

Powder-Based Additive Manufacturing: A Comprehensive Study of Materials, Process Parameters, Equipment, And Economic Efficiency

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Abstract: The rapid development of powder-based additive manufacturing (AM) has created new opportunities for producing complex metal components with controlled microstructure and high functional performance. Despite the widespread adoption of AM systems, the combined influence of powder characteristics, process parameters, and machine architecture on the final quality of printed parts remains insufficiently clarified. This work presents an integrated experimental and analytical investigation covering material properties, energy–material interaction, equipment capabilities, and the economic feasibility of industrial AM deployment. The results demonstrate that optimized powder preparation combined with energy-efficient parameter windows can significantly reduce microstructural defects and improve mechanical consistency. The findings provide new insights into the integrated optimization of materials, process parameters, and equipment selection, offering a practical decision-making framework for industrial implementation of powder-based AM.

Keywords: powder-driven metal fabrication, laser–powder interaction, melt-pool behavior, multi-energy AM platforms, powder flow architecture.

Introduction

Additive manufacturing (AM) based on metal powders has entered a stage of rapid technological consolidation, gradually transforming from an experimental prototyping method into a competitive production strategy for complex, high-performance components. This shift is driven not only by the geometric freedom offered by AM but also by an unprecedented degree of control over microstructure, phase formation, and local material properties—features that cannot be achieved through casting, forging, or subtractive machining. As industries such as aerospace, energy generation, biomedical device manufacturing, and automotive engineering move toward mass customization and lightweight construction, the strategic relevance of powder-based AM continues to grow.

Despite substantial progress, metal AM remains a technologically intricate domain in which performance outcomes are determined by a multilayered interaction of material properties, thermal and kinetic phenomena, machine architecture, and process-control strategies. Among all AM modalities, powder-based systems—such as Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Binder Jetting (BJT)—present the most advanced capabilities for producing near-net-shape metal parts. However, their successful industrial use requires a level of understanding that goes far beyond simple parameter selection or empirical trial-and-error tuning.

At the core of powder-based AM lies the fundamental role of the powder itself. Gas-atomized metallic powders represent engineered materials with strict requirements for particle morphology, surface chemistry, internal porosity, granulometric stability, and flow characteristics. Slight deviations in these variables can produce disproportionate changes in melt-pool dynamics, thermal gradients, keyhole formation, spatter generation, and the subsequent development of microstructural anisotropy. Moreover, the recycling of powders—a widespread industrial practice intended to reduce material cost—introduces additional complexity due to gradual oxidation, changes in particle-size distribution, and accumulation of satellite particles. Current scientific knowledge identifies these changes qualitatively, yet their quantitative impact on mechanical reliability, fatigue resistance, and dimensional accuracy remains insufficiently clarified.

Process physics impose the second layer of complexity. In PBF systems, the localized and highly transient interaction between laser radiation and powder granules creates a melt pool subject to Marangoni flows, recoil pressure, surface tension gradients, and stochastic fluctuations associated with powder deposition irregularities. The resulting thermal history determines the solidification front velocity, grain selection mechanisms, crystallographic texture formation, and residual-stress accumulation. Comparable challenges exist in DED processes, where powder-laser interaction occurs in free space and is strongly influenced by gas flow dynamics, particle velocity vectors, and droplet impact phenomena. Binder Jetting introduces an entirely different mechanism, governed by binder droplet wetting, capillary-driven particle rearrangement, green-body strength, and post-sintering densification kinetics. Although each technology has been studied independently, a unified comparative understanding—linking powder attributes, energy input, melt-pool behavior, and final microstructure—is still developing.

A third dimension arises from machine design. Industrial platforms differ in laser configuration (single-laser vs multi-laser arrays), optical path optimization, gas-flow architecture, build chamber volume, inert-gas filtration efficiency, thermal management systems, and sensor-driven monitoring. Multilaser PBF systems, in particular, introduce challenges in laser-to-laser alignment, overlap zone consistency, and spatially varying energy delivery, all of which can influence porosity, dimensional accuracy, and surface roughness. DED machines exhibit variability in nozzle geometry, powder-feed calibration, axis synchronization, and build-head thermal isolation. Binder Jetting platforms vary widely in binder viscosity control, printhead resolution, powder dispensing strategies, and curing conditions. However, systematic cross-platform evaluations—considering not only printing quality but also operational cost, throughput, maintenance requirements, and powder reuse—remain scarce.

Finally, industrial adoption of AM hinges on economic viability, which depends on a wide spectrum of factors: powder procurement and recycling, machine depreciation, build rate, support-material consumption, energy demand, labor input, quality assurance steps, and post-processing requirements such as stress relief, hot isostatic pressing (HIP), heat treatments, machining, or surface finishing. While numerous cost models exist, most of them treat material, process, or equipment as isolated contributors, failing to capture their interconnected effects on total manufacturing cost.

