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Advances in Additive Manufacturing of Metals: A Review of Processes, Microstructure, and Mechanical Properties

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ABSTRACT

Additive manufacturing (AM) of metals has emerged as a transformative manufacturing technology capable of producing complex geometries, reducing material waste, and enabling unprecedented design flexibility across diverse industrial sectors. Over the past decade, significant advancements in metal AM processes have accelerated their adoption in aerospace, biomedical, automotive, energy, and defense applications. This review provides a comprehensive assessment of recent developments in metal additive manufacturing, with particular emphasis on processing technologies, microstructure evolution, and mechanical performance. Key metal AM techniques, including Powder Bed Fusion, Directed Energy Deposition, and Binder Jetting, are examined with respect to their operating principles, advantages, limitations, and process optimization strategies. The review further explores the complex thermal cycles and rapid solidification phenomena that govern microstructural characteristics such as grain morphology, phase composition, texture development, and defect formation. The influence of these microstructural features on mechanical properties, including strength, hardness, ductility, fatigue resistance, wear behavior, and corrosion performance, is critically evaluated. Recent advances in process monitoring, in-situ sensing, computational modeling, and artificial intelligence-driven optimization are also discussed as emerging approaches for enhancing part quality and manufacturing reliability. Furthermore, current challenges related to residual stresses, anisotropy, porosity, standardization, and large-scale industrial implementation are highlighted. By integrating findings from recent literature, this review provides a comprehensive understanding of the relationships between manufacturing processes, microstructural evolution, and mechanical behavior, while identifying future research directions that will support the broader industrial adoption and advancement of metal additive manufacturing technologies.

Keywords: *Metal additive manufacturing; Powder bed fusion; Directed energy deposition; Microstructure evolution; Mechanical properties; and Process optimization.*

Introduction

Additive manufacturing (AM) of metals, commonly known as metal three-dimensional (3D) printing, has emerged as one of the most significant innovations in advanced manufacturing.

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By fabricating components layer-by-layer directly from digital designs, metal AM enables the production of geometrically complex structures that are difficult or impossible to achieve using conventional manufacturing methods. Compared with traditional subtractive and formative processes, metal AM offers advantages such as reduced material waste, shorter production lead times, enhanced design flexibility, and the ability to manufacture customized components with high precision [1]. These capabilities have accelerated the adoption of metal AM across aerospace, biomedical, automotive, energy, and defense industries, where lightweight structures, optimized performance, and rapid prototyping are increasingly important [2]. Several metal additive manufacturing technologies have been developed to address diverse industrial requirements. Among these, Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Binder Jetting represent the most widely utilized approaches. Each process differs in its energy source, material delivery mechanism, deposition strategy, and achievable part characteristics [3]. Powder Bed Fusion technologies are particularly valued for producing components with high dimensional accuracy and superior surface finish, whereas Directed Energy Deposition is widely applied in component repair, remanufacturing, and large-scale fabrication. In addition to powder-based systems, non-powder-bed approaches have gained increasing attention because of their potential to improve productivity, reduce material costs, and expand the range of manufacturable metallic components [4]. Continuous technological advancements have further enhanced process efficiency, precision, and scalability, thereby expanding the industrial relevance of metal AM.

The performance of additively manufactured metallic components is strongly influenced by the complex thermal conditions experienced during fabrication. Rapid melting and solidification, repeated thermal cycling, and localized heat transfer generate unique microstructural features that differ substantially from those produced through conventional manufacturing routes [5]. These thermal phenomena affect grain morphology, crystallographic texture, phase transformations, residual stress development, and defect formation, including porosity and cracking. Consequently, understanding microstructural evolution is essential for controlling part quality and ensuring reliable performance. Recent studies have also highlighted the growing role of data-driven and computational approaches in predicting process–structure–property relationships and optimizing manufacturing outcomes [6].

Mechanical properties remain one of the most important considerations in the qualification and industrial deployment of metal additive manufacturing technologies. The strength, hardness, ductility, fatigue resistance, wear behavior, and corrosion performance of AM-produced metals are directly influenced by their microstructural characteristics and defect populations [7]. Although many additively manufactured metals exhibit properties comparable to or exceeding those of conventionally produced counterparts, challenges such as anisotropy, residual stresses, and fatigue-sensitive defects continue to limit broader implementation [8]. Furthermore, emerging research has demonstrated that tailored heterogeneous microstructures can be deliberately engineered to achieve exceptional combinations of strength and ductility, thereby creating new opportunities for high-performance metallic materials [9].

