

# Metal Binder Jetting: Green Strength, Depowdering, Debinding, Sintering, Shrinkage, Throughput and Qualification

*Powder-Bed Packing, Binder Delivery, Brown-State Control and Part-Linked Evidence*

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## Statement of Significance

Metal binder jetting can separate rapid, area-independent powder-bed patterning from the high-temperature consolidation step and can place many geometries in one job box without melt-pool supports. Those characteristics do not make it a support-free, shrinkage-free or automatically high-throughput route to finished metal. The printer creates a porous binder-stabilised green object. Excavation, depowdering, binder removal, sintering or another specified densification route, cooling, finishing, cleaning and inspection remain part of the manufacturing definition. Powder packing, liquid delivery and drying establish a spatial green state that later governs gas escape, chemistry, pore evolution and distortion. During sintering, gravity and component-setter friction act while dimensions contract, so a single nominal scale factor cannot qualify local geometry. This review treats metal binder jetting as a complete, state-resolved factory chain. It identifies where its conditional advantages can be realised, where the green and brown intermediates create hidden liabilities, and which part-linked evidence is needed before a component can be accepted.

## Abstract

Metal binder jetting selectively deposits a liquid binder into successive metal-powder layers to form a green component, which is subsequently cured, excavated, depowdered, debound and densified. The process can offer parallel layer patterning, dense nesting and freedom from melt-pool residual stresses during printing, while also decoupling the printer from a furnace fleet. Its delivered performance nevertheless emerges from a coupled powder–binder–geometry–thermal route. Particle morphology, size distribution, moisture, spreading and reuse affect bed packing and green density. Droplet formation, wetting, saturation, drying and feature thickness affect edge growth, layer bonding and handling strength. Debinding must remove organic material without unacceptable residue, oxidation, cracking or loss of fragile brown geometry. Sintering transforms pore topology, chemistry, dimensions and microstructure; optional liquid-phase, infiltration, sinter-HIP or HIP routes create different material states and cannot be treated as synonyms. Shrinkage may be anisotropic and dependent on geometry, position, gravity, support or setter contact and thermal history. This qualitative engineering review defines controls from released powder and binder through final disposition, examines conditional process benefits and limitations for industrial metals, and presents a qualification gate based on complete-cell productivity and registered evidence. It deliberately supplies no transferable powder specification, binder formulation, saturation, furnace recipe, compensation factor or acceptance limit.

**Keywords:** metal binder jetting; green part; depowdering; debinding; brown part; sintering; shrinkage; powder lifecycle; throughput; qualification

## 1. Purpose and scope

ISO/ASTM 52900 places binder jetting among the seven additive-manufacturing process categories: a liquid bonding agent is selectively deposited to join powder materials [1]. In metal binder jetting, that first shape is a green body rather than a final metallic component. This distinction is the organising principle of ER-147. The review begins with released metal powder, binder, equipment and a controlled digital definition; it ends only after thermal conversion, finishing, inspection and documented disposition.

The scope includes powder receipt and lifecycle, dosing and spreading, printhead and droplet control, binder–powder interaction, interlayer drying, curing, excavation, external and internal depowdering, green-part handling, debinding, brown-part handling, sintering or a separately declared densification route, cooling, setter/support strategy, dimensional compensation, finishing, cleanliness, testing, factory throughput, occupational controls, qualification and change management. ISO/ASTM 52920 frames qualification at the industrial site and process level, while ISO/ASTM 52907 and 52928 address powder characterisation and lifecycle control [2,4,5]. Those controls are complementary; none turns an alloy name or machine datasheet into a qualified route.

ER-147 owns the indirect metal route after droplet impact: wetting of powder surfaces, capillary infiltration and redistribution through the porous bed, drying, spatial binder architecture, green/brown conversion and subsequent densification. ER-143 owns material-jetting production architecture, while ER-028 owns the rheology, waveform, primary-drop and satellite-formation physics of photopolymer inkjet [36,37]. Those upstream jetting mechanisms are inherited here only as input conditions; they are not re-derived or reassigned. The direct/indirect distinction follows ER-049, and the process-selection gate follows the state-resolved framework of ER-139 [34,35].

Laser and electron-beam powder-bed fusion are covered in ER-145 and ER-146. They consolidate powder directly through a moving melt pool and have different thermal, support and powder-state architectures. Bound-metal filament or pellet extrusion and lithography-based metal manufacturing are assigned to ER-148 and ER-149. Directed-energy deposition and wire-arc additive manufacturing belong to ER-150. Ceramic binder jetting belongs to ER-153, while other polymer-binder powder shaping followed

by thermal conversion belongs to ER-155. Construction-scale, cementitious, geopolymer, regolith and other macroscopic high-volume applications are excluded.

This paper is qualitative by design. It does not prescribe particle-size distributions, layer thicknesses, binder recipes, droplet volumes, saturation percentages, drying temperatures, cure cycles, excavation times, debinding atmospheres, furnace ramps, peak temperatures, hold times, shrink factors, setter materials, density targets or inspection limits. Every such value belongs to a specified powder–binder–printer–geometry–furnace–post-process–intended-use combination. The aim is to identify the relationships and evidence that must close before those values can be released.

ISO lists ISO/ASTM AWI 52973 as an approved work item for a binder-jetting design guideline under development as checked on 1 September 2026 [3]. Its existence signals a recognised need for process-specific design guidance. It is not a published standard and is not used here as normative authority.

## 2. Process identity and the state-resolved production chain

A simplified description—spread powder, jet binder, repeat and sinter—hides the transformations that determine quality. Powder in the feed system becomes a spread layer with a local packing state. Deposited liquid then wets, infiltrates, redistributes and dries within that porous layer. Curing changes binder distribution and green strength. Excavation exposes a fragile part that can still contain loose powder in channels or cavities. Debinding converts it into a more fragile brown state while changing carbon, oxygen and open-pore transport. Sintering contracts the structure, closes or redistributes pores, develops metallurgical bonds and changes phases and dimensions. Optional infiltration, pressure-assisted densification, heat treatment, machining or surface operations introduce further states.

