

Laser Powder-Bed Fusion of Metals: Density, Geometric Freedom, Residual Stress, Supports, Productivity and Qualification

Powder State, Melt-Pool Control, Post-Processing and Complete-Cell Evidence

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Statement of Significance

Laser powder-bed fusion can produce dense, intricate metal geometries without a shape-specific forming tool, but the printer does not convert an alloy name and a CAD file directly into a qualified component. Powder condition, deposited-layer state, laser delivery, atmosphere and gas flow, melt-pool regime, scan trajectory, thermal accumulation, supports, plate restraint, cooldown and downstream operations are coupled. A high bulk-density result can coexist with unfavourable defect morphology, residual stress, surface condition, inaccessible powder or location-dependent properties. This review defines PBF-LB/M as a complete controlled chain from released powder to accepted component. It compares conditional advantages with their process costs, separates monitoring from acceptance, distinguishes stress relief, heat treatment, hot isostatic pressing and machining, and provides a factory qualification gate that prevents machine settings or vendor labels from replacing evidence.

Abstract

Laser-based powder-bed fusion of metals, designated PBF-LB/M by ISO/ASTM and widely called LPBF, SLM or DMLS, selectively melts successive powder layers to create near-net-shape metal components. Its industrial value can include tool-less geometric complexity, internal features, part consolidation, rapid design iteration and high material utilisation relative to subtractive routes for selected geometries. Those benefits are conditional. The deposited layer is a heterogeneous granular state; laser-matter interaction can move among incomplete fusion, stable conduction-like melting and keyhole behaviour; plume, condensate, ejecta and gas flow redistribute energy and material; supports conduct heat and restrain distortion while adding removal and surface burdens; and rapid cyclic heating creates microstructure, residual stress and location dependence. The as-built object normally requires controlled cooldown, powder removal, plate separation, support removal, heat treatment, machining or finishing, cleaning and inspection. This qualitative engineering review maps that state-resolved chain and its principal failure modes. It explains why volumetric energy density, relative density, scan speed, nominal oxygen level or a single in-situ signal cannot serve as universal qualification metrics. It proposes powder, machine, build, post-process and acceptance records aligned with current ISO/ASTM controls and bounded primary evidence. The resulting selection gate accepts PBF-LB/M only when geometry, alloy state, support/recovery access, complete-cell productivity, safety, inspection coverage and change control are demonstrably compatible with the required delivered component.

Keywords: *PBF-LB/M; laser powder-bed fusion; LPBF; selective laser melting; metal powder; melt pool; keyhole; lack of fusion; residual stress; support structure; hot isostatic pressing; qualification*

1. Purpose and scope

ISO/ASTM 52900 places laser melting of metal powder within powder-bed fusion; process-specific documents use the designation PBF-LB/M [1,3]. LPBF or L-PBF is used here as the readable abbreviation. “Selective laser melting” and “direct metal laser sintering” remain recognisable legacy or commercial labels, but they do not define separate base categories. ER-145 applies the state-resolved selection and decision-gate architecture owned by ER-139 to this process family, and inherits from ER-049 the direct-versus-indirect distinction for advanced metals and ceramics [32,33]. The relevant engineering question is not which label appears on a machine. It is whether a released powder, controlled equipment state, build definition, post-processing route and inspection plan can produce the required delivered metal state.

The scope is direct laser consolidation of metal powder in a bed. It includes powder receipt and lifecycle, recoating, laser delivery, inert or otherwise controlled atmosphere, melt-pool and track formation, supports and plate interaction, thermal history, cooldown, depowdering, heat treatment, hot isostatic pressing (HIP), machining, surface finishing, cleaning, inspection and production qualification. Design recommendations specific to PBF-LB/M and requirements for critical metal powder-bed applications establish that geometry and production controls must be process-specific [3,6]. Site and process qualification remain broader than equipment capability [2].

Electron-beam powder-bed fusion is assigned to ER-146. Metal binder jetting, bound-metal material extrusion and lithography-based metal manufacturing are assigned to ER-147, ER-148 and ER-149 respectively; those routes create green intermediates that require downstream thermal conversion. Directed-energy deposition and wire-arc additive manufacturing are assigned to ER-150. A powder or wire sold for any of those routes is not automatically an LPBF feedstock. ER-145 inherits from ER-141 the generic spreading and deposited-layer-state distinction [34]; it owns here the metal-specific effects of cohesion and electrostatics, oxide state, conduction into the preceding layer, and spatter/condensate addition to the bed. Ceramic vat photopolymerisation belongs to ER-151, ceramic direct ink writing and robocasting to ER-152, ceramic and sand binder jetting to ER-153, and bound-ceramic extrusion to ER-154. ER-155 covers polymer-binder powder-bed shaping of metals, ceramics and unusual powders, including a metal route: its bed is polymer-bound and the binder is subsequently removed so that the delivered metal is created in a furnace,

whereas ER-145 fuses the metal in the machine. Construction-scale, cementitious, geopolymer, regolith and macroscopic high-volume applications are excluded.

