

Ceramic and Sand Binder Jetting

Powder Packing, Binder Distribution, Depowdering, Consolidation, Moulds, Cores and Qualification

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Statement of Significance

Binder jetting can form complex ceramic green bodies and disposable sand moulds or cores without scanning a high-energy beam through every part volume and without permanent pattern tooling. That shared description hides two different industrial products. A printed ceramic compact normally needs curing, depowdering, binder removal and then sintering, infiltration, reaction bonding or another declared consolidation route. A printed sand mould or core is a porous foundry tool: after curing, cleaning, coating or assembly as required, it receives molten metal and is later broken away. The printed sand is not the casting, and the printed green compact is not a dense ceramic. Both routes depend on a coupled powder–liquid–machine system. Particle morphology, agglomeration, packing and layer formation control pore topology. Binder viscosity, surface tension, waveform, drop volume, spacing, wetting, capillary penetration, evaporation and cure control where bonds form. More binder may increase handling strength while worsening bleed, accuracy, burnout, permeability, gas generation or casting defects. Coarser flowable powder may spread well but sinter poorly; fine sinter-active powder may agglomerate and form an uneven bed. Loose powder can support geometry only when it can later be removed. This review establishes a state-resolved factory framework for structural and functional ceramics, infiltrated or reaction-bonded materials, and printed sand moulds and cores. It treats complete-cell economics, exposure, emissions, reclamation, brittle qualification and casting acceptance. It supplies no transferable powder blend, binder, saturation, waveform, layer, cure, debinding, sintering, infiltration, coating or pouring recipe.

Abstract

Binder jetting selectively deposits liquid binder into successive powder layers. The process family can handle ceramics, sands and refractory powders, but the printer normally establishes a porous bonded architecture rather than the final material state. Powder flowability, packing, spreadability and sinterability are distinct coupled properties; no single particle-size, shape or apparent-density measure proves a suitable bed. Binder saturation is an emergent liquid-volume field produced by droplet generation, spacing, powder pores, wetting, capillary flow, evaporation and cure, not an independent quality variable. Printhead addressability is therefore not final resolution. The green body must survive curing, depowdering and handling, while excessive binder can enlarge features, create gradients, obstruct burnout, change permeability and increase emissions. Structural ceramic routes require controlled debinding and either sintering, slurry or precursor infiltration, polymer infiltration and pyrolysis, metal infiltration, reaction bonding or another declared mechanism. These routes can leave residual porosity or retained infiltrant and can change final material identity. Printed-sand routes end at a functional porous mould or core whose strength must be balanced with permeability, gas evacuation, refractoriness, thermal response, coating, collapsibility and shakeout. Casting quality belongs to the combined mould/core–alloy–pouring–solidification chain. This qualitative engineering review connects material release, recoating, droplet deposition, curing, depowdering, consolidation or casting use, finishing, inspection, safety, economics and qualification. It excludes concrete and macroscopic construction deposition and makes acceptance depend on a complete, route-specific evidence chain.

Keywords: binder jetting; ceramic binder jetting; 3D sand printing; powder packing; powder spreading; binder saturation; droplet penetration; depowdering; sintering; infiltration; reaction bonding; sand mould; sand core; casting; qualification

1. Purpose, scope and terminology

ISO/ASTM 52900 defines binder jetting as selective deposition of a liquid bonding agent to join powder materials [1]. The category describes how a layer is patterned; it does not specify powder chemistry, liquid composition, printhead architecture, cure mechanism, final density or product. ‘Binder jetting’, the historical label ‘three-dimensional printing’, and supplier-specific names are treated here as overlapping process terms. They are not evidence that two cells share a process window.

The scope begins with incoming ceramic powder, sand or refractory aggregate; any activator, flow aid or blended constituent; and the binder, solvent, catalyst or curing chemistry. It includes identity and release, storage and conditioning, mixing or granulation, recycling and refresh, feed delivery, layer spreading, compaction, binder preparation and filtration, printhead operation, droplet placement, wetting and penetration, interlayer registration, evaporation or cure, build completion, depowdering and green handling. It then follows one of two routes through its final acceptance state.

In the **structural or functional ceramic route**, the printed object is a green compact. A cure or drying step may strengthen it, but temporary binder normally remains. The route can then include debinding or pyrolysis, a fragile brown or porous intermediate, sintering, one or more infiltration cycles, reaction bonding, cooling, finishing, cleaning, inspection and final property testing. NIST identifies the non-dense printed state and necessary consolidation as a central ceramic-AM measurement and industrialisation problem [13]. ‘Printed alumina’, ‘binder-jetted silicon carbide’ or ‘printed dielectric’ is incomplete unless final phase, porosity, infiltrant and thermal route are stated.

In the **sand mould and core route**, the printed object is a porous tool for metal casting. It may be cured, depowdered, cleaned, coated, assembled with cores, closed and preconditioned before pouring. The casting is produced only after alloy preparation, pouring, solidification and cooling, then shakeout, core removal, cleaning, heat treatment or finishing and inspection. A mould or core can therefore be in its intended final tooling state without sintering to a dense ceramic. Its controlled porosity is functional, not automatically a defect.

ER-147 controls metal binder jetting when the delivered product is principally a metallic component. ER-151 controls ceramic vat photopolymerisation, ER-152 ceramic direct ink writing, ER-154 bound-ceramic filament or pellet extrusion, and ER-155 powder-bed routes in which a polymer binder is itself fused or consolidated rather than selectively jetted as liquid. A ceramic powder bed infiltrated with metal remains in ER-153 when the binder-jetted ceramic preform and its resulting composite identity are the central chain. The boundary is declared by the material state and acceptance requirement, not by a marketing label.

This paper excludes cement, concrete, geopolymer, regolith and other macroscopic construction deposition. Foundry sand moulds and refractory cores remain included because they are precision tooling in a controlled metal-casting chain, not large-volume construction. It also excludes a supplier's advanced-material list as evidence that a given powder–binder–machine system is mature. The current 3Dresyns advanced-material page is used only to define manufacturer-declared scope and validation responsibility [35].

Terminology is state specific. `Feed powder` is the released blend before spreading. `Powder bed` is the machine-created layered state. `Printed region` contains selectively deposited binder; `unbound powder` surrounds and may occupy cavities. `Green part` has enough cohesion for the next operation but has not reached its final ceramic state. `Brown part` is used only when binder removal has left a recognised porous ceramic intermediate. `Infiltrated`, `reaction-bonded` and `sintered` describe different material mechanisms. `Mould` and `core` describe casting tools; `casting` describes the solidified metal product.