This review provides a comprehensive assessment of recent advances in metal additive manufacturing with a particular focus on manufacturing processes, microstructure evolution, and mechanical properties. The review begins by examining the fundamental principles and recent developments of major metal additive manufacturing technologies, highlighting their operational characteristics, advantages, and limitations. Subsequently, it explores the mechanisms governing microstructural evolution during additive manufacturing, including solidification behavior, thermal history effects, grain development, phase transformations, texture formation, and defect generation. Particular emphasis is placed on understanding how processing conditions influence the resulting microstructures and ultimately determine component performance. The review also critically evaluates the mechanical behavior of additively manufactured metals by discussing key properties such as strength, hardness, ductility, fatigue resistance, wear performance, and corrosion resistance. In addition, emerging developments in process monitoring, computational modeling, machine learning, and quality control are examined to illustrate how advanced technologies are improving manufacturing reliability and process optimization. Current challenges associated with residual stresses, anisotropic behavior, porosity, standardization, certification, and large-scale industrial implementation are also discussed. By synthesizing recent findings from the literature, this review aims to establish a clear understanding of the interconnected relationships between manufacturing processes, microstructural evolution, and mechanical properties. Furthermore, it seeks to identify knowledge gaps and future research directions that can support the continued advancement and broader industrial adoption of metal additive manufacturing technologies. The review is intended to serve as a valuable reference for researchers, engineers, materials scientists, and industry practitioners interested in the development, optimization, and application of advanced metal additive manufacturing systems.

Metal Additive Manufacturing Processes

Metal additive manufacturing comprises a group of layer-wise fabrication technologies that transform digital designs into functional metallic components. These processes differ in feedstock form, energy source, deposition mechanism, and consolidation strategy, leading to variations in manufacturing capability, dimensional accuracy, production rate, and component performance. Among the available technologies, Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Binder Jetting (BJ), and Material Extrusion (MEX) have emerged as the most important approaches for metal part production due to their growing industrial adoption and technological maturity [10]. The selection of an appropriate metal additive manufacturing process depends on factors such as component geometry, material requirements, production volume, dimensional accuracy, and economic considerations. While PBF offers superior precision and mechanical performance, DED provides greater flexibility for large-scale fabrication and repair applications. Binder Jetting and Material Extrusion, on the other hand, present cost-effective alternatives for producing complex metallic components with reduced equipment and operational costs [11].

The performance of metal additive manufacturing processes is strongly influenced by processing parameters such as energy input, scan strategy, deposition rate, layer thickness, and feedstock characteristics. Variations in these parameters affect thermal histories, solidification behavior, and defect formation, ultimately determining the resulting microstructure and mechanical properties of manufactured components [12]. Understanding these process–structure relationships is therefore essential for optimizing part quality and manufacturing performance. Recent advances in process monitoring, data-driven modeling, and intelligent manufacturing systems are further improving process control and enabling the development of more reliable and efficient metal additive manufacturing technologies [13, 14]. Continuous advancements in process control, monitoring systems, computational modeling, and material development have further improved manufacturing precision, reliability, and industrial scalability, positioning metal additive manufacturing as a transformative technology for modern engineering applications [15].

Figure 1. *Classification of metal additive manufacturing processes according to ASTM standards. The figure classifies the major metal additive manufacturing technologies into direct and indirect processing routes based on how the final metallic component is produced.*
Source: *[16]*

Powder Bed Fusion (PBF)
Powder Bed Fusion (PBF) is currently the most mature and widely adopted metal additive manufacturing technology due to its ability to produce highly complex components with excellent dimensional accuracy and near-full density. In PBF, a thin layer of metallic powder is selectively fused using a high-energy source, typically a laser or electron beam, before successive powder layers are deposited and consolidated. The two principal variants of this technology are Laser Powder Bed Fusion (LPBF) and Electron Beam Powder Bed Fusion (EB-PBF). These processes have gained substantial industrial acceptance in aerospace, biomedical, and energy sectors because of their capability to manufacture intricate geometries, lightweight lattice structures, and customized components with superior mechanical performance [17]. The widespread adoption of PBF is further supported by continuous improvements in machine design, process control, and material development, which have enhanced part quality and manufacturing reliability [18]. The effectiveness of PBF depends largely on melt pool dynamics and thermal behavior during fabrication. Parameters such as laser power, scanning speed, hatch spacing, layer thickness, and powder characteristics significantly influence energy absorption, solidification behavior, and defect formation. Improper parameter selection can result in porosity, lack-of-fusion defects, keyhole formation, and residual stresses, all of which negatively affect component integrity and performance [19]. Recent advances in process simulation, digital twins, and real-time monitoring systems have improved the understanding and control of melt pool behavior, enabling enhanced process optimization and defect mitigation [20].

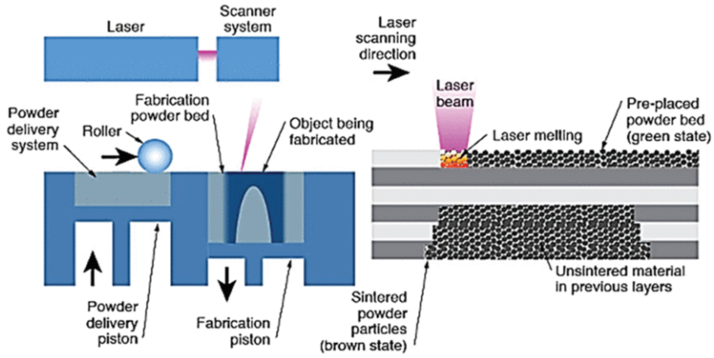

Figure 2. *Schematic illustration of the Powder Bed Fusion (PBF) process. The figure illustrates the layer-by-layer fabrication of metallic components in Powder Bed Fusion through selective melting of powder using a laser or electron beam*
Source: *[18]*