This paper does not publish alloy recipes, parameter windows, support-angle rules, oxygen limits, reuse counts, heat-treatment schedules or inspection acceptance limits. Such values depend on alloy specification, powder, machine, optical state, geometry, atmosphere, build location, post-processing and intended use. The purpose is to define the causal variables and evidence needed to establish a qualified window.

2. Process identity and the state-resolved chain

An LPBF cycle doses powder, spreads a layer, selectively scans regions and lowers the build platform before repeating. That description hides several release states. The powder entering the machine has a lot, composition and history. The spread layer has local thickness, packing, segregation and discontinuities. The laser has a measured power distribution and position state rather than only a nominal setpoint. The as-built object remains attached to supports and a plate, surrounded by powder and carrying a thermal and stress history. The delivered component exists only after the specified downstream sequence and acceptance.

Table 1. State-resolved PBF-LB/M production chain

Stage	Controlled state	Principal evidence	Invalid shortcut
Powder release	Alloy/lot, chemistry, particle characteristics, storage, contamination and lifecycle	Certificate plus verified sampling and defined tests	“Correct alloy label”
Dosing and spreading	Layer mass, thickness/coverage, packing, recoater state and disturbances	Recoater record, layer evidence and machine checks	“Nominal layer thickness”
Atmosphere and laser	Gas identity/flow, chamber state, beam profile/power, focus and positioning	Calibrated machine-state records	“Setpoints loaded”
Fusion	Track geometry, overlap, contour/core/down-skin state, plume and thermal accumulation	Qualified build definition and validated monitoring	“Energy density is in range”
As-built recovery	Cooldown, powder isolation/recovery, plate/support attachment and visible condition	Build genealogy, recovery record and hold point	“Build completed”
Transformation	Stress relief, plate separation, HIP or alloy heat treatment	Furnace/HIP load record and material-state verification	“Post-processed”
Finishing	Support removal, machining, surface treatment, cleaning and inaccessible-feature control	Operation-specific route and inspection	“Near-net shape is final”
Acceptance	Geometry, surface, discontinuities, microstructure, properties and traceability	Part-linked measurements and disposition	“Coupon passed”

ISO/ASTM TS 52930 separates equipment installation, operation and performance qualification [7], while ISO/ASTM 52904 addresses the metal powder-bed process for critical applications [6]. These layers are complementary. Equipment performance qualification does not replace powder release, build-specific evidence or part acceptance. Conversely, a good component test does not demonstrate that an uncontrolled equipment or powder change is equivalent.

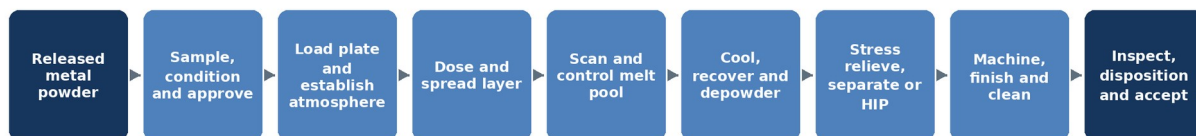


Figure 1. State-resolved LPBF route.

The chain also clarifies ownership. An internal channel is not a geometric success if powder cannot be removed, cleanliness cannot be verified or its surface cannot be inspected. A lattice is not a productivity success if supports, trapped powder or finishing dominate the cycle. A high-density coupon does not release a thin-wall component at another plate position. “As built,” “stress relieved,” “HIPed,” “machined” and “finished” are different material and geometry states and must appear as such in data and certificates [8,12].

3. Powder identity, deposited-layer state and lifecycle

Metal powder is a population, not one diameter. Chemistry and interstitials, particle-size distribution, morphology, satellites, agglomerates, surface oxide, internal porosity, apparent and tapped density, flow response and contamination can affect dosing, spreading and melting. ISO/ASTM 52907 provides characterisation methods but does not create one acceptance limit for all alloys or machines [4]. A method name without sampling location, preparation, instrument, settings, uncertainty and lot genealogy is insufficient.

The property of bulk powder and the property of a deposited layer are related but not identical. Recoater type, edge condition, speed, gap, powder-bed interaction, electrostatic or cohesive behaviour, part protrusion and local disturbance can change coverage and packing. Whiting et al. developed a powder-spreading testbed precisely because the relation between bulk characteristics and

the deposited layer requires direct study [21]. Production controls should therefore distinguish incoming-powder tests, in-machine handling evidence and spread-layer evidence. A flow value from one apparatus is not proof of uniform layers in a different machine.

Powder lifecycle begins before the first exposure. Receipt, quarantine, opening, transfer, atmosphere, machine residence, thermal exposure, spatter deposition, recovery, sieving, blending, sampling, storage and top-up can change or mix populations. ISO/ASTM 52928 addresses both virgin and used powder [5]. The minimum genealogy identifies every source lot and recovered fraction, the build histories that contributed to the blend, all conditioning/sieving steps, sampling points, test results, deviations and final disposition.

