

Polymer-Binder Powder-Bed Routes for Metals, Ceramics and Unusual Powders: SLS/Cold-Fusion Shaping, Debinding, Sintering and Qualification

From Selective Green-Body Shaping to an Accepted Final Material

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Statement of Significance

Polymer-binder powder-bed routes occupy an industrially important space between direct powder-bed fusion and other sinter-based additive-manufacturing processes. A laser or another controlled heat source selectively softens or melts a polymer associated with metal, ceramic, glass, carbide or unusual powder. The resulting polymer necks create a removable green body without having to melt the final inorganic phase during geometric shaping. That decoupling can widen the usable material space, reduce some direct-fusion thermal stresses and permit dense nesting within a powder bed. It also moves decisive manufacturing risk downstream. The printed object is a temporary composite, not the promised metal or ceramic. Powder coating or blending, recoating, optical absorption, binder redistribution, green strength, depowdering, binder removal, sintering, infiltration, isostatic pressing, heat treatment, finishing and inspection all influence the final outcome. A visually complete green body can conceal non-uniform packing, weak interlayer necks, trapped powder, binder-rich regions and thermal history that later become cracks, pores, distortion, chemistry drift or property scatter. Commercial labels such as *cold fusion* do not eliminate those mechanisms, and supplier claims for reuse, shrinkage, cost, density or throughput cannot be transferred between material-machine-furnace systems. This review provides a mechanism-led selection and qualification framework for metals, ceramics and advanced powders. It distinguishes blend, coated-particle, core-shell and composite-granule feedstocks; separates shaping resolution from final dimensional capability; connects green defects to final failure; and defines evidence required at every state. It uses the current 3Dresyns advanced-material portfolio only to map candidate material opportunity, never as independent proof of processability or performance.

Abstract

Indirect polymer-binder powder-bed shaping uses selective thermal energy to join binder-bearing particles into a green geometry, followed by depowdering, debinding and densification. The route is variously described as indirect selective laser sintering, indirect laser powder-bed fusion, polymer-assisted powder-bed processing or, in commercial implementations, cold fusion. These names can obscure the essential distinction between the phase that creates the printed bond and the material expected in the final product. This qualitative engineering review follows the complete state chain from released powder-binder feedstock to accepted metal, ceramic, glass, carbide or other advanced material. It examines composite-powder architecture, binder distribution, powder flow and spreading, bed packing, energy absorption, thermal softening, neck formation, scan history, curl, build layout and green-body removal. It then treats green metrology, depowdering damage, green machining, geometry-dependent binder removal, sintering, infiltration, isostatic pressing, shrinkage, distortion, phase control and final-property qualification. The analysis shows why a broad shaping window can coexist with a narrow final-product window. Binder improves green cohesion but increases organic-removal burden; bed support enables complex green shapes but does not prevent weak-feature damage; dense nesting can improve machine utilisation while overloading depowdering or furnace capacity; and lower shaping temperature does not establish lower total energy or cost. Material-specific examples in alumina, silica, glass, silicon carbide, carbon-fibre/SiC, aluminium and infiltrated metal systems demonstrate feasibility and expose non-transferable assumptions. A three-level qualification gate separates feedstock and machine capability, thermal-conversion capability and final-product acceptance. The paper concludes that the route is selected correctly only when its complete-cell advantage survives evidence for powder genealogy, green integrity, binder removal, dimensional transfer, final composition, defect population, property statistics, safety and accepted-part economics.

Keywords: *indirect selective laser sintering; polymer-binder powder bed; cold fusion; green body; composite powder; coated particle; debinding; sintering; infiltration; shrinkage; advanced ceramics; metals; unusual powders; process qualification*

1. Purpose, scope and terminology

The purpose of this paper is to make polymer-binder powder-bed processing selectable and auditable as an industrial manufacturing chain. It has five objectives. First, it identifies the physical mechanism that creates the printed bond and prevents a

green object from being misreported as a final metal or ceramic. Second, it connects composite-powder architecture with bed behaviour, energy coupling and green integrity. Third, it follows defects and material changes through depowdering, binder removal and densification rather than treating the printer as an isolated process. Fourth, it establishes decision criteria against direct powder-bed fusion, binder jetting and bound-powder extrusion. Fifth, it defines the evidence needed to qualify metals, ceramics and unusual powders without transferring recipes or commercial claims.

ISO/ASTM 52900 provides the shared additive-manufacturing vocabulary [1]. That vocabulary is necessary but not sufficient for the present boundary because historical and commercial sources use *selective laser sintering* for several different bonding mechanisms. Kruth and co-workers classified binding mechanisms in laser powder-bed processing and showed why the word sintering alone cannot identify what physically joins the particles [12]. In this paper, **polymer-binder powder-bed shaping** means that a polymer associated with the powder is selectively softened, melted or otherwise consolidated to create most of the initial green bond. The intended metal, ceramic or other inorganic phase is not required to melt during shaping. It becomes the final continuous or load-bearing material only through a declared downstream operation.

The feedstock may be a dry blend of separate binder and inorganic particles, an inorganic particle carrying a polymer coating, a binder-rich composite particle, a core-shell particle, a granulated mixture or another explicitly characterised powder architecture. The association must exist before or during bed delivery; ER-153 controls processes that selectively jet a liquid binder into the powder bed. ER-148 and ER-154 control bound-metal and bound-ceramic material extrusion. Direct laser melting or direct sintering of the intended inorganic phase remains a direct powder-bed route even if a minor organic processing aid is present. Ordinary polymer SLS, where the polymer itself remains the final part, is outside this review. Ordinary polymer powder-bed fusion, where the polymer remains the delivered material, is controlled by ER-141; ER-155 begins only where a temporary polymer binder creates a green body for later inorganic conversion.

The word **indirect** describes the separation between geometric shaping and development of the final inorganic material state. It does not mean that the thermal-shaping step is unimportant. The binder necks, local packing and printed interfaces define the green skeleton that constrains all downstream transport and shrinkage. Nor does indirect mean low temperature in an absolute sense. The shaping temperature can be low relative to metal or ceramic melting, while the complete process still includes long bed preheating, cooling, debinding and high-temperature densification.

The phrase **cold fusion** is used only when a source or supplier uses it. It can communicate that the base metal is not directly melted during laser shaping, but it is not a standard mechanism definition. **ColdMetalFusion** is a Headmade Materials trademark and implementation [32-34]. The manuscript therefore distinguishes a general polymer-binder powder-bed route from that commercial system. Statements supported only by manufacturer-affiliated sources are labelled as descriptions of the declared workflow, not independent comparisons of cost, reuse, shrinkage, density, speed or quality.

The material states are named at every transition. A released **feedstock** is a controlled powder-binder composite. A delivered layer is a **powder bed**, not a part. Selective bonding produces a **green region** within a surrounding cake. After cooling and removal of loose powder, the object is a **green body**. Partial or substantially complete binder removal can produce a fragile **debound** or **brown body**, provided the remaining constituents and acceptance state are declared. Sintering creates a thermally consolidated body whose pores, composition and dimensions may still be unacceptable. Infiltration creates a composite that must be named by its actual constituents. Only the final inspected and authorised state is the product.

The scope begins with the base-powder and binder requirements. It includes coating, blending, granulation, drying, sieving, packaging, storage, reconditioning and powder refresh. It covers machine loading, atmosphere, powder delivery, recoating, bed packing, energy input, scan sequence, green bonding, build cooling, powder recovery, depowdering, green handling and green machining. It follows solvent, catalytic or thermal debinding; pressureless or assisted sintering; reaction bonding; infiltration; hot or cold isostatic pressing; heat treatment; finishing; cleaning; inspection; testing and final disposition.

Concrete, cement, geopolymer, regolith and macroscopic construction are excluded. The advanced-material discussion is component-scale and includes metals, oxides, glass, carbides, carbon-containing systems and other nano- or micron-derived materials only when the chemical state and industrial purpose are specified. The extensive 3Dresyns portfolio identifies potential powders and functionalities across alloys, oxides, carbides, nitrides, rare-earth compounds, conductive fillers and other advanced materials [35]. A portfolio entry proves only that a material is within a declared engineering opportunity space. It does not prove that the powder can be safely handled, recoated, selectively bound, debound, sintered or qualified.

The final requirement is written before the route is selected. ISO/ASTM 52910 supports requirements-led design communication [3], while ISO/ASTM 52901 frames purchased-part evidence [4]. A useful requirement identifies final composition and phase, residual binder or carbon where relevant, density or designed porosity, critical dimensions, surface, orientation, heat treatment, mechanical or functional test method, service environment, permissible finishing, cleanliness and acceptance population. “Printed metal”, “technical ceramic”, “high density”, “support free” and “suitable for serial production” are not acceptance requirements.

This paper does not prescribe a binder percentage, coating thickness, particle-size distribution, refresh ratio, layer thickness, bed temperature, laser power, scan speed, hatch, energy-density expression, green-machining allowance, debinding schedule, sintering cycle, infiltration condition, isostatic pressure, shrinkage factor or acceptance threshold. Each value belongs to a declared powder-binder-machine-geometry-atmosphere-furnace-product system. The literature is used to reveal mechanisms, failure modes and evidence structures. Numerical transfer requires separate validation.

Evidence transfer is tiered. Evidence is transferable only within the demonstrated material-machine-route-state envelope. A shared process label, nominal chemistry, powder family, binder family, machine class or thermal route does not establish equivalence. Transfer outside the demonstrated envelope requires declared bridging evidence or requalification before acceptance.

2. Process identity and the state-resolved chain

The route begins upstream of the printer. Base powder and binder are received, sampled and released against identity and functional attributes. They are coated, blended or granulated under controlled order, time, temperature, solvent, shear and drying history. The composite powder is then classified and conditioned to provide a bounded particle, binder, moisture and flow state. A certificate for the base powder cannot release the composite feedstock because coating changes surface energy, particle contacts, bulk density, optical response and thermal behaviour.