Directed Energy Deposition (DED)
Directed Energy Deposition (DED) is a versatile metal additive manufacturing process in which metallic feedstock, supplied as powder or wire, is simultaneously deposited and melted by a focused energy source such as a laser, electron beam, or plasma arc. Unlike PBF, DED does not require a powder bed and can fabricate large-scale components or repair damaged structures directly onto existing substrates. This capability has made DED particularly attractive for aerospace maintenance, tooling refurbishment, and the manufacture of large engineering components [19]. The process also enables the fabrication of functionally graded materials and multi-material structures through precise control of feedstock composition during deposition. Despite its advantages, DED faces challenges associated with dimensional accuracy, surface roughness, thermal distortion, and process instability. Complex thermal gradients during deposition can generate residual stresses and microstructural heterogeneity, which influence mechanical performance and structural reliability. Recent developments in wire-based DED systems have attracted considerable attention because of their high material utilization efficiency, lower material costs, and improved deposition rates compared with powder-fed systems [20]. Furthermore, advances in closed-loop control systems, sensor integration, and machine learning-assisted process optimization are improving deposition quality and enabling greater consistency in manufactured components.

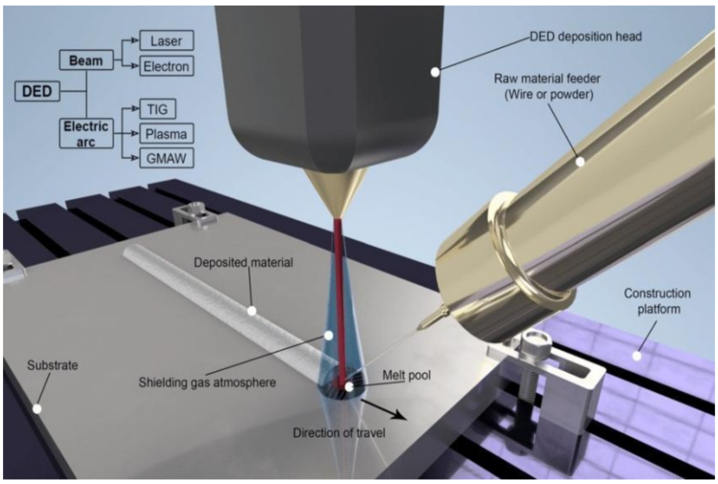

Figure 3. *Schematic illustration of the Directed Energy Deposition (DED) process. The figure illustrates the DED process, where metallic powder or wire feedstock is deposited and simultaneously melted by a focused energy source (laser beam, electron beam, or electric arc) to fabricate or repair metallic components layer-by-layer.*
Source: *[5]*

Binder Jetting and Material Extrusion

Binder Jetting (BJ) has emerged as a promising alternative to fusion-based additive manufacturing technologies. In this process, a liquid binder is selectively deposited onto a powder bed to create a green part, which subsequently undergoes debinding and sintering to achieve final densification. Unlike PBF and DED, Binder Jetting operates without localized melting during printing, resulting in lower thermal stresses, higher printing speeds, and improved scalability for mass production [21]. The technology also supports a wide range of metallic materials and allows simultaneous production of multiple components within a single build volume. However, challenges related to shrinkage control, dimensional accuracy, and achieving full density during sintering remain important areas of research [22].

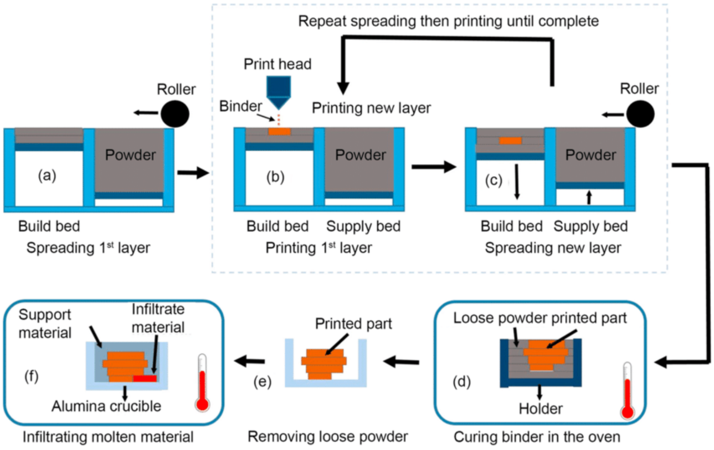

Figure 4. Schematic illustration of the binder jetting process. The figure illustrates the binder jetting process, in which a liquid binder is selectively deposited onto a metal powder bed to form a green part that subsequently undergoes debinding and sintering.
Source: *[20]*

Metal Material Extrusion (MEX), often referred to as bound metal deposition or metal fused filament fabrication, has recently gained attention as a cost-effective and accessible manufacturing route. The process employs metal-filled polymer filaments or feedstocks that are extruded layer-by-layer and subsequently subjected to debinding and sintering. Compared with powder-bed systems, MEX offers lower equipment costs, enhanced operational safety, and simplified material handling [21]. Nevertheless, achieving high density and dimensional precision remains challenging, particularly for complex geometries and high-performance engineering applications.