ISO/ASTM 52901 requires customer and provider to define the delivered state, requirements, inspection and documentation for purchased AM parts [4]. ISO/ASTM 52910 supports requirements-led design communication [3], and ISO/ASTM 52927 can organise relevant characteristics and test methods [5]. A useful ceramic requirement names composition and phase, retained infiltrant if any, intended porosity, surface state, critical geometry, functional properties and inspection. A useful sand-tool requirement names sand and binder system, cure state, strength and permeability targets, gas and thermal behaviour, coating/assembly state, alloy and pouring envelope, and casting acceptance. `Binder-jetted part passed` is not an acceptance requirement.

This review deliberately does not prescribe powder grade or distribution, recycled fraction, blend ratio, humidity, layer thickness, recoater, compaction, binder chemistry, viscosity, surface tension, waveform, droplet size, spacing, saturation, cure, depowdering method, debinding, atmosphere, furnace schedule, infiltrant, coating, preheat, pouring temperature or acceptance threshold. Every such value belongs to a declared material–machine–geometry–post-process–use system.

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 two state-resolved routes

Sachs and co-workers established the powder-layer and selectively printed binder concept for ceramic tooling and preforms [16]. That foundational sequence remains recognisable, but modern equipment can use different feed mechanisms, recoaters, printheads, liquids, environmental controls and thermal routes. The common front end is best understood as material-state creation rather than a list of machine settings.

Released powder is transported to a feed region and spread into a layer. The spreading operation sorts, translates, rolls, shears or compacts particles according to the powder and recoater. A printhead then ejects timed droplets while traversing or while the bed moves. Droplets impact the rough porous surface, spread across particles, penetrate through capillaries, may displace fine particles and may merge with neighbouring drops. Evaporation, reaction or heating changes the liquid while the next powder layer is placed. The cycle repeats, so lower layers accumulate binder, heat, time, compression and possible migration histories different from upper layers.

After the final layer, the build is not automatically ready for extraction. The binder may require an in-machine or external cure, controlled cooling or drying. The unbound bed can temporarily support weak features, but removing it transfers loads to the printed network. Vacuuming, brushing, air flow, vibration, excavation or automated powder removal imposes forces and can erode edges or fracture thin sections. Internal channels require access and a removal path. Residual powder can later sinter to a surface, contaminate an infiltrant, obstruct a mould vent or become an uncontrolled inclusion.

The route then branches. For a structural ceramic, the green compact is debound and consolidated. Sintering relies on powder surfaces and diffusion, so bed density, binder residue, particle distribution, temperature field, atmosphere and support determine shrinkage and pores. Infiltration adds a liquid or precursor to accessible pores; reaction bonding intentionally transforms or combines phases. The final material may therefore be alumina with residual porosity, an infiltrated composite, a silicon-containing reaction-bonded SiC, or another explicitly named state. It is never acceptable to collapse these outcomes into `dense ceramic` without measurement.

For a sand mould or core, the cured porous body can be the final tool. It may receive a refractory coating, be dried, assembled, sealed, vented and supported. Molten metal then imposes pressure, heat, chemical interaction and gas generation. The tool must resist erosion and penetration long enough to control geometry, yet allow gas transport and later collapse or removal without

tearing or cracking the casting. After solidification, the sand tool is destroyed during shakeout or core removal, and the casting becomes the object of acceptance.

Table 1. Dual state-resolved binder-jetting chain

Stage	Common controlled state	Structural or functional ceramic route	Sand mould or core route
Material release	Powder/sand identity, blend, moisture, agglomerates, binder and sampling	Ceramic phase, impurities, sintering aids and final-composition plan	Sand/refractory identity, binder/activator, reclaim fraction and casting compatibility
Layer formation	Feed delivery, spreading, compaction, roughness, density and repeatability	Packing and pore network for printing and later consolidation	Packing and pore network for strength, permeability and surface response
Binder deposition	Droplets, wetting, penetration, coalescence, registration, cure and migration	Green architecture with controlled binder burden	Porous tool architecture with controlled binder and gas burden
Cure and depowder	Strength, dimensions, internal access, residual loose powder and handling	Green compact released for debinding/infiltration/sintering	Mould/core released for cleaning, coating and assembly
Route-specific transformation	Not a common final state	Debind, sinter, infiltrate or reaction bond; finish and test	Pour and solidify metal; shakeout, clean and inspect casting
Delivered acceptance	Genealogy, deviation status and authorised disposition	Declared final ceramic/composite identity, geometry, flaws and properties	Declared tooling state plus acceptable metal casting outcome

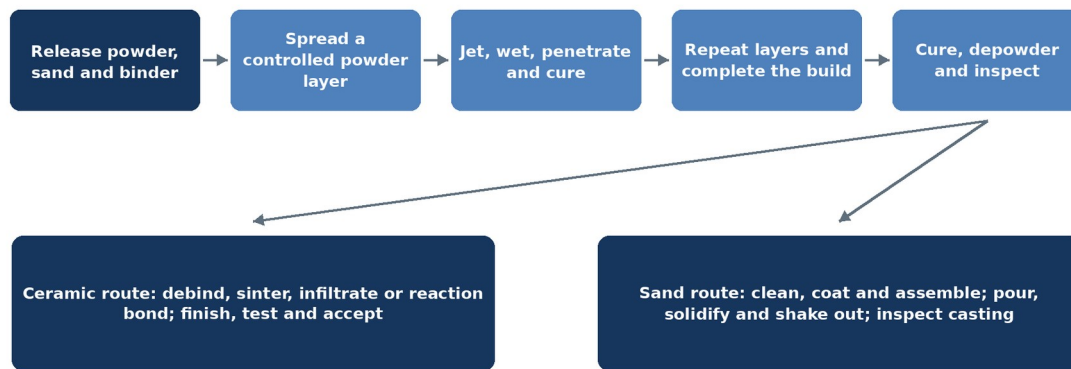


Figure 1. Dual state-resolved ceramic and sand binder-jetting route.

Genealogy links every final disposition to both the common front end and the branch. It includes material lots, supplier certificates and incoming tests; blend, conditioning and recycling history; storage time and environment; feed and build-box identity; recoater geometry and condition; printhead and nozzle status; liquid batch, filtration and age; machine, software and file versions; coordinates and orientation; build, cure and depowder records; and route-specific furnace loads or foundry operations. ISO/ASTM 52951 supports part-linked data packages [7], and ISO 17295 supports unambiguous orientation and coordinates [6].