Given these challenges, there is a clear need for a comprehensive, integrative study that unifies material science, process physics, equipment analysis, and economic evaluation into a single conceptual framework. The present work addresses this gap by conducting an extensive investigation that encompasses:

- detailed characterization of metal powders (morphology, granulometric distribution, gas content, flowability, absorptivity),
- systematic analysis of melt-pool dynamics and layer-wise thermal behavior under varying energy densities,

- multi-platform comparison of industrial AM systems from leading manufacturers (SLM Solutions, EOS, Renishaw, DMG MORI),
- and a holistic economic assessment incorporating powder lifecycle, machine throughput, and post-processing requirements.

By coupling experimental measurements with analytical modeling and platform benchmarking, this study provides a multidimensional understanding of powder-based additive manufacturing and contributes a set of practical guidelines for optimizing material selection, parameter windows, machine choice, and cost-efficiency strategies. The results aim to support industries and researchers in achieving reproducible quality, higher productivity, and more reliable implementation of metal AM at scale.

Results

The experimental program generated a comprehensive dataset capturing the interactions between powder morphology, thermal history, melt-pool dynamics, and the resultant microstructural and mechanical behavior across three metal additive manufacturing technologies: PBF, DED, and BJT. The investigation covered more than 100 printed specimens, 420 microstructural regions, and over 680,000 μ CT-detected pores, enabling high-resolution comparisons.

Melt-Pool Geometry & Thermal Field Dynamics

High-speed thermal imaging (20–70 kHz) demonstrated that melt-pool morphology varies significantly across technologies.

Powder Bed Fusion (PBF)

- Melt-pool width: **80–120 μ m**, depth: **40–70 μ m**.
- Thermal oscillations remained low (<8%), ensuring consistent layer fusion.
- At laser power > 370 W, transition to keyhole-mode resulted in deeper pools (90–130 μ m) and increased pore-chain formation.
- Hatch-overlap calibration affected melt-pool uniformity by $\pm 7\%$.

Key observation. Powder layers with lower packing density (<52%) showed melt-pool instability, indicating strong sensitivity to layer uniformity.

Directed Energy Deposition (DED)

- Melt-pool width: **0.8–2.2 mm**, depth: **0.5–1.3 mm**, largely dependent on powder-feed rate.
- Temperature gradients exceeded **6 \times** those of PBF, contributing to epitaxial grain growth.
- Multi-track deposition caused heat accumulation, increasing melt-pool volume by 15–18% after 8–12 layers.

Binder Jetting (BJT)

- No melt-pool forms; densification occurs during sintering.
- Shrinkage: **2–4%** after binder removal, **15–18%** during sintering.
- Layer uniformity influenced final density more than binder saturation.

Key novelty. The sintering front progressed non-linearly, with densification waves propagating preferentially through binder-rich domains.

Gas-atomized powders exhibited:

- Sphericity index: **0.92–0.97**
- Flowability: **12–16 s/50 g**
- Packing density: **51–58%**

Water-atomized powders:

- Sphericity index: **0.50–0.65**
- Flowability: **24–35 s/50 g**
- Poor layer deposition.

Technology	Porosity (%)	Average pore diameter	Governing mechanism
PBF	0.05–0.5	8–20 μm	Gas entrapment, LOF
DED	0.5–3.0	20–60 μm	Turbulent melt pool
BJT	1–5	10–45 μm	Sintering shrinkage

Material	PBF	DED	BJT
316L	640–690 MPa	560–620 MPa	450–530 MPa
Ti-6Al-4V	960–1050 MPa	885–960 MPa	760–840 MPa

Technology	As-built (μm)	After contouring	After machining
PBF	6–12	4–6	1–2
DED	20–40	18–32	2–4
BJT	10–18	–	1–3

PBF samples showed highest tensile residual stresses due to steep cooling gradients (~200–350 MPa before stress-relief).

Build rates

Technology	Rate (cm^3/h)
PBF (1-laser)	8–15
PBF (8–12 lasers)	50–130
DED	90–250
BJT	200–650

Energy demand

- PBF: **15–24 kWh/kg**
- DED: **9–14 kWh/kg**
- BJT: **4–8 kWh/kg**

Cost-per-part analysis

Normalized Economic Efficiency Index (EEI):

- **PBF = 0.68**
- **DED = 0.74**
- **BJT = 0.89**

Discussion

The results confirm a strong correlation between powder morphology and final part quality. In PBF, spherical powders yielded stable melt pools and minimized recoater-induced defects. Irregular powders caused shadowing effects and incomplete fusion, proving that PBF is highly sensitive to flowability and packing density.

DED was less sensitive to powder shape because particles enter the melt pool with kinetic energy. However, powder-feed irregularities increased porosity and bead-width fluctuation. In

BJT, powder morphology directly dictated packing density and shrinkage behavior; poor powders resulted in non-uniform densification.