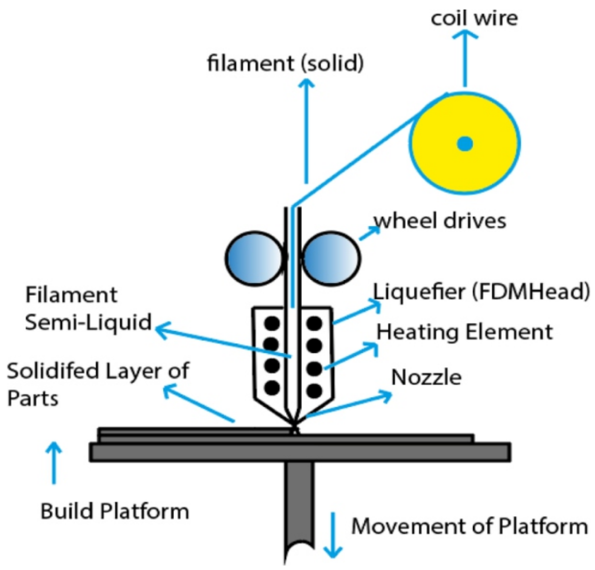

Figure 5. Schematic illustration of the Material Extrusion (ME) process. The figure illustrates the Material Extrusion process, where metal-filled feedstock is deposited layer-by-layer through a nozzle and subsequently subjected to debinding and sintering to obtain the final metallic component.
Source: *[1]*

Microstructure Evolution in Metal Additive Manufacturing

Microstructure evolution in metal additive manufacturing (AM) is fundamentally governed by rapid, localized thermal cycles that arise from layer-wise material deposition and repeated melting–solidification events. Unlike conventional manufacturing routes that operate near equilibrium conditions, metal AM is characterized by highly transient thermal histories involving steep temperature gradients, rapid cooling rates, and cyclic reheating of previously deposited layers. These conditions establish a strong, continuous coupling between process parameters, thermal history, and resulting microstructural features, making microstructure formation a path-dependent and process-sensitive phenomenon rather than a composition-only driven response [22]. In this context, AM must be understood as a thermally driven metallurgical process where process control directly dictates structural evolution.

Solidification behavior in metal AM is strongly influenced by heat transfer conditions and melt pool dynamics. The interaction between thermal gradient (G) and solidification rate (R) determines whether microstructures evolve as planar, cellular, dendritic, or equiaxed morphologies. High cooling rates and directional heat flow typically promote epitaxial grain growth along the build direction, leading to strong crystallographic texture and anisotropic mechanical behavior. This behavior is widely reported across laser- and electron-based processes and is strongly linked to melt pool stability and energy density distribution [23, 24]. However, deviations from ideal columnar growth occur due to local instabilities such as keyhole fluctuations, scan strategy variations, and thermal accumulation effects, which alter nucleation behavior and grain refinement mechanisms. Recent process scaling studies further show that laser spot size and energy distribution significantly influence melt pool geometry and, consequently, grain morphology evolution [25].

Phase evolution in AM-processed metals is also highly non-equilibrium in nature due to rapid solidification and repeated thermal cycling. These conditions often suppress equilibrium transformations and promote the formation of metastable phases, supersaturated solid solutions, and ultra-fine microstructures. Alloy systems such as titanium alloys, steels, and nickel-based superalloys are particularly sensitive to these effects, where minor changes in thermal history can significantly alter phase stability and transformation pathways. Moreover, in-process thermal accumulation can induce partial remelting and localized reheating, leading to microstructural heterogeneity across the build height. This complexity highlights that phase evolution in AM cannot be fully predicted using conventional phase diagrams alone but requires consideration of thermal history-dependent kinetics [26, 27].

Defect formation is one of the most critical challenges influencing microstructural integrity and mechanical reliability in metal AM. Porosity is commonly induced by gas entrapment, unstable keyhole dynamics, or lack-of-fusion between adjacent melt tracks, while solidification cracking is associated with high thermal gradients and alloy-specific brittleness under rapid cooling conditions.

Residual stresses develop due to constrained thermal contraction during solidification and cyclic reheating, often resulting in distortion, delamination, or premature failure. Importantly, these defects are not independent; porosity acts as a stress concentrator, accelerating crack initiation and growth under cyclic loading. Advances in melt pool imaging and in-situ monitoring have significantly improved defect detection capabilities, enabling better correlation between process instabilities and defect formation mechanisms [28]. This reinforces the need for integrated process monitoring and control strategies rather than isolated parameter optimization approaches.

