

Lithography-Based Metal Manufacturing: Metal-Filled Photoresins, Cure–Loading Trade-Offs, Debinding, Sintering and Qualification

Optical–Rheological Coupling, Green-State Evidence and Complete-Cell Control

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Statement of Significance

Lithography-based metal manufacturing can shape fine metal-rich features by patterned photopolymerisation without melting metal in the printer. The apparent precision of projected light does not remove the material difficulty: metal powder must remain dispersed in a binder that can be coated or renewed, transmit or redistribute enough light to create a controlled green layer, release from the exposure interface, survive recovery and cleaning, open safe transport paths during binder removal and densify without unacceptable chemistry change or distortion. Powder loading, viscosity, yield stress, thixotropy, sedimentation, absorption, scattering, cure depth, lateral overcure and green strength are not independent controls. Nor is a support-free green print necessarily support-free in the furnace. This review defines the route as a complete indirect chain from released powder, binder and optical system to an accepted metal component. It separates green photopolymer conversion from debinding and metallurgical densification, bounds published high-resolution and material demonstrations to their tested systems, and replaces printer-centred claims with part-linked factory evidence.

Abstract

Lithography-based metal manufacturing uses patterned light to solidify a photoactive metal-powder/binder system layer by layer, producing a green composite that is subsequently cleaned, debound and sintered or otherwise densified. Literature labels such as LMM, LMAM, metal DLP, micro-DLP and metal stereolithography cover related but not necessarily identical material-delivery and exposure architectures. Liquid suspensions, thixotropic pastes and temperature-conditioned feedstocks impose different mixing, sedimentation, recoating, separation and recovery burdens. Increasing metal loading can reduce organic content and support final densification, while increasing viscosity, reducing layer renewal and changing optical attenuation and scattering. A nominal wavelength, pixel pitch or scalar dose cannot predict cured geometry without the spectrum, irradiance map, powder/resin optical state, initiator response, exposure sequence and measurement method. The exposed object remains a green metal–polymer composite; cure depth, green strength and apparent feature fidelity do not establish final metal. Binder removal is governed by chemistry, transport length, gas evolution, atmosphere and evolving pore pathways. Sintering changes dimensions, pores, chemistry and microstructure under gravity and setter interaction, so shrinkage cannot be qualified by one scale factor. This qualitative engineering review maps material preparation, light delivery, green recovery, debinding, densification, factory economics, safety, inspection and qualification. It provides no transferable formulation, exposure, cleaning, furnace, compensation or acceptance recipe.

Keywords: *lithography-based metal manufacturing; metal DLP; vat photopolymerisation; metal-filled photoresin; cure depth; green part; debinding; sintering; shrinkage; qualification*

1. Purpose and scope

ISO/ASTM 52900 defines vat photopolymerisation as an additive-manufacturing category in which liquid photopolymer in a vat is selectively cured by light-activated polymerisation [1]. ER-149 addresses the indirect metal subset in which patterned exposure retains metal powder inside a photoreactive organic phase. The printer creates a green composite, not molten, bonded or service-ready metal. The delivered metal state exists only after declared recovery and cleaning, binder removal, sintering or another densification operation, cooling, finishing and inspection.

The scope includes metal-powder and binder receipt, photoinitiator/absorber/dispersant and additive control, mixing, deagglomeration, degassing, storage, sampling, temperature conditioning, suspension or paste renewal, layer coating or recoating, optical exposure, separation or platform movement, green release, unexposed-feedstock removal, cleaning, support or raft removal, green storage and inspection, solvent/water/catalytic/thermal binder removal where specified, brown-state control, sintering, setters, dimensional compensation, optional HIP or heat treatment, machining, surface treatment, cleaning, inspection, production economics, safety and qualification.

The terms ‘lithography-based metal manufacturing’, ‘lithography metal additive manufacturing’, ‘metal DLP’, ‘micro-DLP’ and ‘stereolithography of metals’ are used only with the implementation described by the cited source. They do not establish an identical vat, film, paste-delivery, recoating, exposure or separation mechanism. NIST treats VPP as an architecture requiring light and material metrology rather than a generic exposure-time setting [13]. The 2026 NIST photopolymer workshop report likewise identifies unresolved measurement, data, safety and standards gaps across photopolymer AM [14].

Polymer VPP is assigned to ER-142. In that route the post-cured network is the delivered material. ER-149 instead removes the photoactive organic phase and thermally consolidates powder. Metal binder jetting and bound-metal extrusion belong to ER-147 and ER-148; they form green geometry by binder placement in a powder bed or by deposition of a pre-compounded road. Ceramic VPP belongs to ER-151. Polymer-binder powder-bed shaping belongs to ER-155. Laser/electron-beam PBF and DED/WAAM belong to ER-145, ER-146 and ER-150 because they melt metal during deposition or layer consolidation.

The industrial selection gate and the direct-versus-indirect route distinction are inherited from ER-139 and ER-049 [11,36]. ER-044 owns photoabsorbing fillers, optical response and cure-depth control; ER-036 owns rheology, recoating and dispersion in highly filled VPP suspensions; ER-034 owns separation and peel mechanics; ER-031 owns cure shrinkage, residual stress and warpage; and ER-037

owns debinding-defect formation in photopolymer-derived ceramic and metal green bodies [39–43]. ER-149 does not restate those owners. Its own question is whether a **metal-filled, photoactive, layer-delivered system at the loading required for later sintering** can maintain a qualified optical–rheological window through green recovery and then enter a metal-specific debinding/sintering chain without losing geometry, chemistry, pore-state or factory control. Open-vat oxygen inhibition and stabilisation chemistry are inherited from ER-030 and ER-032 [37,38]; ER-149 extends them only where metal powder, reservoir history, green conversion and later binder removal interact. These boundaries preserve the LMM-specific industrial question while preventing duplicate ownership.

Castable photopolymers for investment casting are not equivalent to powder-loaded LMM. The printed object in a castable route is a sacrificial pattern, while the final metal is produced by a mould-and-casting chain. The 3Dresyns LMM instructions explicitly distinguish reactive binder routes intended for debinding/sintering from castable routes intended for jewellery-related indirect manufacture [35]. This paper uses that page only to define declared workflow scope, never as independent proof of compatibility, performance or safety.