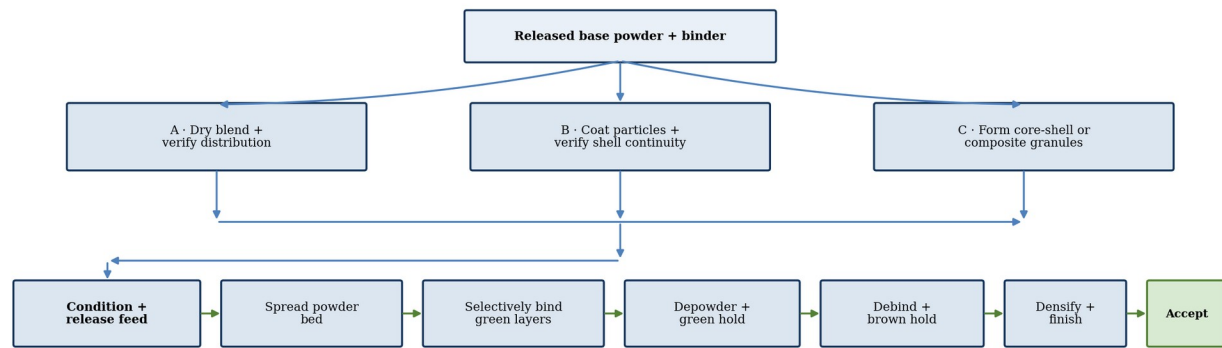
The build system delivers a measured amount of powder and spreads it into a layer. Selective thermal energy raises the binder-bearing material through a softening or melting window. Polymer flows or deforms at particle contacts and forms necks within the layer and across the prior layer. On cooling, those necks carry the green load. The surrounding unbonded powder provides geometric support during shaping, but its packing and temperature also influence heat flow and part boundaries.

The completed build is a cake containing one or more green bodies. Cooling must be controlled because premature removal can distort the binder network, while prolonged exposure can age the powder or reduce productivity. Depowdering exposes the green geometry and applies mechanical, pneumatic, vibratory or manual loads. Powder trapped in channels or weak features can turn an apparently support-free build into a difficult removal operation. The green part is inspected and either rejected, reworked under a controlled procedure or authorised for thermal conversion.

Debinding removes temporary polymer while preserving a porous particle skeleton. Early heating can soften the binder before it decomposes, so gravity and capillarity can redistribute it. Decomposition products must diffuse or convect through evolving pores. If gas generation exceeds transport, pressure, blistering, delamination or cracking can occur. The brown body is then sintered, reaction bonded, infiltrated, pressed or otherwise densified. Every option changes the final chemistry, pore topology and dimensional transfer.

Table 1. State-resolved polymer-binder powder-bed route and process boundaries

State or decision	Polymer-binder powder-bed shaping	Direct inorganic powder-bed fusion or sintering	Binder jetting	Bound-powder extrusion	Required evidence before transition
Feed introduction	Binder is blended with, coated on or integrated into the bed powder	Predominantly inorganic feed; direct energy creates the intended inorganic bond	Powder bed receives selectively deposited liquid binder	Highly filled continuous feed passes through a nozzle	Identity, composition, architecture, moisture, flow, absorption and lot genealogy
Geometric bond	Polymer softening or melting creates the green network	Metal or ceramic melting/sintering creates direct inorganic bonding	Deposited liquid wets, cures or dries to make a green region	Cooling, reaction, gelation or drying stabilises deposited roads	Mechanism map, energy or delivery history, layer integrity and bounded defects
Geometric support	Surrounding powder supports green regions	Surrounding powder supports hot inorganic regions	Surrounding powder supports binder-defined green regions	Toolpath, prior roads and dedicated supports carry the shape	Build layout, removal access, thermal interaction and support evidence
Printed output	Polymer-inorganic green body	Directly consolidated inorganic body, often requiring stress relief or heat treatment	Binder-powder green body	Green road assembly	Green mass, dimensions, strength, powder removal and visible/internal integrity
Downstream conversion	Debinding plus sintering, infiltration, pressing or reaction route	Heat treatment, support removal, finishing and inspection	Curing/debinding plus sintering or infiltration	Debinding plus sintering or other conversion	State-specific mass, chemistry, geometry, atmosphere and load evidence
Final claim	Actual final metal, ceramic or composite after acceptance	Actual direct-route material after acceptance	Actual final material or infiltrated composite after acceptance	Actual final material after acceptance	Composition, pores, dimensions, surface, properties, statistics and disposition



Architecture-specific feed risks close before the shared bed → green → brown → final evidence chain.

Figure 1. Feed architectures converging on one controlled state chain.

The branches do not become equivalent when they enter the same machine. A dry blend can segregate by size, shape or density. A coating can produce more uniform local binder but introduces coating thickness, continuity, solvent removal and storage stability. A composite granule can spread well yet fragment under recoating or change packing after binder softening. The feed architecture therefore remains part of the material specification throughout the process.

Hold points preserve the meaning of each state. Feedstock release authorises machine use, not final-product production. A stable powder bed authorises energy exposure, not green-body release. A complete green geometry authorises depowdering only after cooling and access conditions are met. Green-body acceptance authorises the declared debinding load. Brown-body acceptance authorises densification. A sintered part is still withheld until composition, dimensions, defects, surface and properties meet the final requirement.

Genealogy links powder and binder suppliers, lots, certificates, incoming tests, coating or mixing batch, solvent and drying history, sieves, conditioning, package, age, refresh fraction and reuse cycles. It continues through machine, atmosphere, build file, software, recoater, layer, position, orientation, energy record, interventions, cooling, depowdering, green inspection, furnace load, atmosphere, setter, profile, infiltration or pressing, finishing, inspection and disposition. ISO/ASTM 52951 provides a current framework for AM part data packages [7], and ISO 17295 supports unambiguous position and orientation [6].

The selection question is therefore not whether the printer can draw the shape. It is whether the complete chain can repeatedly transform released feedstock into accepted product with a controlled defect population and a better total outcome than competing routes. The correct comparison uses the same final requirement, production volume, geometry, inspection burden and acceptance yield. Comparing a green build with a finished direct-fusion part or a moulded-and-sintered part is an invalid system boundary.

3. Composite-powder architecture and material release

The base powder establishes the intended inorganic chemistry and much of the densification response. Relevant attributes include alloy or ceramic identity, phase, purity, oxygen or other interstitials, particle morphology, size distribution, surface area, internal porosity, satellites, agglomeration, surface oxide, moisture, sintering aids and lot variability. Sutton and co-workers survey powder-characterisation techniques and their relevance to powder-bed processing [30]. Their broad framework supports test selection, but each attribute must be connected to the present route rather than assumed transferable from direct metal fusion.

The binder is temporary in the final claim but central to manufacturing. It influences particle contacts, powder flow, bed density, optical absorption, preheat stability, melt or softening response, green strength, depowdering, thermal decomposition, residue and furnace contamination. A binder system may contain more than one polymer plus plasticiser, dispersant, wax, lubricant, stabiliser, absorber or processing aid. Every constituent enters the mass balance and safety assessment. “Proprietary binder” cannot justify an unidentified final residue or uncontrolled decomposition pathway.

A dry blend is the simplest conceptual architecture. Separate binder particles are mixed with the inorganic powder. It can be efficient for screening, but differences in density, size, shape, surface charge and friction can drive segregation during transport, hopper vibration, dosing and recoating. Binder-rich local regions can form strong but organic-heavy green zones; binder-poor regions can remain weak. The smallest binder particles may adhere to inorganic surfaces, while larger particles can migrate or be swept by the recoater. Blend homogeneity therefore needs spatial and handling evidence, not only a nominal mass fraction.

Coated inorganic particles place binder closer to the intended contacts. Cardon and co-workers produced polystyrene-coated alumina for indirect selective laser sintering [13]. Their work demonstrates one controlled coating architecture, not a universal coating chemistry or ratio. Coating can reduce macroscopic separation and narrow the distance binder must flow, but it changes

particle roughness, effective diameter, electrostatics, moisture response and thermal transitions. Incomplete coating, binder islands, exposed surfaces and agglomerated coated particles can create a different spatial distribution from the nominal average.

Core-shell and composite-granule architectures offer additional control. A binder-rich shell can improve initial energy coupling and neck formation around an inorganic core. A granule can combine fine base particles into a larger recoatable unit. These benefits introduce new failure modes: shell-thickness variation, fractured shells, hollow or porous granules, internal binder gradients, granule breakage, altered packing and a need for the binder or granule boundaries to disappear without leaving persistent pores. Chen and co-workers studied a core-shell chopped carbon-fibre/phenolic composite powder for a Cf/SiC route [29]. That study establishes a particular material strategy; it does not show that every fibrous or carbide feedstock can be made recoatable by encapsulation.

The binder fraction is an optimisation variable with opposing effects. More binder can increase contact area, tolerate lower local packing and improve green handling. It also increases the volume that must be removed, the potential for flow before decomposition, gas generation, carbon residue and total shrinkage. Less binder can reduce organic burden but narrow the energy and handling window. The optimum is not the highest green strength. It is the smallest robust binder architecture that supports spreading, bonding, removal and transport while remaining safely debindable for the most demanding qualified geometry.

Particle size must be assessed relative to layer thickness, recoater gap, surface requirement and internal feature. A coarse particle can limit edge definition and produce a rough green surface. A high fine fraction can improve apparent packing while increasing cohesion, dust, electrostatic behaviour and binder demand. A bimodal distribution can fill interstices but can also segregate. Nanoparticles can provide surface area or functionality, yet they create strong agglomeration and exposure-control demands. The 3Dresyns material page lists nano- and micron-scale candidates across many chemistries [35]; every candidate requires a new flow, agglomeration, binder, safety and densification assessment.

Powder coating or granulation has its own process capability. Dosing, solution or dispersion preparation, mixing order, temperature, shear, solvent addition, evaporation, drying and classification influence the outcome. Residual solvent can plasticise binder, change flow or generate gas during preheating. Excessive drying temperature can age the polymer or oxidise the base powder. Sieving can remove agglomerates while changing the size distribution or preferentially discarding binder-rich material. A mass yield alone cannot show that the retained fraction has the intended composition.