Table 1. State-resolved metal-binder-jetting production chain

| Stage                      | Controlled state                                                                     | Principal evidence                                                | Invalid shortcut           |
|----------------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------|----------------------------|
| Input release              | Powder lot/fraction, binder batch, storage, equipment and build definition           | Certificates plus verified sampling, tests and release records    | “Correct alloy and binder” |
| Layer formation            | Dose, spread coverage, packing, moisture, disturbance and powder history             | Layer/recoater evidence, powder genealogy and deviation record    | “Nominal layer completed”  |
| Binder deposition          | Nozzle state, droplet delivery, saturation strategy, wetting and local drying        | Qualified printhead/binder record and registered process evidence | “Binder was jetted”        |
| Green consolidation        | Interlayer bonds, cure state, green density/strength and geometry                    | Controlled cure and state-specific measurement                    | “Part is printed”          |
| Excavation and depowdering | Green damage, trapped powder, cleanable access and recovered fractions               | Handling route, mass/visual evidence and powder disposition       | “No print supports”        |
| Debinding                  | Gas evolution, residue, chemistry, cracks, brown strength and furnace load           | Material-specific thermal record and brown-state hold point       | “Binder is gone”           |
| Densification              | Sintering mechanism, atmosphere, pore evolution, chemistry, shrinkage and distortion | Furnace/load history plus mapped material and geometry evidence   | “Standard sinter cycle”    |
| Finishing and acceptance   | Delivered surface, cleanliness, dimensions, chemistry, microstructure and properties | Part-linked inspection, uncertainty and disposition               | “Density or coupon passed” |

The table treats a job as a chain of released states. A measurement is valid only when its object and time are clear. Green density is not sintered density; brown strength is not service strength; as-sintered geometry is not machined geometry; a sinter-HIP result is not a pressureless-sintered result. These distinctions are essential when comparing suppliers, scaling a cell or investigating a deviation.

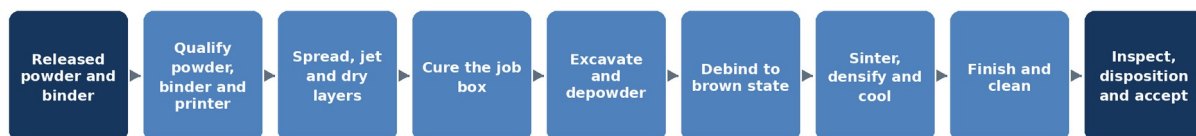


Figure 1. State-resolved metal-binder-jetting route.

Binder jetting is sometimes presented as having no supports because loose powder surrounds the green geometry during printing. That statement applies only to the print-bed shaping stage. A part may still need sacrificial features, setters, fixtures or specialised placement during debinding and sintering, when gravity and friction act on a softening, shrinking structure. It may also need access features for powder removal or machining stock for delivered surfaces. A process-selection claim must therefore state which stage and function “support” refers to.

The state-resolved chain also changes traceability. One printer job can feed multiple furnace loads; one furnace load can contain parts from multiple jobs, powders or geometries; recovered powder can return through sieving and blending. A defensible genealogy links input lots, job-box position, binder batch, printhead/parameter version, green handling, debinding/sintering load position, setter, post-processing, inspection and final serial or batch identity. ISO/ASTM 52920 and 52953 support the broader qualification and registered-data architecture, but the manufacturer must define the actual links [2,11].

### 3. Powder state, spreading, packing and lifecycle

Metal powder must satisfy more than chemical identity. Morphology, size distribution, satellites, surface oxide, moisture, apparent/tap density, flow behaviour, cohesion and contamination can affect dosing, spread uniformity and packing. A conventional powder-metallurgy grade or a powder accepted for laser PBF is not automatically suitable. Binder jetting uses a different layer-formation and liquid-infiltration environment; powder must flow through the actual delivery system, form a reproducible bed under its actual spreading conditions, interact with the binder and survive the specified thermal route.

ISO/ASTM 52907 organises methods for characterising metal powders, and ASTM F3522 addresses assessment of spreadability for metal AM powder beds [4,6]. Neither specifies one universal pass value. Test geometry, sampling, conditioning, humidity and equipment influence the result. A powder release therefore maps laboratory measures to machine-relevant layer evidence and to downstream green and sintered outcomes. Barthel et al. experimentally linked powder condition and spreading parameters to green and sintered density in the studied binder-jetting route [13]. Their result supports coupling the stages; it does not transfer their settings.

Fine particles present a characteristic trade-off. They can fill inter-particle voids, increase green packing and accelerate sintering because of their surface area and short diffusion distances. The same particles can increase cohesion, impair hopper discharge and spreading, carry more surface oxide or adsorbate per unit mass, raise airborne-dust concern and be preferentially lost during recovery. In their copper study, Miyajima et al. evaluated an average particle size of approximately 5  $\mu\text{m}$  and demonstrated coupled effects on recoating, green state, shrinkage and final quality in that route [17]. The proper conclusion is not “finer is better,” but “the candidate distribution must be qualified across the entire cell.”

Layer formation is spatial. A bulk sample may pass a flow test while local starvation, streaking, agglomerates, recoater interaction, bed-edge effects or cumulative packing gradients remain. Job-box position and geometry can then influence green density and later shrinkage. Layerwise optical inspection can reveal some exposed powder-bed anomalies after a validated classifier, as shown by Gourley et al. for their studied systems [28]. It cannot see every subsurface packing variation or prove the absence of later debinding and sintering defects.

Powder lifecycle management separates virgin, used, overflow, excavated, sieved, retained, rejected and blended fractions. Each transition records origin, exposure, moisture/atmosphere, binder contamination, thermal history, sieving, sampling and disposition. Bidare et al. observed moisture change, fine-particle loss and binder residue during repeated use in studied stainless-steel routes [29]. Those observations justify monitoring these attributes; they do not justify a universal refresh percentage or cycle-count retirement rule.