This review does not prescribe powder chemistry or size, surface treatment, solids loading, binder composition, dispersant, initiator, absorber, mixing sequence, viscosity, yield stress, temperature, wavelength, irradiance, exposure, layer thickness, recoating speed, separation motion, cleaning medium, debinding route, furnace atmosphere, thermal ramp, peak temperature, hold, shrink factor, setter material, HIP cycle or acceptance limit. Each value belongs to a specified powder–binder–light-engine–delivery–geometry–thermal-route–intended-use state.

2. Process identity and the state-resolved production chain

The word ‘printing’ hides several material identities. A released metal powder and released organic ingredients become a filled photoactive system. That system may be fluid at rest, shear-thinning, thixotropic, temperature-conditioned or paste-like. It is then distributed as a controlled layer or exposure interface. Patterned radiation converts only part of the binder network, retaining a local particle architecture. The recovered green object still contains binder, unreacted species and powder whose distribution was established during formulation, layer delivery and cure.

Table 1. State-resolved lithography-based metal-manufacturing chain

Stage	Controlled state	Principal evidence	Invalid shortcut
Powder and ingredient release	Metal identity/surface, binder, initiator, dispersant, absorber, additives, storage and sampling	Certificates plus verified identity and specified tests	“Correct alloy and resin”
Filled feedstock release	Solids distribution, agglomeration, rheology, sedimentation, optical response, moisture/air and history	Representative mixture tests and controlled batch record	“Looks homogeneous”
Layer and optical delivery	Coating/renewal, thickness, temperature, interface, spectrum, irradiance map, exposure sequence and machine state	Registered equipment and exposure evidence linked to location	“Correct wavelength/dose”
Green formation	Conversion, cure depth/width, layer contact, packing, geometry, strength and internal unexposed material	State-specific coupons/features and inspection	“Pixel or layer resolved”
Recovery and cleaning	Release, drainage/wiping, hollow-feature clearance, surface condition and damage	Qualified handling and cleanliness evidence	“Support-free”
Debinding/brown state	Extraction/pyrolysis, transport paths, residue, gases, chemistry, cracks and residual strength	Route/load/geometry-specific evidence and hold point	“Binder gone”
Sintering/densification	Atmosphere, load, pore evolution, chemistry, shrinkage, distortion and setter contact	Furnace/load record plus mapped material and geometry evidence	“Standard MIM cycle”
Delivered acceptance	Final geometry, surface, cleanliness, pores, chemistry, microstructure and properties	Part-linked tests, uncertainty, genealogy and disposition	“Density or coupon passed”

The chain prevents three common category errors. First, polymerisation is a geometry-retention reaction, not metal fusion. Second, unexposed material can support a green feature during shaping without becoming a qualified removable support strategy. Third, thermal debinding and sintering can occur in one furnace programme while remaining different transformations with different failure modes.

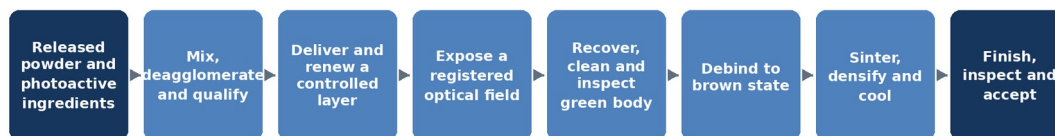


Figure 1. State-resolved lithography-based metal-manufacturing route.

Traceability crosses batch and load boundaries. One feedstock batch can supply multiple builds; one build can contain multiple exposure-field positions; one debinding or sintering load can combine parts from several builds; external thermal processing can add organisational custody changes. The genealogy links powder and binder lots, mixing and ageing history, vat/reservoir and coating state, light-engine map, file/version and build position, green handling, cleaning, furnace load/position, setter, post-processing, tests and final serial/batch. ISO/ASTM 52951 and 52953 provide data-package and monitoring-registration architecture, but they do not decide which signals constitute acceptance [8,9].

For purchased components, ISO/ASTM 52901 requires the provider and customer to define feedstock, final characteristics, inspection, acceptance and documentation [6]. A purchase order that asks only for “metal DLP 316L” leaves the green and thermal route

underdefined. It should state the delivered condition, required chemistry and properties, surface and cleanliness state, critical geometry, test coverage and allowed post-processing.

3. Metal powder, photoactive binder and filled-feedstock release

The metal powder brings alloy chemistry, particle morphology, size distribution, surface oxide or adsorbates, packing behaviour and contamination history. The organic phase brings reactive monomer or oligomer, photoinitiator, inhibitors, absorbers, dispersants, diluents, plasticising or rheology-modifying functions. Their combination is not a neutral carrier around powder: it establishes both the green network and the chemistry/transport burden that must later be removed.

ISO/ASTM 52907 structures metal-powder characterisation [12]. Those methods can inform powder identity and condition before mixing, but do not qualify optical attenuation, dispersion, paste stability, layer formation or debinding. A powder released for PBF, binder jetting, MIM or bound-metal extrusion is not automatically suitable for a photoactive suspension. Surface chemistry that is acceptable during direct melting may inhibit or accelerate polymerisation, change dispersant adsorption or increase oxygen/moisture sensitivity in an LMM formulation.

Solids loading is a system variable rather than a ranking. A higher metal volume fraction may reduce organic mass to remove, increase green powder packing and reduce the densification distance. It can also increase viscosity or yield stress, reduce recoating speed, trap air, magnify agglomeration, limit cure penetration and weaken interlayer contact. A lower loading may improve flow or cure while increasing binder burden, shrinkage and the risk that the green particle network loses continuity during debinding. Scheibler et al. measured coupled effects of loading, particle size, exposure and orientation on green copper specimens [27]. Their results support a multidimensional window, not one preferred loading.

Powder size affects more than nominal resolution. Finer powder can enable thin layers or fine geometries, yet raises surface area, dispersant demand, viscosity, oxidation/adsorbate sensitivity and potential exposure during handling. Coarser particles can reduce specific surface and change scattering, while limiting layer thickness or fine feature reproduction. Alazzawi et al. showed in silver and alumina suspensions that cure depth depended on dispersion/agglomeration, particle size, solids content, refractive index and extinction [20]. The valid conclusion is coupled optical/material control; the tested values do not transfer to 316L, copper, NiTi or tungsten.