Hold points prevent state conflation. Powder release authorises only use within its defined condition. A completed build authorises controlled cure, not handling. A cured bed authorises depowdering only when the green body can survive the selected method. A green ceramic hold authorises debinding or infiltration, not service. A cured mould hold authorises coating or assembly, not pouring with any alloy. Final release belongs to the declared component or casting after inspection and authorised disposition.

Mass balance follows the state chain. Virgin and reclaimed powder or sand are separated; refresh rules are documented. Binder delivered to the bed is distinguished from purge, cleaning liquid, evaporated material and waste. Powder becomes accepted parts or tools, trapped residue, recyclable unbound material, sweepings, contaminated waste, test specimens and rejects. A nominally high material-reuse fraction is not equivalent to stable material condition.

3. Powder and sand identity, morphology, packing and flow

Powder establishes the solid skeleton into which liquid is deposited. Composition, phase, impurity, particle morphology, size distribution, specific surface, porosity, surface chemistry, agglomeration, moisture and electrostatic behaviour can all affect layer formation and binding. In a structural ceramic they also affect debinding, sintering, phase evolution and final properties. In a sand tool they affect permeability, thermal response, refractoriness, surface finish, reclamation and interaction with binder and metal.

‘Flowability’, ‘spreadability’, ‘packing density’ and ‘sinterability’ answer different questions. A funnel or rotating-drum result can characterise one bulk-flow regime but not the thin layer created under a specific blade or roller. Apparent density does not reveal local voids, segregation or roughness. A powder that spreads smoothly can pack loosely. A highly packed bed can have a pore distribution that limits binder penetration or gas transport. A fine powder with high surface area can sinter readily but be cohesive and difficult to spread. Kwiatkowski and co-workers documented substantial grade-dependent differences in alumina particle and surface characteristics and explicitly connected them to both layer formation and sintering selection [23].

Particle shape introduces competing effects. Rounded particles often reduce interlocking and can improve bulk flow, while angular particles may resist rearrangement and increase bed roughness. Yet irregular shapes can pack beneficially in some multimodal blends or improve green interlocking. A broad size distribution can fill interstices, but excessive fines can coat larger

particles, increase binder demand, agglomerate, migrate during spreading or alter permeability. A bimodal or granulated system is therefore a controlled material architecture, not an automatic improvement.

Agglomerates require classification. Soft agglomerates may break during conditioning or spreading; hard agglomerates can protrude through a layer, obstruct the recoater, create local low-density regions or survive into the final component. Granules may be intentionally engineered to improve flow and later disintegrate or sinter, but their binder, porosity and crushing behaviour become additional variables. Sieving removes some oversize material but cannot prove that the distributed bed has the intended microstructure.

Moisture and environment change both ceramic and sand powders. Adsorbed water can modify cohesion, electrostatic charging and wetting. Hygroscopic constituents can change with storage and exposure. Sand binder systems may depend on water or catalyst balance, while uncontrolled humidity can change cure and green properties. Storage container, opening time, conditioning, room state and time at machine therefore belong to the material record.

Powder recycling changes the population. Unbound material can acquire binder droplets, cured fragments, fines depletion, broken granules, foreign particles, moisture or thermal history. Sand reclamation after casting adds a much more severe history: residual binder, dust, altered grains and contaminants can affect subsequent moulds. Virgin/reclaimed ratio is insufficient unless the reclaimed stream has a release specification and representative sampling.

Incoming tests are selected from failure hypotheses. They can include phase and chemistry, moisture or loss on ignition, size distribution under a declared dispersion protocol, morphology, specific surface, bulk and tapped density, flow and shear response, electrostatic tendency, refractoriness and thermal expansion for foundry aggregates, or sintering response for structural ceramics. None alone establishes printability. The release plan needs correlations from incoming attributes to layer, green and final outcomes.

Utela and co-workers framed new binder-jetting material development as a coupled progression through powder, binder, printing and post-processing rather than a powder substitution exercise [18]. Ziaee and Crane similarly show that powder deposition, wetting and post-processing form one system [19]. The practical implication is strict change control: a new supplier, grade, granulation route, reclaim fraction or conditioning method can require more than a certificate comparison.

Functional ceramics add composition-distribution risk. Pruvost and co-workers investigated powder optimisation for BaTiO₃ and Ba_{0.6}Sr_{0.4}TiO₃ binder jetting [24]. Their work supports material-specific control of powder architecture and final functional processing; it does not establish that an oxide dielectric formulation transfers to another composition. For any functional material, segregation, volatilisation, secondary phase and electrode or atmosphere compatibility must be assessed after the full route.

4. Layer spreading, compaction and powder-bed uniformity

The recoater converts a three-dimensional bulk powder into a thin process layer. Blade, roller, counter-rotation, vibration or other mechanism imposes a distinct stress and velocity field. Feed volume, traverse, gap, layer increment, build-box motion, powder temperature, humidity, electrostatics and the roughness of the previously printed layer all affect the result. Layer thickness is therefore a commanded displacement, not proof of a uniform deposited layer.

Common defects include feed starvation, waves, ridges, streaks, dragged agglomerates, segregation, local compaction, powder avalanching, edge effects and disturbance of a weak prior layer. A recoater can push or fracture an emerging feature after binder deposition. Accumulated height error can place the top of a part in the recoater path. A layer image can detect some surface anomalies while missing subsurface density variation.

Bed density and roughness should be treated as spatial fields. Representative evidence can combine mass/volume methods, witness regions, surface imaging, profilometry, computed tomography or destructive sections, depending on scale and material. The measurement must distinguish the feed bed from the printed region because binder can swell, dissolve, migrate or pull particles together. It should also address build position and time, not only a central first layer.

Compaction is conditional. Increasing roller action may improve packing in one powder while sorting particles, crushing granules, disturbing printed regions or changing pore access in another. Structural ceramics can benefit from higher and more uniform green density, but excessive or nonuniform compaction can produce anisotropic shrinkage. Sand tools need adequate surface and strength while retaining gas transport and collapsibility. The desired state is therefore route specific.

Layer validation uses adverse but permitted conditions: beginning and end of a powder lot, maximum reuse fraction, long build duration, edge and corner positions, wide continuous printed areas, isolated small features, interrupted operation and environmental extremes. A stable nominal layer does not close these cases. Process monitoring can flag recoater force, height, image or feed anomalies, but each signal requires a validated relation to a defect and a documented response.

The build layout also changes layer behaviour. Dense nesting can produce broad wet regions and differential evaporation. Large cross-sections may accumulate more liquid and heat than sparse ones. A powder-only witness cannot reproduce those interactions. Qualification artefacts therefore include representative area fractions and transitions, not only small bars or cubes.