Recovered powder from around a printed job is not automatically equivalent to unused feed. It can contain local binder overspray or migrated liquid, cured fragments, green-part debris, foreign matter from tools, and a distribution altered by sieving or preferential loss. Internal cavities can retain powder whose history becomes ambiguous once removed during later cleaning. Powder genealogy and segregation must therefore be planned with the part route, not appended after excavation.

Sampling is itself a control. A scoop from an accessible surface may not represent a stratified hopper, mixed return fraction or large job box. The release plan identifies the sampling location, tool, mass, conditioning, test method, uncertainty and acceptance basis. ISO/ASTM 52928 makes powder history and disposition visible at the system level [5]. A lot remains usable only while the attributes relevant to spreading, binder interaction, thermal conversion, product chemistry and safe handling remain inside the qualified state.

### 4. Binder delivery, saturation, wetting and drying

The binder is simultaneously a printhead fluid, a wetting/infiltration agent, a temporary structural material and a future furnace burden. Its identity includes carrier or solvent, polymer/solid content, additives, viscosity, surface tension, volatility, ageing, storage and compatibility with wetted equipment. A batch change can alter droplet formation or thermal residue even when a commercial product name is unchanged. Binder release therefore needs batch identity, storage history, conditioning and the tests relevant to the qualified print and debinding route.

Printhead performance is not captured by a nominal resolution. Droplet volume and velocity, ligament or satellite formation, jetting frequency, nozzle-to-bed distance, waveform, temperature, meniscus condition, recirculation, nozzle substitution and maintenance affect where liquid arrives. Missing, weak or misdirected jets can create local loss of interlayer bond or dimensional discontinuity. Excess or satellite droplets can promote bleeding and edge growth. A nozzle-check image or purge confirms only what its method and timing can observe; production control must connect nozzle state to the actual layers and response to an excursion.

After impact, liquid spreads over particle surfaces and infiltrates the pore network. The result depends on powder surface state, packing, pore-size distribution, binder chemistry, wetting, capillary forces, evaporation and time before the next layer. “Saturation” is often expressed relative to estimated void volume, but the estimate and the deposited volume both carry uncertainty. A scalar saturation value cannot encode a shell/core pattern, thin-wall overlap, local packing variation, different droplet sizes or loss during drying.

More liquid may increase bonding over part of a window, but it can also expand edges, bleed into unbound powder, disturb the layer, extend drying, trap more organics and complicate debinding. Too little or poorly placed binder can reduce green strength or create delamination. Miyajima et al. examined powder–binder and parameter development for green-part printing [14], while Enneti and Prough measured interactions between saturation, layer thickness and green strength in one WC-Co system [16]. These are evidence of coupling, not transferable saturation settings.

Part thickness and thermal boundary matter. Crane showed that drying conditions and feature thickness affected saturation limits and bleeding in the studied binder-jet process [15]. A broad cross-section, isolated thin wall and edge region do not necessarily experience the same accumulation or evaporation. Interlayer heating may stabilise one feature while overdrying another or altering the next layer's infiltration. The released strategy therefore identifies bed temperature, local time history, layer sequence, feature classes and allowed evidence, without assuming a uniform moisture field.

Shell/core strategies can place different binder amounts or patterns near a boundary and in an interior. They may improve edge control or reduce total organic load, but they also create a spatial binder distribution whose mechanical and thermal consequences require validation. A shell that looks dimensionally sharp may conceal a weak core; a strong shell can constrain gas escape or produce differential contraction. Any strategy change is both a geometry and material-state change.

Drying is not equivalent to curing, and neither is debinding. Drying removes part of a volatile carrier and establishes a condition for the next layer. Curing develops or fixes green bonding after or during printing. Debinding later decomposes, volatilises or removes the organic system under a controlled thermal and gaseous environment. Conflating these operations hides mass transport, residual species and the possibility that material apparently "dry" still contains the full non-volatile binder burden.

## 5. Curing, green strength, excavation and depowdering

The completed job box contains green parts surrounded by loose or lightly affected powder. A controlled cure can increase handling strength, but its temperature, time, atmosphere and thermal uniformity interact with binder chemistry, cross-section and bed mass. The relevant output is not simply that a nominal oven or in-machine cycle completed. It is a green state that supports the planned excavation, gripping, brushing, vacuuming, air or fluid cleaning, transfer and furnace-loading operations without unacceptable deformation, cracking or retained powder.

Green strength is a handling property. It does not establish metallic bonding, final density, fatigue resistance, corrosion performance or service capability. Green density is also an intermediate characteristic: it influences the pore network and the amount of contraction required during sintering, but two green parts of similar bulk density can differ in local binder distribution, pore topology, anisotropy and defects. State and test method must accompany every number.

Excavation is a mechanical operation on a low-strength object. Digging strategy, tool geometry, access direction, bed consolidation, part spacing and operator action can impose bending, point loads, abrasion or collision. High nesting density can increase printer utilisation while making recovery slower and increasing damage risk. The build plan therefore reserves access corridors and handling features based on the actual green strength and extraction route, not merely the software's collision-free packing.

External loose powder may be readily removed while blind channels, lattices, cavities and porous features retain material. Clearance depends on opening size and path, length, turns, orientation, powder cohesion, binder migration, cure state and allowed cleaning energy. A visual exterior check cannot prove an internal channel empty. The design-and-inspection plan specifies access, measurement and acceptance before the powder becomes harder to distinguish after thermal treatment.

"Self-supporting in the powder bed" ends when the part leaves the bed. Large spans or slender members that survived printing can deform during lifting or later under their own weight in a furnace. Sacrificial handling tabs, cradles or setters may be needed. Modular or interlocking green geometries can open useful assembly routes, and Candidori et al. report one geometry-driven co-sintering demonstration [30]. That evidence does not establish that arbitrary joints, tolerances or alloy combinations survive debinding and co-sintering.

