometry, previously deposited material, substrate conditions, and accumulated heat continuously modify the thermal boundary conditions experienced during fabrication. Consequently, identical nominal process parameters may generate different local microstructures and properties at different positions within the same component. This spatial dependency represents one of the major challenges for achieving reproducible and certifiable MAM components.

6.1. Thermal History as the Link between Process and Microstructure

Thermal history represents the central physical link between manufacturing parameters and material response in fusion-based MAM. During L-PBF, LMD, and WAAM, localized energy generates a melt pool whose dimensions and stability depend on the balance between energy input, material delivery, and heat dissipation. Heat is subsequently transferred through the previously consolidated material and substrate, producing temperature gradients and solidification conditions that determine grain morphology, phase evolution, texture, and residual stress [18,21].

The magnitude of these effects varies considerably between technologies. L-PBF combines a highly concentrated heat source with a small interaction volume, resulting in rapid heating and cooling. Conversely, LMD and particularly WAAM operate with larger melt pools and greater thermal accumulation, while previously deposited layers may experience multiple reheating cycles. These differences explain why the same alloy can develop markedly different microstructures when processed through different AM technologies.

The relationship between local process parameters and final properties is therefore mediated by thermal phenomena rather than by process parameters directly. Wolff et al. [22] emphasized the need to establish frameworks linking localized manufacturing conditions to final component properties, while DebRoy et al. [18] demonstrated the fundamental interdependence of processing, heat transfer, solidification, structure, and performance in metallic AM.

For MBJ, the process–structure relationship follows a different pathway. Since material is not melted during printing, the critical thermal history occurs primarily during debinding and sintering. Powder packing and green density determine the initial particle arrangement, whereas sintering temperature, time, atmosphere, and diffusion mechanisms control densification, grain evolution, shrinkage, and residual porosity [7,14,15,50,51]. The resulting properties are therefore determined predominantly by powder → green body → sintering → density/microstructure,

rather than by melt-pool solidification. The original bibliography contains dedicated reviews addressing MBJ processing and sintering.

6.2. Solidification Conditions, Grain Morphology and Texture

In fusion-based AM, grain morphology is strongly governed by the thermal gradient and solidification conditions established at the solid–liquid interface. Directional heat extraction can promote epitaxial grain growth from previously solidified material, frequently resulting in elongated or columnar grains aligned with the dominant heat-flow direction [18].

This phenomenon becomes particularly important in layer-wise manufacturing because successive melt pools partially remelt the previously deposited material. Existing grains can therefore provide preferential nucleation and growth pathways across multiple layers, generating crystallographic texture and direction-dependent properties.

The effect is particularly evident in high-deposition-rate processes such as WAAM and LMD, where larger melt pools and repeated thermal cycling favour persistent directional grain structures. WAAM literature included in the original reference set identifies the metallurgical and technological importance of these thermal characteristics [4,8,9,20].

L-PBF presents a different situation. The smaller melt pool and considerably higher cooling rates can produce much finer microstructures, but directional heat flow and epitaxial solidification can still generate texture. Thus, microstructural refinement does not necessarily imply isotropy.

Controlling grain morphology consequently requires manipulation of the thermal field rather than merely modification of nominal energy density. Scan rotation, deposition-path changes, local remelting, interpass-temperature management, and heat-source control can modify the direction and magnitude of thermal gradients and consequently influence grain growth.

6.3. Phase Transformations and Alloy-Specific Microstructures

The influence of thermal history extends beyond grain morphology to phase constitution. This is especially relevant for alloys undergoing solid-state transformations or precipitation reactions.

Ti-6Al-4V provides a representative example. Its final microstructure is highly sensitive to cooling rate and subsequent thermal exposure, which explains why different AM technologies and post-processing routes can generate substantially different combinations of strength and ductility [17]. The original bibliography specifically includes a comprehensive review of AM Ti-6Al-4V [17] and work on optimizing WAAM Ti-6Al-4V mechanical properties through post-process heat treatment [20].

In rapidly cooled L-PBF Ti-6Al-4V, the as-built microstructure may therefore require subsequent thermal modification when ductility, dimensional stability, or fatigue performance are critical. In WAAM, slower cooling and repeated thermal cycling produce a different microstructural evolution, meaning that the optimal post-processing route cannot simply be transferred from one technology to another.

Nickel-based superalloys present another important case because their performance depends not only on grain morphology but also on segregation and precipitation behaviour. The as-built condition should consequently not be assumed to represent the optimal service condition, particularly for high-temperature applications.

Steels exhibit similarly diverse responses. Depending on composition, rapid solidification and subsequent thermal cycling may influence phase balance, precipitation, hardness, and transformation behaviour. This further demonstrates why process parameters cannot be optimized independently of alloy metallurgy.

The central implication is that AM process optimization is fundamentally an exercise in microstructural engineering. The objective is not merely to produce a geometrically correct and dense component, but to generate, or subsequently obtain through post-processing, the microstructure required for the intended service condition.

The alloy-dependent nature of microstructural evolution in MAM is further illustrated in Figure 6, which compares representative experimental microstructures of Ti-6Al-4V, IN718, 316L stainless steel, and AlSi10Mg produced by L-PBF. Despite being processed by the same general AM technology, these alloys develop markedly different microstructural architectures, ranging from columnar prior-β grains and acicular α′ martensitic features in Ti-6Al-4V to cellular/dendritic solidification structures in IN718 and 316L, and a fine α-Al cellular structure surrounded by a Si-rich network in AlSi10Mg. This comparison demonstrates that the relationship between thermal history and microstructural evolution is intrinsically alloy-dependent and that process optimization must therefore account for alloy-specific solidification, phase-transformation, and segregation behaviour.

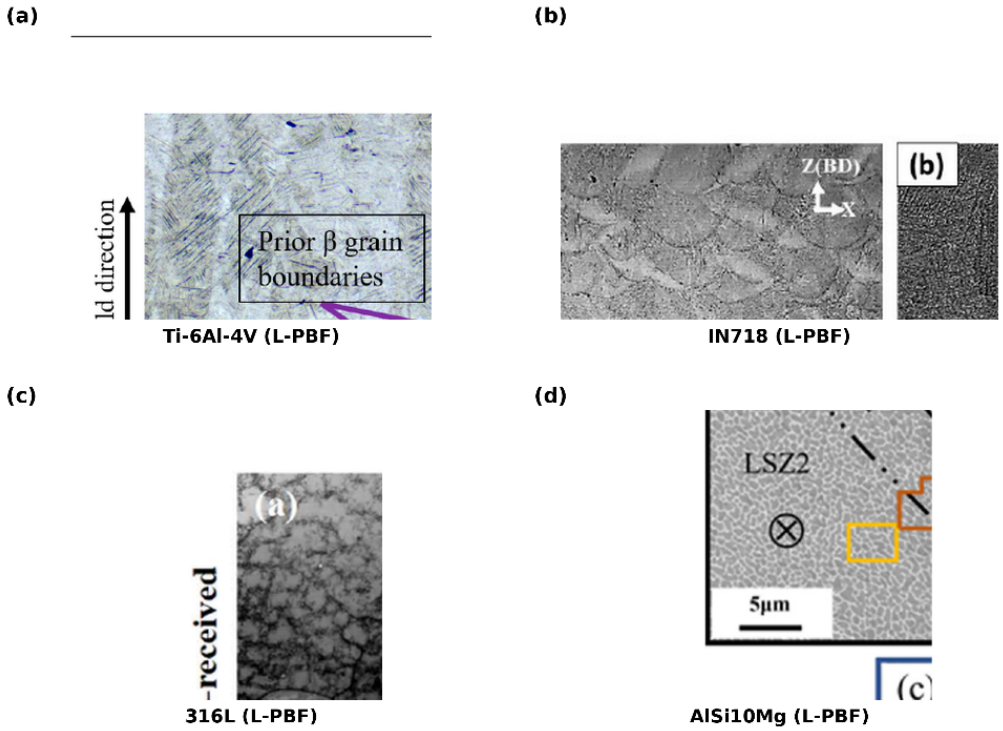


Figure 6. Representative experimental microstructures of engineering alloys produced by laser powder bed fusion (L-PBF): (**a**) Ti-6Al-4V, illustrating columnar prior-β grain architecture and acicular α′ martensitic morphology [58]; (**b**) IN718, showing columnar/cellular-dendritic solidification features and epitaxial growth [59]; (**c**) 316L stainless steel, exhibiting the characteristic fine cellular substructure generated by rapid solidification [60]; and (**d**) AlSi10Mg, showing α-Al cellular structures surrounded by a Si-rich network [61]. Panels adapted from the corresponding original Open Access sources under the applicable Creative Commons licenses.