A reuse count is a poor state variable by itself. One build can expose a large fraction of the inventory to heat and condensate while another consumes little and has a different atmosphere or geometry. Das et al. modelled reuse as a mixture of powder fractions with different histories and explicitly did not recommend a universal strategy [22]. Cordova et al. measured reuse-associated changes for specific material and process histories [23]. These sources support tracking and testing; they do not support “reuse N times” as a transferable rule.

Retirement criteria must be tied to failure mechanisms and the qualified alloy/process state. A powder can fail chemistry, contamination, spreadability, packing or downstream-property controls even if its size distribution remains nominal. A blend can meet a bulk average while containing a small history fraction that is poorly represented by the sample. Conversely, visual colour change alone may not define rejection without a validated connection. Sampling uncertainty and segregation risk belong in the disposition.

The current 3Dresyns nano/micron page lists alloy, elemental and other raw-material families and distinguishes direct from indirect manufacturing routes [30]. That page is a portfolio-scope source only. Availability of a composition or particle family does not establish that it is gas-atomised, spherical, contamination-controlled, safely handled, spreadable, optically compatible or qualified for LPBF. Any proposed 3Dresyns-related metal powder must pass the same external feedstock and process evidence gate as any other source.

4. Laser–powder interaction and the limits of energy density

Laser delivery is described by more than nominal power. The spatial power-density distribution, focal position, beam quality, scan position, acceleration, turn behaviour, calibration state, contamination of protective optics and timing interact with powder absorption and the evolving surface. The powder bed is not an optically uniform solid: particles, gaps, multiple reflections and local packing change energy coupling. The previous track and surrounding material establish a thermal boundary that varies with geometry and build time.

A commonly reported descriptor is volumetric energy density:

$$E_v = P / (v \cdot h \cdot t)$$

where P is nominal laser power, v scan speed, h hatch spacing and t nominal layer thickness. This expression can label settings within a controlled study. It cannot prove equivalent melt-pool physics. Different combinations with the same value change residence time, peak intensity, track width/depth, overlap, cooling and plume interaction. Beam distribution, absorptivity, trajectory, contours, remelting, multiple lasers and thermal accumulation are absent. Coupling efficiency is not an independent correction term: it depends on the evolving melt regime, so the same nominal E_v can correspond to different absorbed energies and prior-state histories. Adding one absorptivity term therefore cannot convert the scalar into a valid process window or technology-comparison metric.

At insufficient or poorly coupled input, the melt may not wet and fuse the intended powder/previous layer, leaving irregular lack-of-fusion discontinuities. In a stable conduction-like regime, melt-pool geometry and overlap can be controlled for the local state. With stronger vaporisation-driven depression, keyhole behaviour and collapse can trap pores. Cunningham et al. used ultrahigh-speed X-ray imaging to resolve regime-dependent keyhole morphology [15]. Khairallah et al. coupled fluid dynamics and experiment to examine recoil, surface-tension-driven flow, pores, spatter and denudation [16]. Martin et al. showed that trajectory changes and laser turnaround can create time-localised keyhole pores and that matched power control mitigated them in the studied configuration [17]. None supplies a universal threshold.

This mechanism separation matters in production. Increasing power to eliminate lack of fusion can move a system toward keyholing, spatter or overheating; increasing speed to limit keyholing can reduce fusion or change track continuity. Hatch and contour states differ, as do up-skin, down-skin, thin-wall, support-interface and bulk regions. A qualified build file may therefore contain several validated parameter classes, each with geometry eligibility and transition logic. Transitions at starts, stops, corners, islands, contours and laser-field boundaries deserve the same evidence as steady straight tracks.

Multi-laser architecture creates an additional controlled state rather than a simple multiplication of scan capacity. The qualification record must identify the number of lasers, field assignment and scheduling; establish relative inter-field geometric calibration with a defined verification interval; and qualify the overlap-zone parameter class and its transition logic. Boundary evidence must challenge relative positioning, the distinct thermal history of the stitch/overlap zone, and laser-scheduling-dependent accumulation separately from geometry-dependent accumulation. Witnesses or coupons must include a field boundary when that condition is present; coupons placed only within one field cannot represent its defect population.

Nominal “full melting” does not guarantee chemical or microstructural acceptability. Evaporation, oxidation, segregation, cracking sensitivity and rapid-solidification pathways depend on the alloy and local thermal history. The process specification should define the material state that must be achieved after all heat treatment, not simply the existence of a continuous melt track.

5. Atmosphere, gas flow, plume, condensate and spatter

The chamber atmosphere has chemical and transport functions. Gas identity and residual reactive species affect oxidation or other reactions; the flow field removes or redistributes vapor, condensate and ejecta. A single oxygen reading at one sensor does not describe spatial flow, transient leakage, local byproduct concentration or the state at powder loading and recovery. Gas supply, purification, recirculation, filters, nozzles, seals, sensor calibration, purge sequence, pressure and flow profile are machine states.