Release testing combines chemical, physical and functional attributes. Representative checks can include base-powder identity, binder identity and fraction, thermal transitions, decomposition and residue; particle size and morphology; coating or granule integrity; moisture or volatiles; bulk and tapped behaviour; angle or shear-based flow tests; electrostatic response; optical absorption at the process wavelength; and a controlled spreading and bonding test. No single test releases the feedstock. A funnel can show gravity discharge while missing thin-layer spreading; thermogravimetry can show small-sample mass loss while missing thick-part transport; and a spectroscopy average can miss binder-rich agglomerates.

Storage and ageing can change binder crystallinity, plasticiser distribution, moisture, oxidation, electrostatic charge and particle contacts. Package headspace, temperature, humidity, light, vibration and opening history belong to control. Feedstock reconditioning must have a defined purpose and endpoint. Drying may remove water while changing binder state. Mixing may restore apparent uniformity while breaking granules. Aged powder is not made new by passing it through a sieve.

Powder reuse is especially consequential because material outside the green part has still experienced the machine atmosphere, bed preheat, local scan heating, cooling and recovery. Binder can age, migrate or partially soften. Fines and fragile shells can accumulate. Segregation can change the recovered composition. Refresh with virgin powder creates a blend of histories rather than erasing the old history. Reuse therefore requires bounded cycles or a state-based release test, a mixing protocol, traceability and evidence that adverse properties and final performance remain controlled.

The development sequence should move from architecture to mechanism. First demonstrate that the feedstock remains compositionally stable through handling. Then show thin-layer spreading and packing in the actual delivery system. Next establish a bounded energy window that creates reproducible green bonds without damaging surrounding powder. Only then should complex geometry, depowdering and thermal conversion be used to optimise the complete process. Optimising laser exposure before feed architecture and bed behaviour are stable can fit machine parameters to an uncontrolled powder state.

4. Powder delivery, spreading and bed packing

The recoater converts bulk feedstock into a thin, spatially distributed manufacturing state. This operation can be more selective than a hopper-flow test because the powder must move, rearrange and stop within a gap comparable to a few particle diameters. Roller, blade, brush and counter-rotating systems impose different shear, compression and disturbance. Recoater material, edge condition, speed, acceleration and cleanliness can change the deposited layer even when the powder lot is unchanged.

Flowability is not a single material number. Gravity discharge, shear-cell response, avalanche behaviour and dynamic image tests probe different stress states. The relevant question is whether the powder forms a repeatable layer across the full bed under the

qualified recoater, atmosphere, humidity and thermal condition. A powder can pour well while leaving streaks, waves or low-density regions. A cohesive powder can spread acceptably with a roller yet bridge in the dosing system. Test selection follows the actual failure mode.

Packing determines the local inorganic and binder inventory before scanning. Low packing can require binder to bridge longer distances and can increase final shrinkage. High apparent packing can conceal binder-rich contacts or agglomerate voids. Layer density can differ near walls, prior green regions, recoater direction changes and feed boundaries. The first layer interacts with the base surface, while upper layers interact with a thermally cycled composite below. A build-average density cannot close this spatial field.

Segregation can occur during delivery and spreading. Large or dense particles may move differently from small binder particles. A blade can push coarse particles while fines fill the wake. Granules can roll, fracture or flatten. Repeated passes can align fibres or elongated particles. These mechanisms create direction-dependent packing and composition before the laser is involved. Representative sampling should therefore consider feed reservoir, early and late layers, recoater direction, bed centre and edges, and recovered powder.

Layer thickness is both a geometric command and a material challenge. If the commanded thickness approaches the upper particle or agglomerate size, protrusions can be struck and dragged. If it is too large relative to the energy penetration and binder distribution, interlayer bonds can be weak. A thinner layer can improve local definition while increasing recoating cycles, exposure time, thermal ageing and opportunities for a disturbance. The optimum belongs to the complete process, not resolution alone.

Temperature alters bed behaviour. Preheating can reduce the energy needed for binder softening and limit thermal gradients, but it can also soften powder contacts, promote caking, change electrostatics, accelerate binder ageing or make recovery difficult. The temperature measured at a chamber sensor may not equal the powder-surface or subsurface temperature. Build edges, prior scans, heater geometry and airflow can create gradients. A stable setpoint is not proof of a uniform bed.

Atmosphere can protect metals or reactive materials and influence binder oxidation, fumes and surface chemistry. Oxygen, humidity, pressure and gas flow must be specified where they matter. Gas flow that removes emissions can disturb fine powder or cool one area. An inert label does not quantify residual oxygen or control leaks, purge history and door opening. For unusual powders, atmosphere compatibility must consider both the base material and the polymer decomposition products.

Recoater interactions with growing green regions can reveal or create defects. Curling or swelling can raise an edge into the blade path. A weak layer can be displaced. A hard inclusion or agglomerate can scratch a long streak across the bed. The machine may complete the layer while the defect remains buried. Recoater force, motor current, acoustic signals or layer images can support detection, but only after the relationship to real defect states and false negatives is validated.

Bed qualification uses designed challenges rather than a single flat coupon. It should include long recoater spans, isolated and densely nested regions, thin and thick cross-sections, edges, channels, multiple heights and beginning-to-end powder history. Mass, topography, images and selected destructive sections can connect observed layer behaviour to final defects. The challenge should include allowable environmental and machine limits, not only nominal conditions.

Powder recovery begins at the bed. Unbonded material from high-temperature zones, part-adjacent zones and remote zones may have different histories. Combining them destroys information unless equivalence has been demonstrated. Vacuum, brushes, vibration and sieving can remove foreign matter while generating fines or static charge. Recovery equipment can cross-contaminate alloys or ceramics. Dedicated or validated-clean equipment, container identity and mass balance are therefore part of the route.

The bed creates an important industrial trade-off. It can support complex green geometry and permit three-dimensional nesting without discrete support structures. At the same time, every nested part increases the powder volume to recover, the interfaces to inspect, the chance of green contact during removal and the downstream furnace load. Bed packing efficiency is valuable only when accepted-part yield and complete-cell capacity remain high.

5. Energy coupling, binder softening and green-bond formation

Selective energy must transform the binder-bearing contact network without unintentionally transforming the surrounding powder or damaging the base material. The material response depends on wavelength-specific absorption, reflection and scattering; binder and inorganic thermal properties; local packing; layer thickness; initial temperature; spot shape; power; speed; hatch; scan order; prior exposure and cooling. A nominal energy-density expression can organise experiments, but it cannot collapse these variables into one transferable number.

The binder may soften over a range, melt with a defined transition or react through a more complex thermal pathway. Its viscosity and wetting determine whether it forms useful necks, spreads over particle surfaces, retreats into binder-rich regions or bleeds beyond the intended boundary. Surface tension can draw molten polymer into pores while leaving some contacts dry. The base

powder can act as a heat sink, optical absorber or reflector. The same machine setting can therefore produce different neck morphology in alumina, silica, metal or carbide systems.

Kruth and co-workers distinguish mechanisms including solid-state sintering, liquid-phase behaviour, full melting and chemically induced binding [12]. The relevant ER-155 regime is one in which polymer-assisted binding dominates green formation. Mixed regimes can exist: a polymer may melt while a low-melting inorganic constituent softens, or local base-powder heating may change oxide or phase. Such a route must be described by measured evidence rather than forced into a marketing category. If direct inorganic bonding materially contributes, its effect on powder reuse, composition and final densification becomes part of the process definition.

Sassaman and co-workers modelled bonding in nylon/alumina blends and linked polymer-mediated contact formation with the reported indirect laser powder-bed system [16]. The study is valuable because it treats the green bond as a physical structure rather than an exposure setting. Its binder, particle distribution and machine conditions remain bounded to that system. The transferable lesson is to measure or infer the neck network and connect it to green tasks, not to copy a parameter.

Insufficient energy can leave isolated binder particles, small necks and poor interlayer contact. The surface may look complete while the body has low strength or delaminates during depowdering. Excessive energy can degrade polymer, generate gas, change colour, produce binder loss, cause swelling, curl the layer, cake adjacent powder or blur boundaries. Both conditions can produce similar final porosity after the binder disappears. Green-state evidence helps distinguish their origins.

Preheat narrows the additional energy required at the scan and can reduce thermal gradients. It also moves the entire powder bed closer to binder softening or ageing. A narrow difference between bed temperature and selective-binding temperature can improve speed but reduce powder-recovery margin. Commercial use of the word cold does not remove this balance. The appropriate thermal window must protect unexposed feedstock as well as bond exposed regions.

Optical absorption can be dominated by binder, base powder, pigment or an added absorber. Coating changes the outer surface seen by the energy source. A dark additive can improve coupling while changing decomposition residue or final chemistry. A reflective metal core with an absorbing polymer shell may respond differently after shell thinning or reuse. Spectral and thermal tests should use the actual composite state, not separate handbook properties.

Scan order creates a time-dependent thermal field. Long vectors can accumulate heat differently from islands or short contours. Contours can overheat edges or create a binder-rich skin. Repeated exposure at intersections can thicken necks or degrade binder. The prior layer remains part of the thermal boundary. A local strategy that improves one coupon can produce gradients in a densely nested build. Build layout and scan strategy therefore require joint qualification.

Green resolution is created by the spatial distribution of useful bonds, not nominal spot size. Heat can diffuse beyond the scan, molten binder can move, particles have finite size and the edge is later changed by depowdering, binder removal and shrinkage. An exposure may draw a narrow green line that cannot survive removal. Conversely, a wider green feature may shrink or machine to the required final dimension. The meaningful resolution is the smallest repeatable accepted final feature under the complete chain.

Cardon and co-workers used polystyrene-coated alumina [13], and Deckers and colleagues examined shaping ceramics through an indirect route [14]. These studies show that controlling binder location can support green formation and that final conversion remains decisive. They do not establish a generic ceramic powder-bed recipe. Alumina surface, polymer chemistry, coating, bed condition and furnace route remain linked.