Dispersion must be tested across scales. A visually uniform reservoir can contain agglomerates, entrained air, settling gradients or particle/binder segregation. Mixing energy and time can break agglomerates while heating, incorporating gas, changing inhibitor content or damaging sensitive powder surfaces. Milling media and vessels can add contamination. A controlled batch record defines order of addition, equipment, atmosphere where relevant, energy/time history, temperature, degassing, filtration or screening, sampling locations and allowable hold/rework.

Pan et al. studied dispersant-dependent stability and cure behaviour in a defined 316L slurry [24]. Wu et al. developed a thixotropic 316L paste and linked formulation, stability, cure and final properties in one route [25]. Those studies demonstrate that dispersion, rheology, light response and thermal conversion can be engineered together. They do not authorise copying the dispersants, loadings, viscosities, exposure or furnace conditions into another powder, binder or machine.

Stability is time- and history-dependent. Sedimentation can create powder-rich and binder-rich regions; a thixotropic network can resist settling at rest but must recover reproducibly after coating shear. Temperature changes viscosity, reaction kinetics and particle mobility. Repeated circulation, scraping, replenishment or heating can change the mixture. Feedstock release therefore includes a defined age, container position, conditioning procedure, sampling plan and allowed exposure to light, air and heat.

Reclaimed unexposed material is not automatically virgin equivalent. It may carry cured debris, fines, contamination, changed initiator/inhibitor balance, solvent or cleaning carryover, altered particle distribution and a different light/thermal history. A reuse rule specifies segregation, screening, refresh ratio where applicable, testing and maximum history. Yield calculations count rejected or downcycled material rather than labelling all surrounding paste recoverable.

4. Optical attenuation, oxygen inhibition, scattering and the cure-loading trade-off

ER-044 owns general photoabsorber/filler effects on optical response and cure depth [39]. ER-149 retains only the metal-specific extension: conducting, absorbing or reflecting particles at a solids loading intended to survive debinding and sintering. Photopolymerisation requires enough absorbed photons in the intended volume to create a network that retains that powder and connects layers. The binder, initiator and absorber also shape the spectrum-dependent response. The result is a three-dimensional exposure field whose boundaries need not align with projector pixels or the commanded layer plane.

In an unfilled resin, a fitted working curve can relate cured depth to exposure for a declared method. Even there, it is not an immutable material constant. Kolibaba et al. found large interlaboratory variation when multiple laboratories measured aliquots from one resin batch [18]. Differences in procedure, hardware, fitting and measurement changed the inferred parameters. A metal-filled system adds particle scattering, absorption, agglomeration and spatial composition, so transfer becomes still less defensible.

Nominal wavelength is also insufficient. Caplins et al. showed that spectral bandwidth and the resin absorption gradient can make a monochromatic interpretation inadequate [19]. A light engine must be characterised by spectrum, irradiance, spatial uniformity, divergence or numerical-aperture context, focus/distortion and stability at the relevant interface. Their earlier light-engine mapping work demonstrated position-dependent irradiance/spectral behaviour and printed response in one LCD system [17]. The transferable requirement is registration of a measured optical field, not an assertion that one architecture is uniformly superior.

Metal loading can simultaneously increase the amount of final material per green volume and reduce optical penetration. Cure depth may fall, while lateral scattering or reflection enlarges a line or closes a gap. Pan et al. quantified pronounced scattering in their studied 316L slurry [24]. Scheibler et al. used single-layer exposure and green bending tests to connect copper loading, particle size and exposure to cure thickness and green strength [27]. A process window must therefore include both insufficient cure and excessive cure. More exposure is not a universal correction: it can increase lateral overcure, heat, stress, feature closure or adhesion to an interface while still failing to cure uniformly through a thick, compositionally non-uniform layer.

Wieckowski and Erb varied particle, resin and light variables in photoabsorbing filled resins and showed that cure depth can be changed through multiple coupled routes [21]. Their framework reinforces a qualification sequence: characterise particle and resin optical response; choose a compatible light package; measure rather than assume a working curve; then verify representative lines, gaps, holes, walls and layers. It does not define one optimal particle size, wavelength or initiator concentration.

Cure depth is not the same as network conversion or green strength. A layer can appear continuous at its boundary while containing a conversion gradient. Sarkar et al. simultaneously measured conversion, stress, temperature and shrinkage during photopolymerisation and showed that cure protocol changes network state [22]. Metal-filled systems can further redistribute light and heat. Green release therefore specifies minimum state evidence tied to handling and debinding, rather than a single measured thickness.

ER-030 and ER-032 own the general radical-photopolymerisation account of oxygen inhibition and open-vat stabilisation [37,38]. In the LMM-specific extension, dissolved or interfacial oxygen scavenges propagating radicals and forms less-reactive peroxy species. The result may be an induction period or a conversion threshold rather than a constant scalar dose penalty. Oxygen transport from the free surface, a permeable film or a re-aerated reservoir can therefore create a depth or interface gradient; degassing can shorten the induction state, but transfer, recoating and dwell can restore it. Phenolic or other stabiliser packages interact with this radical balance, so a changed powder surface, binder lot, headspace, film permeability, degassing history or reuse fraction can move the cure window even when commanded irradiance and exposure are unchanged. Reservoir atmosphere, degassing/re-aeration interval and interface condition are registered variables, and their change triggers recalibration of conversion and green release rather than an assumed exposure offset.

Green conversion is difficult to measure in a highly filled, strongly absorbing body. Transmission infrared may lack a usable optical path; attenuated-total-reflection sampling is surface-limited and particle-confounded; and calorimetry must resolve a minority organic phase against dominant metal filler. A production plan therefore declares whether conversion is measured directly or inferred from qualified surrogates. Permissible candidates include extractables or residual-monomer analysis on a witness geometry; solvent resistance or swelling under a fixed procedure; green mechanical response under a declared test; or thermal analysis on a deliberately under-loaded witness formulation whose loading difference is recorded as a validity boundary. Each is labelled a **surrogate**, not conversion itself, and is calibrated to the relevant location and geometry with uncertainty, detection limits and correlation to both handling survival and later debinding behaviour. Cure depth, visual continuity or one green-strength value is never silently relabelled as conversion.

Optical dose accumulates across layers and neighbouring features. Light intended for a new layer can penetrate into earlier material; scattered radiation can expose adjacent regions; anti-aliasing or grayscale changes local history. Small islands, thin walls, large solid cross-sections, edges and closely spaced channels do not share one exposure environment. Calibration artefacts include those geometries and positions, and their green and final states are measured separately.