The central implication is that AM process optimization is fundamentally an exercise in microstructural engineering. The objective is not merely to produce a geometrically correct and dense component, but to generate, or subsequently obtain through post-processing, the microstructure required for the intended service condition.

6.4. Microstructure and Mechanical Performance

Microstructure directly influences strength, hardness, ductility, fracture behaviour, fatigue resistance, creep response, and anisotropy. However, these properties are simultaneously affected by defects and surface condition. Consequently, MAM performance emerges from the interaction between intrinsic microstructure and extrinsic defect population.

Fine microstructures generated by rapid solidification may contribute to high strength, but this benefit can be offset by residual stresses, porosity, rough surfaces, or unfavourable texture. Conversely, slower cooling may reduce certain residual-stress effects while promoting grain coarsening. Thus, optimizing a single microstructural characteristic does not necessarily optimize component performance.

Fatigue is particularly sensitive to this interaction. Surface irregularities, lack-of-fusion defects, pores, inclusions, and microstructural heterogeneity can all act as crack-initiation sites. The original literature set already notes that powder degradation and oxide accumulation may eventually compromise fatigue performance even when tensile properties remain comparatively stable [34–37].

This distinction is important because tensile strength alone is an insufficient indicator of AM component quality. Components intended for aerospace, rotating machinery, or other cyclically loaded applications require simultaneous control of internal defects, surface integrity, residual stress, and microstructure.

Comparative mechanical-property studies between AM technologies are therefore useful but must be interpreted cautiously. The original bibliography includes a direct comparison between WAAM and L-PBF components [62], demonstrating that mechanical performance is inherently related to the manufacturing route. However, comparisons should account for alloy condition, build orientation, post-processing state, defect population, and testing methodology rather than attributing property differences solely to the AM process.

6.5. Post-Processing as Microstructural and Property Engineering

Post-processing should not be regarded merely as a corrective operation applied after an imperfect AM process. For many alloy–process combinations, it constitutes an integral stage of the manufacturing route and provides an additional opportunity for microstructural and property engineering.

Heat treatment can reduce residual stresses, modify metastable phases, control precipitation, and alter grain- or phase-scale morphology. Its importance is demonstrated by the optimization of WAAM Ti-6Al-4V through post-process heat treatments [20] and by recent approaches combining heat treatment and surface modification for L-PBF Ti-6Al-4V [45].

Surface post-processing is equally important when fatigue, tribology, corrosion, or dimensional accuracy govern component performance. The original literature includes recent studies investigating surface post-processing of L-PBF IN718 [47] and plasma electrolytic polishing of additively manufactured titanium alloys [44]. The manuscript also reports that plasma electrolytic polishing can substantially improve surface morphology, although this introduces additional processing requirements.

Machining remains particularly important for high-deposition-rate technologies such as WAAM and LMD, where near-net-shape deposition can be combined with subtractive finishing. Hybrid additive–subtractive manufacturing therefore provides a route for combining high deposition efficiency with final dimensional accuracy and surface integrity [51,55,63]. For titanium alloys, the integration of additive manufacturing with dedicated post-processing operations is particularly relevant because as-built surface condition, dimensional deviations, and process-induced material characteristics may restrict the direct use of components in demanding engineering applications [63].

Hot Isostatic Pressing (HIP) represents an important post-processing strategy for reducing internal porosity in additively manufactured metallic components through the combined application of elevated temperature and isostatic pressure. Under suitable processing conditions, enclosed pores may undergo plastic deformation, creep, and diffusion-assisted closure, thereby improving material consolidation and potentially enhancing fatigue performance. Nevertheless, HIP effectiveness depends strongly on pore morphology and connectivity. Surface-connected porosity and open defects may not be effectively closed because the pressurizing gas can penetrate these discontinuities, preventing the development of the pressure differential required for pore closure. Furthermore, the thermal exposure associated with HIP may promote grain growth, precipitate coarsening, or changes in phase constitution, depending on the alloy and treatment conditions. Consequently, HIP parameters should be selected considering both defect reduction and the preservation of the desired microstructural state. For critical components, HIP should therefore be integrated with appropriate heat treatment, surface finishing, and inspection rather than regarded as a universal solution for defect elimination.

6.6. Multi-Objective Performance Optimization

The relationships discussed above demonstrate that optimization of metal AM cannot be defined through a single objective such as maximum density, minimum porosity, highest strength, or maximum productivity. Improvements in one response can produce undesirable changes in another.

For example, increasing energy input may improve interlayer fusion but increase thermal accumulation or keyhole instability. Increasing cooling rate may refine microstructure but intensify residual stresses. Increasing deposition rate improves productivity but may compromise geometrical control and thermal stability. Similarly, extensive post-processing may improve properties but increase cost, manufacturing time, and environmental burden.

Process optimization should therefore be formulated as a multi-objective problem involving, depending on the application:

Density/defect population ↔ microstructure ↔ residual stress ↔ strength ↔ ductility ↔ fatigue ↔ dimensional accuracy ↔ surface integrity ↔ productivity ↔ cost ↔ environmental impact

The relative importance of these objectives changes according to the component. An aerospace bracket may prioritize low mass, fatigue performance, and geometrical complexity, whereas a large structural component may prioritize deposition rate, cost, and material utilization. Repair applications introduce additional requirements associated with dilution, substrate compatibility, and local property restoration.

This explains why no universal set of “optimal AM parameters” exists. Optimization is meaningful only when material, process, geometry, post-processing route, and functional requirements are considered simultaneously.

Data-driven approaches may provide an important route for managing this high-dimensional parameter space. The original manuscript already reports the application of Machine Learning to optimize WAAM processing parameters such as travel speed, current, and voltage while maintaining mechanical properties [25]. In addition,

the literature set includes measurement requirements for real-time control of PBF [57] and recent work on model-based control of L-PBF [11].

These approaches represent an important transition from parameter optimization based predominantly on offline experimentation towards data-informed and potentially adaptive manufacturing.

6.7. Towards Performance-Driven Metal Additive Manufacturing

The process–structure–property relationships discussed in this section demonstrate that manufacturing parameters should ultimately be selected backwards from the desired component performance rather than forwards from machine capability alone. In a conventional process-centred approach, process selection is frequently dictated by machine availability and subsequently followed by parameter definition and experimental evaluation of the resulting properties. A performance-driven strategy reverses this logic by defining the functional requirements first and subsequently identifying the material state, alloy–process combination, processing conditions, and post-processing route required to achieve them. This performance-driven optimization pathway is schematically illustrated in Figure 7.