Process-window development should separate four responses: bed integrity, green bond, adjacent-powder condition and downstream conversion. A useful exposure must make a green body strong enough for the declared tasks, keep boundaries within allowance, avoid unacceptable binder damage and leave unexposed powder in a releasable state. It must also avoid a green microstructure that debinds or densifies poorly. Maximising green strength without evaluating removal and conversion can move the defect downstream.

Monitoring can include source power, optical condition, scan position, chamber and bed temperatures, layer images, emissions, recoater signals and post-build green tests. None proves bond quality by itself. Source calibration does not measure absorbed energy; a thermal camera sees a surface and needs emissivity control; an image can miss buried weak necks; emission may indicate degradation but not locate it. Sensors become evidence only through a validated relation to defined defect states and an authorised response.

6. Build layout, thermal interaction and geometric capability

The powder bed permits parts to be placed across a plane and, where removal access allows, nested through height. This is a genuine productivity opportunity because unbonded powder carries green surfaces that would require discrete supports in another route. The opportunity is often expressed as high build-volume utilisation. That metric is incomplete. A layout also determines heat accumulation, powder access, green-part collision risk, furnace loading, inspection traceability and the economic consequence of a build-wide deviation.

Part spacing must preserve both thermal and removal independence. Two green regions can interact through overlapping heat fields even when their nominal contours do not touch. Adjacent scans can raise the local baseline temperature, increase binder flow, cake intervening powder or change cooling. In depowdering, a narrow gap can retain powder and force tools or gas jets between fragile surfaces. The minimum useful spacing is therefore a validated process value, not a nesting-software default.

Vertical nesting adds another interaction. Upper parts are built after lower regions and after more cumulative bed exposure. Their powder may have experienced longer preheat and different compaction. Heat from later scans can affect material below. Removing the surrounding cake can release bodies in an order that applies weight or impact to lower parts. A full-height build challenge is needed even when individual layers have been validated near the base.

The build envelope must be separated into machine reach and qualified capability. A recoater may physically span the entire platform while temperature, gas flow, optical focus or layer density vary with position. Corner and edge regions can cool differently from the centre. Scan-vector calibration and spot shape can change across the field. ISO 17295 supports coordinate traceability [6]; the qualification plan then maps relevant material and property responses against those coordinates.

Orientation trades several risks. Rotating a feature can improve powder escape, reduce unsupported green span or shorten a scan vector. It can also create a longer debinding path, align weak interlayers with service stress, increase setter contact or worsen final distortion. Orientation is therefore selected against the full chain. A green-strong orientation is not automatically the final-property orientation.

Indirect routes can reduce some residual stresses associated with directly melting a metal, but the green body still experiences thermal gradients, polymer shrinkage and differential cooling. Large continuous areas can accumulate heat and curl. Thin isolated features can cool quickly and form weak bonds. A sudden cross-section change can create different neck density and later different binder-removal and sintering response. The absence of a molten metal pool does not imply an absence of thermomechanical distortion.

Geometry limits are state-dependent. During shaping, particle size, layer, heat spread and binder flow control edge definition. During removal, green strength and access control survival. During debinding, wall thickness and enclosed paths control gas transport. During sintering, local packing, gravity and setter contact control shrinkage. Sassaman and co-workers studied geometry limitations in indirect alumina processing [15]. The broader engineering lesson is that a printable feature can fail downstream, and the qualified limit must name the final accepted state.

Channels demonstrate the need for complete-chain design. A channel must be large and connected enough for powder removal without damaging its walls. It must then allow binder-decomposition products and furnace gases to move. Its curved or helical path can create long transport distance, retained powder and inaccessible surfaces. Nissen and co-workers developed a methodology for helical channels in a glass route [17]. Their design rules belong to that system; the transferable method is to connect feature geometry with shaping, cleaning, conversion and measurement.

Thin walls can be resolution artefacts rather than robust components. A wall may consist of only a few particle and binder contact networks. Its green dimension can vary with edge bleed and depowdering. During binder softening it can slump; during sintering it can warp or grain-coarsen differently from a thick section. A minimum wall is qualified through survival and final evidence, not a single green build.

Enclosed volumes create multiple penalties. Powder can remain trapped and add mass, contaminate later furnace equipment or block functional passages. Trapped binder-bearing powder can release products during heating outside the intended body. A nominal drain hole may bridge, cake or become inaccessible after shrinkage. The design should include verified removal paths, inspection access and a disposition for residual powder.

Scale changes the controlling mechanism. A larger plan area increases scan time and thermal accumulation. A taller build increases powder age and vertical history. A thicker section extends debinding distance and increases thermal gradients. A heavier green body loads its own weak features and setters. Successful small coupons do not qualify large housings or densely nested production builds. Scale qualification should challenge the worst combination of mass, thickness, span, height, enclosed path and furnace load.

Dimensional compensation cannot be set from the green edge alone. Shaping bias, depowdering loss, green machining, binder loss, sintering shrinkage, distortion and finishing all contribute. Each can be direction-, geometry- and position-dependent. A compensation model should preserve the sign and source of each contribution so that a furnace change is not hidden by a scan adjustment. The model is versioned with feedstock, build orientation, layout, conversion route and final machining allowance.

Design freedom remains valuable, but it is bounded by inspectability and failure consequence. A deeply internal lattice can improve surface area or weight while becoming impossible to depowder, debind or inspect. A nested set can improve machine utilisation while coupling parts to one furnace loss. The useful design is not the most geometrically complex green body; it is the geometry that achieves the final function with a controllable manufacturing and evidence path.

7. Cooling, depowdering, green handling and green machining

Cooling is the first post-build process. The binder network gains or changes stiffness as the cake temperature falls, and the bed can restrain differential contraction. Opening or excavating too early can release constraint while the green body is weak or dimensionally unstable. Cooling too slowly can reduce equipment productivity and extend thermal ageing of recoverable powder. A release condition should therefore be based on representative bed and part state, not elapsed time alone.

The build cake can conceal both acceptable bodies and process evidence. Excavation order, tool, vacuum, vibration, gas pressure and operator motion affect the green part. A rigid brush can abrade an edge. A gas jet can bend a wall or drive particles into a pore. Vibration can free powder from a channel while propagating a weak interlayer crack. Manual removal can introduce operator-dependent selection and unrecorded repair. Depowdering must be treated as a controlled manufacturing operation.

Powder removal access is designed before building. External surfaces can often be vacuumed or brushed, while channels require connected entry and exit paths. Dead ends and cellular structures can retain composite powder. Weight difference, borescope, imaging or computed tomography can support evidence, but each has detection limits. A clean-looking opening does not prove an empty internal network.

Powder recovered from the cake needs material segregation and mass balance. Powder attached to accepted parts, removed from remote zones, collected in filters, spilled, discarded as caked material and retained in channels should not disappear into one reuse number. The balance helps detect unexpected binder loss, agglomeration or excessive waste. It also prevents a high theoretical reuse percentage from masking uncontrolled mixing.

Green strength must be specified by task and geometry. A coupon compression or bend test can compare batches, but it may not represent a thin wall, suspended channel or heavy nested body. Required loads include excavation, lifting, brushing, fixture contact, measurement, transport, machining, furnace loading and early debinding softening. The release test should challenge the most relevant mode with a margin and a defined failure response.

Handling fixtures distribute loads across green geometry. Soft contact can reduce local stress while leaving particles or contamination. Hard references can establish position while indenting binder-rich surfaces. Vacuum gripping can extract binder or deform a wall. Fixture material must be compatible with the binder, cleaning and furnace route. A fixture qualified at room temperature is not automatically a setter for the hot debinding state.

Green storage is a process state. Polymer can creep, relax, absorb moisture, oxidise or lose volatiles. A body can distort under its own mass or a fixture. Dust and fingerprints can change surface chemistry. Storage time, orientation, support, temperature, humidity, packaging and maximum hold are therefore controlled. A green part is not a stable warehouse item merely because it feels rigid.

Green machining can exploit the relative softness of the polymer-bound body. It may remove stair steps, establish references, open holes, improve a surface or prepare a joining interface before the material becomes hard. Steinhilber and co-workers reported green-part surface processing in a company-affiliated ColdMetalFusion study [33]. This supports a bounded demonstration, not a universal guarantee that green machining improves final surface or economics.

Machining changes the defect and mass state. A cutting tool can pull particles from a weak matrix, smear binder over pores, heat the surface, create subsurface cracks or leave loose debris. A smoother green surface can reveal more sintering distortion or grain pull-out later. Tool, speed, feed, engagement, support, chip removal and allowable stock are linked to the specific feedstock. Green and final surface measurements should be correlated rather than assumed equivalent.

Green joining or repair is especially risky. Adding binder, solvent or loose powder to a chip creates a local composition and thermal history that differs from the original bed. A visually successful repair can become a residue, pore or crack after sintering. Unless a repair method is qualified for the feature and final property, damage should trigger rejection or a formally authorised concession. Informal patching destroys traceability.

Green inspection should occur after depowdering and any authorised machining. It can include mass, dimensions, external topography, visible flaws, channel clearance, selected internal imaging and a representative strength witness. Mass is a useful indicator of gross underbinding, trapped powder or material loss, but it cannot locate the cause or prove composition. Dimensions establish the starting point for state-resolved shrinkage but should be measured with low contact load.

The green hold answers a narrow but important question: is this body sufficiently known and intact to enter the declared binder-removal process? It does not accept the final product. Rejects are recorded against feed lot, bed position, geometry and removal history so that failures become process evidence. A high green yield achieved by silently discarding fragile features or repairing chips is not a capable process.

8. Metrology, monitoring and digital genealogy

Metrology follows the changing object rather than applying one final inspection to an unknown history. The feedstock, bed, green body, brown body and final material have different measurands and damage sensitivities. State-specific measurements create a causal record. Without them, final distortion or porosity may be attributed to the furnace even when the root cause was segregation, a recoater streak or a green-handling crack.