5. Rheology, sedimentation, layer delivery and material renewal

ER-036 owns general rheology, recoating and dispersion control for highly filled VPP suspensions [42]. ER-149 narrows the question to the solids-loading, powder-surface and time-history state needed to leave a sinterable metal skeleton after binder removal.

Layer formation asks a filled system to flow, level or transfer under a controlled stress and time, then resist sedimentation or drainage long enough for exposure. A low apparent viscosity can aid renewal but permit settling or edge flow. A high viscosity or yield stress can retain particles while trapping air, resisting levelling and increasing blade, film or separation loads. Thixotropy can provide both flow under shear and recovery at rest only if the recovery time matches the machine sequence.

Rheology must be reported with method, geometry, shear history, temperature and time. A single viscosity at an unspecified shear rate cannot predict coating. Yield stress inferred by one fitting model may not equal the stress distribution in a doctor blade, gap, roller, reservoir or moving platform. Oscillatory recovery, creep or step-shear tests can be useful when connected to actual machine events. Feedstock qualification links these measurements to layer thickness, surface uniformity, particle distribution and green outcomes.

Material-delivery architectures differ. A liquid-vat route may require bulk recirculation, recoating and separation through a fluid suspension. A paste route may use a blade, roller, moving carrier or temperature-conditioned transfer. A feedstock that resolidifies or rebuilds structure between layers may provide green support while increasing renewal and interface sensitivity. The equipment record declares the architecture instead of using 'LMM' as a complete mechanism description.

Coating creates gradients. Particle migration, wall slip, filtration at a narrow gap, agglomerate exclusion, meniscus behaviour and evaporation can alter the layer relative to the reservoir. A blade that produces a visually smooth surface can still create local thickness or composition differences. Temperature across the reservoir, coating element and exposure interface must be mapped where it affects rheology or polymerisation.

Sedimentation control is not proved by a short observation in a static vial. A production job imposes vibration, periodic shear, stops, replenishment and exposure heat. The qualification interval covers the longest intended dwell, restart and job duration, with samples from positions that could become powder-rich or binder-rich. Pan et al. and Wu et al. provide material-specific examples of stability engineering [24,25]; their measured times and values remain bounded to their systems.

Air and volatile content matter. Bubbles can interrupt a layer, scatter light and become green or sintered pores. Vacuum degassing can remove air while changing volatile composition or accelerating settling. Mixing and recovery from a partially used batch can reintroduce gas or debris. The work instruction therefore controls degassing endpoint, post-degassing handling and the interval before use.

Because degassing also changes the oxygen-inhibited induction state, the material-release record includes reservoir headspace, interface permeability where relevant and the time/shear history by which the feedstock can re-aerate [37,38]. A change in any of those conditions invokes optical/green-state recalibration; it is not cleared solely by absence of visible bubbles.

Renewal time contributes to cycle time. Whole-field exposure may illuminate many parts simultaneously, but a larger or more viscous cross-section can change separation, coating, levelling, temperature and material transport. A thin exposure does not imply a thin factory cycle. Throughput claims must include the slowest required layer renewal and downstream operation.

6. Exposure architecture, working curves and feature formation

ER-034 owns general bottom-up separation and peel mechanics [41]. ER-149 addresses only separation of a powder-loaded layer whose green strength is a handling and debinding-entry property rather than the service property of a delivered polymer component.

The exposure system converts digital geometry into an irradiance field at the material interface. Projector micromirror pitch, magnification and focus can define a sampling grid, but pixel pitch is not final feature resolution. Optical blur, distortion, divergence, scattering, threshold conversion, overcure, shrinkage, layer registration, green cleaning and sintering all modify geometry. A `35 µm feature` demonstrated in one study is not a general equipment class.

Melentiev et al. demonstrated a high-resolution 316L route with fine features, complex hollow structures and measured final surface/properties [26]. The study is important evidence that a complete metal-DLP chain can achieve such outcomes in its tested system. Its resolution, lack of printed supports and final properties remain conditional on its feedstock, machine, geometries, cleaning and thermal route. They cannot be assigned to another metal or LMM platform by process name.

A working-curve campaign begins with measured light delivery and a released feedstock. Single-layer thickness and lateral dimensions are measured over relevant dose and position, but the result is only a screening map. Multilayer artefacts then test interlayer contact, cumulative exposure, small islands, thin walls, gaps, holes, contours and large cross-sections. Green conversion or a declared, uncertainty-bearing surrogate, together with strength, sets the lower processing boundary; visual continuity alone does not. Excess growth, trapped material, separation damage and loss of negative features set the upper boundary. The campaign records reservoir atmosphere, degassing/re-aeration history and exposure-interface permeability where these can alter the inhibition gradient [37,38].

Exposure-field stitching or tiled projection adds another state where present. Overlap, intensity mismatch, geometric distortion and timing can create seams. A homogeneous flat field does not prove consistent cure in a filled medium whose temperature or composition varies across the build. Position-aware coupons and registered monitoring are required.

Separation mechanics depend on whether the exposed layer contacts a window, film, carrier, bath surface or prior feedstock layer. Cross-sectional area, viscosity, adhesion, motion and interface condition can affect force and damage. A process with surrounding paste support can still experience detachment or distortion at the exposure interface. Window/film wear, contamination or clouding changes optical and mechanical behaviour simultaneously.

Layer registration includes platform motion, material thickness, optical distortion, file rasterisation and machine control. A repeated systematic error can remain hidden in average dimensions while closing a critical channel or changing a lattice strut. Calibration is therefore geometry- and position-aware. Software, antialiasing, grayscale, compensation and build-preparation versions are controlled changes.

Green anisotropy can arise even without extruded roads. Layerwise conversion, exposure gradients, particle settling, coating direction, separation damage and cumulative stress can vary with orientation. Scheibler et al. found orientation-dependent green copper strength in their studied LMM system [27]. Sintering may reduce polymer-layer identity but does not guarantee that green composition, pores or cracks become irrelevant. Final orientation effects must be measured rather than presumed absent.

7. Green recovery, support claims, cleaning and state release

The green body must be separated from surrounding unexposed material and the machine interface without cracks, delamination, bending or surface loss. Green strength depends on binder network, conversion, powder loading, geometry, layer contacts and time. It is a release property for handling and downstream survival, not a metal performance metric.