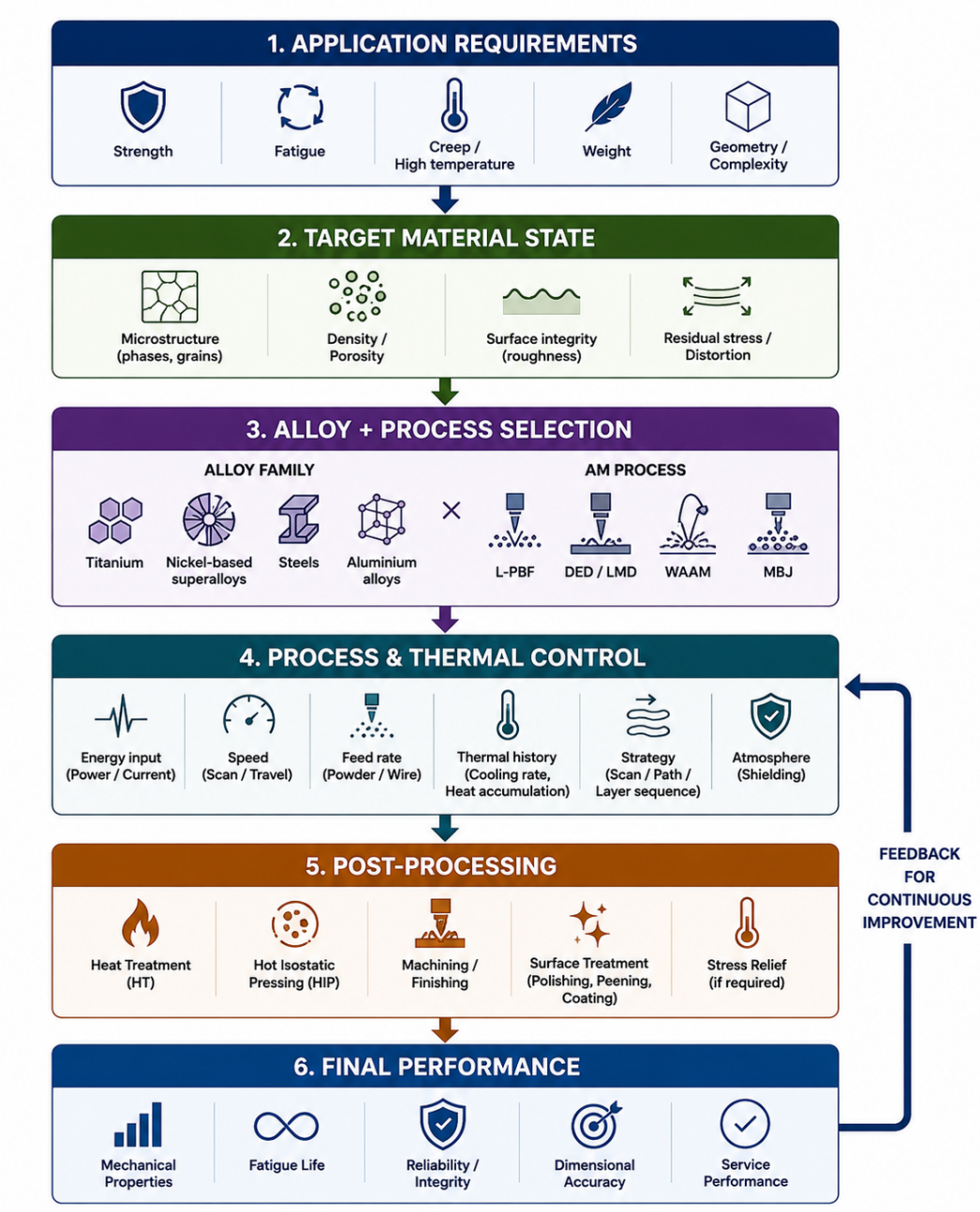


Figure 7. Performance-driven optimization pathway for metal additive manufacturing, linking application requirements and target material state to alloy–process selection, process and thermal control, post-processing, and final component performance through a continuous feedback loop.

As shown in Figure 7, application requirements such as strength, fatigue resistance, high-temperature performance, weight, and geometrical complexity define the target material state in terms of microstructure, density, surface integrity, and residual stress. These requirements subsequently guide alloy and AM process selection, followed by the optimization of processing parameters, thermal history, atmosphere, and deposition strategy. Post-processing should then be regarded as an integral component of the manufacturing route rather than as an isolated corrective stage, since heat treatment, HIP, machining, surface treatment, and stress relief can substantially modify the final material state and component performance [20,44,45,47]. Importantly, the pathway is not strictly linear. The feedback loop represented in Figure 7 indicates that measured final performance should be used to refine processing and thermal-control conditions iteratively. Deviations in mechanical properties, fatigue life, dimensional accuracy, or service performance can therefore be traced backwards to the relevant material-state variables and processing conditions. This closed-loop philosophy provides a conceptual basis for integrating *in-situ* monitoring, data-driven optimization, and adaptive process control into future MAM systems [22,57].

In a conventional process-centred approach, the reasoning is typically:

Available machine → Process parameters → Manufactured component → Measured properties

A performance-driven approach instead begins with:

Application requirements → Required properties → Target microstructure and allowable defects → Suitable alloy–process combination → Processing window → Post-processing strategy

This reversal represents an important conceptual transition for metal additive manufacturing. It moves process selection away from the question of "Can this component be printed?" towards the more relevant engineering question of "Which manufacturing route can generate the material state required for this component to perform reliably in service?"

Such an approach is particularly relevant for safety-critical applications, where geometrical conformity and nominal material composition alone are insufficient for qualification. Robust AM design therefore requires integration of process physics, metallurgy, defect control, post-processing, monitoring, and final performance requirements [18,22,64]. The existing bibliography already contains work on robust development of AM components for demanding applications and the foundational process–structure–property literature required to support this interpretation.

The combination of the process–alloy relationships established in Section 4, the defect mechanisms and mitigation strategies identified in Section 5, and the process–structure–property relationships discussed in the present section provides the scientific basis for integrating these dimensions into a unified decision framework. Collectively, these relationships demonstrate that the performance of an additively manufactured component emerges from a coupled system involving process, material, defect formation, microstructural evolution, post-processing, and functional requirements. Integrating these dimensions into a unified decision-making structure therefore represents the necessary next step toward scientifically grounded process selection and optimization.

7. Integrated Process–Material–Defect–Property Framework for Metal Additive Manufacturing

The preceding sections demonstrate that process selection in metal additive manufacturing cannot be performed effectively through isolated comparisons of deposition rate, geometrical capability, energy input, or nominal mechanical properties. The final performance of an additively manufactured component emerges from a sequence of strongly coupled interactions involving the selected alloy, manufacturing technology, local processing conditions, thermal history, defect formation, microstructural evolution, and post-processing route [18,22].

To integrate these relationships into a unified decision-support structure, this review proposes a Process–Material–Defect–Property (PMDP) framework. Rather than treating process, material, defects, and properties as independent categories, the framework considers them as interconnected domains in which changes introduced at one level propagate through the entire manufacturing chain. The central principle is that an AM process should be selected and optimized according to the response of a specific material and the performance required from the final component.

The PMDP framework can therefore be represented through the following fundamental relationship:

PROCESS × MATERIAL → THERMAL/PHYSICAL RESPONSE → DEFECTS + MICROSTRUCTURE → PROPERTIES → PERFORMANCE

Importantly, this relationship is not strictly linear. Final performance, inspection data, and *in-situ* monitoring can provide feedback to earlier stages, enabling refinement of process parameters, thermal management, material selection, and post-processing. This transforms the framework from a descriptive classification into an iterative methodology for process optimization.

7.1. Process Domain: Definition of the Manufacturing Environment

The first domain of the PMDP framework corresponds to the selected manufacturing process. As demonstrated in Section 3, L-PBF, LMD, WAAM, and MBJ impose fundamentally different physical conditions on the material.