Feedstock metrology establishes the material entering the machine. Composition and binder fraction can be measured by complementary chemical and thermal methods. Microscopy can examine coating and agglomeration. Size analysis and flow tests characterise bounded aspects of delivery. Optical and thermal analysis can support energy-window design. Sampling must represent the package, coating batch and reuse history. A precise measurement of an unrepresentative sample is not control.

Bed metrology can include delivered mass, layer images, topography, temperature field and recoater response. Image normalisation, illumination, focus and calibration are necessary before image features can be compared across builds. A powder streak can be visible but not harmful, or harmful but hidden by lighting. Detection algorithms need labelled defect evidence and false-negative challenge. The disposition for missing or corrupted data is part of qualification.

Green-body metrology provides mass, geometry and surface before thermal conversion. Non-contact optical methods can capture accessible shape but may fail on dark, reflective or powder-covered surfaces. Contact methods can deform the part. Computed tomography can reveal internal channels, retained powder and low-density regions where material contrast and voxel size are adequate, but a scan protocol must be validated against known defects. CT is a measurement system, not an automatic truth source.

Brown-body measurements close binder removal. Mass change can be compared with the declared organic inventory, but a plateau does not prove spatially uniform removal. Residual carbon, solvent, decomposition products or migrated binder can remain locally. Dimensions and visible integrity show whether the skeleton survived, while representative chemical or thermal analysis can support residue closure. The inspection must not damage a body that cannot be safely handled.

Final metrology establishes actual composition, phase, density or designed porosity, dimensions, surface, defects and required properties. ISO/ASTM 52927 organises main characteristics and corresponding test methods [5]. Method selection remains driven by the product requirement. Density can be measured by several techniques with different sensitivity to open pores, closed pores and infiltrant; the reported method and conditioning are essential.

Process monitoring earns value by answering a defined decision. Recoater force can flag a raised region. Thermal imaging can flag local heat accumulation. Optical-source monitoring can detect drift. Layer images can locate disturbance. Furnace atmosphere and thermocouples can detect conversion excursions. None directly proves final acceptance. Each signal needs a calibrated acquisition chain, a bounded normal condition, alarm or analysis rule, link to defect evidence and authorised response.

Machine-learning classification does not remove this burden. A model trained on visually obvious defects may miss a binder-distribution shift or a new powder lot. Class imbalance can make reported accuracy look high while rare critical defects remain undetected. Training, validation and challenge data should preserve build position, material lot, reuse, geometry and adverse conditions. Model version, input availability and human override belong to genealogy.

Witness coupons are useful only when they share the causal history relevant to the product. A coupon at the bed edge cannot represent the centre thermal field without evidence. A thin bar cannot represent thick-part debinding. A separately sintered coupon cannot represent a dense furnace load. Coupon design should target specific mechanisms and be placed, removed and converted with the associated parts.

Measurement uncertainty and process variation must remain separate. If a dimensional shift is smaller than the measurement capability, tightening the process based on apparent values is misleading. Gauge studies, calibration and uncertainty budgets should cover green, brown and final states as applicable. Fragile-state fixturing and temperature conditioning can dominate the measurement.

Digital genealogy connects requirements with evidence. It includes material and binder lots; feed architecture and preparation; reuse and refresh; machine, recoater, optics and maintenance; file and software versions; build coordinate and orientation; layer and monitoring data; cooling and depowdering; green and brown holds; furnace, atmosphere and load; finishing; measurements; deviations and disposition. ISO/ASTM 52920 places such controls within production-site qualification [2], and ISO/ASTM 52951 supports the part-linked data package [7].

Data completeness has a release rule. A successful-looking part with missing critical genealogy is not automatically accepted. The organisation defines which missing signals can be replaced by independent evidence and which require rejection or concession. This prevents monitoring from becoming decorative data collection and prevents a database outage from silently weakening product assurance.

9. Debinding as geometry-dependent transport and chemistry

Debinding removes the polymer network that made the green body possible while preserving a connected inorganic skeleton. The operation is intrinsically unstable because the body can lose stiffness before the particles have gained strong inorganic bonds. The binder can soften, flow, evaporate, react or decompose. Products must leave through pores that are being created by the same removal process. Geometry, composition, atmosphere and support determine whether that transition succeeds. For corpus governance, ER-037 controls the generic binder-removal, gas-transport and brown-body defect architecture for binder-bearing powder-loaded green bodies; ER-155 retains powder-bed-specific feed architecture, depowdering, atmosphere, setter and final-conversion evidence.

A multi-component binder can use staged removal. A soluble or catalytic fraction may be removed first to create connected pores while a backbone preserves shape. A later thermal stage removes the remaining polymer. A single polymer can also be thermally decomposed through controlled ramps and holds. The correct sequence depends on chemistry and part geometry. Lotfizarei and co-workers review debinding mechanisms for powder-filled material extrusion [31]; those mechanisms are relevant here, but their schedules cannot be transferred into a powder-bed part.

Thermogravimetric analysis and calorimetry can identify transitions and small-sample mass-loss regions. They do not directly establish a production heating rate. A small sample has short transport paths and a different heat-transfer condition from a thick, enclosed or densely loaded body. The furnace adds temperature lag, gas flow and decomposition-product concentration. Kinetic or transport models can guide experiments only when their parameters and boundary conditions are validated.

Early heating can be more dangerous than the main mass-loss peak. Binder softening reduces green stiffness and can allow particles to settle, walls to slump or binder to migrate under gravity and capillary pressure. A surface skin can form if binder moves outward or decomposes faster near the surface. That skin can then restrict gas transport from the core. Setter contact, part orientation and local thickness should be chosen with this transient state in mind.

Gas generation must remain below the evolving transport capacity. Thick sections, dense contour skins, binder-rich zones, trapped powder and blind channels can extend the path. If internal pressure rises, it can create bubbles, cracks, delamination or rupture. A part may survive visually while developing internal pores. Development should therefore include deliberately adverse geometries and internal evidence, not only thin coupons.

Solvent debinding adds diffusion, swelling, bath loading, agitation, drying and solvent recovery. The binder may dissolve unevenly, redeposit during drying or carry fine powder from the surface. A mass plateau can indicate reduced extraction rate without proving uniform removal. Solvent identity, concentration, temperature, part spacing, bath age, flow, rinse and drying are process variables. Safety and waste controls follow the actual solvent and dissolved constituents.

Oxidising and inert thermal routes create different chemistry. Oxidation can assist polymer removal but can alter metals, carbides, carbon fibres or sintering aids. Inert conditions can protect the base powder while leaving carbonaceous residue. Vacuum or reducing environments introduce their own transport, flammability and equipment risks. The atmosphere is selected against both the binder products and the intended final material.

The furnace load changes local conditions. Closely packed green bodies release more organic products per gas volume. Parts can shield one another or change flow. Filters and cold surfaces can collect condensate that later contaminates equipment or subsequent loads. Load size, spacing, setter, packing media, gas direction, pressure and exhaust state belong to the validated cycle. A chamber setpoint and one thermocouple cannot prove uniform part experience.

Brown-body acceptance separates debinding from densification. It can include expected mass loss, geometry, visible and selected internal defects, residue or carbon evidence and setter condition. The body may be too fragile for routine transfer. A qualified procedure can keep it on the same setter or within a controlled support medium. If the body must be moved, the handling load is validated.

The mass balance connects original binder, extracted or volatilised products, trapped residue, filters, condensate, solvent, lost powder and part mass. It can reveal unexplained retention or loss. It also supports emissions and maintenance control. A clear exhaust does not prove complete or harmless decomposition; representative measurement follows the actual constituents and regulatory context.

Debinding capability should be expressed as a geometry and load envelope, not one recipe. The envelope includes maximum transport distance, wall and section transitions, enclosed features, green density, binder state, part mass, setter, orientation and furnace load. A new geometry outside that envelope requires additional evidence. This is one reason a broad printer build envelope can coexist with a much narrower qualified production envelope.

10. Densification, infiltration, shrinkage and distortion

After binder removal, the particle skeleton contains intentional pore volume approximately related to the removed binder plus pores from packing, green defects and any processing damage. Sintering reduces surface energy through particle neck growth,

diffusion, pore evolution and grain change. The final outcome depends on powder chemistry, surface, additives, green packing, residue, atmosphere, temperature, time, pressure and constraint. The printed pattern remains relevant because local binder and packing histories define the starting skeleton.

Pressureless sintering can produce a single-phase or multi-phase material when the powder and additives support densification. Pores may shrink, become isolated, migrate to grain boundaries or remain trapped. A low-density green interface can persist as a pore band. Binder residue can change local chemistry or inhibit sintering. Grain growth can close some pores while enlarging others. Final density is an outcome, not an explanation.

Isostatic pressing can increase green or sintered density and reduce some pore populations. Liu and co-workers combined indirect alumina shaping with isostatic pressing [18] and reported a metal route with isostatic assistance [22]. These studies establish specific combined chains. Pressure assistance adds equipment, encapsulation or handling, pressure uniformity, deformation and a new geometry transfer. A pressed outcome should not be attributed to powder-bed shaping alone.

Infiltration fills connected pore space with a second phase. Zeng and co-workers combined indirect alumina shaping with sol infiltration [19]. Liu and colleagues reported a copper-infiltrated Fe-Cu-Ni-C composite route [23]. Infiltration can improve density or functionality, but it changes composition and can create gradients, unfilled pores, reaction layers or excess surface material. The final product is an infiltrated composite and requires evidence for infiltrant distribution and service compatibility.

Reaction bonding deliberately changes chemistry during conversion. Dong and co-workers studied a porous alumina route combined with reaction bonding [20]. Reaction can create new phase and volume change, and it may preserve designed porosity rather than maximise density. The process should report the actual final phase assemblage and pore objective. “Near dense” and “porous with enhanced strength” are different design targets and cannot share an acceptance rule.