A broader synthesis of microstructure evolution in metal AM reveals a strongly interdependent process–structure relationship governed by thermal physics, metallurgical transformations, and mechanical constraints. Recent studies emphasize that controlling mechanical performance requires not only tuning process parameters but also understanding their coupled influence on melt pool behavior and solidification pathways. Closed-loop control strategies and data-driven optimization frameworks are increasingly being explored to reduce microstructural variability and improve repeatability in manufacturing outcomes [29]. Similarly, thermal analysis of layered deposition processes demonstrates that mechanical properties can be significantly enhanced through careful management of thermal histories, particularly in extrusion-based metal AM systems, where heat accumulation and cooling rates strongly influence final part performance [30]. Collectively, these insights indicate that future advancements in metal AM will depend on the integration of real-time monitoring, thermal modeling, and adaptive control systems to achieve deterministic microstructure engineering across different material systems and process platforms.

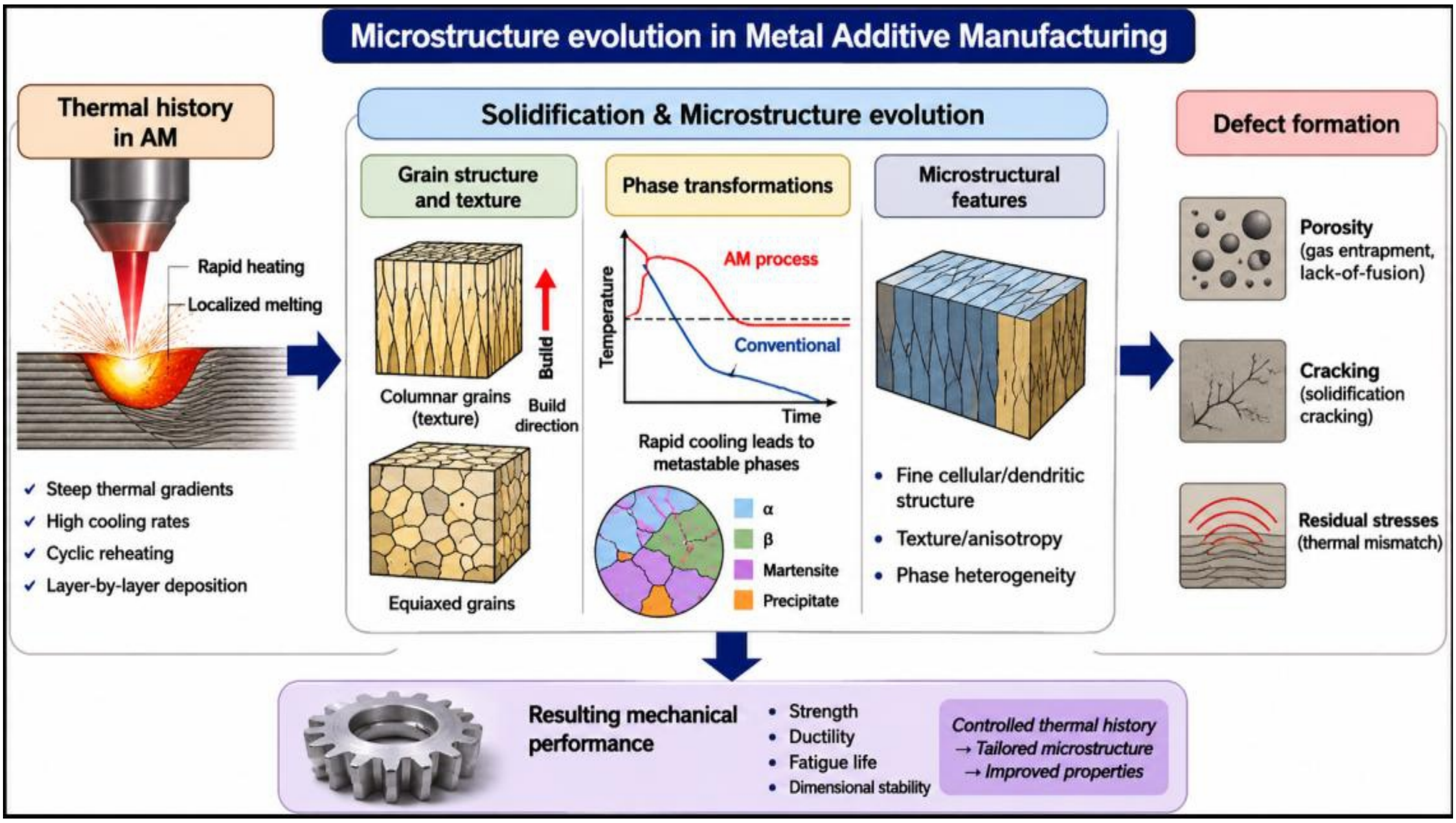

Figure 6. Microstructure evolution in metal additive manufacturing. The figure summarizes the relationship between thermal history, solidification behavior, grain structure evolution, phase transformations, and defect formation in metal additive manufacturing, and their combined influence on mechanical properties.
Source: *[14]*

Mechanical Properties of Additively Manufactured Metals

The mechanical performance of additively manufactured metals is determined by the intricate interactions among processing conditions, thermal history, microstructural evolution, and defect formation. The rapid melting and solidification cycles inherent to additive manufacturing (AM) generate unique microstructures that differ significantly from those produced by conventional manufacturing methods. Consequently, mechanical properties such as strength, hardness, ductility, fatigue resistance, wear performance, and corrosion behavior are strongly influenced by process-induced microstructural features, anisotropy, and defect populations [15]. As metal AM technologies continue to expand into aerospace, biomedical, automotive, and energy applications, understanding the relationships between microstructure and mechanical performance has become essential for ensuring component reliability and structural integrity [16].