For fusion-based technologies, the process domain defines the mode and intensity of energy delivery, melt-pool dimensions, material-feed mechanism, interaction time, cooling conditions, and repeated thermal cycling. L-PBF produces highly localized thermal fields and rapid solidification, whereas LMD and WAAM progressively increase melt-pool dimensions, deposition rates, and thermal accumulation. These differences directly affect solidification behaviour and final material state [18,21,65]

MBJ represents a fundamentally different processing pathway because shaping and consolidation are separated. The critical process variables therefore shift from melt-pool dynamics to powder spreading, binder deposition, green-part integrity, debinding, and sintering [7,14,15,50,51].

The process domain consequently establishes the physical manufacturing environment to which the selected material will be subjected.

7.2. Material Domain: Alloy Response to the Imposed Processing Conditions

The second domain represents the metallurgical response of the selected material. Identical processing conditions cannot be expected to produce equivalent outcomes across different alloy families because thermal conductivity, absorptivity, melting range, phase-transformation kinetics, oxidation tendency, solidification behaviour, and crack susceptibility vary considerably.

For Ti-6Al-4V, thermal history strongly controls α/β phase evolution and final mechanical behaviour [17]. Nickel-based superalloys introduce additional concerns associated with solidification behaviour, segregation, cracking susceptibility, and precipitation. Steels exhibit a broad range of phase-transformation and precipitation responses, while aluminium alloys introduce additional challenges associated with high thermal conductivity, oxide formation, and solidification-related defects.

This material dependency explains why process windows should not be considered transferable between alloys. The process parameters define the thermal input, but material characteristics determine the physical and metallurgical response to that input.

The material domain therefore acts as the principal mediator between machine-level process parameters and the microstructural or defect-related outcomes observed in the component.

7.3. Defect Domain: Process–Material Instability as a Source of Defects

The third domain of the framework describes defect formation as a consequence of inappropriate or unstable process–material interactions.

For fusion-based MAM, insufficient energy input may result in incomplete fusion, whereas excessive energy concentration may destabilize the melt pool and promote keyhole-type porosity. Thermal gradients can generate residual stresses and distortion, while alloy-dependent solidification behaviour may promote cracking. Feedstock condition and atmosphere further influence gas-related porosity, oxidation, contamination, and surface integrity.

In MBJ, the defect pathway differs substantially. Residual porosity and dimensional deviation are primarily related to powder packing, binder distribution, debinding, shrinkage, and incomplete densification during sintering [7,15,50,51].

The PMDP framework therefore interprets defects not simply as undesirable final observations but as diagnostic indicators of the underlying process–material interaction.

This distinction is important for corrective action. A pore detected during inspection cannot be mitigated effectively until its formation mechanism has been identified. Lack-of-fusion porosity, keyhole porosity, gas porosity, and sintering-related residual porosity may appear under the same general category of “porosity”, yet each requires a fundamentally different mitigation strategy.

7.4. Property Domain: From Microstructure and Defects to Component Performance

The fourth domain connects the resulting material state to final properties. Mechanical performance is determined not by a single variable but by the interaction between microstructure, defect population, residual stress, surface integrity, texture, and post-processing condition.

A fine microstructure may increase strength but cannot compensate for severe lack-of-fusion defects. Similarly, high relative density does not guarantee satisfactory fatigue performance when rough surfaces or tensile

residual stresses remain present. Conversely, post-processing may substantially modify the relationship between the as-built microstructure and final component properties.

This distinction is particularly important for AM qualification because conventional acceptance criteria based solely on chemical composition and tensile properties may fail to capture the spatial heterogeneity and process-induced defect populations characteristic of additive manufacturing.

The property domain should therefore include multiple performance indicators according to the intended application, including strength, ductility, hardness, fatigue resistance, fracture behaviour, creep resistance, corrosion behaviour, dimensional stability, and surface-dependent performance.

7.5. Post-Processing as a Cross-Domain Modification Route

An important feature of the proposed PMDP framework is that post-processing is not treated as an isolated final stage. Instead, it acts across several domains by modifying the material state, defect population, residual stresses, surface integrity, and ultimately component performance.

Heat treatment can alter phase constitution and precipitation while simultaneously relieving residual stresses. Bermingham et al. [20], for example, demonstrated the importance of post-process heat treatments for optimizing the mechanical properties of WAAM Ti-6Al-4V. Surface treatments can modify roughness and surface morphology, as demonstrated for IN718 and titanium alloys in the literature already included in the manuscript [44,47].

Machining can correct dimensional deviations and remove surface irregularities, which is particularly important for high-deposition-rate technologies. Hybrid additive–subtractive manufacturing therefore represents an integrated route rather than merely a finishing operation [23,24].

Post-processing should consequently be selected simultaneously with the process–material combination rather than only after fabrication. Based on the process–material interactions, defect mechanisms, microstructural responses, and property relationships identified throughout this review, these individual dimensions can be integrated into a unified conceptual structure. Figure 8 presents the proposed Process–Material–Defect–Property (PMDP) framework, which constitutes the central conceptual outcome of this review. The framework connects the manufacturing environment to the physical and metallurgical response of the material, the resulting defect and microstructural state, the achieved properties, and ultimately the in-service performance of the component.

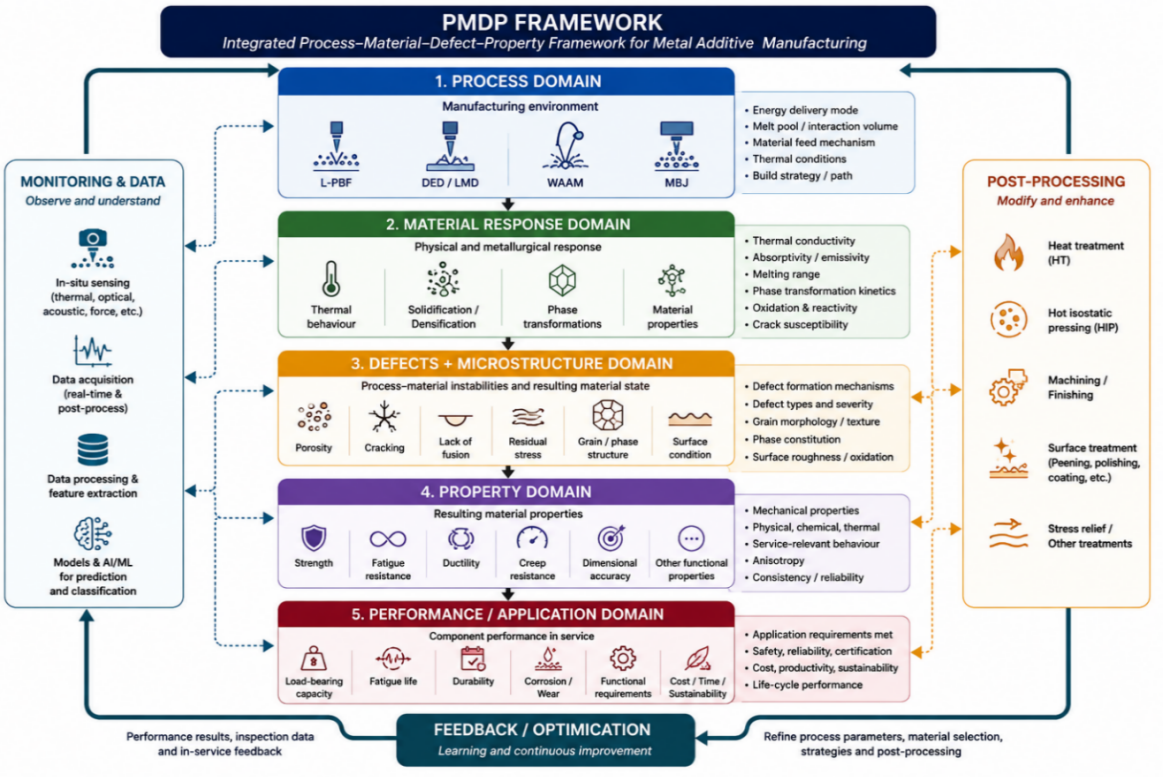


Figure 8. Integrated Process–Material–Defect–Property (PMDP) framework proposed for metal additive manufacturing, linking manufacturing process conditions and material response to defect formation, microstructural evolution, resulting properties, and in-service performance, while incorporating post-processing, monitoring, data-driven analysis, and feedback-based optimization.