Depowdering also closes a material-accounting loop. Recovered powder must be assigned to a known fraction; damaged green fragments must not silently enter reusable material; loose powder trapped in a part is either removed and accounted for or remains a nonconformance. Tools and cleaning stations need material-compatible contamination controls. A process that prints quickly but requires prolonged manual excavation, creates frequent green scrap or cannot verify internal cleanliness may fail complete-cell economics.

The green-state hold point records identity, cure, visible condition, mass or other validated cleanliness evidence, damage, repair prohibition or allowance, and fitness for the next handling step. It is deliberately narrower than final acceptance. Passing it means only that the controlled intermediate can enter debinding.

## 6. Debinding and the brown state

Debinding removes the temporary organic system while the metal particles remain connected mainly through packing and developing necks. It is a mass-transport and chemistry operation, not an administrative prelude to sintering. Binder components can melt, evaporate, depolymerise, oxidise or leave carbonaceous residue. Gases must reach open pathways and leave the component and furnace load without creating pressure damage, condensation, contamination or unsafe exhaust conditions.

The thermal programme depends on binder chemistry, binder distribution, green density, section thickness, geometry, load arrangement, atmosphere, gas flow, furnace volume and downstream alloy requirements. Thin and open features can release products differently from thick or enclosed regions. A ramp that works for one coupon may generate internal pressure, blistering, cracking or residue in a larger component. No universal debinding schedule follows from the alloy label.

Atmosphere presents coupled trade-offs. Zissel et al. measured, for a specific binder-jetted 17-4 PH system, how oxygen content affected binder removal, residual carbon, powder oxidation and brown strength [22]. The permissible inference is that binder removal, chemistry and mechanical survival must be balanced and measured. Their oxygen levels and temperatures are not

transferable setpoints. Nandwana et al. likewise showed that binder-derived carbon and the thermal route matter to phase and distortion in one H13 route [20].

The brown part can be more fragile than the cured green part because the polymeric bridge has been removed before full metallic densification. Handling between a separate debinding furnace and sintering furnace can therefore be a critical step. Even when one furnace programme combines debinding and sintering, the transformations remain analytically distinct. A brown-state hold point may be established through validated mass-loss, gas analysis, chemistry, witness specimens, thermal history or other route-specific evidence rather than through physical handling.

Debinding can alter the subsequent sintering response. Zissel et al.'s companion study linked the tested debinding atmosphere to sintering activity, chemistry, microstructure, density and shrinkage [23]. Thus, a part cannot be cleared for sintering merely because its exterior appears intact or because a furnace reached a temperature. The record must connect debinding conditions and evidence to the actual sintered outcome.

Furnace loading and maintenance are part of the process. Parts and setters influence gas access and local thermal mass; released gases can affect neighbouring parts or furnace surfaces. Condensation, residue and filter/exhaust state can change with repeated loads. A qualification plan states load family, spacing/orientation, compatible materials, sensor locations, cleaning, maintenance and response to an out-of-limit gas or mass-loss signal.

The brown-state acceptance question is limited but demanding: has the specified binder-removal transformation occurred without unacceptable damage, residue or chemistry change, and can the part proceed through densification under controlled support? It is not “does the part look like metal?” and it is not a prediction of final conformance.

## 7. Sintering, densification, chemistry and material condition

Sintering converts the porous particle assembly toward a metallurgically bonded solid through temperature- and time-dependent transport. Neck growth, pore evolution, grain and phase changes, surface-oxide reactions and macroscopic contraction occur together. The driving force and kinetics depend on particle state and alloy, while atmosphere, thermal profile, green density, binder residue, geometry, setter contact and furnace position influence the result. A furnace recipe cannot be qualified independently of the printed intermediate it receives.

The atmosphere controls oxygen potential at the particle surface and therefore whether oxide films are reduced, retained or renewed while necks form. In hydrogen-bearing gas, the declared hydrogen fraction and water content—commonly monitored by a measured dew point—must be interpreted with temperature; in nominally inert gas, residual oxygen partial pressure, leak state and gas delivery remain material controls. Zissel et al. showed in binder-jetted 17-4 PH that removal of surface oxides is a prerequisite for strong sintering necks and that stable chromium-, silicon- and manganese-rich oxides can resist reduction [23]. Wendel et al. likewise demonstrated alloy- and initial-powder-state dependence during hydrogen reduction of water-atomised iron and steel powders [33]. Consequently, an oxide that is not reducible within the qualified atmosphere and thermal window is a material-system limit, not a defect that a generic gas name can waive.

Do, Kwon and Shin developed a coupled printing, debinding and sintering route toward full-density 316L components [19]. Bai and Williams explored copper binder jetting and documented the limitations of their powder and thermal route [18]. Together these studies show that high densification is experimentally achievable for some defined systems and incomplete for others. Neither justifies a universal claim that binder jetting produces fully dense metal.

Pressureless solid-state sintering, supersolidus liquid-phase sintering, infiltration, sinter-HIP and HIP create different paths and delivered states. A transient liquid can accelerate densification but also increase shape sensitivity or change phases. Infiltration adds a second material and chemistry architecture. HIP applies pressure at high temperature to a pre-existing state and does not erase every surface-connected feature, chemistry deviation or dimensional error. Mostafaei et al. examined a sinter-HIP WC-Co route and showed that print-stage variables can persist into its microstructure and properties [21]. That result reinforces, rather than removes, the need to name the route.

The target may legitimately include porosity. Meenashisundaram et al. manufactured high-porosity 316L metal foams by binder jetting [24]. Such a component should be accepted against its intended pore fraction, distribution, connectivity and function, not rejected for failing an unrelated maximum-density target. Conversely, a high average density does not prove that critical pores, oxide films or cracks are absent.

Chemistry must be measured in the declared final condition. Binder residue, powder oxides, furnace atmosphere, setter interaction and evaporation or contamination can affect carbon, oxygen, nitrogen or alloy balance. Copper [18], stainless steel [19,22,23], H13 [20] and WC-Co [21] studies in the source set use different powders, binders and densification mechanisms. Their achieved properties belong to those routes. A commercial alloy designation alone cannot carry the result to another supplier, binder or furnace.