Melt-Pool Behavior Governs Microstructural Development

The melt-pool geometry dictated grain morphology in both PBF and DED.

- **PBF:** Shallow, narrow melt pools → steep cooling → fine columnar grains → higher strength.
- **DED:** Large pools → slow cooling → coarse grains → higher anisotropy.
- The findings support thermal-management approaches, such as:
 - preheating platforms (>200 °C)
 - multi-laser synchronization
 - active cooling
 - scan-vector rotation
 - re-melting strategies

These significantly reduced porosity and refined the microstructure.

Porosity Mechanisms Differ Across Technologies

The root causes of porosity vary:

- **PBF:** keyhole porosity, gas entrapment, lack-of-fusion due to insufficient energy density.
- **DED:** turbulence-driven pore engulfment, inconsistent powder feeding.
- **BJT:** sintering pores and incomplete binder removal.

Each mechanism requires specific mitigation strategies.

Mechanical Performance Reflects Microstructural Stability

PBF consistently provided the highest tensile strength and fatigue life due to:

- fine grains
- low porosity
- uniform thermal cycles

DED mechanical performance depended strongly on scanning strategy and bead overlap.

BJT mechanical limitations highlight reliance on post-sintering densification methods (HIP, infiltration).

Dimensional Accuracy and Surface Quality Determine Application Suitability

- **PBF** is ideal for high-precision components and medical/ aerospace applications.
- **DED** is suited for large structures, repairs, and hybrid machining.
- **BJT** is optimal for mass production of small components.

Dimensional fidelity strongly correlates with thermal regime during printing and sintering

Economic Implications and Manufacturing Strategy

The economic analysis demonstrates that:

- PBF provides highest performance but at highest cost.
- DED offers balanced performance for large parts.
- BJT yields lowest production cost in high-volume manufacturing.

Mass-production strategy therefore depends on:

- part size
- complexity
- required mechanical properties
- acceptable post-processing

Conclusions

This study provides a comprehensive comparative assessment of metal additive manufacturing technologies employing powder materials—Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Binder Jetting (BJT)—under controlled experimental and analytical conditions. The results demonstrate that the final performance of additively manufactured components is governed by the synergistic interaction between powder morphology, thermal field dynamics, melt-pool behavior, densification mechanisms, and machine-level process control. Although each technology uses powdered feedstock, their processing principles lead to fundamentally different microstructural pathways and engineering outcomes.

PBF exhibited the highest precision, microstructural uniformity, and mechanical strength, primarily due to its stable, shallow melt-pool geometry and rapid solidification rates. Its fine columnar grains, low porosity levels (0.05–0.5%), and high tensile properties (up to 1050 MPa for Ti-6Al-4V) reinforce its suitability for high-performance aerospace, medical, and energy applications. However, PBF remains sensitive to powder quality, oxygen content, and layer uniformity, and it exhibits moderate build rates even with multi-laser systems.

DED demonstrated unique advantages for large, structural, and repair-oriented components. Its high deposition rates (90–250 cm³/h), tolerance to powder morphology, and ability to fabricate meter-scale parts highlight its industrial relevance. However, its large melt pools and steep thermal gradients promote coarse grains and elevated porosity (0.5–3.0%), which can limit fatigue performance without extensive post-processing or hybrid machining.

BJT achieved the highest volumetric productivity and most favorable cost indicators due to layer-wide material deposition and excellent powder recyclability. Yet its reliance on binder burnout and sintering introduces 15–18% shrinkage and microstructural porosity, requiring predictive compensation models and additional densification steps (e.g., HIP) to reach mechanical performance comparable to PBF or wrought materials.

Across all technologies, powder characteristics—namely particle shape, size distribution, and gas composition—emerged as primary determinants of melt-pool stability, packing density, pore formation, and mechanical performance. High-sphericity, gas-atomized powders consistently produced superior layer deposition, reduced porosity, and more repeatable properties. Elevated oxygen and nitrogen levels unfavorably altered melt-pool absorptivity, increased pore density, and reduced ductility.

Economically, Binder Jetting demonstrated the highest manufacturing efficiency (EEI = 0.89), followed by DED (0.74) and PBF (0.68). This highlights a clear trade-off between precision and throughput. The optimal selection of additive technology is therefore application-dependent rather than universal. High-precision components benefit from PBF, large-scale structures from DED, and mass-produced components from BJT.

Overall, the study establishes a unified framework integrating thermal behavior, powder-material science, microstructure, mechanical properties, and cost-performance metrics. These findings provide actionable insights for material engineers, designers, and manufacturers seeking to optimize additive manufacturing strategies, and they reveal clear pathways for improving powder quality, thermal management, and process control. The consolidated dataset supports future development of predictive digital twins, machine-learning models, and adaptive laser

strategies aimed at further increasing reliability, repeatability, and industrial scalability of powder-based additive manufacturing.

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