Surrounding suspension or paste can support overhangs during exposure in some architectures. The statement `no printed supports` is therefore plausible for specified features, but incomplete. Unexposed material must drain, be wiped, displaced or dissolved from surfaces and internal passages. A narrow, blind, tortuous or closed feature that exposes successfully can fail the cleaning gate. The design file must provide recovery access and a verifiable cleanliness method.

Cleaning is a material transformation. Solvent or aqueous contact can extract unreacted species, swell or plasticise the green binder, mobilise particles, leave residue or cause differential stress. Mechanical wiping or jetting can damage fine features. Drying can create gradients or surface deposits. A qualified cleaning sequence names the medium, purity, agitation/flow, temperature, time, exchange, drying and reuse/disposal rules, but this review supplies none of those values.

Printed green supports, rafts and sacrificial features serve build or handling functions. They can also obstruct cleaning or create damage during removal. Furnace setters serve a later purpose: supporting the weak brown/sintering body while allowing binder gases and shrinkage. A green support removed before debinding cannot control sintering sag. A setter that prevents sag can constrain contraction, mark or contaminate a surface.

Green inspection includes mass or density where validated, dimensions, surface, visible damage, feature clearance, residual unexposed feedstock and relevant internal evidence. Bulk green density does not resolve a local agglomerate, binder-rich zone or partially cleaned cavity. Computed tomography or other imaging may be useful when resolution/contrast are adequate, but a non-detection is not proof below the method capability.

Storage and transfer can change the green state. Light, heat, oxygen, humidity and residual solvent can continue reaction or alter mechanical behaviour. A green part may creep under its own weight or a fixture. Time between printing, cleaning and debinding is therefore controlled, and transport packaging supports the part without blocking volatile release or adding contamination.

A green release record identifies build, position, feedstock batch/history, optical state, direct conversion method or declared surrogate, measurement uncertainty, cleaning lot, inspection result, supports/fixtures, deviations and authorisation to enter debinding. Passing it does not pre-accept the final metal. It prevents known green defects from entering a furnace load where they become harder and more expensive to diagnose.

8. Debinding and brown-state control

ER-037 owns the cross-route thermal-debiding mechanisms, hazard taxonomy and general qualification logic [43]. ER-149 inherits that framework and narrows this section to the distinctive entry state created by LMM: a particle-filled, spatially non-uniform photocured network whose crosslinking, cleaning residue, powder/binder distribution and optical history determine transport paths into the brown state. The industrial task here is to establish that this specific green state can enter the ER-037 framework without concealed conversion gradients or metal-specific chemistry loss; it is not to duplicate the corpus-wide debinding review.

A binder may contain fractions intended for water or solvent extraction before thermal pyrolysis. Catalytic or direct thermal routes may be used in other systems. For an LMM green body these choices begin from an exposure-defined network and are not interchangeable: compatibility depends on crosslink distribution, powder surface, section thickness, feature openness, cleaning history, support and furnace state. The 3Dresyns IFU declares separate water- and solvent-debindable binder-route families and explicitly assigns user validation of the actual solids and workflow [35]. It does not prove that either route is complete or suitable for a particular metal.

The initial green network can affect debinding beyond total organic mass. Overexposure may increase crosslink density or change accessibility; undercure can leave weak regions; conversion gradients can create non-uniform decomposition. Cleaning residues can alter local transport. ER-031 owns general cure-shrinkage, residual-stress and warpage mechanics [40]; the LMM-specific extension is that shrinkage of a constrained binder around comparatively rigid particles can generate interfacial and packing-scale stress before thermal shrinkage. That stress can open microcracks, weaken particle bridges or create non-uniform transport paths that later amplify gas-pressure damage during debinding [22,23,40]. Exposure strategy is therefore a debinding-entry variable because it sets part of the interfacial stress population on which binder removal acts. A debinding model that begins from nominal binder percentage alone is incomplete.

Small-sample thermogravimetric or evolved-gas analysis can screen the actual LMM feedstock, but the qualification link is geometry- and load-specific because optical conversion and cleaning accessibility establish the starting transport field. Roumanie et al. linked debinding/sintering conditions to copper composition and thermal conductivity in one highly loaded photocurable route [28]. Melentiev et al. investigated faster crack-free debinding and later sintering of thin-walled 316L metamaterials within a defined system [29]. Their outcomes remain bounded to those formulations, metals and geometries.

The brown body can be weaker than the green body after polymer support is lost and before metallurgical necks mature. It can crack during transfer, setter adjustment or early furnace motion. Some factories may integrate thermal debinding and sintering in one programme, but the brown transition still exists physically. A defined hold point can rely on mass change, gas response, thermal record, witness specimens, chemistry or other route-specific evidence.

The LMM brown-state hold links feedstock batch, spatial conversion or declared surrogate, cleaning state, part section/feature family, furnace load/location, mass or gas evidence, chemistry and integrity. A completed time-temperature trace alone cannot show that the photocured network was removed uniformly or that metal chemistry remained acceptable. Binder, powder-surface or conversion changes also trigger renewed exhaust/condensate and contamination assessment under the ER-037 framework [43].

9. Sintering, shrinkage, setters and dimensional compensation

Sintering forms metallurgical bonds and reduces pore volume through temperature- and time-dependent transport. Powder chemistry and surface condition, green packing, residual binder, atmosphere, thermal profile, part geometry, load position and setter interaction affect densification, grain/phase evolution, chemistry, dimensions and properties. The route is not a low-temperature metal printer followed by generic firing.

Shrinkage begins from the spatial green architecture. Local powder fraction, agglomerates, cure and cleaning can vary. During debinding, organic removal creates pore pathways and may rearrange particles. During sintering, neck growth and pore closure interact with gravity, thermal gradients and friction. The result can be anisotropic and geometry-dependent even when a nominal bulk scale factor appears stable.

Compensation models may include axis factors, local feature offsets, anticipated sag, setter contact and final machining stock. They are trained on representative parts and load/furnace locations, then tested on independent geometry. A model fitted to one alloy, thickness or orientation is not a universal machine correction. Any powder, binder, exposure, cleaning, furnace, setter or software change can invalidate it.

Setters must carry the part as its stiffness falls and it contracts. A broad contact can resist sag while increasing friction and constraining in-plane shrinkage. A point or rib support can reduce contact while concentrating load or leaving marks. Setter chemistry, surface, reuse and contamination are controlled. Sacrificial features and separable powder beds can be considered only after their gas-flow, shrinkage and cleanliness effects are qualified.