Microstructure and properties also depend on post-sinter operations. Heat treatment, solution/ageing, HIP, machining, surface removal or infiltration can change phase, pores, residual stress and test location. Reports and drawings must state whether a value is green, brown, as-sintered, infiltrated, HIPed, heat-treated, machined or delivered. Comparing an as-sintered coupon with a machined and heat-treated datasheet value is not a qualification.

Furnace uniformity is three-dimensional and load-dependent. The programme identifies usable volume, sensor/control scheme, load family, part and witness locations, setter condition, atmosphere flow and cooling. A successful empty-furnace calibration does not prove a densely loaded production cycle equivalent. Likewise, one witness coupon cannot represent every thick, thin, shielded or edge component without a validated correlation.

## 8. Shrinkage, distortion, setters and dimensional compensation

Dimensional contraction is a necessary consequence of densifying a porous green body, but “shrinkage” is not one isotropic scale factor. Local green density, powder packing, binder distribution, feature thickness, orientation, gravity, temperature, atmosphere, sintering mechanism, phase evolution and constraints all affect the path. Even if three overall dimensions can be summarised by scale factors, local holes, walls, fillets, spans and interfaces may respond differently.

Zago et al. measured dimensional and geometric errors, including anisotropic shrinkage and dependencies on build position, green density and feature form, in the studied 316L and 17-4 PH routes [25]. Vafaei et al. combined in-situ measurement and simulation to investigate anisotropic shrinkage in their system [26]. These studies support a spatial, validated compensation model. They do not establish coefficients for another powder, binder, furnace, geometry or loading condition.

Constraints change while the part is softening and contracting. Gravity can cause sag or slump. Friction against a setter can restrain one surface while another contracts more freely, generating distortion or differential strain. Blunk and Seibel measured component–setter friction under specific sintering conditions and related it to distortion control [27]. The correct transfer is to treat friction and setter state as measurable process variables—not to select their tested material or value universally.

A setter can support a vulnerable surface, define orientation, distribute load or permit controlled sliding. It can also mark the surface, contaminate the part, change heat/gas access or over-constrain contraction. Sacrificial features can stabilise geometry but add powder, binder, furnace capacity, separation work and waste. The fixture decision therefore belongs to complete-cell design and must be validated in the actual material and thermal state.

Compensation is a model with a validity domain. It may include global axis factors, local feature offsets, orientation-dependent terms, gravity and setter interaction, anticipated machining stock and empirical corrections. Its inputs and software version are controlled. Training artefacts cover the geometry and build/furnace positions relevant to production; verification parts test prediction outside the fitted data. A compensation model is not validated by fitting the same parts from which it was derived.

Process drift can invalidate compensation before average density visibly changes. Powder packing, binder delivery, cure, furnace loading, atmosphere, setter surface or thermal uniformity may shift local contraction. Dimensional data should therefore be analysed with upstream state evidence and job/load position. A corrected CAD file that masks an uncontrolled cause is not a stable process.

Geometric acceptance occurs in the declared state. An as-sintered blank may intentionally exceed final dimensions for machining. A net-shape feature may be accepted as-sintered. Heat treatment or HIP can introduce further change. Drawings, measurement plans and inspection reports identify datum establishment, state, temperature, surface preparation, uncertainty and any subsequent material removal. Only then can compensation be tied to the delivered geometry.

## 9. Geometry, surface state, finishing and cleanliness

Binder jetting can create complex green shapes without melt-pool supports and can nest parts through a job-box volume. Design freedom is still bounded by powder spreading, binder placement, green handling, depowdering, gas transport, sintering stability, inspection and finishing access. A feature that can be digitally sliced is not necessarily recoverable or deliverable.

Minimum walls and gaps are not one-number machine capabilities. A wall needs enough bonded cross-section to survive spreading, cure, excavation and debinding, then must retain shape during sintering. A gap can close through bleeding, loose-powder retention or differential shrinkage. Holes may change form with orientation, layer stair-stepping, binder spread, powder packing and gravity. Capability should be mapped with representative artefacts through the complete route, not taken from the printed green state alone.

ISO/ASTM 52902 supplies a framework for geometric capability artefacts [9]. For metal binder jetting, the artefact and its measurements must be identified by state. Print-stage measurements can diagnose spreading or binder placement; sintered measurements include the thermal transformation; delivered measurements include finishing. Combining these into one “printer accuracy” obscures the causal source and the operation that owns correction.

Surface condition likewise evolves. Particle size and packing, layer thickness, droplet spread, edge bleed, staircase orientation, adhered powder, sintering and pore opening shape the as-sintered surface. Blasting, tumbling, machining, polishing, coating or chemical treatment may reduce some roughness or contamination while rounding edges, opening or closing surface-connected pores and altering dimensions. Surface specification needs a measurement method, sampling location, direction, filtering/cut-off and final state, not an isolated average roughness number.

Internal surfaces are harder. Trapped powder or binder residue can survive in blind paths; finishing media or cleaning fluids may also become trapped. A channel’s nominal diameter does not establish cleanability when its turns, length, surface, outlet arrangement and part orientation differ. Design qualification combines a removal route with measurable cleanliness evidence and declares inaccessible zones. If the intended inspection cannot reach a critical feature and no validated indirect method exists, the geometry may be a no-go for the selected route.

Finishing can dominate both yield and cost. Part separation is often simpler than in melt-pool PBF because there may be no welded build plate, but setters, sacrificial features and machining stock still need removal. Highly nested production can create many individual handling, fixturing, inspection and serialisation steps. A truthful factory comparison counts these operations, their queues and their scrap contribution.

Cleanliness is application-specific. Loose metallic powder, organic residue, setter transfer, blasting media, machining chips, process fluids and corrosion products are different contaminants with different measurement routes. “Visually clean” is not

equivalent to a particle, extractables or surface-chemistry requirement. Cleaning qualification states the contaminant family, accessible surfaces, validated method, acceptance threshold, sampling and evidence uncertainty.