Shrinkage begins from the local inorganic volume and packing. A binder-rich region contains less inorganic skeleton and can shrink or distort differently after removal. A low-packed recoater streak can remain as a dimensional valley or pore zone. Scan heating can redistribute binder and alter edge composition. The furnace then adds gravity, setter friction, thermal gradients and phase change. Shrinkage is consequently a spatial and directional transfer field.

One linear compensation factor is rarely sufficient for complex geometry. Long, transverse and build directions can differ. Thick and thin regions can densify at different rates. Channels can ovalise. A flat surface can dish against a setter. An infiltrated region can change dimension differently from a pressureless-sintered one. Compensation should be fitted and validated for geometry families, orientations, build positions and furnace loads, with residual error and uncertainty reported.

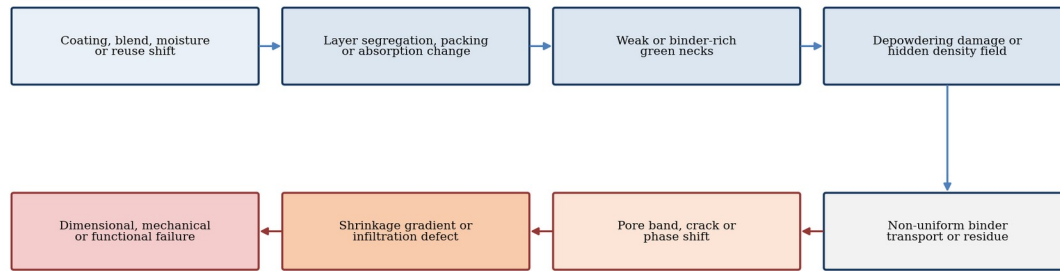
Distortion can dominate accuracy even when mean shrinkage is predictable. Hopkinson and Sercombe identified process repeatability and sources of error in indirect aluminium SLS, including important downstream contributions [25]. Zakaria and Dalgarno treated distortion in indirect metal processing [26]. Their work reinforces a critical industrial point: dimensional error can be created or amplified after a geometrically accurate green build.

Setters, packing media and supports influence shape. A flat setter can constrain one surface through friction. A powder bed or sacrificial support can distribute load while changing gas flow and surface condition. A reactive setter can contaminate or bond to the part. Support geometry must remain stable through debinding and densification while permitting shrinkage. Removal must not introduce final surface damage.

Atmosphere controls oxidation, reduction, evaporation, carbon and phase. Metals can require protection from oxygen and control of interstitials. Oxide ceramics can tolerate or require oxidising conditions that would destroy carbon-containing systems. Carbides and carbon fibres can react with oxygen or furnace constituents. One furnace platform does not imply one transferable atmosphere or load practice.

Furnace capacity should be evaluated in accepted parts per load and per time. A densely nested printer build can exceed debinding-gas capacity, setter area or sintering uniformity. Splitting one build into several furnace loads adds queue, genealogy and variable history. Conversely, a partially filled furnace can waste energy and produce a different thermal field. Printer and furnace capacity must be balanced during route selection.

Finishing can establish dimensional references, remove green-machined or sintered allowance, improve surface and prepare functional interfaces. It also exposes internal pores, introduces grinding or machining damage, changes residual stress and adds cost. For brittle ceramics, surface damage can control strength. For metals, machining and heat treatment can change the tested condition. Final acceptance names the finished state and preserves the route used to obtain it.



State-resolved evidence traces each final failure to the earliest observable and controllable cause.

Figure 2. Causal chain from feedstock variation to final-product failure.

The chain prevents root-cause collapse. A final crack is not automatically a sintering problem; it may have begun as a recoater streak or green-handling event. A surface pore is not automatically an energy problem; it may reflect binder removal or machining. State-resolved evidence allows corrective action at the earliest controllable cause rather than repeatedly adjusting the final furnace cycle.

11. Metals, ceramics and unusual powder systems

The route is attractive when direct melting is difficult, unnecessary or inconsistent with the required production system. It can shape powders on a comparatively low-temperature bed and defer final microstructure to a furnace process that shares knowledge with powder metallurgy or ceramic processing. That common architecture does not make all powders equally mature. Each material family has different oxidation, binder, densification, atmosphere, phase and property constraints.

For metals, the base powder must retain controlled alloy chemistry through coating, bed exposure, debinding and sintering. Fine metal powder can oxidise during preparation and reuse. Binder decomposition can change carbon or other interstitials. Sintering can produce porosity, grain growth and chemistry gradients. If infiltration is used, the final composition is a metal-metal or metal-other-phase composite rather than the original alloy. Heat treatment and machining become part of the tested condition.

Liu and co-workers demonstrated indirect metal routes combined with isostatic pressing [22], copper infiltration [23] and tooling manufacture [24]. These papers show that useful metal components can emerge from carefully defined downstream chains. They also illustrate why the word metal is insufficient. Near-dense pressure-assisted material, copper-infiltrated Fe-Cu-Ni-C composite and an injection-mould tool have different composition, pore, thermal and service requirements.

Aluminium is a useful test of process integration because its surface oxide and sintering behaviour complicate consolidation. Hopkinson and Sercombe examined repeatability and error sources in an indirect aluminium route [25]. A successful green shape cannot overcome uncontrolled oxide, furnace or distortion behaviour. Any modern aluminium implementation requires its own atmosphere, chemistry, density, microstructure and property evidence rather than transfer from a historical system.

Metal qualification begins with final alloy or composite identity. Chemical analysis addresses major elements and relevant interstitials. Density and pore morphology are linked to load-bearing section. Microstructure and heat treatment are documented. Tensile testing under ASTM E8/E8M can provide method-labelled strength and ductility [8], but specimens must preserve orientation, build position, furnace position, surface and extraction condition. A machined coupon is not whole-part proof, and a mean tensile result is not process capability.

Alumina is the most developed ceramic example within the selected literature. Cardon and co-workers examined coated alumina [13]; Deckers and colleagues treated indirect ceramic shaping [14]; Sassaman and co-workers studied geometry and bonding [15,16]; Liu and colleagues added isostatic pressing [18]; Zeng and co-workers used sol infiltration [19]; Dong and co-workers used reaction bonding [20]; and Li and colleagues provide a current phenolic-coated alumina study [21]. Together these works show a rich design space. They do not define one alumina process.

The alumina examples differ in binder, feed architecture, printer, pressure assistance, infiltration, reaction route, porosity target and final property. A route intended for dense structural alumina should not cite an intentionally porous reaction-bonded outcome as equivalent. An infiltrated body should identify the infiltrant and phase. A pressure-assisted body should include the pressure step in its qualification and economics. The evidence must follow the actual chain that produced the claimed product.

Ceramic acceptance is flaw-sensitive. Final density helps describe the material state but does not close pore size, pore location, interfaces, inclusions, phase or surface damage. Flexural strength under ASTM C1161 provides method-labelled data [9], and

ASTM C1239 supports population reporting [10]. Orientation, specimen preparation, surface finish and censored failures remain visible. Fracture origins should be investigated when strength or reliability matters, even when the mean value appears high.

Silica and glass routes emphasise viscosity, phase and geometry. Fan and co-workers examined fusion behaviour in a TrueForm/SiO₂ composite powder [27], while Nissen and co-workers developed channel design rules for glass components [17]. Glass can soften or crystallise through a distinct thermal history, and residual porosity can affect optical, fluidic or mechanical use. A helical channel that is shapeable still needs powder removal, internal-surface and final-function evidence.

Silicon carbide exposes the difference between a polymer composite and a final carbide body. Hon and Gill studied SiC/polyamide composites [28]. Chen and co-workers developed a core-shell chopped carbon-fibre/phenolic powder for Cf/SiC manufacturing [29]. These feedstocks can be suitable green intermediates or composite precursors, but the polymer-bound printed state is not dense SiC. Carbon retention, reaction, oxidation, fibre damage, phase formation and pore structure must be reported for the final material.

Carbon fibres, whiskers, platelets and elongated particles create directional behaviour before and after printing. Mixing and recoating can orient them. A coating can change fibre-fibre contacts and powder flow. During debinding, a network can help or obstruct gas transport. During sintering or reaction, differential shrinkage and interface chemistry can create cracks. A nominal fibre fraction cannot establish spatial orientation or load transfer.

Functional ceramics and unusual powders require property-specific closure. A dielectric ceramic requires phase, porosity, electrode preparation, frequency, temperature and loss conditions. A magnetic material requires composition, density, orientation and magnetic test conditions. A thermally conductive ceramic requires interface, porosity and measurement direction. A catalyst or porous structure may intentionally retain pores, but pore size, accessibility, surface chemistry and mechanical survival become requirements. Generic density and strength cannot substitute for the intended function.

Nano- and micron-scale powders listed by 3Dresyns include alloys, oxides, carbides, nitrides, rare-earth compounds, conductive carbon materials and other specialised candidates [35]. The range is useful for generating research and product hypotheses. It also makes transfer control essential. A rare-earth oxide, nitride, magnetic alloy, conductive carbon and bioceramic do not share binder compatibility, safe handling, atmosphere, densification or acceptance methods. The manufacturer page is therefore a scope map, not a qualification table.

Mixed and graded material systems can be considered only after each constituent route is stable. Composition gradients can alter optical absorption, binder demand, packing and shrinkage. Interfaces can react or separate during conversion. Powder recovery becomes difficult because unused material may contain mixed chemistries. A graded green body is not evidence of a controlled final gradient. Spatial chemistry and function must be measured after all thermal steps.