Pressureless sintering, sinter-HIP, separate HIP, heat treatment and infiltration produce different states. HIP can reduce some internal porosity but cannot restore a missing feature, remove trapped contamination or automatically correct chemistry. Heat treatment can change strength or corrosion behaviour without eliminating geometric defects. Reports and drawings name the actual delivered state.

Copper routes illustrate atmosphere and chemistry sensitivity. Roumanie et al. linked thermal conditions to composition and conductivity [28]; Ye et al. followed a pure-copper slurry route through oxidation, densification and conductivity [33]; Lyu et al. reported a separate high-resolution copper stereolithography route [34]. These studies are not interchangeable recipes. Their collective lesson is that final conductivity and density depend on formulation, oxygen/carbon control, pore state and the complete thermal history.

NiTi creates another boundary. Cohen et al. demonstrated sinter-based LMM of a NiTi shape-memory alloy and identified carbon/phase sensitivity in the tested route [31]. A successful 316L or copper binder and furnace path therefore does not establish NiTi phase transformation, composition or functional response. The same restriction applies to refractory and reactive materials.

Dimensional acceptance names the state. Green, cleaned, brown, as-sintered, HIPed, heat-treated, machined and finished dimensions answer different questions. A drawing and report that omit state make compensation and conformance ambiguous. Stable final dimensions require part and load evidence, not only a shrinkage percentage from coupons.

10. Material windows, pore state, microstructure and properties

Metal-filled VPP/LMM has been demonstrated for several material systems, but each result belongs to a particular powder, binder, optical route, geometry, cleaning and thermal chain. Material breadth is evidence of research possibility, not proof that a shared feedstock architecture can print ‘any metal’.

Stainless-steel 316L has the widest evidence in this source set. Pan et al. coupled slurry preparation, scattering, cure and thermal conversion [24]. Wu et al. coupled a stable paste with cure and final tensile behaviour [25]. Melentiev et al. demonstrated high-resolution complex structures [26] and separately examined thin-walled metamaterial debinding/sintering [29]. Pires et al. compared supplied micro-DLP specimens with binder-jet and laser-fused 316L using microstructure, density, surface and mechanical tests [30]. These results support multiple viable 316L routes, not one universal density, surface, tensile property or feature limit.

Comparisons require matched states and specimens. Pires et al. reported differences related to density, surface and grain state, while noting supplier-proprietary process details and different specimen scales [30]. A micro-tensile specimen, standard coupon and final thin-walled component do not have identical surface-to-volume ratio, defect sensitivity or test uncertainty. Route ranking without matched geometry, surface, thermal state and method is weak evidence.

Copper studies demonstrate optical and thermal challenges without defining one best route. Scheibler et al. focused on green cure/strength [27]; Roumanie et al. on debinding/sintering, composition and thermal conductivity [28]; Ye et al. on a pure-copper slurry route [33]; and Lyu et al. on another stereolithographic process/property window [34]. Powder oxide, organic residue, porosity and atmosphere can dominate conductivity. A green feature result cannot be converted into final electrical or thermal performance.

Cai et al. demonstrated DLP processing of tungsten through a water-based precursor and multistage thermal route [32]. The work broadens the evidence boundary to a refractory metal while remaining formulation-specific. It does not establish that conventional metal-powder photoresins, debinding cycles or inspection methods transfer to tungsten.

Density is necessary for many applications but not sufficient. Equivalent bulk density can hide different pore size, shape, connectivity and location. A surface-connected pore can govern leakage or corrosion; an aligned internal defect can govern fatigue; a closed pore may respond differently to HIP. Archimedes density, image area fraction and CT have different sampling, resolution and uncertainty. Acceptance selects methods against the failure mode.

Microstructure reflects the thermal route. Sintered 316L can show equiaxed grains and annealing twins rather than PBF melt-pool/cellular structures, as observed in the bounded comparison by Pires et al. [30]. That difference is descriptive, not inherently superior. Grain size, phase balance, inclusions, carbon/oxygen/nitrogen, porosity and heat treatment must meet intended-use requirements.

Mechanical, thermal, electrical, magnetic, corrosion, fatigue, creep or shape-memory claims require state-specific tests. ISO/ASTM 52927 structures main-characteristic and corresponding test-method selection [7]. It does not convert a literature coupon into a product guarantee. Evidence must include orientation, surface, geometry, environment, sample count, uncertainty and genealogy.

11. Geometry, surface, inspection and monitoring

LMM can make fine green features because patterned exposure avoids the melt-pool scale of fusion processes and can expose many pixels in parallel. That conditional capability does not mean every digital feature survives cleaning, debinding and sintering. Positive walls, negative gaps, blind holes, open channels, lattices and large solid sections have different exposure, cleaning and thermal risks.

The minimum printable positive feature and minimum cleanable negative feature are separate quantities. Scattering and lateral overcure can enlarge a wall while closing a gap. Cleaning can erode a thin wall or leave paste in a channel. Sintering can round, sag or close a feature. Qualification maps digital, green, cleaned and final geometries rather than quoting projector pixel pitch.

Surface state inherits layer thickness, optical edge response, coating marks, particle size, cleaning, support/raft removal and sintering. A low final roughness reported by Melentiev et al. [26] is evidence for their route. It is not a guarantee for another orientation, alloy, section or finishing state. Surface measurement reports cutoff/filter, direction, area/line method and whether inaccessible surfaces were included.

Inspection combines complementary methods. Dimensional metrology measures accessible geometry. Mass/density methods average a volume. Metallography samples cut planes. CT can detect some internal pores or retained material subject to resolution, contrast and artefacts. Chemical analysis addresses selected elements; surface analysis may be required for residue. Mechanical tests address a specimen population and direction. No single method clears all failure modes.

ISO/ASTM TR 52905 provides a risk-based NDT framework for metal AM [10]. It does not promise that CT, ultrasound or another method will detect every LMM defect. The inspection plan considers fine walls, dense high-attenuation metals, tortuous channels, surface condition and required probability of detection. A ‘no defect found’ statement is bounded by method capability and coverage.

Process monitoring can include reservoir/feedstock temperature, coating force or image, layer surface, optical power/map, exposure state, separation load, platform motion, green mass/geometry, cleaning records and furnace gases/temperature. Each signal requires calibration, time/position registration, detection limits and a response rule. A normal camera image cannot prove internal cleanliness, conversion, chemistry or final density.