5. Binder formulation, droplets, wetting, penetration, saturation and curing

Binder liquid must be compatible with storage, delivery, nozzle materials, droplet formation, powder wetting, cure and downstream thermal or casting operations. Relevant attributes can include identity, concentration, viscosity, surface tension, density, conductivity or charge behaviour where applicable, pH, volatility, particle or gel contamination, filtration, dissolved gas, aging and temperature. A change in solvent, resin, catalyst, humectant or biocide can affect printhead reliability and final properties.

Moon and co-workers demonstrated that binder properties interact with ceramic powder-bed roughness and pore size to govern penetration and printed line width [17]. The enduring lesson is a coupling, not a recipe. A liquid that forms stable droplets may wick too far in one bed, remain at the surface of another, or penetrate differently after the powder has been recycled or humidified. The binder must therefore be qualified against the actual bed state and cure history.

Droplet generation depends on the declared printhead. Waveform, actuator response, nozzle geometry, liquid temperature, viscosity, surface tension, back pressure, meniscus condition, dissolved gas, nozzle wetting, contamination and firing frequency can change volume, velocity, trajectory, satellites and missing jets. Nominal printhead resolution describes addressable positions; it does not measure where liquid and particles finally reside.

After impact, the drop can spread across the rough surface, penetrate vertically and laterally, merge with neighbours, move particles, evaporate or begin reacting. Capillary pressure depends on the local pore distribution and wetting, while viscous resistance and cure change with time. Repeated droplets can encounter already wet material. A newly spread layer can absorb liquid from the layer beneath. These histories create gradients through thickness and around edges.

‘Saturation’ is often used to express a liquid volume relative to an estimated pore volume. The value is meaningful only when its basis, powder-bed density, droplet calibration, spacing, overlap and computation are declared. Two cells with the same displayed saturation can deliver different liquid fields. Local saturation can differ from the programmed average because jets fail, droplets merge, pores vary, edges wick and evaporation proceeds.

Binder quantity creates a two-sided window. Too little binder can produce discontinuous necks, low green strength, delamination and depowdering failure. Too much can cause lateral bleed, dimensional growth, rough or swollen edges, blocked pores, long drying, cure migration, debinding cracks or residue. In sand tooling it can also reduce permeability, increase gas or emissions and impair collapse. The target is not maximum green strength; it is enough route-specific integrity with acceptable downstream behaviour.

Cure mechanism is identified rather than assumed. Thermal drying removes solvent but can produce gradients and skinning. A thermosetting binder can continue reacting after solvent loss. Inorganic systems can depend on water removal, salt chemistry or gas exposure. Catalyst or activator may reside on the powder or in the jetted liquid. Each architecture changes pot life, nozzle exposure, cure location and reclaimed-powder condition.

The printhead fluid path needs its own control plan. Tank, tubing, filters, degassing, temperature, recirculation, purge and cleaning can change liquid condition. Filters protect nozzles but can adsorb constituents or shed contamination. Purging verifies ejection only if droplet health is measured. A nozzle check before and after a build cannot prove uninterrupted deposition; in-build monitoring and the consequence of an unobserved missing jet must be considered.

Mostafaei and co-workers review the coupled effects of print parameters, materials and post-processing and the limitations of current models [20]. Models can support hypotheses for impact, penetration, drying and bond formation, but inputs require representative measurements and predictions require validation against geometry and properties. A model calibrated to metal powder, for example, is not transferred to porous sand or an agglomerated ceramic bed without evidence.

The binder-development record includes composition and tolerances, raw-material lots, mixing order and energy, filtration, container and age, temperature, degassing, printhead compatibility, droplet tests, bed-interaction tests, cure response, green properties, downstream residue or emissions, and disposal. Proprietary chemistry can remain confidential while identity, change control and acceptance evidence remain available to authorised parties.

6. Printhead, path, feature formation and process monitoring

Feature formation combines the address grid with the liquid–powder interaction. Drop spacing, pass strategy, edge compensation, scan direction, layer registration, timing between passes and thermal history influence continuity and edges. A compensated digital contour is not evidence of final accuracy until the complete route is measured.

Small positive features can fail because they receive too few reliable droplets, are displaced by recoating or break during depowdering. Small negative features can close through lateral penetration, residual powder, coating or post-process shrinkage. Thin walls can have different binder-to-powder ratios from bulk regions. Corners can receive overlapping liquid and grow. Down-facing surfaces inherit powder-bed roughness and may collect partly bound particles.

Resolution is therefore reported as a feature capability with geometry, orientation, position, material state and measurement method. Green dimensions, sintered dimensions and casting dimensions answer different questions. A minimum demonstrated wall in one orientation does not establish a minimum channel or gap. A printed core that can be extracted from loose powder may still fail during assembly or pouring.

Process monitoring can include nozzle-status tests, drop observation, printhead temperature and pressure, bed images, recoater force, build-height measurements, thermal maps, mass or humidity and cure signals. Each is a leading indicator. It becomes a quality surrogate only after its detection limit, false responses and correlation to a relevant defect are established. The absence of an alarm is not final acceptance.

Control logic includes response to a missing jet, streak, feed fault, head strike, pause, power interruption, environmental excursion or cure deviation. Reprinting over a region can add liquid but may not restore the intended vertical bond. Continuing after a pause can create a dry or over-cured interface. A deviation record identifies affected layers, geometry and disposition rather than relying on a completed-build image.

Machine capability is position and time dependent. Nozzle populations age; plates can distort; recoaters wear; build boxes accumulate damage; filters load; liquids evaporate; environmental control drifts. Qualification spans the permitted printhead, build

area and duration. Maintenance and replacement create controlled equipment states with defined verification before production resumes.

7. Curing, drying, green strength, depowdering and handling

The finished powder bed contains a spatially patterned but fragile bonded network. Cure or drying must develop enough cohesion without unacceptable migration, distortion, residual stress or chemical change. Build size, local printed fraction, section thickness, container, airflow, temperature, humidity and time influence the path. The centre of a large build may not follow the same history as an exposed coupon.

Green strength is task specific. A part needs enough integrity for bed excavation, powder removal, lifting, transport and the next fixture. A sand core may need assembly and coating strength; a ceramic preform may need to survive infiltration or a debinding setter. Test geometry, loading direction, cure state and environment are stated. A mean strength from a dense bar does not prove survival of a thin wall or junction.

Depowdering is an engineering operation, not housekeeping. Forces from brushing, suction, air, vibration, tumbling, excavation tools and part self-weight can chip edges or open weak interfaces. Internal powder removal depends on channel diameter and length, bends, access ports, orientation, powder cohesion and static charge. A channel that exists in the digital model but retains powder is not manufactured as intended.