Deisenroth et al. found that gas-flow speed and direction influenced track variability and an in-line thermal signature in bare-substrate IN625 tests [19]. Their measured values belong to that nozzle, geometry and experimental system; they are not production limits. O'Brien et al. combined computational and experimental work to show that spatter trajectories depended on particle and flow variables and that build placement relative to downstream transport mattered in one machine [20]. The appropriate inference is that flow field and placement require qualification, not that one spacing or orientation rule transfers.

Plume and condensate can attenuate or distort delivered energy, contaminate optics or redeposit on powder and parts. Spatter can be hotter, larger, compositionally altered or morphologically different from virgin feedstock. It may disturb an unscanned region, be incorporated into a layer or enter recovered powder. The powder-lifecycle plan must therefore define how collector, overflow, surrounding-bed and machine-reservoir fractions are segregated or combined. "Unused" powder is not automatically unexposed powder.

Gas-flow evidence should be spatial and task-specific. Velocity at an empty plate, flow with a tall build, pressure drop through a filter, removal of hot ejecta and the response to multi-laser activity are different measurements. With multiple lasers, plume or condensate generated in one field can be transported through the beam path or powder region of another; the active laser combination, scheduling and field occupancy therefore form a specific gas-flow qualification case. A qualification record states measurement position, height, gas, machine configuration, filter condition and uncertainty. When a signal changes with gas direction or laser trajectory, the monitoring model must account for that bias rather than label every change a defect.

6. Geometric freedom, orientation, supports and recovery access

LPBF can create enclosed passages, lattices, conformal channels, topology-optimised forms and consolidated assemblies that are difficult or uneconomic to machine or cast. This is conditional geometric freedom. Every feature must be spread, fused, supported where needed, cooled, depowdered, detached, finished and inspected. ISO/ASTM 52911-1 provides process-specific design recommendations, not a universal permission for arbitrary geometry [3].

Orientation determines projected area per layer, build height, scan length, recoater exposure, support contact, heat path, upward/downward-facing surfaces, anisotropy and access. A low height can increase cross-sectional area and thermal accumulation. A vertical orientation can extend cycle time and create direction-dependent properties. Nesting parts can improve nominal occupancy while changing gas-flow interaction, spatter exposure, heat accumulation and access for removal. The best orientation is therefore a multi-objective production decision tied to critical surfaces and loading directions.

Supports do at least five jobs: anchor the object; conduct heat to the plate; restrain thermally driven motion; stabilise vulnerable overhangs or islands; and reduce the chance that distortion interferes with recoating. They also consume powder and scan time, create stress concentrations or rough interfaces, obstruct powder removal, require access and removal effort, and can damage the component. Hussein et al. examined lattice support designs and demonstrated trade-offs among support volume, overhang behaviour and manufacturability in their studied system [26]. Their geometry is evidence that support architecture matters, not a universal design.

Nominal overhang angle alone ignores alloy conductivity, local section, scan strategy, plate/support temperature, contour state, gas direction and accumulated height. A bridge, downward-facing skin, internal roof and thin cantilever at the same angle are different thermal/mechanical cases. A support-free claim must state feature dimensions, orientation, alloy, machine, parameters, surface and acceptance. If a support cannot be removed without damaging the part, or the interface cannot be inspected, the design may be ineligible even if it builds.

Powder removal must be designed. Blind cavities, tortuous channels, lattices and porous structures can retain powder and create cleanliness, mass, safety or service risks. Drain paths, access ports, validated agitation/flow/vacuum methods and verification must be part of the design. An internal channel that cannot be depowdered or verified is a no-go, not an undocumented post-processing problem.

7. Thermal history, residual stress, distortion and microstructure

Each scan rapidly heats a small region while surrounding material and the plate constrain expansion and contraction. Repeated layers create spatially varying thermal cycles, microstructure and residual stress. The result depends on alloy properties, baseplate, supports, preheat, geometry, scan order, local heat accumulation and cooldown. Residual stress can distort the build during processing, lift an edge into the recoater, crack a susceptible alloy or cause motion when supports or the plate are cut.

Mercelis and Kruth measured large residual stresses and showed that material, sample/substrate height, scan strategy and heating affected the stress profiles in the studied 316L system [24]. Carraturo et al. compared laser-control strategies with an experimentally validated model for IN625 [25]. These studies support mechanism-based control and modelling. They do not justify transferring a scan strategy or stress magnitude between alloys, machines or geometries.

In a multi-laser build, thermal accumulation also depends on the time schedule and relative activity of independent fields, not only on part geometry and scan order within one field. Qualification must challenge the active-laser combinations and scheduling states used by the released build, including boundary regions, rather than infer them from a single-laser coupon.

The build plate is part of the thermal and mechanical system. Material, thickness, flatness, surface preparation, attachment, preheat, contact and reuse state affect conduction and restraint. Support stiffness and distribution change load transfer. The point at which a part is stress relieved and separated from the plate can determine final geometry. The route plan must therefore freeze the plate/support/cut sequence and record any allowed rework.