As illustrated in Figure 8, the PMDP framework is organized into five interconnected domains. The Process Domain defines the manufacturing environment through energy delivery, material feeding, thermal conditions, and build strategy. These conditions interact with alloy-specific characteristics within the Material Response Domain, governing thermal behaviour, solidification or densification, phase transformations, and other metallurgical responses. Their interaction subsequently determines the Defects + Microstructure Domain, including porosity, cracking, lack of fusion, residual stresses, grain and phase structure, and surface condition. These features collectively determine the Property Domain, which encompasses mechanical, physical, dimensional, and functional properties, and ultimately the Performance/Application Domain, where component behaviour is evaluated against service requirements. Two cross-domain mechanisms complement this central pathway. Monitoring and data analysis provide information across multiple stages of the manufacturing chain, enabling process signals and material-state indicators to be associated with defect formation and final performance. Conversely, post-processing acts as a cross-domain modification route capable of altering defect populations, microstructure, residual stresses, surface integrity, and final properties. The framework therefore recognizes that the final material state is determined not exclusively during deposition but throughout the complete manufacturing route. The feedback and optimization loop transforms the PMDP framework from a linear process–property representation into an iterative engineering methodology. Performance results, inspection data, and in-service information can be fed back to refine process parameters, material selection, thermal-management strategies, and post-processing conditions. In this context, monitoring, predictive modelling, and data-driven approaches can progressively support the transition from empirical parameter optimization towards adaptive and performance-oriented metal additive manufacturing. The PMDP framework therefore shifts the central question in metal additive manufacturing from "Which process can manufacture this component?" to "Which process–material–post-processing pathway can reproducibly generate the material state required for the intended service performance?

7.6. Using the PMDP Framework for Process Selection

The practical value of the PMDP framework lies in converting the relationships identified throughout this review into a structured selection methodology.

Instead of asking "Which AM process is the best?", the decision process should begin by defining the intended application and required performance. The following reasoning can then be applied (Figure 9):

For example, a geometrically complex Ti-6Al-4V component requiring high specific strength may favour L-PBF, but the corresponding PMDP analysis immediately identifies rapid thermal cycling, residual stress, phase constitution, porosity, and surface condition as critical variables requiring control. Conversely, a large Ti-6Al-4V structural component may favour WAAM because productivity and material utilization dominate, shifting the primary concerns towards heat accumulation, columnar grain growth, anisotropy, distortion, and machining requirements.

For a high-value nickel-based component requiring localized repair, LMD may become preferable because material can be deposited selectively onto the existing component. The PMDP analysis then redirects optimization towards substrate–deposit interaction, dilution, thermal cycling, cracking susceptibility, and restoration of the required material state.

For high-volume production of relatively small stainless-steel components, MBJ may provide greater technological value. In this case, the PMDP pathway shifts away from melt-pool control and towards powder packing, binder distribution, debinding, sintering shrinkage, residual porosity, and dimensional compensation.

These examples demonstrate that the PMDP framework does not identify a universally superior technology. Instead, it identifies the most compatible manufacturing pathway for a defined material–application–performance combination.

7.7. Towards Closed-Loop PMDP Optimization

The PMDP framework becomes particularly powerful when combined with process monitoring and data-driven control. Conventional AM optimization generally relies on predefined process windows followed by post-build inspection. This approach identifies defects after they have already been incorporated into the component.

A more advanced strategy would integrate sensing and monitoring directly into the PMDP chain. Thermal signatures, melt-pool characteristics, layer images, geometrical information, and other process signals could provide information about the evolving material state and potential defect formation. The existing bibliography already identifies measurement requirements for real-time PBF control [57], while Wolff et al. [22] emphasize the relationship between localized process parameters and final properties.

The long-term objective can therefore be represented as:

Sense → Interpret → Predict → Correct → Validate

Such an architecture would allow process parameters to be modified when deviations from the target process–material condition are detected rather than relying exclusively on subsequent inspection.

Machine learning and data-driven models may further assist in identifying complex relationships within this multi-dimensional parameter space. The original manuscript already reports ML-based optimization of WAAM parameters while maintaining mechanical performance, illustrating the potential value of data-driven methods within this framework.

Nevertheless, data-driven optimization should complement rather than replace process physics and metallurgy. Models trained exclusively on process inputs and final outputs may exhibit limited transferability between machines, geometries, and alloy systems if the underlying thermal and metallurgical mechanisms are not considered. The PMDP framework therefore provides a physically grounded structure within which monitoring, modelling, and data-driven optimization can be integrated.