Table 2. Material opportunity, critical risk and non-transfer rule

Material or outcome	Why the route may be attractive	Critical complete-chain risk	Evidence required in the final state	What must not be transferred
Sintered metal alloy	Shape without direct melt-pool physics; dense bed nesting; furnace-led microstructure	Oxidation, carbon or interstitial drift, pores, distortion and heat-treatment variability	Chemistry, density and pore map, microstructure, orientation-labelled properties, dimensions and surface	Supplier shrinkage, density, reuse, cost or tensile values from another alloy or furnace
Infiltrated metal composite	Green geometry followed by pore filling and potential property tailoring	Incomplete or non-uniform infiltration, reaction, excess infiltrant and composition gradient	Actual phase fractions, infiltrant distribution, pores, interface, properties and service compatibility	Claiming the base powder as the sole final material or calling infiltration full density without method
Dense oxide ceramic	Avoid direct high-temperature optical coupling; complex green geometry	Binder residue, packing gradients, sintering cracks, grain and brittle flaw population	Phase, density and pore topology, dimensions, surface, statistical strength and fracture evidence	Alumina parameters or properties transferred to another oxide, coating or geometry
Glass or silica-based material	Low-temperature green shaping and internal-channel opportunity	Devitrification, viscosity history, trapped powder, pores and inaccessible internal surface	Composition and phase, pores, channel clearance, optical or functional evidence and dimensions	Green channel resolution treated as accepted final capability
Carbide or carbon-containing system	Access to difficult-to-melt or reaction-formed material systems	Oxidation, residual carbon, fibre damage, reaction gradients and high-temperature conversion	Final phases, carbon balance, porosity, interface, atmosphere history and required function	Polymer-composite green performance reported as dense carbide performance
Functional or exotic composition	Tailored electrical, magnetic, thermal, optical, catalytic or biological function	Agglomeration, contamination, phase loss, toxic or reactive powder, property gradients	Property-specific method under declared conditions plus composition, phase and geometry	Portfolio listing, theoretical property or base-powder data used as printed-product proof
Intentionally porous or reaction-bonded body	Controlled permeability, surface area, lower mass or reaction-derived phase	Weak pore network, non-uniform reaction, blockage and dimensional change	Pore distribution and connectivity, phase, strength or function, cleanliness and geometry	Dense-material acceptance logic or mean porosity alone

The material discussion leads to a practical selection rule. A candidate is not advanced because its chemistry is exotic or because it appears on a supplier page. It is advanced when a controlled route preserves or creates the required composition, structure and function with evidence. Polymer-binder powder-bed shaping is valuable only if it contributes to that outcome more effectively than a competing shape-making route.

12. Defects, properties and final-product acceptance

Defects should be classified by origin, state and consequence. Feedstock defects include incorrect binder fraction, coating discontinuity, agglomerates, contamination, moisture and reuse ageing. Bed defects include streaks, segregation, low packing and foreign material. Green defects include weak necks, delamination, curl, boundary bleed, trapped powder and handling cracks. Conversion defects include residue, blistering, pore bands, reaction gradients, distortion and setter contamination. Finishing defects include machining damage, opened pores and cleanliness failure.

The same final appearance can arise from different origins. A pore band can begin as a low-density recoater streak, binder-poor blend region or debinding crack. A warped edge can begin as scan heating, green creep or setter friction. Discolouration can reflect binder degradation, oxidation or furnace contamination. Corrective action therefore depends on state-resolved evidence. Increasing scan energy in response to a furnace-origin pore can worsen green caking without improving the product.

Defect criticality follows function and location. A surface-connected pore can control leakage or corrosion. An internal pore at a neutral mechanical axis can be less critical than a small edge flaw in a brittle ceramic. A trapped powder region can be harmless in one sealed demonstrator and unacceptable in a fluidic, medical, optical or vacuum component. Acceptance criteria should be connected to failure analysis and service requirements, not generic AM defect language.

Density is reported with method and material state. Archimedes, gas pycnometry, geometric mass-volume and image or CT methods measure different aspects. An infiltrated part can show high bulk density while retaining unfilled local pores. A porous design can be correct at lower density. The requirement may need open and closed porosity, pore size, distribution and connectivity rather than one relative-density value.

Dimensional acceptance uses the final coordinate system, measurement method and uncertainty. Critical features are selected before manufacturing. A global best-fit scan can hide a functional datum shift. Channel and lattice measurements need resolution and access evidence. Compensation is verified across lots, build positions, orientations and furnace loads. A one-time accurate part cannot establish capability.

Surface condition changes at every state. Binder bleed, particle size and depowdering affect the green surface. Debinding can open pores. Sintering can smooth necks or reveal grain and pore pull-out. Green machining, final machining, blasting or polishing changes the surface and may introduce damage or contamination. Surface acceptance therefore names the final processing state and functional direction.

Metal mechanical evidence includes declared orientation, build and furnace position, specimen extraction, machining, surface and heat treatment. ASTM E8/E8M gives a recognised tensile method [8], but the process must decide how coupon results relate to parts and how variability is sampled. Fatigue, creep, impact, corrosion or wear require separate service-driven evidence. Tensile strength cannot substitute for them.

Ceramic strength is a flaw-population result. ASTM C1161 and C1239 support method-labelled flexural testing and population reporting [9,10]. Specimen volume, surface, edge preparation, loading configuration and environment influence results. A small set of polished bars can overstate the reliability of an as-sintered complex part. Fractographic linkage between process-created flaws and failure should guide improvement and acceptance where consequence is high.

Functional materials need performance under declared conditions. Electrical conductivity can depend on direction, contact and temperature. Dielectric response depends on frequency, field and electrode. Thermal conductivity depends on density, phase and direction. Magnetic response depends on field history and orientation. Optical response depends on wavelength, surface and pores. Biological or chemical use requires composition, cleanliness and application-specific testing. The AM route does not supply these methods automatically.

Statistical planning distinguishes development from production. Development can use designed experiments to reveal mechanisms and interactions. Qualification demonstrates the frozen process across intended limits, lots, positions, geometries and equipment. Production control monitors variables shown to matter and samples outputs at a justified rate. Requalification rules cover material, binder, coating, machine, optics, recoater, software, geometry envelope, furnace, atmosphere, setter, finishing and inspection changes.

Nonconformance has a documented path. A deviation is identified against requirement and genealogy. Additional inspection can reduce uncertainty only if the method can detect the relevant defect. A concession is authorised by the responsible party with service consequence visible. Rework follows a qualified method. Scrap and recovered powder are segregated. Quietly repeating a build until one part passes hides process variation and understates true cost.

The final certificate or data package names the actual route and state. It should not describe a copper-infiltrated composite as a homogeneous steel, a pressure-assisted ceramic as simply SLS alumina, or a green polymer-SiC body as silicon carbide. It records permitted finishing and heat treatment, material lots, orientation, conversion route, inspection and disposition. Honest naming is a technical control because it prevents inappropriate design data and process transfer.

13. Selection, economics, safety, sustainability and factory qualification

Technology selection begins with a neutral final-product requirement. Polymer-binder powder-bed shaping is favoured when powder-bed support, dense nesting, a low-temperature geometric step, access to sinterable or difficult-to-melt materials, or separation of shaping and microstructure creates a complete-chain advantage. It is disfavoured when binder removal paths are long, trapped powder cannot be verified, final shrinkage tolerance is incompatible with geometry, furnace capacity is limiting, material is unsafe in powder form, or direct or mould-based routes meet the requirement with lower evidence burden. Direct metal powder-bed fusion is controlled by ER-145, with ER-146 providing the complementary direct metal-route qualification boundary; binder jetting is controlled by ER-147. ER-155 preserves these comparisons but owns only the pre-associated polymer-binder powder-bed route and its downstream inorganic conversion.

The comparison with direct powder-bed fusion should include feedstock cost and reuse, machine and atmosphere, energy source, support and removal, residual-stress or heat-treatment burden, surface, dimensional capability, final material properties, inspection and accepted yield. The indirect route can avoid a molten base-material pool but adds binder preparation, depowdering, debinding and large shrinkage. Neither route wins by definition.

The comparison with binder jetting separates how the green bond is placed. Binder jetting selectively deposits a liquid and can avoid scanning heat, but adds droplet, wetting, saturation, drying and printhead controls. Polymer-binder SLS carries binder throughout the feedstock and selectively activates it, adding composite-powder and thermal controls. Both require green handling and downstream conversion. The preferred route follows feature, material, production and evidence requirements.

The comparison with bound-powder extrusion distinguishes powder-bed support and nesting from road interfaces and feed mechanics. Extrusion can place only the required feedstock and simplify powder recovery, but it creates roads, seams and dedicated supports. The powder bed can support complex green shapes and many parts, but it exposes a large material inventory to thermal history and requires depowdering. Economics should include both advantages and all downstream capacity.

Complete-cell cost includes base powder, binder, coating or granulation, analysis, conditioning, losses, refresh, machine preparation, build, cooling, powder recovery, depowdering, green handling, debinding, sintering, infiltration or pressing, heat treatment, finishing, cleaning, inspection, rejects, maintenance, consumables, labour, energy, capital and queue. The denominator is accepted parts, not started builds or green bodies. Yield is state-resolved so that improvement targets the dominant loss.

Throughput is constrained by the slowest coupled resource. A printer can complete green builds faster than depowdering or furnaces can convert them. Dense nesting can improve printer output while creating an organic load that exceeds the debinding envelope. Furnace batches can wait for compatible materials or atmospheres. Green parts can require controlled storage. A factory model therefore includes buffers, maximum holds, load compatibility, maintenance and rework.

Commercial sources describe ColdMetalFusion as a serial-production metal-AM workflow [32-34]. Those sources are useful for identifying the declared system and the use of green-part processing. They are manufacturer-affiliated and cannot independently establish a universal powder reuse fraction, shrinkage, cost reduction, density, speed or part quality. Any such value must be verified in the buyer's material, geometry, equipment, furnace and accounting boundary.

Safety is task- and substance-specific. Fine metal powders can be combustible or reactive. Nickel-, cobalt- or other alloy constituents can present sensitisation or toxicity concerns. Ceramic and carbide dust can be respirable or otherwise hazardous. Nanoparticles can agglomerate while still creating exposure during handling or cleaning. Binder powders, additives, solvents and decomposition products add chemical and thermal hazards. The NIOSH AM resource supports process-specific hazard recognition and controls [11], not a generic declaration that all AM powders share one risk.