Rapid solidification can create fine, directional, metastable or textured microstructures. Layer reheating and local dwell modify them through the build. A density result does not declare phase state, grain structure, segregation or residual stress. ISO/ASTM 52909 requires explicit attention to orientation and location dependence of metal properties [9]. Coupons should be selected to challenge the critical thermal, orientation and location conditions, but they cannot represent every component region without a validated equivalence model.

Distortion compensation in CAD or build preparation is only acceptable when it belongs to a controlled model, machine state and geometry class. A compensation field can hide a changing process if measured geometry is corrected without investigating cause. The uncompensated prediction, compensation revision, input state and final measurement must remain traceable.

8. Density, imperfections and acceptance relevance

Bulk or image-based relative density is useful but incomplete. Two specimens with the same void fraction can have different fatigue or leak performance because defect size, shape, orientation, distribution, surface connection and location differ. Lack-of-fusion discontinuities tend to be irregular and may align with layers or scan boundaries; keyhole/gas pores can be more rounded; cracks and inclusions have different consequences. ISO/ASTM 52948 supplies current imperfection classification, while acceptance still belongs to the application and material specification [14].

Table 2. Imperfection mechanisms and evidence boundaries

Condition	Plausible process contributors	Evidence required	What density alone misses
Lack of fusion	Inadequate/local coupling, layer disturbance, hatch/contour transition, beam attenuation	Section/CT or qualified NDT linked to build state	Irregularity, orientation and connectivity
Keyhole porosity	Vapor-depression dynamics, collapse and trajectory transients	Defect morphology/location plus scan and melt-regime evidence owned by §4	Formation regime and critical location
Entrapped gas porosity	Internal porosity and atomisation route of feedstock powder	Powder characterisation, section/CT evidence and lot/reuse genealogy owned by §3	Feedstock origin and gas identity
Inclusion/contamination	Powder history, spatter/condensate, foreign material, equipment cleaning	Chemistry/microscopy and genealogy	Composition and interface weakness
Crack	Alloy susceptibility, thermal gradient, restraint, contamination or heat treatment	Surface/volumetric inspection and metallurgy	Crack acuity and propagation path
Surface-connected defect	Down-skin/support interface, attached particle, machining allowance, open pore	Surface method after final finishing state	Leak/fatigue exposure to service
Geometry/distortion	Thermal strain, support/plate release, recoater interaction, compensation error	Datum-linked metrology at declared state	Functional fit and machining stock
Microstructure/property shift	Location/orientation, thermal accumulation, heat treatment variation	Material-state tests with sampling rationale	Phase, texture and local performance

Measurement itself requires controls. Metallographic area fraction depends on section location, preparation, imaging and thresholding. Computed tomography depends on material attenuation, geometry, resolution, reconstruction and detection probability. Surface methods depend on final surface condition and accessibility. Archimedes or mass/volume methods cannot classify defects. A report must name the method, state, coverage, threshold, uncertainty and decision rule.

ISO/ASTM 52927 organises principal characteristics and corresponding test methods [11]. It does not make every test appropriate to every part. The drawing and qualification plan should identify critical zones, load paths, sealing surfaces, channels, support interfaces, machining allowances and inaccessible volumes, then assign methods with demonstrated capability. A method that cannot see the relevant defect in the actual geometry is not acceptance evidence.

9. Post-processing: separate operations, separate claims

Controlled cooldown is the first post-build operation. Opening or disturbing the system too early can alter stress, oxidation, powder handling and dimensional state. Depowdering must preserve lot segregation and identify any powder exposed to cleaning agents, foreign media or uncontrolled atmosphere. The plate-bound object is then held for the defined thermal and separation sequence.

Stress-relief heat treatment aims primarily to reduce residual stress and may also change microstructure. Alloy heat treatment can include solution treatment, ageing, annealing or other transformations designed for a target phase/property state. HIP applies heat and isostatic pressure and can reduce some internal porosity. These are not synonyms. Eshawish et al. measured treatment-dependent porosity, microstructure and fatigue in one Ti-6Al-4V SLM route [27]. Leuders et al. connected pores and residual stress to fatigue behaviour and evaluated HIP in a specific TiAl6V4 system [28]. Their schedules and outcomes are not universal.

HIP is not a rescue rule. Its effectiveness depends on alloy, temperature/pressure/time, defect morphology, gas, surface connection and prior state. It may not heal oxide-lined lack-of-fusion interfaces, cracks, inclusions, open channels or surface-connected defects; it does not correct geometry and can change microstructure. An inert gas trapped in a pore is compressed when HIP closes that pore but is not thereby removed. In additively manufactured titanium studied by Tammis-Williams et al., argon-containing spherical pores reappeared and grew during a subsequent unpressurised high-temperature treatment [31]. This bounded

result establishes the failure mechanism, not a universal regrowth schedule: the route plan must fix the order of HIP and later heat treatments, and acceptance inspection must address the delivered state after all thermal operations rather than only the immediate post-HIP state. A HIPed part still requires the specified inspection and material-property evidence. Similarly, stress relief can reduce distortion risk during cutting but does not remove porosity, and machining can remove accessible rough surfaces but not internal defects.