Loose powder nominally supports overhangs during printing, but it does not remove the need for access. Enclosed cavities can trap material permanently. Narrow tortuous channels may be impossible to verify or clean. Fragile internal lattices can be damaged by the very flow needed to remove powder. Geometry review therefore includes an explicit powder-release analysis and an inspection method for residual powder.

Residual powder has route-specific consequences. In a ceramic compact it can sinter onto a surface, alter a local dimension, contaminate an infiltrant or hide a defect. In a sand mould it can obstruct vents, alter a cavity, wash into the metal or change coating behaviour. Cleaning acceptance is based on a validated method and relevant limit, not a visual statement where interiors are inaccessible.

Handling fixtures distribute loads and preserve orientation. A green ceramic can crack under point contact while leaving no obvious surface indication. A large sand mould can distort under its own mass or during crane movement. Packaging and environmental exposure between print and next operation are controlled. Time-to-process can matter when binders continue curing, absorb moisture or lose volatile components.

Dimensional inspection at the green stage can identify gross error and provide compensation evidence, but it is not final conformance. Ceramic dimensions change during debinding and consolidation. Sand mould dimensions combine with coating thickness, assembly, metal contraction and foundry conditions. Green data remain valuable as a leading measure when linked to final outcomes.

8. Structural and functional ceramic debinding, sintering, infiltration and reaction bonding

A cured ceramic green body contains particles, pores and temporary binder. Debinding removes or transforms organics and volatile constituents through a geometry-dependent transport problem. Decomposition can produce gas faster than pores can release it, causing pressure, cracks, blisters, delamination or residue. Thermal analysis of a small sample can inform chemistry but cannot alone validate a large or internally closed component. 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-153 retains binder-jetting-specific green structure, infiltration, reaction-bonding and final-material evidence.

The debinding plan identifies binder mass and distribution, decomposition products, oxygen demand or sensitivity, gas paths, section thickness, load packing, setter contact, furnace flow and off-gas control. Heating and holds are validated for the actual formulation and geometry. A copied cycle is not accepted merely because the binder family name is similar. Brown-state inspection is used only when the state can be handled and the method can detect a relevant defect.

Sintering converts particle contacts into a ceramic microstructure while dimensions shrink. Initial bed density, local binder field, particle size, agglomerates and layer interfaces create a nonuniform starting state. Temperature, time, atmosphere, gas flow, furnace position, load mass, setter, gravity, phase reactions and volatile loss affect densification. A single scale factor cannot capture local and anisotropic shrinkage.

Vogt and co-workers used slurry infiltration before sintering to increase alumina green and final density, while showing that infiltration can be nonuniform [22]. The study supports a route option and a warning: infiltration adds liquid access, drying and distribution problems. It can leave gradients between exterior and interior, and repeated treatment can close pores before the centre receives equivalent material. A density gain measured from the whole part can conceal local variation.

Other routes intentionally leave a second phase. Polymer infiltration and pyrolysis adds a precursor that converts with yield and shrinkage. Metal infiltration fills accessible pores and may react with the ceramic or remain as a continuous phase. Reaction bonding uses that reaction to create or join ceramic phases. Chen and co-workers report a specific cyclic post-impregnation and silicon-infiltration chain for binder-jetted SiC [25]. Its evidence is bounded to that system. The final product must identify retained silicon or other phases rather than being described simply as monolithic SiC.

Open and closed pores govern infiltration. Surface tension, wetting, viscosity, pressure, temperature, atmosphere and pore connectivity affect access. A trapped gas volume or closed pore cannot be filled by capillary contact alone. Infiltrant can drain,

pool, react prematurely, contaminate setters or change dimensions. Mass gain is useful but does not prove spatial uniformity or phase identity.

Sintered density is not a complete quality measure. Two components with similar bulk density can have different pore size, connectivity, inclusions, layer defects, grain structure, residual stress and surface damage. Mechanical reliability depends on the critical flaw population. Functional ceramics require application properties after final electrodes, surfaces, atmosphere or aging as relevant.

Finishing can remove bound powder and dimensional stock, but it can also expose pores, introduce grinding damage or change surface residual stress. Machining allowances interact with shrinkage variation and fragile sections. Cleaning must remove abrasive, infiltrant residue and process contamination without altering the functional surface. Inspection follows the finished state unless a controlled intermediate is intentionally accepted.

The final ceramic data package names powder and binder lots, green density or other relevant state measure, debinding and furnace load, atmosphere, position and setter, infiltration material and cycles if any, mass and dimensional changes, final phase and porosity, finishing, inspection and test results. The word `ceramic` never substitutes for this identity.

9. Sand mould and core final-tool state, coating, pouring and casting acceptance

Printed sand tooling uses binder to create a porous shape strong enough for handling and casting. Unlike structural ceramic routes, densification would normally destroy the permeability and collapsibility that make the tool useful. The relevant final state is a cured, clean and possibly coated mould or core assembled for a declared alloy and pouring process. Downstream casting-acceptance qualification is controlled by ER-038; ER-153 owns the printed sand mould/core contribution and the evidence required before that casting endpoint.

Sand and binder selection balances multiple responses. Green or cured strength supports excavation, transport, coating, assembly and metallostatic load. Permeability permits gases to escape. Refractoriness resists softening and reaction. Thermal expansion affects distortion and cracking. Surface grain size and coating affect metal penetration and casting finish. Collapsibility permits contraction and later core removal. Increasing binder or compaction can improve one response while impairing several others.

Sivarupan and co-workers review these coupled printed-sand challenges and warn that maximum strength or permeability need not be the optimum [29]. The acceptance target belongs to a mould/core–alloy–geometry–pour combination. A thin aluminium casting, a ferrous casting and a hot internal core impose different thermal, gas and mechanical demands.

Organic binder systems can provide useful cure and strength but can generate volatile decomposition products during heating and metal contact. Inorganic systems can reduce some organic emissions but can introduce moisture sensitivity, different cure needs, brittle behaviour, reclamation problems or other emissions. Garitaonandia and co-workers measured markedly different harmful-emission profiles across binder systems at pilot casting scale [33]. The permitted conclusion is that chemistry and process matter; `organic unsafe` and `inorganic safe` are invalid shortcuts.

Kamyab, Hajialimohammadi and Sglavo investigated inorganic powder-based mould compositions through thermo-mechanical behaviour and aluminium casting performance [34]. The work supports a material-specific qualification route that joins coupon characterisation to actual casting. It does not provide a universal inorganic formulation or prove suitability for a different alloy, section or foundry.

