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Typical Processes of Metal Additive Manufacturing and Their Application Progress in High-End Equipment: A Mini-Review

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Abstract. Metal additive manufacturing uses metallic powders or wires as feedstock and produces near-net-shape components through layer-wise melting, deposition, binding or sintering. It has attracted sustained attention in aerospace, biomedical implants, rail transit and energy equipment because it can fabricate complex internal channels, integrated lightweight structures, porous functional architectures and customized components. Process characteristics, application fit, engineering constraints and development trends are examined for laser powder bed fusion, electron beam melting, directed energy deposition, wire arc additive manufacturing and metal binder jetting. Powder bed fusion is generally suitable for small-to-medium precision components and porous structures, whereas directed energy deposition and wire arc additive manufacturing are more suitable for large components, near-net-shape deposition and local repair. Metal binder jetting has potential for batch production of small and medium-sized complex parts, although dimensional control after sintering remains challenging. Engineering use is still limited by pores, lack-of-fusion defects, cracking, residual stress, microstructural anisotropy, fatigue reliability, post-processing consistency and qualification. Further development requires coordinated progress in material-process-structure design, in-situ monitoring, closed-loop control, part-level performance evaluation and traceable quality data.

Keywords: metal additive manufacturing, powder bed fusion, directed energy deposition, wire arc additive manufacturing, high-end equipment

1. Introduction

Additive manufacturing converts a three-dimensional digital model into a physical part by accumulating material layer by layer [1]. Metal additive manufacturing extends this principle to load-bearing metallic components, allowing titanium alloys, nickel-based superalloys, stainless steels, aluminium alloys and cobalt-chromium alloys to be formed into complex structures with engineering value [2]. Its significance is not limited to replacing casting, forging or machining. In suitable scenarios, it changes the relationship among structural complexity, material utilization, manufacturing response and component integration [3].

The processing science of metal additive manufacturing involves rapid melting and solidification, repeated thermal cycling, non-equilibrium microstructural evolution and defect formation [4]. These features provide geometric freedom but also introduce pores, lack-of-fusion defects, residual stress and microstructural heterogeneity [5]. For components used in high-end equipment, process selection should not be based on printability alone. Process window, alloy response, part scale, post-processing, inspection and qualification need to be considered together.

The demand for lightweight structures, functional integration, patient-specific manufacture and rapid response in high-value production has moved metal additive manufacturing from rapid prototyping toward direct fabrication of functional parts. Standard process classifications and equipment families are now relatively mature [6], yet the differences among process routes remain substantial. Aerospace applications show that the value of additive manufacturing often comes from part consolidation, mass reduction and supply-chain flexibility in addition to geometric freedom [7].

High-end equipment components usually operate under complex loading and severe environments. Room-temperature tensile strength or hardness alone is insufficient for evaluating engineering suitability. Fatigue life, fracture toughness, corrosion behaviour, surface integrity and defect tolerance also influence service reliability [8]. Broad reviews have also indicated that cost, accuracy, material compatibility, post-processing and certification differ substantially among application fields [9]. Accordingly, the discussion is limited to representative metal additive manufacturing processes and their application progress in high-end equipment, with emphasis on process capability, application demand and engineering constraints. The review framework is shown in Figure 1.

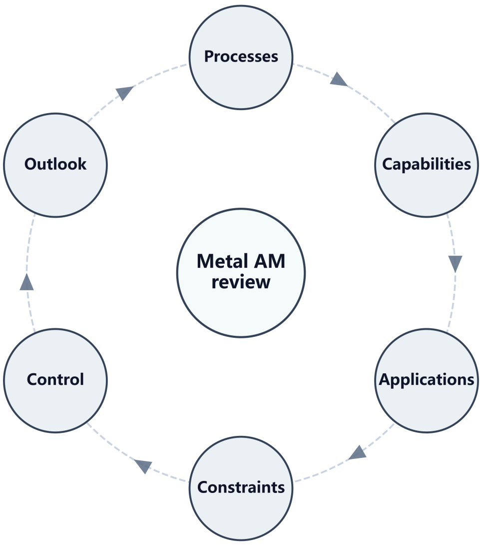


Figure 1. Circular review framework for metal additive manufacturing in high-end equipment