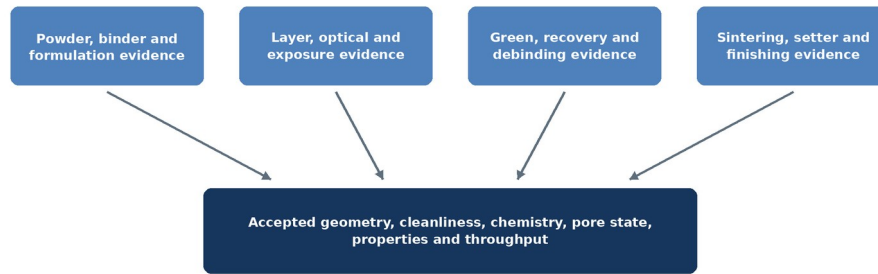


Figure 2. Part-linked evidence architecture for lithography-based metal manufacturing.

Disposition integrates rather than substitutes evidence. A light-output excursion can require a targeted hold, but a normal light trace cannot clear a part whose channel remained filled. A furnace excursion can affect chemistry and dimensions even when green evidence was normal. Missing genealogy or unregistered software compensation is itself a controlled deviation.

Table 2. Conditional opportunities and controlling liabilities in metal-filled photolithographic routes

Process or product condition	Conditional opportunity	Controlling liability	Evidence required
Patterned whole-field exposure	Parallel exposure within a field and fine digital geometry	Optics, scattering, field non-uniformity and cumulative overcure	Position- and geometry-resolved green/final correlation
Highly loaded feedstock	Less organic burden and potentially favourable green packing	Viscosity, settling, agglomeration, cure loss and renewal delay	Batch, rheology, optical and layer evidence
Thixotropic or paste support	Can retain particles and support some green features	Coating stress, recovery time, trapped material and cleaning access	Time/history-resolved layer and recovery qualification
Fine metal powder	Can support thin layers and small features	Surface/oxide, viscosity, agglomeration and handling exposure	Powder-to-final state correlation and controls
No printed supports in a route	Can reduce green support removal for compatible geometry	Unexposed material removal, debinding paths and sintering sag remain	Cleanability, green handling and setter evidence
Small intricate components	Geometry and surface can favour a photolithographic route	Thick/closed regions can debind slowly or remain uninspectable	Representative family and failure-mode coverage
Multiple material demonstrations	Shows route extensibility across selected alloys/metals	Optical, binder, chemistry and thermal windows are material-specific	Complete material-specific qualification
Sinter-based microstructure	Avoids printer melt-pool solidification in the tested route	Pores, residue, grain growth and furnace chemistry remain	State-labelled microstructure/properties

12. Complete-cell productivity, economics, safety and environment

Exposure time is only one interval in the factory cell. The route includes powder and binder preparation or purchase, sampling, conditioning, reservoir loading, layer renewal, exposure, separation, part recovery, unexposed-material removal, cleaning, drying, green inspection, debinding queues, debinding, transfer where applicable, sintering, cooldown, setter removal, heat treatment/HIP where specified, finishing, cleaning, inspection, rework, scrap and release.

Effective cell throughput, $T_{cell} = N_{accepted} / t_{complete-cell}$, reports accepted components per complete elapsed factory-cell time.

Material efficiency, $\eta_{material} = m_{accepted-parts} / m_{released-input}$, is a separate mass ratio. Neither metric substitutes for the other; both declare boundary, period, queue state and disposition of recovered, rejected and downcycled material.

Whole-field exposure can reduce dependence of exposure time on part count within one image, but nesting, cross-sectional area, layer renewal, separation and thermal capacity still matter. A full plate of thin parts may expose efficiently and overload cleaning or furnace fixturing. A single thick component may print successfully and become the debinding bottleneck. Cycle models use accepted yield and queue capacity rather than ideal exposure speed.

Feedstock preparation can dominate development or changeover. Mixing, deagglomeration, degassing, stability testing, vat cleaning and contamination clearance require labour and equipment. Purchased proprietary feedstock can move that burden to the supplier while increasing supply-chain and equivalence risk. A qualified incoming test remains necessary.

Recovered unexposed material can reduce waste only when its identity and history remain controlled and it can be reused without degrading output. Cleaning media, contaminated wipes, cured debris, filters, purge/feedstock residues, failed green parts, debinding condensate, furnace fixtures and finishing waste remain. Environmental claims require a declared boundary, mass balance, energy/utilities and accepted yield.

Printer capital cost is not complete-cell cost. Optical calibration, reservoirs or carriers, coating elements, temperature control, cleaning equipment, ventilation, solvent/water management, debinding and sintering furnaces, gas supply, setters, metrology, maintenance and qualified personnel are part of the route. Cost per accepted part includes amortisation, occupancy, consumables, labour, queues, yield loss and failed qualification.

Safety is state-resolved. Uncured photoactive material can contain reactive acrylates or other sensitising/irritating ingredients; NIOSH desktop-VPP guidance identifies dispensing, uncured resin, cleaning, curing and sanding as task-specific control points [15]. Metal loading adds powder-related hazards during material preparation, spills, dried residues, maintenance and waste. The NIOSH metal-powder facility evaluation demonstrates task- and site-specific exposure assessment, not a universal cross-process limit [16].

ISO/ASTM 52931 requires metallic-material risk assessment across the complete process [4]. Hazards can include chemical contact, inhalable aerosol or dust, combustible/reactive powder, cleaning solvent, UV/visible radiation at unintended access points, moving/coating/separation equipment, hot surfaces, furnace atmosphere, asphyxiation, off-gas, brittle brown parts, sharp finishing debris and maintenance exposure. Operator competence and responsibility follow the tasks actually performed, consistent with ISO/ASTM 52926-1 [5].

Water-debindable does not mean safe to discharge; solvent-debindable does not define one solvent or ventilation control; a high-solids paste does not mean powder exposure is absent. Waste classification, emissions, fire/explosion protection, environmental permits and occupational limits are established locally for actual materials and equipment. This review supplies no universal PPE list or exposure limit.

13. Qualification architecture and selection gate

Qualification links requirements, materials, formulation, optical delivery, layer mechanics, green recovery, thermal conversion, inspection and change control. The initial route-choice and evidence gate is inherited from ER-139, and the direct-versus-indirect classification from ER-049 [11,36]. ISO/ASTM 52920 supplies the production-site framework [2]. ISO/ASTM 52910 supports requirements-led design [3]. ISO/ASTM 52901 clarifies customer/provider exchange [6]. ISO/ASTM 52927 structures main characteristics and corresponding test-method selection [7]. Data registration and packages follow ISO/ASTM 52953 and 52951 [8,9]. None alone qualifies LMM.