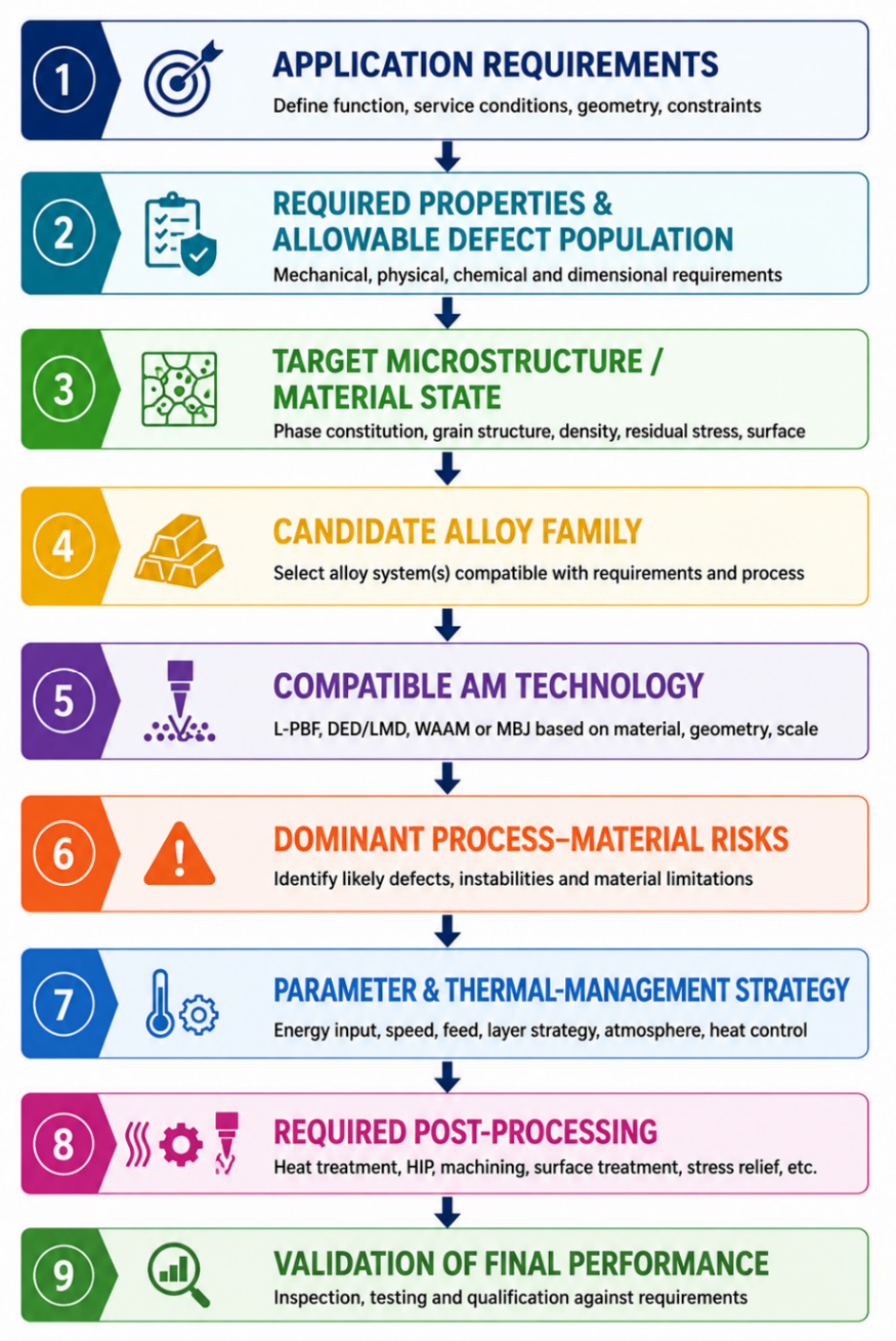


Figure 9. PMDP-based decision-making pathway for metal additive manufacturing, from application requirements and target material state to alloy–process selection, risk identification, process optimization, post-processing, and final performance validation.

7.8. Scientific and Industrial Implications of the Framework

The principal contribution of the PMDP framework is the integration of traditionally separated decisions concerning process selection, material behaviour, defect mitigation, microstructural engineering, post-processing, and performance validation.

From a scientific perspective, the framework emphasizes that AM research should move beyond isolated parameter–property correlations. Reporting that laser power or travel speed changes tensile strength provides limited transferability unless the corresponding changes in thermal history, microstructure, and defect formation are understood. Mechanism-based relationships provide a more robust basis for transferring knowledge between machines, geometries, and related alloy systems.

From an industrial perspective, the framework provides a structured basis for process selection and qualification. Rather than qualifying the manufacturing machine independently from the material and application, qualification can be approached as a connected process–material–property system in which critical variables and defect mechanisms are identified according to service requirements.

This philosophy is particularly relevant to high-value and safety-critical applications, where reproducibility, traceability, and confidence in local material properties are essential. Robust AM component development therefore requires integration of process physics, metallurgy, monitoring, post-processing, and performance validation [18,64].

Ultimately, the PMDP framework provides a pathway from technology-centred additive manufacturing towards material- and performance-centred manufacturing, where process selection is guided not by the capability to fabricate a geometry alone but by the capability to reproducibly generate the material state required for reliable service.

8. Research Gaps, Challenges and Future Perspectives

Despite the rapid development of metal additive manufacturing, the transition from successful laboratory-scale fabrication to robust, reproducible, and industrially qualified production remains constrained by several scientific and technological challenges. The analysis conducted throughout this review indicates that these limitations cannot be attributed to individual processing parameters alone. Instead, they emerge from incomplete understanding and control of the interactions between process physics, alloy behaviour, defect formation, microstructural evolution, post-processing, and final component performance.

The proposed PMDP framework further highlights that substantial progress has been achieved within individual domains, while the connections between these domains remain comparatively less mature. Future research should therefore move beyond isolated optimization of process parameters and increasingly focus on integrated, transferable, and performance-oriented process–material relationships.

8.1. From Empirical Processing Windows to Physics-Based Process–Material Maps

A persistent limitation in MAM research is the widespread use of empirical processing windows developed for specific combinations of machine, material, geometry, and operating conditions. Laser power, scanning speed, travel speed, wire-feed rate, layer thickness, and related parameters are frequently optimized experimentally, but the resulting processing windows may exhibit limited transferability to other equipment or component geometries.

This limitation originates from the fact that nominal process parameters do not directly determine material properties. Instead, they establish local thermal and physical conditions that govern melt-pool behaviour, solidification, phase transformation, residual stress, and defect formation [18,22]. The process–structure–property relationships identified in the literature therefore indicate that future optimization should increasingly rely on physically meaningful variables associated with thermal history and material response rather than exclusively on machine-specific parameter combinations.

A major research opportunity consequently lies in the development of process–material maps capable of predicting stable manufacturing conditions across different machines, geometries, and alloy systems. Such maps should integrate energy input, heat transfer, melt-pool or densification behaviour, solidification kinetics, and alloy-specific metallurgical characteristics.

8.2. Alloy Design Specifically for Additive Manufacturing

Many alloys currently processed through AM were originally developed for casting, forging, welding, or powder metallurgy rather than for the thermal conditions imposed by additive manufacturing. Consequently, their compositions are not necessarily optimized for rapid solidification, repeated thermal cycling, steep temperature gradients, or AM-specific defect mechanisms.

This represents an important limitation of the current material portfolio. The process–alloy relationships discussed in Section 4 demonstrate that alloy chemistry strongly influences cracking susceptibility, phase transformations, oxidation behaviour, segregation, and final microstructure. Therefore, optimization of the manufacturing process alone may eventually reach a limit beyond which further improvements require modification of the material itself.

Future research should increasingly explore AM-specific alloy design, where chemical composition is tailored according to the thermal history and solidification conditions of the selected manufacturing route. Such an approach would reverse the conventional paradigm of adapting the AM process to an existing alloy and instead enable the alloy to be engineered for the AM process.

This direction is particularly relevant for alloy families exhibiting narrow processing windows or strong cracking susceptibility. However, the original reference set does not provide sufficient dedicated literature on AM-specific alloy design to support a detailed quantitative discussion, and additional references should be incorporated if this topic is expanded in the final manuscript.

8.3. In-Situ Monitoring and Defect Prediction

Conventional AM quality control remains strongly dependent on post-process characterization. While this approach can identify pores, cracks, dimensional deviations, or unacceptable mechanical properties, defects are detected only after they have already been incorporated into the component.

In-situ monitoring provides an opportunity to shift from defect detection towards defect prediction and prevention. Depending on the manufacturing process, thermal, optical, acoustic, geometrical, and other signals can potentially provide information regarding melt-pool behaviour, deposition stability, layer quality, or evolving thermal conditions [66].

The existing bibliography already identifies measurement requirements for real-time PBF control [57], while recent studies have increasingly explored the integration of *in-situ* monitoring with machine-learning-based defect detection and quality-assurance strategies [66]. However, collecting process data alone is insufficient. The principal challenge lies in establishing reliable relationships between measured signals, underlying physical mechanisms, resulting defects, and final properties [67].

Within the PMDP framework, monitoring should therefore be interpreted as a means of observing the transitions between domains:

Process signal → Material response → Defect/microstructure → Property

Future research should prioritize monitoring variables that possess clear physical or metallurgical significance rather than generating increasingly large datasets without mechanistic interpretation.

8.4. Artificial Intelligence, Machine Learning and Digital Twins

The large number of interacting variables involved in MAM makes purely experimental optimization increasingly inefficient. Data-driven methods, including Machine Learning (ML), offer considerable potential for identifying complex relationships between process parameters, defect formation, and manufacturing outcomes [66]. The original literature already reports ML-based optimization of WAAM parameters such as travel speed, current, and voltage while maintaining mechanical performance [25,68,69].

Nevertheless, purely data-driven models present important limitations. Predictions obtained from datasets generated for a particular machine, geometry, alloy, or parameter range may not remain valid when operating conditions change. Moreover, high predictive accuracy does not necessarily provide physical understanding of why a defect or property change occurs. These limitations reinforce the importance of combining data-driven prediction with physically meaningful descriptors of process behaviour and material response.