2. Typical metal additive manufacturing processes and technical features

Metal additive manufacturing processes can be grouped according to feedstock form, energy source and forming mechanism. The routes most closely related to high-end equipment include laser powder bed fusion (LPBF or SLM), electron beam melting (EBM), directed energy deposition (DED or LMD), wire arc additive manufacturing (WAAM) and metal binder jetting. No single route is universally suitable for all component types. Their suitability depends on part size, feature scale, alloy system, surface quality, productivity, post-processing capacity and qualification requirements. Table 1 summarizes the forming principles and application boundaries of the main process routes.

Table 1. Principles and application boundaries of representative metal additive manufacturing processes

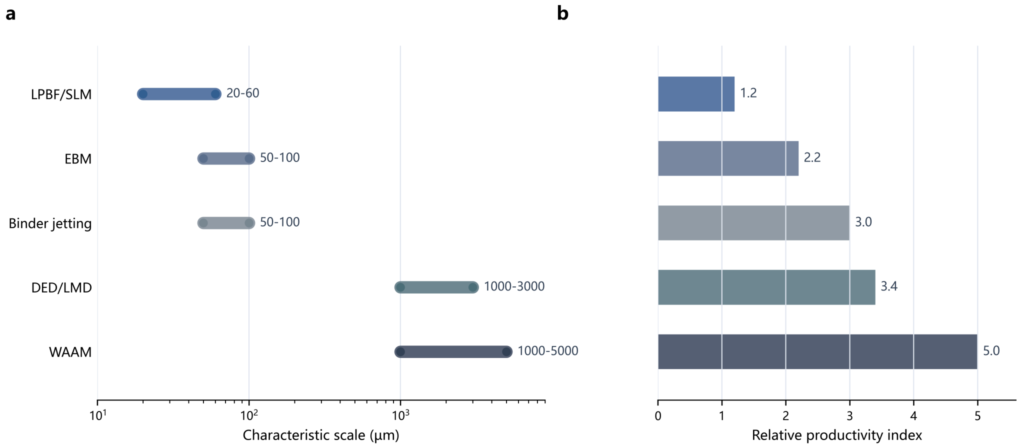
Process	Forming principle	Typical advantages	Main limitations	Application orientation
LPBF/SLM	Selective laser melting of thin powder layers	High precision; internal channels; lattices; porous structures	Limited build size; powder handling; support removal; surface roughness	Aerospace brackets, heat exchangers and biomedical implants
EBM	Electron-beam melting in vacuum with powder-bed preheating	Useful for reactive alloys; reduced residual stress in some titanium parts	Lower surface finish and feature resolution; specialized equipment	Titanium and porous biomedical components
DED/LMD	Laser or electron-beam melt pool with synchronous powder or wire feeding	Large parts; repair; graded deposition; material flexibility	Lower dimensional accuracy; dilution and heat accumulation	Large near-net-shape parts and high-value repair
WAAM	Arc heat source and wire feedstock for layer-wise deposition	High deposition rate; high material utilization; low feedstock cost	High heat input, distortion and large machining allowance	Large load-bearing structures and blanks
Binder jetting	Binder deposition into powder followed by debinding and sintering	No direct melting; high build speed; batch shaping	Sintering shrinkage, residual porosity and dimensional control	Small-to-medium complex parts and batch production

Laser powder bed fusion forms a thin powder layer and selectively melts it with a laser according to sliced geometry. It offers relatively high resolution and is suitable for thin walls, lattice structures, internal channels and small-to-medium precision components [10]. Process stability is strongly affected by powder quality, recoating behaviour, laser power, scan speed, hatch spacing and scanning strategy [11]. Inadequate energy input may produce lack-of-fusion defects, whereas excessive energy input may induce keyhole porosity and surface instability.