## 10. Porosity, microstructure, properties and material windows

Metal binder jetting is often compared by final density, but density alone compresses several materially different states. Pores can be open or closed, spherical or irregular, isolated or connected, uniformly distributed or clustered, surface-connected or internal. A similar bulk density can coexist with different fatigue, leak, corrosion, thermal or mechanical behaviour. Qualification links pore morphology and location to the intended failure modes.

Microstructure depends on alloy, powder surfaces, green packing, binder residue, atmosphere, peak thermal state, time, cooling and post-treatment. Grain size, phases, precipitates, carbides and inclusions can change without a large density change. Nandwana et al.'s H13 work illustrates how binder carbon and supersolidus processing interact with microstructure and distortion [20]. It is evidence for route sensitivity, not a generic tool-steel window.

Copper presents a different challenge set involving powder state, oxide reduction and thermal transport. Bai and Williams established feasibility and limitations for their tested route, while Miyanaji et al. investigated fine-powder effects [17,18]. Their data do not allow a supplier to assert a universal copper conductivity, density or surface. The delivered result must be measured after the declared sinter and finishing state.

WC-Co further demonstrates non-equivalence. Enneti and Prough investigated green-strength inputs, and Mostafaei et al. followed print variables through a sinter-HIP route [16,21]. The relevant product state includes carbide grain/binder distribution, pore state and properties after that route. It cannot be compared directly with a pressureless-sintered stainless steel or used as evidence that HIP will cure every earlier defect.

Material qualification is hierarchical. A powder/binder pair first needs printable, handleable and debindable behaviour. The thermal route must then demonstrate chemistry, densification or intended porosity, microstructure and geometry. Finally, component-relevant specimens and parts must demonstrate the properties and failure modes of the intended use. Generic datasheets, conventional wrought standards or test bars from another orientation and load are useful context but not acceptance evidence.

The 3Dresyns nano/micron raw-material page lists metals, alloys and other advanced material families and distinguishes direct and indirect manufacturing contexts [32]. In ER-147 it establishes portfolio scope only. A listed material is not thereby qualified for powder delivery, binder compatibility, green handling, debinding, sintering, safe operation or delivered performance. Each candidate passes the same independent gates.

Table 2. Conditional opportunities and controlling liabilities in metal binder jetting

| Process or product condition     | Conditional opportunity                                                     | Controlling liability                                                                      | Evidence required                                        |
|----------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------|
| Many parts or variants per layer | Area-parallel patterning and dense nesting can use printer time effectively | Excavation, identification, furnace loading, finishing and inspection grow with part count | Accepted parts per complete-cell time and released input |
| No melt pool during printing     | Low green-stage thermal stress and no welded print supports                 | Green fragility, large thermal shrinkage and setters during sintering remain               | State-resolved geometry and damage/yield record          |
| Fine or tailored powder          | Packing and sintering kinetics may improve in a qualified route             | Cohesion, poor spreading, oxidation, dust and lifecycle shift                              | Powder-to-layer-to-final correlation                     |
| Complex internal geometry        | Powder-bed support can enable green cavities and lattices                   | Powder removal, gas escape, sag and inspection access can fail                             | Cleanability, debinding and final internal evidence      |
| Shared furnace fleet             | Printer and thermal assets can be scheduled separately                      | Batching, load compatibility, queues and long thermal cycles can constrain output          | Load-family qualification and queue/capacity model       |
| High or controlled porosity      | Functional metal foam or transport behaviour may be designed                | Weakness, leak, variability and surface-connected contamination may result                 | Pore topology and function-specific acceptance           |
| Near-net geometry                | Reduced subtractive material can be possible                                | Compensation, surface and tolerance may require machining or sacrificial stock             | Delivered-state dimensional and finishing yield          |
| Broad alloy aspiration           | Indirect shaping can avoid some melt-pool limitations                       | Binder, oxide, atmosphere, phase and sintering windows remain alloy-specific               | Material-specific complete-route qualification           |

The table prevents benefits from being stated without their burdens. Binder jetting may be the correct industrial choice when its parallel patterning and furnace batching match demand, when green parts can be handled and cleaned, and when the target alloy and geometry densify reproducibly. It may be the wrong choice when sealed channels cannot be cleared, local shrinkage cannot be compensated, the required surface is inaccessible, the alloy chemistry is unstable in the route or furnace capacity dominates lead time.

## 11. Monitoring, inspection and part-linked evidence

Monitoring can make otherwise hidden process states more visible, but evidence remains method-specific. Powder-bed images may detect streaks, incomplete spreading, surface displacement or visible binder-related contrast. Printhead checks may detect non-jetting or deflection. Thermal or environmental sensors may record drying and chamber conditions. Furnace systems may record temperature, pressure, gas flow or atmosphere indicators. Each signal has spatial and temporal resolution, calibration, uncertainty, detection limits and false-result behaviour.

Gourley et al. demonstrated semantic segmentation and three-dimensional reconstruction of visible spreading anomalies from layerwise binder-jet powder-bed images in tested metal and ceramic systems [28]. That supports classification of defined surface

anomalies after validation. It does not detect hidden green delamination, internal binder distribution, residual carbon, sintering cracks or final chemistry. A monitoring model must be challenged against known states and bounded to what its sensor can observe.

Data registration is as important as detection. ISO/ASTM 52953 addresses registration of process-monitoring and quality-control data for metal AM [11]. In binder jetting, layer coordinates must remain linked through a shrinking, possibly distorting object and through job-box excavation, furnace batching and post-processing. A detected layer location is useful only if it can be associated with the eventual component and relevant final region.

ISO/ASTM 52927 provides a general structure for characteristics and measurement methods, while ISO/ASTM TR 52905 frames NDT method selection and defect-detection boundaries [10,12]. Neither gives universal acceptance criteria. Density measurement, dimensional metrology, microscopy, chemical analysis, mechanical testing, radiography, computed tomography, penetrant testing or leak testing answer different questions. Surface condition, geometry and material attenuation affect coverage and uncertainty.