A particularly promising future direction is therefore the integration of physics-based models with data-driven approaches. Rather than replacing metallurgical understanding, artificial intelligence (AI) and ML should complement thermal modelling, solidification theory, process monitoring, and experimental characterization. Recent developments combining machine-learning algorithms, *in-situ* monitoring strategies, defect detection, and quality-assurance frameworks demonstrate the potential of this integration for more predictive control of MAM processes [66].

Digital twins represent a further development of this concept by integrating process data, numerical models, material behaviour, and component history into dynamically updated virtual representations of manufacturing systems [70]. Within additive manufacturing, this approach offers a potential pathway for linking real-time monitoring with process prediction, quality assessment, and decision-making throughout the manufacturing cycle [70]. When

combined with physics-based models and data-driven algorithms, digital twins may support the prediction of process deviations and evolving material states, providing a foundation for adaptive and closed-loop manufacturing. However, further development is required to establish robust and transferable relationships between real-time process information, model predictions, material-state evolution, and final component performance.

8.5. Closed-Loop and Adaptive Manufacturing

The ultimate extension of *in-situ* monitoring and predictive modelling is closed-loop process control. Instead of maintaining fixed process parameters throughout fabrication, future AM systems may increasingly adapt energy input, feed rate, scanning strategy, deposition path, or thermal-management conditions according to the evolving state of the component.

The original bibliography already contains work addressing real-time PBF control requirements [57] and a model-based control approach for L-PBF [11]. These studies support the transition from conventional open-loop manufacturing towards adaptive process control.

Within the PMDP framework, such a system can be conceptualized as:

Sense → Identify deviation → Interpret mechanism → Predict consequence → Correct process → Validate response

The major challenge is therefore not merely sensing deviations but determining which corrective action should be applied without creating another defect mechanism. For example, increasing energy input may suppress lack of fusion while simultaneously increasing keyhole instability or thermal accumulation. Effective closed-loop control therefore requires process physics and material response to be incorporated into the control architecture.

Beyond the adaptive control of the additive stage itself, the integration of additive and subtractive operations represents another important pathway towards more complete manufacturing architectures. Hybrid manufacturing systems combine the geometrical flexibility and material efficiency of additive processes with the dimensional accuracy and surface quality achievable through machining, enabling different manufacturing requirements to be addressed within an integrated process chain [71]. Such integration is particularly relevant for complex metallic components and difficult-to-machine materials, for which the as-built condition may not satisfy the required dimensional or surface specifications. From the PMDP perspective, hybrid manufacturing extends process control beyond deposition by incorporating strategically selected post-processing operations according to the evolving geometry, material state, and functional requirements of the component [72].

8.6. Qualification, Standardization and Transferability

One of the most significant barriers to broader industrial adoption is the qualification of AM components, particularly for safety-critical applications. Variations in machine architecture, feedstock condition, geometry, build orientation, thermal history, post-processing, and inspection methodology complicate the establishment of transferable qualification procedures.

A more comprehensive qualification philosophy should connect process history to material state and material state to performance. This is particularly important because two components manufactured from nominally identical feedstock may exhibit different microstructures, defect populations, residual stresses, and fatigue behaviour when produced under different thermal histories.

The PMDP framework may therefore provide a conceptual basis for future qualification strategies in which critical process variables, material-state indicators, defect acceptance criteria, and final performance requirements are considered as interconnected rather than independent elements.

8.7. Sustainability beyond Process-Level Energy Consumption

The original manuscript placed substantial emphasis on sustainability and contains a considerable body of literature addressing energy consumption, material efficiency, waste reduction, powder reuse, repair, and life-cycle considerations. These references should not be discarded, because they provide an opportunity to retain one of the strongest elements of the original work while integrating it into the new scientific framework.

The existing literature demonstrates substantial differences in energy consumption and material utilization among MAM technologies. WAAM, for example, combines high deposition rate with comparatively low specific energy consumption, whereas L-PBF exhibits considerably higher energy demand per unit mass produced [1,31,32]. Repair and remanufacturing through LMD may also extend component service life and reduce replacement requirements [13,38].

However, process-level energy consumption alone provides an incomplete representation of sustainability. A comprehensive assessment should also consider material circularity, feedstock recovery and reuse, manufacturing waste, component lifetime, repairability, and end-of-life pathways [73]. Although recycling mechanisms and degradation phenomena are strongly material-dependent, circularity-oriented studies in additive manufacturing demonstrate the importance of extending sustainability assessment beyond the manufacturing stage and considering the complete material and product life cycle [73].

Future sustainability assessments should therefore extend across the complete PMDP pathway:

Feedstock → Manufacturing → Defect/rejection rate → Post-processing → Use phase → Repair → End of life

This life-cycle perspective is particularly important when comparing technologies with fundamentally different manufacturing architectures.

8.8. Research Priorities Emerging from the PMDP Framework

The analysis conducted in this review suggests that future progress in metal additive manufacturing will increasingly depend on the integration of disciplines that have traditionally been investigated independently. Process physics, physical metallurgy, sensing, numerical modelling, post-processing, mechanical performance, and sustainability should no longer be treated as separate optimization problems.

Based on the PMDP framework, six research priorities can be identified:

(1) Transferable process–material maps based on thermal and metallurgical mechanisms rather than machine-specific empirical parameters.
(2) AM-specific alloy development tailored to rapid solidification, repeated thermal cycling, or sintering conditions.
(3) Mechanism-informed *in-situ* monitoring capable of relating process signals to defect formation and microstructural evolution.
(4) Physics-informed AI/ML and digital twins integrating experimental data with process and material models.
(5) Closed-loop adaptive manufacturing capable of correcting process deviations before defects become permanently incorporated into the component.
(6) Performance-based qualification and life-cycle assessment, linking manufacturing history to component reliability, service performance, repairability, and sustainability.

The convergence of these research directions could ultimately enable a transition from parameter-controlled additive manufacturing towards state-controlled manufacturing, in which the objective is not simply to maintain predefined machine settings but to maintain the evolving material state within the conditions required to achieve the desired final performance. The research priorities identified above collectively indicate a broader transition in the technological maturity of metal additive manufacturing. As summarized in Figure 10, current MAM practice remains largely dependent on empirical parameter optimization, post-process inspection, fixed processing conditions, and alloys originally developed for conventional manufacturing routes. The next stage of development requires the integration of process–material maps, *in-situ* monitoring, physics-informed data analysis, and AM-specific alloy design, establishing the scientific and technological foundations for predictive and adaptive manufacturing.

The long-term evolution of MAM is expected to progress towards manufacturing systems capable not only of predicting process outcomes but also of adapting processing conditions in real time to maintain the required material state. In this context, closed-loop architectures integrating sensing, physical interpretation, predictive modelling, corrective action, and subsequent validation may substantially reduce process variability and improve component reliability. Such developments would progressively shift quality assurance from the detection of defects after fabrication towards their prediction and prevention during manufacturing. Within this transition, the PMDP framework proposed in this review provides a conceptual basis for connecting these emerging capabilities. Process monitoring supplies information regarding the manufacturing state; physics-based and data-driven models interpret the material response; defect and microstructural evolution provide indicators of process stability; and performance validation closes the optimization loop. The ultimate objective is therefore not simply greater automation, but the development of performance-driven MAM systems capable of reproducibly generating the required material state while simultaneously satisfying reliability, productivity, economic, and sustainability requirements.