Electron beam melting is normally conducted under vacuum and usually uses powder-bed preheating. These features are beneficial for reactive alloys such as titanium and can reduce residual stress in selected material systems [12]. However, surface condition and feature definition in powder-bed metal parts can still require post-processing and application-specific assessment [13]. The process is therefore more appropriate when vacuum processing, powder-bed preheating and titanium alloy compatibility are more important than fine surface finish.

Directed energy deposition forms a melt pool on a substrate while powder or wire is fed into the molten region. Compared with powder bed fusion, it usually provides higher deposition rates, larger build envelopes and greater flexibility for repair or composition adjustment [14]. Wire arc additive manufacturing uses an electric arc and wire feedstock, which gives high deposition efficiency and high material utilization for large structures [15]. This capability is accompanied by larger heat input, which can produce distortion, residual stress and coarse microstructures if the thermal history is not controlled [16].

Metal binder jetting selectively deposits binder into a powder bed and then obtains the final part through debinding and sintering. Because it avoids direct high-energy-beam melting, it can reduce thermal stress during shaping and may support batch production of complex small and medium-sized parts. However, shrinkage, residual porosity and dimensional repeatability after sintering remain important barriers to engineering use [17]. Figure 2 compares characteristic scale and relative productivity among typical process routes.



Ranges are typical order-of-magnitude values; productivity index is normalized for comparison.

Figure 2. Typical scale range and relative productivity index of representative metal additive manufacturing processes

3. Application progress in high-end equipment

Biomedical equipment is one of the most representative application areas for patient-specific metal additive manufacturing. Titanium and cobalt-chromium alloys can be fabricated into hip, knee, maxillofacial and spinal implants based on CT or MRI data [18]. Porous structures produced by powder bed fusion can provide connected pore networks and adjustable elastic modulus, which are difficult to obtain by conventional machining [19]. For implants, the key evaluation factors include patient-specific fit, biocompatibility, surface condition, fatigue performance, sterilization and regulatory approval.

Aerospace is another active field because it places persistent demand on lightweighting, part consolidation, internal flow passages and high-performance alloys [20]. LPBF is often considered for topology-optimized brackets, fuel nozzles, combustor components, heat exchangers and satellite support structures. DED and WAAM are more often associated with large structures, expensive material systems and repair or remanufacturing of high-value parts. Nevertheless, aerospace applications require defect tolerance, fatigue resistance, batch consistency and certification; therefore, practical adoption usually proceeds from auxiliary or non-critical components toward critical load-bearing parts [21]. Representative components and structures are shown in Figure 3.

Rail transit and energy equipment emphasize both structural performance and manufacturing economy. In rail transit, wheels, rails, shafts and connectors may experience wear, local damage or fatigue during long-term service. DED, laser cladding and WAAM can be used for local material addition, surface strengthening or large near-net-shape blanks. In energy equipment, complex flow channels, heat exchangers, turbine-related components and conformal cooling structures are relevant because additive manufacturing can combine structural support with thermal-management functions.