Strength, Hardness, and Ductility

Strength, hardness, and ductility are among the most important indicators of the structural performance of additively manufactured metals. The rapid cooling rates associated with AM processes often promote grain refinement, high dislocation densities, and the formation of metastable phases, which collectively contribute to enhanced strength and hardness [17].

In particular, laser-based AM technologies frequently produce fine cellular and dendritic microstructures that provide effective barriers to dislocation motion, thereby increasing yield and tensile strengths relative to conventionally processed materials [18]. Recent advances in microstructure engineering have demonstrated that heterogeneous microstructures can significantly improve the balance between strength and ductility. By combining regions with different grain sizes, phase distributions, or deformation mechanisms, heterogeneous architectures enhance strain hardening capacity while maintaining high strength levels [19]. This approach addresses the traditional strength–ductility trade-off that has historically limited the performance of metallic materials. Nevertheless, process-induced defects such as porosity, lack-of-fusion regions, and residual stresses can reduce ductility and compromise overall mechanical performance. These defects act as stress concentration sites and promote premature deformation or failure under loading conditions [20]. Consequently, post-processing treatments including heat treatment and hot isostatic pressing (HIP) remain critical for improving density, reducing residual stress, and optimizing mechanical performance.

Table 1. Mechanical properties of additively manufactured AlSi10Mg alloy under different processing conditions. The table summarizes the reported mechanical properties of additively manufactured AlSi10Mg alloy, highlighting the influence of processing and post-processing conditions on strength, hardness, and ductility.

Property	Units	Value
Yield Strength	MPa	251
Elastic modulus	MPa	76600
Tangent modulus	MPa	5000
Poisson's coefficient	-	0.33
Bulk modulus	MPa	7.5098×10^4
Shear modulus	MPa	2.8797×10^4

Adapted from [2]

Fatigue and Fracture Behavior

Fatigue performance is one of the most important considerations for the structural application of additively manufactured metals because many engineering components are subjected to cyclic loading during service. Although AM metals often exhibit excellent static mechanical properties, fatigue resistance is generally more sensitive to manufacturing defects and surface quality than tensile behavior [21]. Internal porosity, lack-of-fusion defects, and residual stresses can serve as preferential sites for crack initiation, thereby significantly reducing fatigue life. Surface condition is particularly influential in fatigue performance. As-built surfaces often contain partially melted particles, rough surface features, and geometric irregularities that create localized stress concentrations. [22] demonstrated that surface roughness can substantially reduce the fatigue strength of additively manufactured Ti–6Al–4V, emphasizing the importance of surface finishing operations for fatigue-critical applications. In addition, microstructural anisotropy arising from directional solidification can influence crack propagation pathways and fracture mechanisms [23]. Recent studies have highlighted the role of crystal plasticity and microstructural heterogeneity in governing fatigue behavior. Fatigue crack initiation and propagation are strongly affected by grain orientation, local stress distributions, and defect interactions, indicating that fatigue performance is controlled by both microstructural and manufacturing factors [24]. Consequently, improvements in fatigue resistance require a comprehensive strategy involving process optimization, defect mitigation, residual stress control, and microstructural engineering. Advanced post-processing techniques, particularly HIP and stress-relief treatments, have been shown to significantly enhance fatigue life by reducing internal defects and improving microstructural homogeneity [25].