Coupons and artefacts help establish machine, material and load behaviour but must have a declared relationship to the component. A small, open coupon may debind more readily than a thick enclosed part and may experience different setter friction or furnace position. Coupon conformance is therefore supporting evidence, not an automatic proxy. Component inspection remains risk-based and linked to critical features and failure modes.

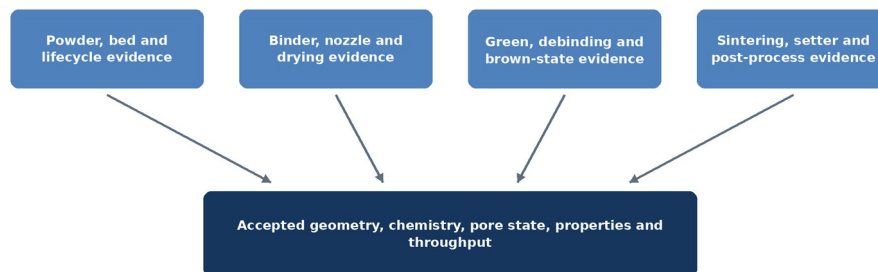


Figure 2. Part-linked evidence architecture for metal binder jetting.

Disposition integrates the streams. A visible layer anomaly can trigger targeted final inspection or rejection according to a validated rule; a normal image cannot waive required final inspection. A furnace excursion can affect multiple parts and requires load-level evaluation even if one coupon passes. A dimensional drift can point back to powder packing, binder delivery, load position or setter state. The record preserves both the measurement and the decision rationale.

Digital evidence requires governance. Sensor/software versions, model training data, thresholds, operator interventions, missing frames, clock synchronisation, storage, access and retention are controlled. A classifier or dashboard update is a process change when it influences acceptance. The objective is not maximum data volume but sufficient, interpretable evidence to reconstruct the relevant history and support a defensible decision.

## 12. Complete-cell productivity, factory economics and safety

Nominal print speed is not factory throughput. The complete cycle includes powder conditioning and loading, printing and interlayer drying, curing, job-box conditioning, excavation, depowdering, green inspection, furnace queue, debinding, sintering, cooling, setter handling, finishing, cleaning, inspection, rework and scrap. It also includes maintenance, powder recovery, binder replenishment, filter or exhaust service, changeover and quality release.

**Effective cell throughput = accepted components ÷ complete elapsed factory-cell time.**

**Material efficiency = accepted-component mass ÷ released input mass across the same declared cell boundary.**

Area-parallel deposition can make layer time less sensitive to the number of patterned parts than a pointwise melt process, and a job box can hold many components. Yet high nesting may extend excavation, increase identification risk or exceed a furnace/load family. Printer capacity can outpace thermal capacity; a large furnace can create long queues or mix incompatible parts; a short printer cycle does not shorten debinding and sintering. Bottleneck and yield must be measured across the cell.

Furnace utilisation is not simply filled volume. Parts must have compatible powder/binder/alloy states, thermal routes, setters, gas access and contamination constraints. A load plan considers thermal mass, spacing, sensor coverage, local atmosphere, safe handling and traceability. Overpacking can degrade uniformity or gas transport. Underloading may change a qualified thermal response. The economic model uses released load families and observed yield.

Labour can migrate rather than disappear. Automated printing may be followed by manual excavation, delicate cleaning, setter placement, separation, surface finishing and serialised inspection. Internal passages or fragile green geometries can dominate touch time. Capital comparisons therefore include printer, cure and powder stations, furnaces, gas/exhaust, monitoring, finishing, metrology, floor/utility needs, spares and qualified personnel—not only machine purchase price or binder-consumption.

Safety is also state-resolved. Metal powder tasks include receipt, sampling, loading, spreading-system access, excavation, sieving, transfer, spill recovery, cleaning, waste and maintenance. Hazards depend on alloy, particle distribution, surface state, quantity, containment and ignition or exposure pathways. ISO/ASTM 52931 supplies general principles for metal-AM

environmental, health and safety management, and ISO/ASTM 52926-1 frames general operator capability [7,8]. Site-specific law and competent hazard assessment remain controlling.

Binder tasks add chemical and physical considerations: receipt and storage, mixing or conditioning, skin/eye or inhalation exposure where applicable, flammability, incompatible materials, heated drying, spills and waste. The safety data and process risk assessment must cover the actual formulation; “water-based” or “low odour” is not a complete hazard determination. Debinding generates gases and condensable products that require material- and load-specific exhaust, monitoring and maintenance controls.

Sintering adds high temperatures, hot and brittle components, combustible or asphyxiating gases where used, pressure/vacuum systems where applicable, stored energy and atmosphere verification. Setter and furnace-surface residues can create exposure during cleaning. Lockout, cooldown confirmation and safe maintenance states are verified rather than inferred from elapsed time. Emergency plans address credible powder, binder, gas, furnace and exhaust deviations.

NIOSH’s evaluation of one metal-powder additive-manufacturing facility illustrates how exposures and control performance depend on actual tasks and locations [31]. It is not a binder-jetting exposure limit, a universal PPE prescription or proof that another facility complies. ER-147 therefore avoids cross-site quantitative claims. The factory must verify its own exposures, containment and controls for routine work and foreseeable maintenance.

Environmental accounting follows mass and energy through the same cell. Powder recovery can reduce material waste, but unusable fractions, contaminated media, binder, solvents, filters, exhaust products, setters, supports, machining stock and scrap remain. Furnace energy and utilisation can dominate some routes. A sustainability claim needs declared boundaries, measured yield and disposition—not merely a high recycled-powder percentage or near-net-shape label.

### 13. Qualification architecture and selection gate

Qualification joins site, personnel, equipment, materials, process, geometry, inspection and change control. ISO/ASTM 52920 provides industrial AM process and production-site principles [2]. ISO/ASTM 52907, 52928 and ASTM F3522 inform powder measurement, lifecycle and spreadability [4–6]. ISO/ASTM 52931 and 52926-1 address metal-AM EHS principles and general operator qualification [7,8]. ISO/ASTM 52902, 52927, 52953 and TR 52905 organise geometric artefacts, characteristics, registered data and NDT boundaries [9–12]. No single document closes the entire binder-jetting route.