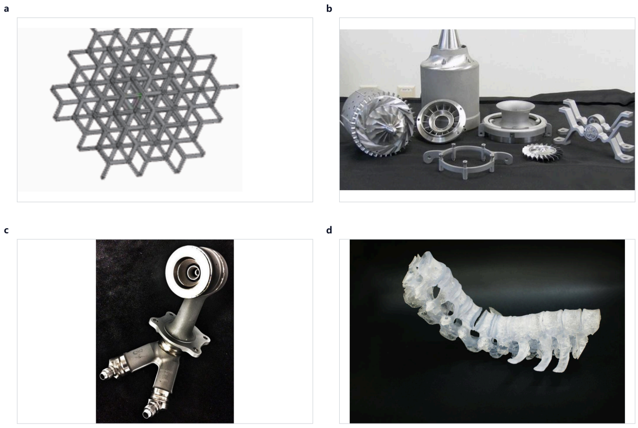
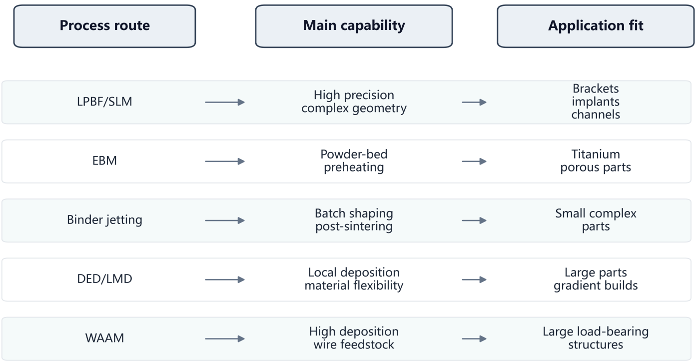


Figure 3. Representative components and structures related to metal additive manufacturing

From an application-maturity perspective, metal additive manufacturing tends to enter scenarios with high added value, small or medium production volume, high structural complexity or strong customization demand. Conventional forming and machining remain advantageous for simple, mass-produced and highly cost-sensitive parts. The application decision is therefore a process selection problem rather than a simple substitution problem. The relationship among process route, main capability and application fit is summarized in Figure 4. Process-selection concerns for representative scenarios are listed in Table 2.



Process route	Main capability	Application fit
LPBF/SLM	High precision complex geometry	Brackets implants channels
EBM	Powder-bed preheating	Titanium porous parts
Binder jetting	Batch shaping post-sintering	Small complex parts
DED/LMD	Local deposition material flexibility	Large parts gradient builds
WAAM	High deposition wire feedstock	Large load-bearing structures

Figure 4. Application fit between representative metal additive manufacturing processes and high-end equipment scenarios

Table 2. Process-selection concerns in representative high-end equipment scenarios

Scenario	Typical requirements	Suitable process routes	Key engineering concerns
Aerospace	Weight reduction, part consolidation, internal channels and heat resistance	LPBF, EBM, DED, WAAM	Fatigue reliability, defect tolerance, surface quality and certification

Table 2. (continued)

Biomedical implants	Patient-specific geometry, porous structure and biocompatibility	LPBF, EBM	Pore architecture, surface state, sterilization and regulatory approval
Rail transit	Large components, repair efficiency and wear resistance	DED, WAAM, laser cladding	Heat input, residual stress, dimensional recovery and service verification
Energy equipment	Thermal management, flow channels and high-temperature capability	LPBF, DED, WAAM	Material compatibility, corrosion resistance, inspection and post-processing
Batch complex parts	Shorter production chain and small-to-medium complex geometry	Binder jetting, LPBF	Sintering shrinkage, density, dimensional tolerance and cost

Existing studies can be broadly grouped into design-driven, performance-driven and maintenance-driven applications. Design-driven applications exploit structures that are difficult to manufacture by conventional routes, including topology-optimized brackets, integrated manifolds and internal channels. Performance-driven applications use porous architectures, microstructural control or composition gradients to improve function, as in implants and thermal-management components. Maintenance-driven applications focus on extending the service life of high-value parts through local material addition or surface repair. Table 3 lists representative studies that support these application categories.