Plate separation by wire EDM, band saw or another method creates its own datum, heat/contamination and stock conditions. Support removal can gouge or deform the component. Machining and grinding can expose subsurface defects, alter residual stress or close/open surface-connected paths. Shot peening, blasting, polishing, chemical or electrochemical treatment, coating and cleaning each change a specific surface state. The drawing must identify final critical surfaces and which state is inspected.

ISO/ASTM 52908 places post-processing, inspection and testing within the finished-part route [8]. A generic line reading “heat treated and machined” is insufficient. The part history requires furnace/HIP identity and calibration, load configuration, atmosphere, actual cycle trace, quench/cooling state, separation method, support-removal route, machining program/tool state where relevant, surface operation, cleaning and any rework or deviation.

10. In-situ monitoring, ex-situ inspection and evidence fusion

Layer images, recoater signals, photodiodes, coaxial or off-axis cameras, thermography, acoustics and machine telemetry can reveal process changes. Their value depends on a defined measurand, calibration, spatial/temporal resolution, field of view, data synchronisation, missing-data handling and connection to a physical or acceptance state. Lane et al. documented thermographic calibration and uncertainty challenges, including emissivity and resolution, in a commercial LPBF system [18]. A bright pixel or hotspot is not a defect label without a validated causal and statistical model.

ISO/ASTM TR 52958 addresses coaxial photodiode monitoring for lack-of-fusion flaw detection [13]. Its existence demonstrates maturing evidence architecture, not permission to waive final inspection. Monitoring can fail through blind geometry, saturation, optical contamination, sensor drift, signal dependence on gas/scan direction, algorithm revision or poor registration. The qualification plan must measure probability of detection or an equivalent performance characteristic against a traceable reference set and declare false-positive/false-negative handling.

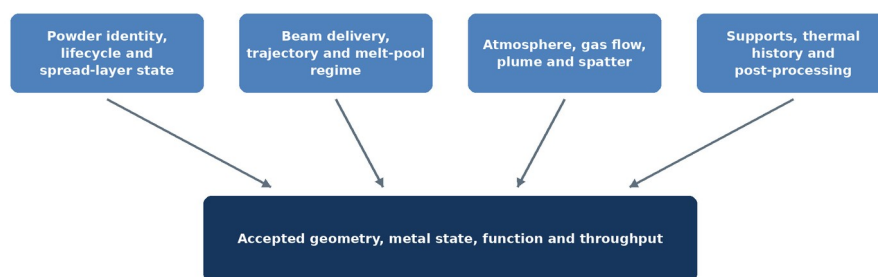


Figure 2. Evidence-closure architecture.

Evidence fusion should preserve independence. If the same model both selects a region and judges its conformity, validation must account for that dependence. If CT is used to train a monitoring classifier, the CT detection capability and registration uncertainty limit the labels. If coupons substitute for a component zone, their thermal and orientation equivalence must be demonstrated. Data retention must preserve raw or appropriately controlled source data, calibration, algorithm/software version, transformations, thresholds and operator actions.

The objective is not maximum data volume. It is adequate coverage of failure modes with known uncertainty. A simpler sensor with a proven response to a critical state can be more valuable than a high-dimensional stream with no disposition logic. Conversely, a good global process signature cannot rule out a local, surface-connected or inaccessible defect beyond its resolution.

11. Productivity, material utilisation and factory economics

LPBF productivity is often reduced to build rate, layer time or number of lasers. The factory denominator is longer:

$$\text{Effective cell throughput} = \text{accepted components} / \text{elapsed time from released powder to final acceptance}$$

Elapsed time includes powder release and conditioning, machine preparation, plate preparation, loading, purge/atmosphere establishment, recoating and scanning, recoater interruptions, cooldown, unloading, powder recovery/sieving/sampling, heat treatment or HIP queues, plate/support removal, machining, finishing, cleaning, inspection, nonconformance, rework and maintenance. A multi-laser system may shorten exposure while shifting the bottleneck to powder handling, field-overlap qualification, thermal accumulation, cooldown, furnaces, machining or CT.

Material utilisation must distinguish powder purchased, powder loaded, powder fused into accepted components, supports, witness specimens, overflow/collector fractions, sieving loss, sampling, contamination loss, retained inventory and retired powder. Unfused powder is not zero-cost merely because it can sometimes be reused. It occupies capital and controlled storage and accumulates genealogy/testing burden. A high buy-to-fly advantage over machining is meaningful only for the same delivered alloy state, geometry, yield and acceptance.