Table 3. Metal-binder-jetting factory qualification and selection gate

| Gate                        | Minimum evidence                                                                                                                                                                                                               | Fail or hold condition                                                   |
|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Intended delivered state    | Drawing/specification, alloy/chemistry, pore state, surface, properties, cleanliness and service boundary                                                                                                                      | Material state or critical failure modes undefined                       |
| Powder and binder release   | Lot/batch genealogy, storage, sampling, relevant tests and compatibility evidence                                                                                                                                              | Alloy or product name used alone                                         |
| Equipment and layer release | Qualified powder delivery, spreading, printhead, drying, cure, sensors and maintenance status                                                                                                                                  | Relevant change or degraded nozzle/layer state uncontrolled              |
| Green and depowdering route | Green density/strength window, extraction/handling, internal clearance and damage evidence                                                                                                                                     | Part cannot be removed, cleaned or transferred reliably                  |
| Debinding and brown state   | Binder-removal route, gas/residue/chemistry evidence, brown integrity and furnace-load definition                                                                                                                              | Residue, cracking, atmosphere or load equivalence unresolved             |
| Sintering and support       | Qualified load; gas identity; measured dew point or oxygen partial pressure; atmosphere-sensor location, calibration, flow architecture and leak/verification state; setter; densification; chemistry; and distortion evidence | Gas name alone, universal recipe or unsupported scale factor substituted |
| Delivered part              | Dimensions, surface, cleanliness, pore state, chemistry, microstructure and properties                                                                                                                                         | Density, coupon or datasheet used as sole acceptance                     |
| Monitoring and inspection   | Calibrated registered signals, validated detection, NDT coverage, uncertainty and disposition rules                                                                                                                            | Monitoring treated as automatic final clearance                          |
| Factory and safety          | Complete-cell capacity/yield, trained personnel, task controls, utilities and applicable legal compliance                                                                                                                      | Bottleneck, exposure, gas, furnace or maintenance controls incomplete    |
| Change and transfer         | Defined equivalence/requalification for powder, binder, machine, software, geometry, furnace, setter and post-process                                                                                                          | “Same settings” or equipment model used as equivalence                   |

A selection decision starts with the intended delivered function, not with the printer. The route is attractive when the geometry can be spread, bound, excavated, cleaned, thermally converted and inspected; when the alloy and binder have a stable material window; and when accepted yield through printer and furnace capacity meets demand. It is rejected or held when a critical internal feature cannot be cleared, a brown geometry cannot survive, chemistry or pore state is unstable, local distortion cannot be controlled, an essential surface cannot be finished or inspected, or the factory lacks safe and traceable thermal capacity.

Transfer is a new evidence question. A different powder supplier, binder batch/formulation, printhead, recoater, drying system, job-box scale, software strategy, furnace, atmosphere supply, setter, load arrangement or finishing route can change relevant outputs. Nominally identical equipment can differ in calibration, maintenance and environment. The change plan defines what is equivalent, what must be verified and what triggers partial or full requalification.

Production control also includes deviations. Missing nozzle evidence, layer anomaly, interrupted cure, green damage, changed powder fraction, furnace excursion, broken setter, incomplete data, outlying shrinkage or failed inspection initiates a documented hold and investigation. Rework is permitted only when its effect on state and acceptance is qualified. Averaging a nonconforming part into a batch result is not disposition.

The qualification file therefore preserves requirements, risk analysis, input releases, parameter and software versions, equipment state, operator responsibility, job and load genealogy, monitoring, state-specific tests, uncertainty, deviations, final inspection and release authority. It should allow an independent reviewer to reconstruct why the particular component—not merely the technology family—was accepted.

Equivalence is tiered. A change that can introduce a new failure mode, alter an unrepresented powder, binder, jetting, green, debinding, sintering, setter or delivered-part state, or affect 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 minimum evidence set confirms input genealogy, calibrated deposition and drying state, representative green geometry, actual debinding and furnace execution, setter/load position, delivered-state chemistry, pores, dimensions and properties, inspection capability and acceptance against existing limits. If that set is incomplete, its uncertainty overlaps a limit or the changed condition lies outside the validated domain, equivalence is not demonstrated and the route remains on hold.

## 14. Conclusions and research priorities

Metal binder jetting is a sequence of porous-body and thermal transformations, not a printer-only route. Selective liquid deposition creates a green geometry whose powder packing, binder distribution and drying history govern handling and later gas transport. Debinding creates a fragile brown state and sets chemistry conditions for sintering. Densification contracts and can distort the component under geometry-, gravity- and setter-dependent constraints. The delivered metal is the outcome of that full chain.

A defensible industrial programme follows five rules:

1. release powder, binder and equipment as a coupled layer-formation system rather than by product names alone;
2. state and verify green, brown, sintered and delivered conditions separately;
3. qualify debinding, sintering, shrinkage and support with representative geometry and furnace loads rather than transferable recipes;
4. count excavation, powder recovery, thermal queues, finishing, inspection and yield in complete-cell productivity; and
5. accept parts through registered, uncertainty-aware evidence that links upstream states to delivered geometry, chemistry, pore structure and properties.

Priority research includes in-bed measurement of packing and binder distribution; robust printhead-to-layer anomaly detection; green-strength tests that predict automated handling; validated internal depowdering and cleanliness methods; debinding gas/residue models for complex sections; in-situ brown-to-sintered chemistry and shrinkage measurement; setter friction and distortion models; geometry-aware compensation with external validation; monitoring-to-final-defect correlation; powder and binder lifecycle markers; and transfer protocols across printers and furnaces.

Until those links close for a specified route, the honest capability statement is conditional: metal binder jetting can be highly productive for compatible materials and geometries, but only a qualified powder–binder–printer–thermal–post-process–factory system can deliver an accepted component. “Support-free,” “fully dense,” “mass production,” “any alloy” and one shrinkage factor are not process identities.

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