Table 3. Representative studies relevant to process characteristics and engineering applications

Theme	Representative work	Main contribution	Relevance
General process taxonomy	Gibson et al. [6]	Provided a systematic classification of additive manufacturing principles	Basis for process grouping
Metal AM review	DebRoy et al. [4]	Discussed digital manufacturing, metallurgy and process science	Links process and material response
Aerospace application	Blakey-Milner et al. [7]	Reviewed metal additive manufacturing in aerospace	Clarifies high-value application drivers
Laser powder bed fusion	King et al. [11]	Reviewed physics and materials challenges in laser powder bed fusion	Supports defect-control discussion
Biomedical implants	Murr et al. [18]	Reported additively manufactured biomedical structures	Supports implant application analysis
Directed energy deposition	Thompson et al. [14]	Reviewed transport phenomena, modeling and diagnostics in direct laser deposition	Supports DED application scope
Wire arc additive manufacturing	Williams et al. [15]	Reviewed WAAM process capability and constraints	Supports large-structure discussion
Binder jetting	Mostafaei et al. [17]	Reviewed metal binder jetting materials and sintering issues	Supports batch-production discussion

4. Key issues in engineering application

Although metal additive manufacturing provides complex-forming capability, engineering application depends on forming quality, microstructural stability and service reliability. X-ray tomography-based studies indicate that internal defects can substantially affect mechanical performance in metal additive manufacturing [22]. Rapid melting and solidification, steep thermal gradients and repeated thermal cycles can produce lack-of-fusion porosity, hot cracking, residual stress and anisotropic microstructures [23]. These defects are especially important for high-end equipment because they can reduce fatigue life and increase uncertainty in long-term service.

Defect and microstructure control directly affect load-bearing reliability. Pores and lack-of-fusion defects reduce effective cross-section and serve as fatigue-crack initiation sites. Cracking and segregation may reduce ductility, fracture toughness and high-temperature stability [24]. High-speed X-ray observations have clarified the transition between stable conduction melting and keyhole instability during laser processing [25]. Such results indicate that the quality of additively manufactured parts is controlled by coupled interactions among energy input, powder behaviour, melt-pool flow and solidification.

DED and WAAM are attractive for large structures and repair, but their quality-control problems are different from those of powder bed fusion. Heat accumulation, melt-pool fluctuation, bead overlap, deposition path and machining allowance affect dimensional accuracy and microstructural uniformity [26]. Post-processing is therefore often required for engineering applications. Heat treatment, hot isostatic pressing, machining and surface finishing can reduce defects, relieve residual stress and improve surface condition, but they also introduce additional cost and may change dimensions or microstructure.

Process monitoring and quality evaluation need to cover printing, post-processing and service validation. Melt-pool images, infrared radiation, acoustic signals, powder-bed images and layer-wise morphology can provide information about forming state [27]. However, monitoring signals must be connected to defect detection and mechanical performance before they can support qualification decisions. Reviews of powder bed fusion have summarized process defects and in-situ monitoring methods, but signal-to-quality mapping and industrial validation remain difficult [28]. The main issues and development route are summarized in Figure 5.

Part-level performance assessment is also required. Many studies report tensile strength and hardness using standard coupons, but real components often contain local stress concentration, variable section thickness, support-contact regions and multiaxial loading. Build direction in powder bed fusion, layer-wise thermal history in DED and WAAM, and sintering shrinkage in binder jetting can all produce spatial heterogeneity. Design and structural optimisation studies indicate that lightweight components should consider manufacturability constraints, structural performance and evaluation targets simultaneously [29]. Reported anisotropy and heterogeneity in additively manufactured metals further show that build direction and thermal history can strongly affect component properties [30]. Engineering evaluation should therefore move from coupon-level testing toward part-level validation that connects non-destructive testing, defect tolerance and service performance.