Coating is its own controlled process. It can improve surface finish, reduce penetration or chemical interaction and protect weak surfaces, but thickness and penetration can change cavity dimensions and permeability. Carrier removal or drying can add gas and crack risk. Coating identity, solids, application, drainage, dry state and repair are recorded. A mould designed without coating cannot be assumed equivalent after coating.

Assembly introduces seams, core prints, chaplets or supports where used, adhesive or sealant, vents and closure loads. Dimensional inspection of individual halves does not prove assembled cavity geometry. A core can float, shift, distort or fracture during pouring. Handling and rigging plans are therefore part of tooling qualification.

Pouring couples the tool to alloy preparation, temperature, head, flow, gating, venting and solidification. The printed tool can enable non-conventional gating or integrated features; Sama, Wang and Manogharan demonstrate such design opportunities [30]. Opportunity is not automatic benefit. A new gating architecture changes fill, turbulence, oxide formation, pressure and feeding and must be validated with the intended alloy and defect criteria.

Upadhyay, Sivarupan and El Mansori place printed sand within the complete rapid-casting route [26]. Snelling, Williams and Druschitz directly connect printed moulds to the mechanical and material properties of resulting castings in their tested system [31]. These sources support a core principle: tooling evidence and casting evidence are both necessary. A strong, accurate mould can still produce an unacceptable casting through gas, erosion, penetration, reaction, cold shut, shrinkage or inclusions.

After solidification, shakeout and core removal should be effective without damaging the casting or creating uncontrolled dust exposure. Reclamation separates reusable sand from fines, binder residue and contaminants and requires a release rule before reuse. Waste classification follows actual binder and metal contamination. Yield includes mould breakage, misassembly, pour failure and casting rejection, not only successful printing.

Casting inspection uses failure hypotheses: dimensional deviation, surface roughness and penetration, veining, scabs, erosion, inclusions, gas porosity, shrinkage, cracks, incomplete fill and internal geometry. Method capability and coverage are matched to the feature and alloy. The printed mould is accepted for use at a tooling hold point; the casting is released only after its own requirements pass.

10. Material families and final material identity

Oxide ceramics such as alumina are common development systems because powders, firing routes and test methods are relatively accessible. Evidence from alumina remains formulation specific. Purity, particle surface, additives, packing, binder residue, atmosphere and grain growth change densification and strength. An oxide result does not establish non-oxide capability.

Non-oxide ceramics such as SiC can require controlled atmospheres, sintering aids, reaction bonding or infiltration. Surface oxygen and residual carbon can change the route. A reaction-bonded material can retain free silicon; a polymer-derived route can retain porosity or secondary phases. Final identity therefore includes phase fractions and distribution relevant to function.

Functional ceramics add property-specific controls. A dielectric material requires phase, density, grain and electrode-related evidence in its final test state. Thermal, electrical, magnetic, ionic, optical or catalytic materials each require their own measurement and environment. Vasudevan and Vaidhyanathan survey recent advanced-ceramic binder-jetting progress and persistent limitations [21]. Their breadth supports technology exploration, not a general statement of production readiness.

Refractory ceramic moulds and cores can support casting at temperatures or chemistries beyond conventional silica sand, but thermal shock, expansion, reaction, leachability or removal become material-specific. Fine ceramic investment-casting cores, large sand cores and dense structural parts are not one qualification family even if all use jetted binder.

Sand systems include silica and alternative refractory aggregates, new and reclaimed fractions, and organic or inorganic binders. Crystalline-silica exposure, thermal expansion and phase change require attention where silica is used. Alternative aggregates can reduce one risk while changing cost, density, heat transfer, binder demand, surface or reclamation.

Composite and infiltrated routes require an explicit material name. A ceramic preform infiltrated with metal is a composite with a connected or partly connected second phase. A porous body infiltrated with slurry and then sintered can have spatially varying composition. A preceramic polymer can convert with gas evolution and volume loss. Supplier or literature labels are not accepted without final phase, porosity and relevant property evidence.

Material substitution triggers route review. A powder that fits the same nominal chemistry can have a different surface area or agglomeration. A new binder can wet differently and decompose differently. A reclaimed sand fraction can change gas and permeability. Change control assesses effects from layer formation through final component or casting rather than approving substitution at incoming inspection alone.

11. Defects, anisotropy, permeability, brittle statistics and casting evidence

Binder-jet defects arise from powder, liquid, machine and post-process interactions. Powder-layer defects include streaks, density gradients, dragged particles and disturbed regions. Deposition defects include missing or deflected jets, satellites, bleed, insufficient overlap and registration error. Cure and depowder defects include cracks, delamination, erosion, retained powder and dimensional change. Ceramic post-processing adds debinding cracks, nonuniform shrinkage, pores, inclusions, reaction gradients and finishing damage. Sand use adds coating cracks, erosion, penetration, gas, mould fracture and casting inclusions.

Layering and scan direction can create anisotropy. Bond networks differ within and between layers, and recoating can orient or segregate particles. Coniglio, Sivarupan and El Mansori measured anisotropic properties in a declared printed-sand system [28]. The result supports orientation-labelled testing; its ratios cannot be transferred to another powder, binder or machine.

Permeability is a structural transport property, not simply the inverse of strength. It depends on pore size, connectivity, tortuosity, moisture, coating and gas conditions. Mitra and co-workers used X-ray computed tomography to study the evolution of transport properties in additively processed sand moulds [32]. Imaging can reveal pore architecture, but conversion to casting performance still requires representative gas, temperature and geometry evidence.

Structural ceramics are brittle and flaw controlled. ASTM C1161 provides a flexural-strength method for advanced ceramics [8], ISO 14704 provides an alternative fine-ceramic method [11], ASTM C1239 governs population reporting and Weibull estimation [9], and ASTM C1322 addresses fractography and fracture origins [10]. The selected method, specimen preparation, orientation, surface, environment and censoring are reported. Values from different methods are not pooled without justification.

Density and mean strength can miss rare critical defects. A qualification family includes sufficient specimens across build positions, orientations and post-process states, with fracture-origin analysis connecting failures to pores, layer interfaces, agglomerates, inclusions or machining. Non-destructive inspection is validated against the defect size, orientation, material contrast and geometry; 'CT scanned' is not a detection-capability statement.

Sand-tool tests are similarly tied to use. Tensile or bending strength, permeability, loss on ignition, gas evolution, abrasion, thermal expansion and distortion can support hypotheses. They do not replace a representative casting. The final evidence joins tool measurements to fill, solidification and casting inspection. Hackney and Wooldridge provide bounded characterisation of a direct printed-sand process [27]; the method is useful only when its material and conditioning context remains explicit.