Exposure points include receiving, sampling, blending, coating, drying, sieving, machine filling, recoating upset, cake excavation, vacuum and filter service, recovered-powder handling, green machining, debinding exhaust, furnace maintenance, blasting, grinding and waste. Enclosure, local exhaust, compatible vacuum systems, grounding, inerting, housekeeping, personal protection and monitoring are selected through a formal assessment. Compressed air can disperse hazardous dust and is not a default cleaning method.

Combustible-dust and reactive-material controls depend on powder chemistry, size, concentration, ignition sources and jurisdiction. A polymer coating can change ignition and electrostatic behaviour. Inert machine operation does not protect open transfer or filter service. Cross-contamination can change both material performance and hazard. Emergency planning must include fire response appropriate to the actual powder rather than generic water use.

Debinding and sintering add hot surfaces, flammable or toxic decomposition products, solvents, controlled atmospheres, vacuum, pressure and asphyxiation risks. Exhaust design and monitoring follow the binder mass and chemistry. Condensate, filters and furnace residue are managed as potentially contaminated waste. An odour threshold is not an exposure limit, and the absence of visible smoke is not evidence of adequate capture.

Sustainability assessment uses the complete route and a functional unit such as one accepted part meeting a stated requirement. Powder-bed nesting and powder recovery can reduce support material or improve machine utilisation. Coating losses, refresh, filters, solvent, long thermal cycles, furnace underfill, rejected parts and finishing can offset those benefits. A lower shaping temperature does not establish lower energy when high-temperature densification dominates.

Reuse should distinguish avoided virgin powder from degraded or down-cycled material. Recovered feedstock that requires increasing refresh, causes defects or is discarded after few cycles does not support a simple closed-loop claim. Mass balance records virgin input, recovered powder, accepted-part mass, process loss, filters, samples, spills, caked material and rejects. Energy and emissions are allocated across accepted output.

Factory qualification integrates organisation, material, equipment, process and product. ISO/ASTM 52920 provides production-site and process qualification principles [2]. The site controls trained roles, suppliers, material quarantine and release, calibration, maintenance, software, environment, cleaning, cross-contamination, deviations, records and requalification. Outsourced coating, debinding, sintering, HIP or testing remains within the qualified supply chain.

Table 3. Polymer-binder powder-bed qualification and publication gate

Gate	Required closure	Representative evidence	Mandatory rejection condition
A. Final requirement and route identity	Product state, function, composition, process boundary and alternatives are explicit	Requirements review; mechanism map; direct-PBF, binder-jetting and extrusion comparison	Green body or marketing process name is treated as the final product
B. Feedstock and powder bed	Composite architecture, lots, binder, moisture, coating, flow, spreading, absorption, reuse and contamination are controlled	Incoming and batch tests; coating/blend records; spreading challenges; reuse genealogy	Unknown composition, mixed history, unqualified reuse or unreleased feedstock
C. Selective shaping	Energy window, layer integrity, build position, layout, cooling and green bond are bounded	Calibration; layer and green tests; worst-position and full-height challenges; monitoring response	Missing critical process data, unbounded thermal interaction or fragile green features
D. Depowdering and green state	Removal access, trapped powder, handling, machining, storage and green hold are controlled	Removal trials; mass and geometry; channel evidence; task-specific green strength	Unverified trapped powder, informal repair, damage or exceeded green hold
E. Binder removal	Chemistry, transport distance, atmosphere, load, support, residue and mass balance are closed	Thermal analysis; representative geometry; brown-body inspection; exhaust and mass records	Unexplained residue or mass, cracking, unqualified geometry or overloaded cycle
F. Densification and finishing	Sintering, infiltration or pressing, shrinkage, phase, furnace position, setter and finishing are controlled	Load maps; profiles; dimensions by state; phase and pore evidence; finishing records	Universal shrinkage factor, undisclosed infiltrant, phase drift or uncontrolled distortion
G. Final product	Actual composition, geometry, surface, defects, properties, statistics and service evidence meet requirements	Method-labelled testing; orientation and population; uncertainty; authorised disposition	Mean density or strength alone, wrong material name, failed requirement or missing genealogy
H. Release and publication	Independent review, issue disposition, author countersignature, file parity and metadata are complete	Controlled audit; checksums; source and hyperlink verification; publication checklist	Open major discrepancy, DRAFT marker, unapproved author metadata or incomplete file

The final gate deliberately extends beyond manufacturing into document release. An engineering paper can influence material selection and safety. A manuscript with an unresolved technical discrepancy, wrong author control, broken source or mismatched PDF should not be published merely because the manufacturing argument is attractive. The same evidence discipline applied to the process must apply to the record that describes it.

14. Conclusions and research priorities

Polymer-binder powder-bed shaping is not a colder version of direct metal fusion and not binder jetting without a printhead. It is a distinct indirect state chain in which a pre-associated polymer is selectively activated to create a green geometry and the intended inorganic material emerges later. Its industrial value lies in decoupling shape formation from final densification while preserving powder-bed support and nesting. Its central risk is that the decoupling also separates visual printing success from material success.

The first conclusion is that route identity must be mechanism-based. *SLS*, *indirect laser powder-bed fusion*, *cold fusion* and commercial names can describe overlapping implementations, but they do not establish what melted or what final state exists. A reliable specification names the feed architecture, dominant green-bond mechanism and downstream conversion.

The second conclusion is that the composite powder is the primary process material. Base-powder certification alone cannot release it. Binder distribution, coating or granule integrity, moisture, absorption, flow, spreading, thermal state, ageing and reuse determine the bed and green network. The most useful feedstock test programme connects each measurement with an actual failure mode.

The third conclusion is that powder-bed support is conditional. It can enable channels, overhangs and dense nesting without discrete green supports, but the powder must still be removed without damage and with verified cleanliness. Internal geometry that cannot be emptied, debound or inspected is not industrial design freedom.

The fourth conclusion is that the green bond is a controlled temporary structure. More energy or binder can improve immediate strength while worsening boundary accuracy, powder recovery, decomposition burden, residue or distortion. The correct shaping window protects four outputs simultaneously: bed integrity, adequate green strength, recoverable adjacent powder and downstream convertibility.

The fifth conclusion is that geometry capability is the intersection of shaping, removal, transport and densification. Spot size, layer thickness and green-feature survival are only early constraints. Final minimum wall, channel, span, scale and tolerance must survive powder removal, binder loss, shrinkage, furnace constraint and finishing.

The sixth conclusion is that debinding often defines the qualified envelope more strongly than the printer. Gas and solvent transport scale with geometry and load. Early binder softening can destabilise the body before sintering provides strength. A small thermogravimetric sample or thin coupon cannot qualify a thick, enclosed production part.

The seventh conclusion is that shrinkage is a field rather than a number. Feedstock distribution, layer packing, scan history, orientation, geometry, gravity, setter, atmosphere and furnace position create spatial and directional dimensional transfer. Compensation must be versioned and validated against geometry families and final-state measurements.

The eighth conclusion is that post-densification route names matter. Isostatically pressed, infiltrated, reaction-bonded and pressureless-sintered materials are different products and evidence chains. An infiltrated composite must not be reported as the uninfiltrated base powder, and an intentionally porous body must not be judged by a dense-material target.

The ninth conclusion is that material maturity is uneven. Alumina provides multiple documented architectures and post-process routes, while many unusual powders remain hypotheses requiring feed, safety, atmosphere, phase and function development. The breadth of the 3Dresyns advanced-material portfolio supports opportunity generation [35], not blanket processability.

The tenth conclusion is that performance evidence must match material failure. Metals require chemistry, pores, microstructure, heat-treatment and orientation-labelled properties. Ceramics require phase, flaw population, surface and statistical strength. Functional materials require the actual electrical, thermal, magnetic, optical, catalytic or biological property under declared conditions. Density alone is never a universal proxy.

The eleventh conclusion is that complete-cell productivity can contradict printer productivity. Dense nesting, low shaping temperature or rapid scanning can appear favourable while powder preparation, cooling, depowdering, debinding, furnace capacity, finishing and rejects dominate cost and energy. Comparisons must use accepted parts and the same final requirement.

The twelfth conclusion is that manufacturer evidence and independent evidence have different roles. Headmade Materials sources can describe the declared ColdMetalFusion implementation [32-34], and 3Dresyns can define a broad material and route opportunity [35]. Neither independently proves numerical performance for another factory. Commercial claims become engineering evidence only after controlled validation in the intended system.

Research should prioritise measurements that link states. High-value work includes quantitative maps from coating and bed packing to green-neck topology; validated in-situ indicators of weak bonding and binder degradation; models that couple part geometry, organic load and furnace transport; spatial shrinkage prediction with uncertainty; non-destructive detection of retained powder and brown-body cracks; and property datasets that preserve feed lot, build position, furnace position and finishing.

Feedstock research should compare dry blends, coatings, core-shell particles and granules under identical spreading, energy, reuse and conversion tests. Reporting should include binder distribution and residue, not only nominal fraction. Reuse studies should challenge repeated thermal and handling history and report composition, fines, absorption, bed behaviour, green strength and final properties. A claimed reuse fraction without those data has limited transfer value.

Design research should move beyond isolated minimum features. Representative artefacts should combine thin and thick regions, long and blind channels, nested bodies, full-height histories and furnace interactions. The output should be a state-resolved capability map: shapeable, removable, debindable, densifiable, inspectable and finally acceptable.

Qualification research should develop common evidence structures without forcing common recipes. Standardised data fields for composite-powder architecture, binder state, green and brown holds, furnace load and dimensional transfer would improve comparison. Material-specific acceptance would remain tied to chemistry, function and service. This separation between shared evidence architecture and non-transferable process values is essential for responsible scale-up.

The practical final decision is clear. Select polymer-binder powder-bed shaping when its powder-bed support, nesting and material-temperature separation create a verified advantage across the whole cell. Reject or redesign the route when trapped powder, binder transport, shrinkage, atmosphere, safety, furnace capacity or evidence burden cannot be closed. Do not release the product, and do not publish the process claim, until the actual final material, defects, properties, files and metadata pass their respective gates.

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