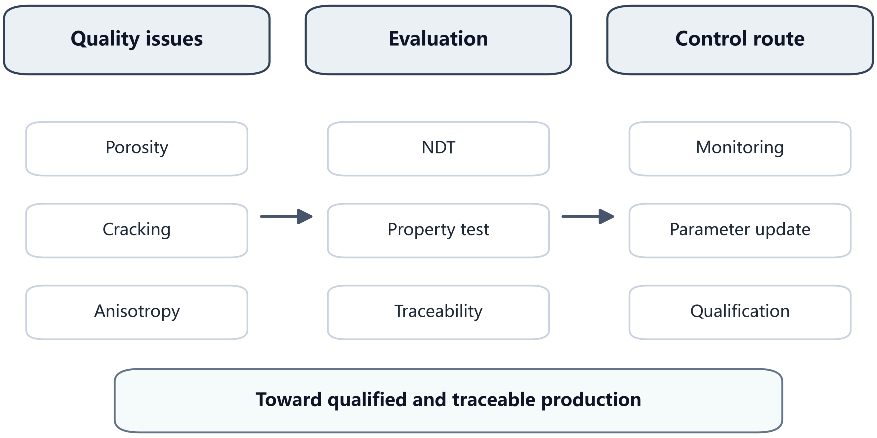


Figure 5. Key issues and development route for engineering application of metal additive manufacturing

5. Development trends

Future development may place greater emphasis on coordinated design of materials, process parameters and component structures. Material-structure-performance integrated laser-metal additive manufacturing provides one route for linking process control, structural design and functional performance [31]. Conventional alloys are not always optimized for rapid solidification and repeated thermal cycling. Materials-focused reviews also emphasize that feedstock selection and alloy compatibility remain central to process stability [32]. Alloy systems, powder or wire quality, support strategy, topology optimization, lattice architecture and post-processing routes need to be considered together at the early design stage. Such integration may reduce trial-and-error cycles and improve the manufacturability of lightweight and functionally integrated components.

In-situ monitoring and closed-loop control are likely to become increasingly important. Process data alone do not guarantee part quality; a central requirement is to establish reliable relationships among process signals, defect types and final properties. Melt-pool image recognition, thermal-field analysis, acoustic monitoring and non-destructive inspection can be combined to support anomaly detection and quality prediction. Closed-loop control may then adjust laser power, scan speed, powder-feed rate, wire-feed rate or arc parameters according to process state.

Multi-material and functionally graded manufacturing also remain relevant development directions. High-end equipment often requires local combinations of wear resistance, toughness, heat resistance or thermal conductivity. DED and multi-wire arc additive manufacturing provide possible routes to composition gradients and heterogeneous deposition, but metallurgical compatibility, thermal-expansion mismatch, interfacial bonding and inspection of graded regions remain challenging. Alloy-specific results for Ti-6Al-4V, including review, directed energy deposition and selective laser melting studies, indicate that process route and thermal history influence microstructure and mechanical anisotropy [33-35]. For structural components, build direction, thermal history and service loading should be considered simultaneously rather than treated as separate issues.

Qualification and traceable manufacturing are likely to remain important for broader adoption. Component properties are influenced by feedstock batch, machine state, build location, process parameters, post-processing and inspection method. A traceable data chain covering raw material, forming process, post-processing, non-destructive testing and service evaluation is needed. As stable process windows, batch-consistency evaluation and part-level certification become more mature, the application boundary of metal additive manufacturing in high-end equipment may continue to expand.

6. Conclusions

Representative metal additive manufacturing processes and their application progress in high-end equipment are summarized. LPBF, EBM, DED, WAAM and metal binder jetting have distinct process characteristics and application boundaries. Powder bed fusion is suitable for precision complex components and porous functional structures, DED and WAAM are more suitable for large components and local material addition, and binder jetting has potential for batch preparation of small and medium-sized complex parts.

For aerospace, biomedical implants, rail transit and energy equipment, the value of metal additive manufacturing mainly lies in lightweight design, part integration, patient-specific geometry, complex flow channels and life extension of high-value components. At the same time, pores, cracking, residual stress, surface roughness, fatigue reliability, post-processing consistency and qualification remain important barriers. Progress in alloy design, process optimization, monitoring, part-level evaluation and data traceability is needed to support more repeatable and service-reliable engineering manufacturing.

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