Geometric freedom creates value when it eliminates assembly, enables a function, reduces conventional tooling or avoids otherwise uneconomic material removal. It does not have a universal monetary value. Internal channels can reduce assembly but add depowdering and inspection. Part consolidation can remove joints but increase the consequence of a build failure and make repair harder. Nesting can spread fixed build cost but couples part schedules and can create correlated rejection.

The cost comparison must freeze annual volume, part mix, alloy and powder policy, machine utilisation, plate/support design, build strategy, accepted yield, post-process route, inspection level, labour, inert gas, filters, consumables, energy, data/storage and nonconformance. A route that makes fewer machining chips can still be less economical if scanning, supports, HIP and inspection dominate. Conversely, LPBF can be rational for low-volume complex components even when deposition is slow, if conventional tooling or multi-part assembly is avoided.

Production scaling requires more than duplicating machines. Powder genealogy, calibration transfer, build-file control, furnace capacity, machining fixtures, inspection throughput and personnel qualification must scale. Cross-machine transfer is a change, not a clerical copy. ISO/ASTM 52929 helps structure material-property data sheets, but comparable reporting still requires the state and route to be declared [12].

12. Occupational safety, fire/explosion and contamination control

Metal LPBF combines combustible or reactive fine powders, inhalation/dermal exposure potential, inert-gas asphyxiation, high-power laser systems, hot parts/powder, moving recoaters, pressure or vacuum systems, electrical energy, sieving and post-processing dust. Hazard severity depends on alloy chemistry, particle form, oxide/passivation state, quantity, dispersion, ignition energy, atmosphere, task and facility. A single phrase such as “metal powder hazard” is not an adequate assessment.

ISO/ASTM 52938-1 specifies safety requirements for PBF-LB machines [10]. Machine conformity does not replace the site risk assessment, local law, combustible-dust/explosion analysis, oxygen-deficiency controls, grounding/bonding, housekeeping, compatible collection methods, fire response, PPE, maintenance and waste decisions. Powders of aluminium, titanium, magnesium or other reactive systems can impose very different controls from nickel or steel alloys; mixtures and contaminated filters require their own disposition.

NIOSH evaluated metal exposures in defined tasks at one metal powder additive-manufacturing facility [29]. The report can identify task pathways and control questions, but its results cannot prove exposure, compliance or control adequacy elsewhere. Production evidence should cover receiving/opening, transfer, sieving, machine cleaning, filter change, depowdering, support removal, blasting/grinding, spill response and waste. Exposure measurements need worker/task/location and method context.

Inert gas creates both process and life-safety dependencies. Chamber leakage, purge exhaust, supply failure and confined or low areas require assessment. Opening the machine, vacuuming or handling hot/recovered powder can change ignition or exposure state. Cleaning equipment and extinguishing media must be compatible with the specific powder; generic workshop vacuuming or water response may be unsafe for some metals. ER-145 does not prescribe emergency methods. The facility plan must use the current SDS, supplier information, competent hazard analysis and applicable requirements.

Contamination control is also product control. Tools, sieves, vacuums, containers, PPE and rooms can transfer alloy or foreign material between systems. A safety control that mixes powder streams can invalidate feedstock traceability, while a quality procedure that disperses powder can be unsafe. The powder-handling workflow must close both objectives together.

13. Qualification, change control and the selection/no-go gate

Qualification is a linked hierarchy: site and personnel; equipment IQ/OQ/PQ; powder and consumables; build definition; post-processing; inspection/test methods; component acceptance; and controlled change. ISO/ASTM 52920, 52904 and TS 52930 provide complementary frameworks [2,6,7]. ISO/ASTM 52909 requires orientation/location awareness, and 52927 links characteristics to test methods [9,11]. None makes one coupon, machine certificate or parameter set universal.

Table 3. Minimum industrial qualification and release record

Record block	Minimum controlled content	Release question
Powder	Supplier/lot, chemistry, characteristics, sampling, storage, blend/reuse genealogy and disposition	Was every feed fraction in the released state?
Machine/optics	Machine ID, maintenance, calibration, beam profile/power/position, number of lasers, field assignment/overlap calibration and verification interval, recoater, gas and sensor state	Was equipment performance, including relative inter-field performance, demonstrated for this build state?
Build definition	Geometry revision, orientation, placement, supports, plate, parameter classes, overlap-zone transitions, laser scheduling and software revision	Does the record reproduce the qualified build intent and boundary conditions?
Process execution	Layer/recoater events, atmosphere, alarms, monitoring coverage, deviations and operator actions	Did the actual build remain inside the qualified boundary?
Recovery	Cooldown, powder segregation/recovery, plate-bound inspection and hold-point disposition	Was recovery controlled without losing genealogy or geometry?
Post-processing	Furnace/HIP load/cycle and order, all later thermal operations, plate/support removal, machining, finishing, cleaning and rework	Was the inspected object the delivered state after every specified thermal operation, rather than only the immediate post-HIP state?
Measurement	Geometry, surface, volumetric/material tests, method capability, uncertainty and critical-zone coverage	Can the plan detect the acceptance-relevant failure modes?
Release/change	Part-linked results, nonconformance, disposition, traceability and equivalence decision	Is acceptance attributable to an unchanged qualified chain?