Defect taxonomies improve response. A detected streak can be traced to feed, agglomerate, recoater or nozzle causes; a casting inclusion can trace to erosion, loose powder, coating or core failure. The corrective action addresses the mechanism. Sorting final parts without controlling the upstream cause does not establish a stable process.

12. Geometry, scale, productivity, economics, safety and environmental control

Binder jetting can build unsupported-looking geometries because surrounding powder carries some load, and multiple parts can be nested in a build volume. The benefit is conditional. Powder must be spread into every layer, cure and cool; every part must be

excavated and depowdered; internal powder must be removed; and the full build must fit furnace or foundry capacity. Dense nesting can increase depowdering labour, liquid load, thermal gradients and damage risk.

Feature rules are state resolved. Minimum wall, gap, hole, channel, span, edge and embedded core feature are established at green, final ceramic or casting state as relevant. Powder-removal access, tool reach, coating, assembly, shrinkage and inspection are included. A nominally support-free cavity can be a no-go if trapped powder cannot be removed or verified.

Scale changes process physics. A larger bed amplifies recoater straightness, feed uniformity, environmental gradients and printhead-population risk. A larger ceramic part increases debinding transport, furnace gradient, shrinkage and setter interaction. A larger sand mould increases handling, rigging, assembly and metalostatic demands. Demonstration at small coupon scale does not establish scale-up.

Productivity is accepted output per constrained complete-cell time. For ceramics it includes powder conditioning, loading, recoating and printing, cure, depowdering, debinding, infiltration cycles if any, sintering, cooling, finishing, inspection, maintenance and yield. For sand tooling it includes print, cure, depowder, coating, assembly, pouring, cooling, shakeout, reclamation and casting yield. A high print rate can feed a slower furnace, depowder station or foundry and create inventory rather than throughput.

Economics compare the complete qualified route with pressing, slip casting, injection moulding, green machining, conventional pattern and core-box tooling, investment casting, DIW, VPP or another relevant process. Binder jetting can reduce hard tooling and design-change lead time for low or changing volumes. Powder cost, printhead care, manual depowdering, furnace time, infiltrant, coating, inspection and late rejects can reverse the advantage. Cost per accepted component or casting is the decision measure.

Safety begins with the actual substances and tasks. Fine ceramic powder and sand handling can create inhalation exposure; silica-containing sand can add crystalline-silica risk. Binder, activator, catalyst, cleaner and coating can introduce skin, eye, inhalation, flammability or incompatibility hazards. NIOSH's current additive-manufacturing resource supports task-based exposure assessment and the hierarchy of controls [14]. It does not replace substance- and process-specific evaluation.

Powder transfer, sieving, reclaim blending, machine loading, excavation, vacuuming, brushing, filter change, spill response and dry finishing are evaluated separately. Enclosure, local exhaust, closed transfer, suitable filtration, housekeeping and compatible protective equipment are selected from the assessment. Compressed air is not used to disperse powder into the workplace. Recovered powder remains identified and segregated until released.

Ceramic debinding and infiltration add hot surfaces, combustible or toxic decomposition products, furnace atmospheres, vacuum or pressure, molten infiltrant and off-gas. Foundry use adds coatings, hot moulds, molten metal, splash, radiant heat, lifting, smoke and shakeout dust. NIOSH foundry control recommendations provide a public ventilation and exposure-control anchor [15], but each foundry must assess its alloys, binders, pouring and reclamation tasks.

Emissions are measured or otherwise bounded at the stages where they occur. A water-based liquid can still contain hazardous constituents; an inorganic binder can still release dust or reaction products; an organic binder's emission profile depends on chemistry and casting conditions. Ventilation is not a substitute for reducing or enclosing a source where practicable. Exhaust, fire protection, gas detection and waste handling are designed for credible abnormal conditions as well as normal production.

Environmental accounting includes virgin powder or sand, reclaim yield, binder and solvent, purge and cleaning waste, filters, furnace or curing energy, infiltrant, coating, rejected tools and castings, shakeout dust and final disposal. A high nominal sand-reuse fraction is not credible without contaminant, dust and performance control. Claims of sustainability require a stated boundary and comparator.

13. Qualification architecture and technology-selection gate

Qualification begins with the final requirement and works backward through the correct branch. For a ceramic, the specification defines final composition and phase, intended porosity, geometry, surface, cleanliness, mechanical or functional properties, environment, reliability, inspection and traceability. For sand tooling, it defines the tool state, assembly, alloy/pour context and casting acceptance. ISO/ASTM 52920 provides the general architecture for industrial process and production-site qualification [2]. Cross-process direct/indirect route comparison is inherited from ER-049; ER-153 contributes the binder-jetting and printed-tool evidence used within that selection architecture.

The developing ISO/ASTM 52973 work item specifically addresses design guidance for metal binder jetting and is therefore adjacent to, rather than governing of, the ceramic and sand routes treated here; on the control date it is an Approved Work Item under development [12]. It can be monitored as evidence of standards activity. It cannot be cited as a published normative requirement or used to close an engineering gap. Its current AWI scope is limited to single-alloy metal parts (BJT-MSt/M) and is not used here as ceramic- or sand-specific design authority.

Material qualification identifies powder or sand specifications, binder and activator, conditioning, recycled or reclaimed content, allowed age and environment, and relevant layer, green and final responses. Equipment qualification covers feed, recoater, build box, printhead, liquid delivery, environmental control, cure, depowdering and branch-specific furnaces or foundry interfaces. Personnel qualification covers material release, machine operation, nozzle response, green handling, coating/assembly, thermal processing, casting, inspection and deviation authority.

Installation and operational qualification demonstrate that equipment and utilities operate and control their intended ranges. Performance qualification uses representative and adverse permitted combinations of powder state, reuse fraction, printhead population, build position, cross-section, layer count, nesting, cure, feature access and route-specific post-processing. It includes repeat builds and more than one favourable central coupon.

Table 2. Route and material outcomes with transfer boundaries

Route family	Printed/cured state	Declared final state	Evidence that does not transfer automatically
Pressureless-sintered oxide	Binder-held oxide powder compact	Sintered oxide with measured phase, pores and properties	Powder grade, binder, shrinkage or furnace cycle from another oxide
Infiltrated or reaction-bonded ceramic	Porous ceramic preform	Named ceramic/composite with retained infiltrant and phase distribution	Density gain as proof of homogeneous monolithic ceramic
Functional ceramic	Composition-controlled green architecture	Final electrical, thermal, optical or other functional state	Structural density or strength as proof of function
Organic-binder sand tool	Cured porous mould/core	Coated/assembled tool plus accepted casting	Green strength as proof of permeability, emissions or casting quality
Inorganic-binder sand tool	Cured porous mould/core with different moisture/cure behaviour	Qualified tool plus accepted casting	'Inorganic' as proof of safety, reclaimability or alloy compatibility

The control plan connects leading measures to final outcomes. Incoming powder, layer images, recoater signals, droplet tests, cure state and green strength can identify drift. Their limits are justified by correlation to relevant defects and properties. Final inspection does not retroactively validate uncontrolled inputs, and a stable leading signal does not replace required final tests.