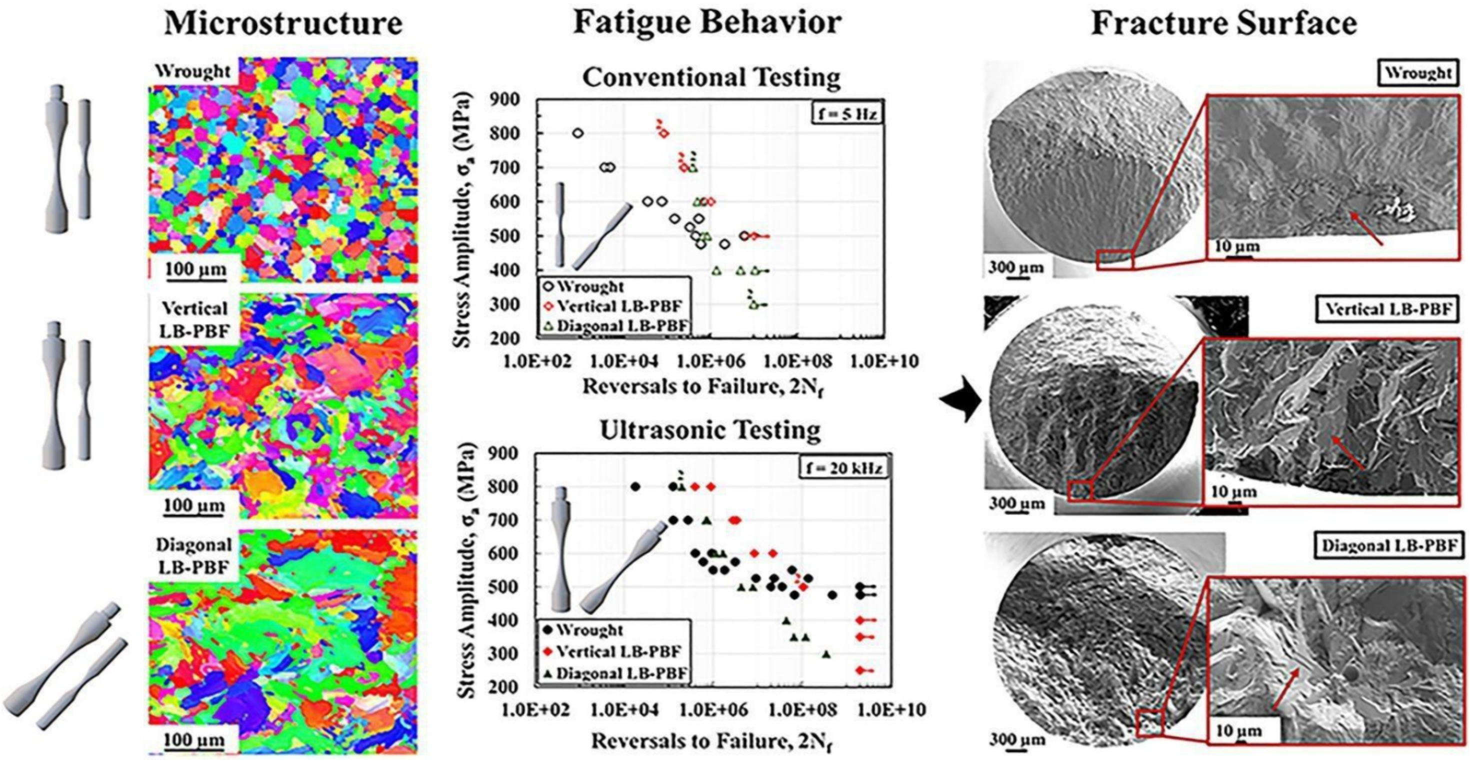

Figure 7. Comparative fatigue performance of wrought and LB-PBF additively manufactured alloys. The figure summarizes differences in fatigue performance and associated microstructural characteristics between conventionally wrought and laser beam powder bed fusion (LB-PBF) additively manufactured alloys, highlighting the influence of processing route on fatigue behavior.
Source: *[21]*

Wear and Corrosion Performance

Wear and corrosion resistance are increasingly important for the utilization of additively manufactured metals in demanding environments such as biomedical implants, marine structures, chemical processing systems, and energy applications. Wear performance is strongly influenced by hardness, microstructural homogeneity, surface roughness, and defect content. The refined microstructures generated by rapid solidification can enhance hardness and improve resistance to abrasive and sliding wear. However, process-induced porosity and surface irregularities may accelerate material removal and increase wear rates under severe service conditions [26]. Corrosion behavior is similarly dependent on microstructural characteristics and manufacturing quality. Fine microstructures produced through rapid solidification often promote more uniform passive film formation and improved corrosion resistance. However, defects such as pores, microcracks, and lack-of-fusion regions can act as preferential sites for localized corrosion initiation and propagation [27]. Furthermore, residual stresses generated during fabrication may influence electrochemical stability and accelerate environmentally assisted degradation mechanisms.

In biomedical applications, where both wear resistance and corrosion performance are critical, the long-term reliability of additively manufactured metallic implants depends heavily on microstructural integrity and surface quality. Recent investigations have shown that appropriate process optimization and post-processing treatments can significantly improve tribological and corrosion performance by reducing defect populations and enhancing microstructural uniformity [28]. These findings underscore the importance of integrating materials design, process control, and surface engineering to maximize the environmental durability of AM-produced metallic components.

Overall, the mechanical properties of additively manufactured metals are governed by the complex interplay between processing conditions, microstructure evolution, and defect formation. While significant progress has been made in improving strength, fatigue resistance, wear behavior, and corrosion performance, challenges associated with anisotropy, residual stresses, and defect sensitivity remain important barriers to broader industrial adoption. Continued advances in process optimization, microstructure engineering, real-time monitoring, and post-processing technologies are expected to further enhance the performance and reliability of additively manufactured metallic components.