Change control should include powder supplier or atomisation route, chemistry/specification, size distribution or sampling, reuse/blending policy, storage, sieving, machine, recoater, optics/protective window, number of lasers, laser scheduling, field assignment and field-overlap calibration, gas/nozzle/filter, plate/support, firmware/control, build processor, orientation, nesting, parameter class, scan order, monitoring hardware/software/algorithm, heat-treatment/HIP route and order, machining, surface treatment, cleaning, inspection and acceptance.

Equivalence is tiered. A change that can affect a new failure mode, an unrepresented parameter class or transition, an inter-field condition, a material state or delivered-part acceptance requires full requalification of the affected chain. A bounded change may use verification only when a documented causal assessment identifies the affected characteristics and a predeclared evidence set confirms feedstock genealogy, calibrated machine/optical and atmosphere state, representative geometry/location—including a field boundary where applicable—process execution, delivered-state material/geometry results, inspection capability and acceptance against the existing limits. If that minimum set is incomplete, its uncertainty overlaps a limit or the affected condition lies outside the validated domain, equivalence is not demonstrated and the chain remains on hold.

The selection gate begins with the delivered part:

1. Define alloy/material state, geometry, surface, cleanliness, dimensional, mechanical, physical and service acceptance.
2. Confirm that an LPBF-compatible released powder and safe factory workflow exist; reject selection based only on a listed raw-material name.
3. Verify feature, orientation, support, recoater, heat-flow and depowdering eligibility, including inaccessible regions.
4. Establish melt/track/layer and atmosphere/gas controls for every parameter class and transition used by the geometry.
5. Demonstrate distortion, microstructure and properties in critical orientations and build locations after the actual post-process route.
6. Assign monitoring and ex-situ inspection with adequate coverage and uncertainty for the relevant failure modes.
7. Compare accepted-part throughput, yield and complete-cell cost with a declared conventional or additive route.
8. Define traceability and change-control limits; issue no-go when a critical state cannot be controlled or inspected.

LPBF is a no-go when powder state cannot be released or safely handled; the alloy has no demonstrated processing route for the required state; geometry cannot be recoated, supported, depowdered, finished or inspected; distortion/microstructure/property requirements cannot be met across critical regions; required post-processing is unavailable or unqualified; accepted yield makes the route uneconomic; or the evidence chain cannot link each component to an unchanged process.

This review is limited by the diversity of alloys, machines, optical systems, gas architectures, geometries and acceptance regimes. Its cited studies establish mechanisms and evidence boundaries, not pooled process windows. Priority research needs include deposited-layer metrology tied to powder genealogy; beam-profile and optical-state calibration under production conditions; validated transient models at corners and multi-laser boundaries; spatial gas/plume/spatter measurement; support–distortion–removal optimisation; in-situ signal registration with probability-of-detection evidence; inspection of complex internal geometry; and open complete-cell yield/productivity datasets.

14. Conclusions

Laser powder-bed fusion is a coupled metal production route, not a universal high-density printer. The following conclusions control its industrial use:

1. PBF-LB/M, LPBF, SLM and DMLS terminology must not obscure the common process category or the need for implementation-specific evidence.
2. Powder release includes composition, particle state, contamination, sampling, storage, spread behaviour and complete reuse/blending genealogy; nominal alloy and reuse count are insufficient.

3. Laser power, speed, hatch and layer thickness cannot be collapsed into one transferable energy-density window. Beam, trajectory, material, atmosphere and thermal boundary determine melt-pool regime.
4. Relative density does not classify lack of fusion, process-derived keyhole porosity, feedstock-derived entrapped-gas porosity, inclusions, cracks, surface connection, residual stress or location-dependent microstructure.
5. Geometric freedom is bounded by recoating, heat flow, supports, distortion, depowdering, finishing and inspection. Inaccessible powder or an uninspectable critical feature invalidates selection.
6. Supports are thermal and mechanical process structures as well as removal burdens; gravity or overhang angle alone cannot qualify them.
7. Stress relief, alloy heat treatment, HIP, machining, finishing and cleaning create different states. No one operation repairs every defect or geometry problem.
8. In-situ monitoring is useful evidence only when measurand, calibration, coverage, uncertainty, registration and acceptance correlation are validated.
9. Productivity is accepted components per complete powder-to-release cycle, including yield, queues, post-processing and inspection—not scan speed or laser count.
10. Qualification must connect site, machine, powder, build, recovery, post-process, measurement, disposition and change control to each accepted component.

LPBF is advantageous when its geometry and material-state benefits survive the complete factory chain and can be demonstrated at acceptable yield. The correct alternative may instead be electron-beam PBF, directed-energy deposition, an indirect sinter-based route, casting, forging, machining or a hybrid chain. The engineering outcome is the controlled delivered component, not the successful completion of a laser build.

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