Table 3. Ceramic and sand binder-jetting qualification gate

Gate	Question that must close	Minimum evidence family	Stop condition
Requirement	Is the final ceramic or casting/tool state unambiguous?	Drawing, material identity, use environment, failure modes and acceptance plan	Generic 'binder-jetted ceramic' or 'printed sand passed'
Powder bed	Can released powder form repeatable layers over position, time and reuse?	Powder attributes, layer density/roughness, recoater and build-position evidence	One flow value or visual first-layer check
Droplet field	Is liquid delivered and distributed reproducibly in the actual bed?	Binder release, nozzle health, droplet and feature tests, cure/penetration evidence	Displayed saturation or printhead resolution used as proof
Green handling	Can representative geometry cure, depowder and move without hidden damage or residue?	Access analysis, green tests, residual-powder and dimensional evidence	Trapped powder or fragile inaccessible feature
Ceramic branch	Can debinding and consolidation produce the declared material uniformly?	Load-linked phase, pores, dimensions, defects and final properties	Copied cycle, density alone or undeclared retained infiltrant
Sand branch	Can the tool survive handling and pouring while controlling gas and collapse?	Strength, permeability, thermal/gas, coating/assembly and representative casting	Maximum strength target or coupon without casting evidence
Inspection	Can critical geometry and flaw hypotheses be detected with known capability?	Validated method, coverage, uncertainty and destructive correlation	'Visually acceptable' or 'CT inspected' without capability
Production	Is the complete cell safe, repeatable and economic at accepted-output level?	Yield, constrained time/cost, exposure, emissions, maintenance and change control	Build rate or material reuse quoted without system boundary

Change control is broad because variables couple across states. Powder supplier, morphology, granulation, reclaim fraction, binder raw material, filter, printhead, waveform, recoater, layer strategy, environment, cure, depowdering, furnace, infiltrant, coating, sand assembly, alloy or pouring condition can affect several outcomes. A risk review identifies which evidence remains representative and which qualification elements repeat.

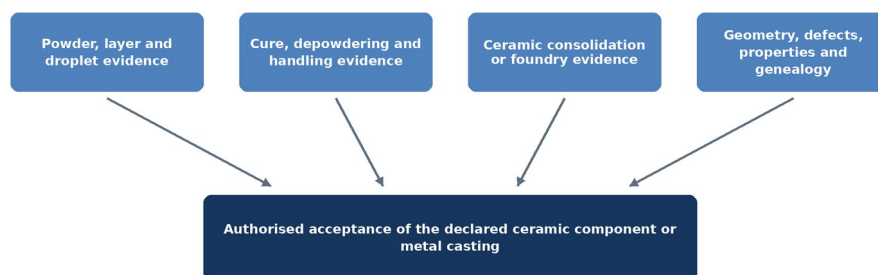


Figure 2. Evidence closure for accepted binder-jetted output.

Technology selection asks what binder jetting uniquely enables and what it costs to close this evidence. It is favoured when mould or pattern avoidance, batch nesting, internal geometry, rapid design change, porous preforms or non-conventional sand tooling outweigh powder, depowdering, post-process and inspection burdens. Pressing, slip casting, injection moulding or machining can dominate simple ceramic shapes and high volumes. VPP or DIW can dominate other feature or feedstock regimes. Conventional core boxes and patterns can dominate stable high-volume castings.

No-go conditions include a powder that cannot form stable layers; a binder field that cannot be controlled; critical missing-jet risk without detection; inadequate green strength; inaccessible powder; debinding or infiltration gradients; unacceptable sintering distortion; undeclared final phases; a sand tool that cannot satisfy strength, gas and collapse together; an unobservable critical defect; or complete-cell safety, yield or economics outside the programme boundary. A successful demonstration print does not override a closed stop condition.

14. Conclusions and research priorities

Ceramic and sand binder jetting share selective liquid deposition into powder layers but do not share one delivered product. The structural or functional ceramic route creates a green compact that must be transformed into a declared ceramic or composite. The sand route creates disposable porous tooling whose performance is proven only together with an accepted casting.

Powder quality cannot be reduced to particle size or flow. Morphology, agglomeration, packing, layer formation, pore topology and sinterability conflict. Binder quality cannot be reduced to saturation. Droplet formation, wetting, penetration, evaporation and cure create a spatial liquid field. Printhead resolution is not feature capability, and loose powder is not support when it cannot be removed.

Green strength is a route-specific minimum, not a quantity to maximise. Excess binder can impair accuracy, burnout, permeability, gas behaviour and emissions. Ceramic consolidation introduces debinding transport, shrinkage, atmosphere, phase and infiltrant identity. Sand tooling introduces coating, assembly, pouring, gas, thermal response, collapsibility and shakeout. Each branch needs final-state evidence.

Qualification follows defects and states. Brittle ceramics require method- and orientation-labelled population statistics, fractography and inspection capability. Sand tools require strength, permeability, thermal and gas evidence joined to representative casting results. Density, mean strength, a clean print or a passed mould coupon cannot close the full chain.

Priority research should develop reference powders and binders, interlaboratory layer-spreading tests, spatial bed-density and liquid-distribution metrology, reliable in-build nozzle and recoater monitoring, models validated across actual pore networks, and depowdering-access rules with residual-powder detection. Ceramic research needs better prediction of anisotropic shrinkage, infiltration uniformity, retained phases and defect populations. Foundry research needs binder-specific emissions, gas transport at temperature, coating-pore interactions, reclaim aging and casting-defect correlations.

Scale-up studies should report accepted output per complete constrained cell, including cure, depowdering, furnaces or foundry operations, maintenance, exposure, waste and yield. Advanced-material studies should state final material identity and application property rather than treating a powder label or density as success.

Factory adoption should proceed through a requirements-led gate: define the final ceramic or casting; release powder and liquid; prove layer and droplet fields; validate cure, depowdering and handling; close the correct consolidation or foundry branch; demonstrate final geometry, defect and property evidence; then establish safe, repeatable and economic production. Only that route-specific chain supports authorised acceptance.

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