Table 2. Summary of dominant factors influencing the mechanical properties of additively manufactured metals

Property	Dominant AM Influence	Primary outcome
Strength	Rapid solidification, grain refinement	Generally increased vs. wrought alloys
Ductility	Residual stress, porosity, anisotropy	Often reduced or direction-dependent
Fatigue resistance	Surface roughness, internal defects	Significantly lower without post-processing
Fracture behavior	Lack-of-fusion defects, microcracks	Early crack initiation and anisotropic failure
Wear resistance	Hardness vs. surface quality trade-off	Improved hardness but variable wear performance
Corrosion resistance	Porosity, microstructural heterogeneity	Localized corrosion susceptibility

Recent Advances, Challenges, and Industrial Applications

Recent developments in metal additive manufacturing (MAM) have been strongly driven by advances in in-situ process monitoring, computational modeling, and artificial intelligence (AI), aimed at improving process reliability, part quality, and certification readiness. Modern monitoring systems now integrate high-speed imaging, thermal sensing, acoustic emission, and multi-sensor fusion to detect defects such as porosity, lack of fusion, and melt pool instabilities during fabrication. These approaches enable real-time quality assessment and are increasingly linked to closed-loop control strategies that adjust process parameters dynamically to reduce defects and improve consistency [29, 30, 31]. However, industrial deployment remains limited by challenges in data standardization, sensor calibration, and robust transferability across machines and materials [32, 33]. Computational modeling and AI have become central to accelerating process optimization in metal AM. Machine learning and physics-informed models are increasingly used to predict temperature fields, melt pool behavior, residual stress, and final mechanical properties, reducing reliance on expensive trial-and-error experimentation. Recent studies highlight that hybrid physics–AI frameworks and digital twins are particularly effective in capturing the coupled thermo-mechanical and microstructural behavior of AM processes [35, 36]. These tools are also being extended toward process qualification and certification support in high-value manufacturing sectors.

Metal AM is now widely applied across aerospace, biomedical, automotive, and energy industries due to its ability to produce lightweight, complex, and customized components. Aerospace applications benefit from topology-optimized parts with high strength-to-weight ratios, while biomedical implants leverage patient-specific geometries and controlled porosity for osseointegration. In automotive and energy sectors, AM enables rapid prototyping, lightweight structures, and repair of high-performance components, reducing downtime and material waste [32] Despite these advances, several critical limitations still hinder large-scale industrial adoption. Key challenges include process variability, residual stress formation, anisotropic mechanical behavior, high production costs, and limited qualification standards. Additionally, data scarcity and poor generalization of AI models across different machines and alloys restrict full automation and predictive reliability. Addressing these issues will require integrated frameworks combining real-time monitoring, standardized datasets, multi-scale modeling, and robust AI-driven control systems to achieve consistent and certifiable manufacturing outcomes [33, 34].

Future Perspectives

The future development of metal additive manufacturing (AM) is expected to be driven by advances in process control, materials design, and digital manufacturing integration. Emerging research is increasingly focused on improving process reliability through real-time monitoring, closed-loop control systems, and data-driven optimization approaches. The integration of machine learning and physics-informed modeling is enabling more accurate prediction of process–structure–property relationships, thereby reducing trial-and-error experimentation and accelerating process qualification [23].

In addition, multi-material printing, functionally graded materials, and heterogeneous microstructure engineering are expanding the design space of AM components, enabling tailored mechanical performance for specific engineering applications [27]. From a scalability perspective, challenges remain in achieving consistent quality for large-scale and high-throughput manufacturing. Process variability, residual stress accumulation, and defect control continue to limit widespread industrial adoption, particularly in safety-critical sectors. Future progress will depend on the development of robust standardization frameworks, improved in-situ diagnostic tools, and hybrid manufacturing approaches that combine additive and subtractive processes for enhanced precision and efficiency [28]. Furthermore, advancements in alloy design specifically tailored for AM processing are expected to improve printability, reduce defect sensitivity, and enhance mechanical performance across a wider range of materials [29].

Sustainability is another key direction shaping the evolution of metal AM. Compared with conventional subtractive manufacturing, AM offers potential reductions in material waste, energy consumption, and supply chain complexity. However, high energy input requirements and powder production processes remain important environmental considerations. Life-cycle assessment studies suggest that optimizing process parameters, recycling feedstock powders, and improving energy efficiency are essential for reducing the environmental footprint of AM technologies [30]. As the technology matures, integrating circular economy principles and sustainable manufacturing strategies will be critical for ensuring environmentally responsible and economically viable production systems. Overall, the convergence of digital manufacturing, advanced materials engineering, and sustainable production strategies is expected to define the next generation of metal additive manufacturing technologies, enabling broader industrial adoption and enhanced functional performance.

Conclusion

Metal additive manufacturing has emerged as a transformative approach for producing complex metallic components with tailored microstructures and enhanced functional capabilities. Across different processes, the interplay between rapid solidification, thermal cycling, and layer-wise fabrication governs microstructure formation, defect evolution, and ultimately mechanical performance. While significant progress has been made in achieving high strength, improved fatigue resistance, and application-specific property optimization, challenges related to anisotropy, residual stresses, and process-induced defects remain critical limitations. Continued advancements in process control, in-situ monitoring, and microstructure engineering are expected to further improve reliability and accelerate the industrial adoption of metal additive manufacturing technologies.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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