Table 3. Lithography-based metal-manufacturing factory qualification and selection gate

Gate	Minimum evidence	Fail or hold condition
Intended delivered state	Drawing/specification, alloy/chemistry, surface, pores, properties, cleanliness and service boundary	State or critical failure modes undefined
Powder/ingredient release	Lot genealogy, identity, powder surface/distribution, binder/additive state, storage and tests	Product/alloy/resin name used alone
Filled-feedstock release	Homogeneity, agglomeration, rheology, sedimentation, optical response, moisture, reservoir atmosphere, degassing/re-aeration and history	Batch position, age, oxygen state or stability unresolved
Equipment and optical release	Layer delivery, temperature, interface, spectrum, irradiance map, focus/distortion, calibration and software	Relevant optical/coating change or drift uncontrolled
Green and cleaning release	Direct conversion or declared surrogate with uncertainty, strength, geometry, layer contact, recovery, cleanliness, support removal and damage	Pixel, cure depth, uncalibrated surrogate or visual exterior used alone
Debinding/brown state	Validated removal mechanism, section/load family, mass/gas/chemistry evidence and brown integrity	Incomplete removal, residue, cracking or route equivalence unresolved
Sintering and setter	Furnace/load/atmosphere, setter, shrinkage, distortion, pores, chemistry and microstructure	Generic MIM cycle or unsupported scale factor substituted
Delivered part and inspection	Dimensions, surface, cleanliness, pores, chemistry, properties, coverage and uncertainty	Density, coupon or one micro-feature used as sole acceptance
Factory, productivity and safety	Complete-cell capacity/yield, trained personnel, task controls, utilities and legal requirements	Cleaning/furnace bottleneck, exposure or maintenance control incomplete
Change and transfer	Equivalence/requalification for powder, binder/additives, optics, machine, software, cleaning, furnace and post-process	“Same alloy/wavelength/dose/printer” used as equivalence

The route is selected when a stable metal-filled photoactive system can be delivered reproducibly, representative geometry can be cured and cleaned, the green part survives handling, binder can escape without damage, sintering reaches the required chemistry/pore/dimensional state, and the complete cell meets demand and safety requirements. It is held or rejected when the mixture segregates, layer renewal or optical cure is unstable, critical channels cannot be cleaned, thick/closed features cannot debind, shrinkage cannot be predicted, setters cannot control distortion, chemistry is unstable or inspection cannot cover a critical region.

Change control is broad because the route is coupled. Powder supplier, surface or size distribution; binder, initiator, absorber, dispersant or additive; mixing/degassing; storage/age; reservoir, carrier, blade or film; temperature; optical spectrum, projector/mask, focus, calibration or software; exposure/antialiasing; layer strategy; cleaning medium/equipment; debinding; furnace/atmosphere; setter/load arrangement; HIP/heat treatment; machining or inspection can change the delivered state. Nominally identical printers or wavelengths do not establish equivalence.

Equivalence is tiered. A change that can introduce a new failure mode, alter an unrepresented powder, photoactive-binder, dispersion, layer, optical, green, debinding, sintering 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, formulation and reservoir history, calibrated optical and layer-delivery state, representative green geometry and conversion surrogate, 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.

Deviation handling preserves genealogy. Sedimentation, agglomerate, bubble, coating defect, optical excursion, layer separation, green crack, trapped feedstock, cleaning damage, mass-loss anomaly, furnace excursion, broken setter, unexpected shrinkage, failed chemistry or missing data creates a hold and documented disposition. Rework is permitted only if its effect on the relevant material state is qualified.

The qualification file lets an independent reviewer reconstruct why the particular component was accepted. It includes requirements, risk analysis, incoming releases, formulation and feedstock version/history, equipment/calibration, build and exposure definitions,

operator responsibility, green cleaning/release, furnace load/location, monitoring, state-specific inspection, uncertainty, deviations and release authority. A commercial technology label or one high-resolution demonstration is not production qualification.

14. Conclusions and research priorities

Lithography-based metal manufacturing is not optical metal fusion. It is patterned formation of a metal-filled photopolymer green body followed by binder removal and metallurgical densification. Its potential for fine geometry and smooth surfaces comes from a coupled powder–binder–light–layer system whose optical and rheological demands compete. The green object must then be recovered and cleaned without damage, converted to a porous brown body without internal pressure or residue, and sintered under controlled gravity, setter and atmosphere conditions.

A defensible industrial programme follows five rules:

1. qualify powder, photoreactive binder, additives, mixture and delivery architecture as one time-dependent feedstock system;
2. measure spectrum, irradiance field, scattering, cure depth, lateral growth and green state instead of transferring wavelength, dose or pixel pitch;
3. keep exposed, cleaned green, brown, sintered, HIPed, heat-treated, machined and delivered states separate;
4. qualify cleaning access, debinding, shrinkage, setters and final properties on representative geometry and furnace loads; and
5. compare LMM with other routes using accepted complete-cell throughput, safety, yield and part-linked evidence.

Priority research should improve in-line dispersion and sedimentation metrology; rheology-to-layer-transfer models for suspension and paste architectures; three-dimensional light transport in metal-filled media; spatially resolved conversion metrology for highly loaded and opaque green bodies; validated conversion surrogates with uncertainty and debinding correlation; oxygen/stabiliser and degassing/re-aeration maps at permeable interfaces; conversion and particle-packing maps; optical-field calibration tied to final geometry; non-destructive detection of trapped feedstock and green cracks; geometry-aware cleaning and debinding transport; brown-state monitoring; shrinkage/setter/friction models; small-feature inspection with quantified probability of detection; material-specific chemistry control for copper, NiTi, tungsten and other advanced metals; and transfer protocols across feedstock batches, machines and furnaces.

Until those links close for a specified route, claims such as “pixel resolution,” “support-free,” “any metal,” “powder-free,” “safe,” “zero waste,” “MIM-equivalent,” “fully dense,” “high throughput” and one shrinkage factor remain incomplete. The capability belongs to a qualified powder–photoactive-binder–layer-delivery–optical-cleaning–thermal–post-process–factory system.

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