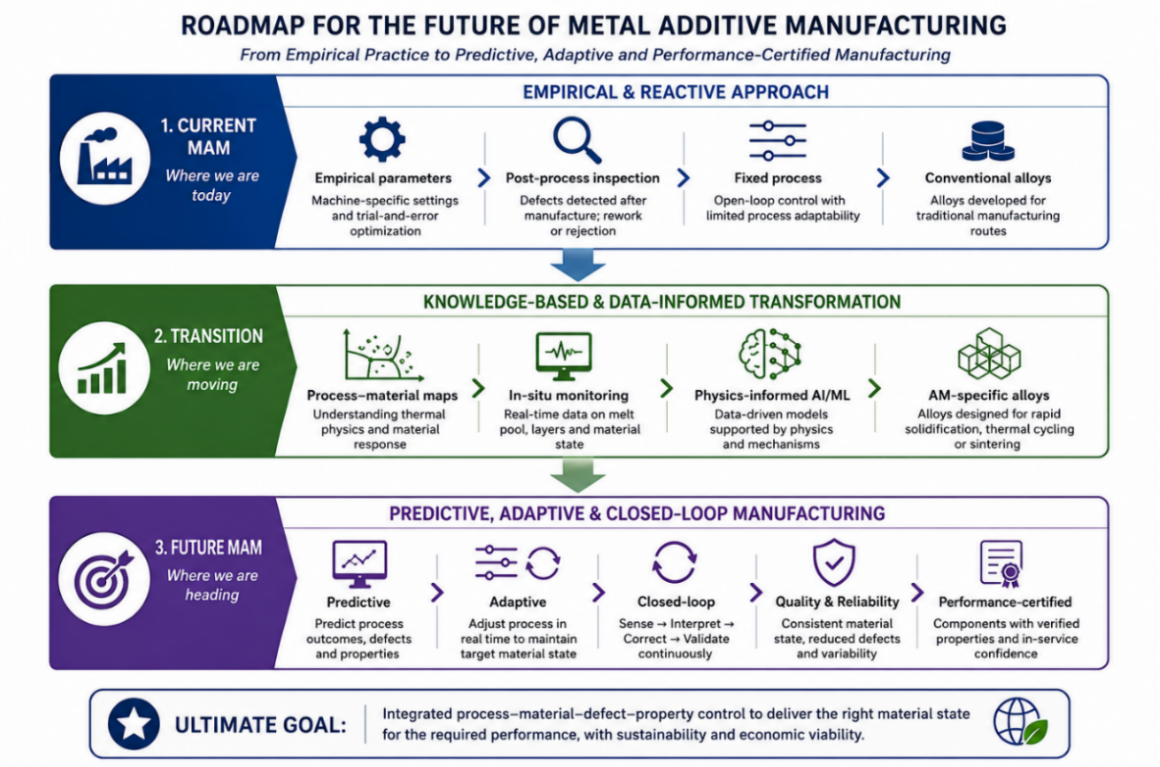


Figure 10. Research roadmap for the future development of metal additive manufacturing, illustrating the transition from empirical and reactive processing towards knowledge-based, predictive, adaptive, closed-loop, and performance-certified manufacturing.

9. Conclusions

Metal additive manufacturing has evolved from a technology primarily associated with geometrical freedom and rapid prototyping into a family of manufacturing routes capable of producing, repairing, and remanufacturing high-value metallic components. However, the analysis conducted in this review demonstrates that the technological maturity of MAM cannot be assessed solely in terms of deposition rate, geometrical capability, material utilization, or nominal mechanical properties. The performance of an additively manufactured component ultimately emerges from the interaction between the manufacturing process, alloy-specific behaviour, thermal or densification history, defect formation, microstructural evolution, post-processing, and service requirements.

The comparative assessment of L-PBF, LMD, WAAM, and MBJ revealed fundamentally different process–material interaction regimes. L-PBF provides high geometrical resolution and complex design capability but requires stringent control of energy input, powder characteristics, thermal gradients, and residual stresses. LMD offers considerable flexibility for repair, remanufacturing, and local material addition, although dilution, thermal cycling, and microstructural heterogeneity must be carefully controlled. WAAM provides the highest deposition rates and strong material-utilization advantages for large-scale components, while heat accumulation, distortion, anisotropy, and surface quality remain major challenges. MBJ avoids localized melting during printing and offers considerable potential for batch production, but shifts process control towards powder packing, debinding, sintering, shrinkage, and densification.

A central conclusion of this review is that there is no universally optimal MAM technology. Process suitability depends on the metallurgical response of the selected alloy and the functional requirements of the component. Ti-6Al-4V, nickel-based superalloys, steels, and aluminium alloys respond differently to the thermal and physical environments generated by each technology. Consequently, process and material selection should be treated as coupled engineering decisions rather than sequential and independent choices.

The analysis of defect formation further demonstrated that defects should be interpreted according to their underlying physical mechanisms rather than exclusively according to their final morphology. Lack of fusion, keyhole porosity, gas porosity, cracking, residual stresses, distortion, anisotropy, surface irregularities, and sintering-related porosity originate from different combinations of process conditions and material response. Effective mitigation therefore requires identification of the cause–mechanism–consequence relationship before corrective action is selected. This is particularly important because strategies that suppress one defect may simultaneously increase susceptibility to another.

Similarly, the relationships between processing conditions, thermal history, microstructure, and properties demonstrate that achieving high relative density alone is insufficient to guarantee satisfactory component performance. Grain morphology, crystallographic texture, phase constitution, residual stresses, surface integrity, and defect population collectively determine mechanical and functional behaviour. Post-processing should therefore be considered an integral component of the manufacturing route, capable of modifying the material state and enabling the properties required for service rather than simply correcting deficiencies in the as-built component.

Based on these findings, this review proposed the Process–Material–Defect–Property (PMDP) framework as an integrated structure for understanding and optimizing metal additive manufacturing. The framework connects the manufacturing environment with alloy-specific material response, defect and microstructural evolution, resulting properties, and final in-service performance, while incorporating monitoring, post-processing, and feedback-based optimization. Its principal contribution lies in shifting process selection away from technology-centred reasoning towards a material- and performance-driven approach, in which the manufacturing route is selected according to its ability to reproducibly generate the material state required by the intended application.

The PMDP-based decision pathway further translates this conceptual framework into a practical engineering methodology. Rather than beginning with an available machine or predefined process, the proposed approach begins with application requirements and progressively defines the allowable defect population, required properties, target microstructure and material state, candidate alloy family, compatible AM technology, dominant process–material risks, processing and thermal-management strategy, post-processing requirements, and final performance validation.

Future development of MAM should therefore increasingly move beyond empirical, machine-specific processing windows towards transferable process–material relationships, AM-specific alloy development, mechanism-informed *in-situ* monitoring, physics-informed data-driven modelling, and adaptive closed-loop manufacturing. These developments may progressively enable a transition from conventional parameter-controlled production towards state-controlled manufacturing, in which processing conditions are continuously adapted to maintain the evolving material state required for predictable final performance.

Finally, the industrial success of metal additive manufacturing will depend not only on the ability to manufacture increasingly complex geometries, but on the capacity to guarantee repeatable material states, controlled defect populations, predictable properties, reliable in-service performance, and economically and environmentally viable manufacturing routes. Integrating these requirements through process–material–defect–property relationships provides a pathway towards more robust qualification, broader industrial adoption, and ultimately performance-certified metal additive manufacturing.

Author Contributions

N.P.V.S., J.R. and V.S.: conceptualization; N.P.V.S. and M.B.: methodology; N.P.V.S., J.R. and A.F.V.P.: data curation, visualization; N.P.V.S.: writing—original draft preparation, investigation; R.C. and V.S: supervision; V.S.: validation; A.F.V.P. and R.C.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to improve the English language, grammar, clarity, and readability of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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