

Ceramic Direct Ink Writing and Robocasting

Rheology, Nozzle Flow, Shape Retention, Drying, Sintering and Qualification

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Statement of Significance

Ceramic direct ink writing can deposit highly loaded powders without a mould and can create walls, lattices, graded paths and near-net shapes that are difficult to machine after densification. The apparent simplicity of pushing a paste through a nozzle is misleading. The printed object is a wet or binder-containing green body, not a final ceramic. Its geometry depends on powder and additive release, mixing and aging, the full shear and extensional history from reservoir to free filament, start/stop response, filament contact, evaporation and time under increasing self-weight. Its final state depends on drying gradients, organic removal, atmosphere, setters, three-dimensional shrinkage, pore and grain evolution, finishing and inspection. These stages compete. More solids may reduce shrinkage while increasing pressure, slip and clogging. More yield resistance may improve stacking while weakening interfilament fusion. Interlayer drying may enable taller shapes while creating shrinkage gradients and voids. A support bath may stabilise a filament while adding interface and removal risks. This review supplies a state-resolved factory framework for colloidal, hydrogel-carrier and binder/solvent ceramic inks; pneumatic, displacement and other metering architectures; oxide, non-oxide, refractory, ultrahigh-temperature and functional ceramics; and final brittle-component qualification. It provides no transferable formulation, nozzle, rheology, pressure, speed, drying, burnout, sintering or compensation recipe.

Abstract

Ceramic direct ink writing (DIW), often called robocasting in ceramic implementations, selectively deposits a particle-loaded ink, slurry or paste through a nozzle as continuous filaments. The filaments must flow under the imposed reservoir, line and nozzle history, form a controlled free surface, contact neighbouring material, resist spreading, sagging and buckling, then survive drying and handling as a green body. Where temporary organics remain, burnout or debinding must remove them without unacceptable pressure, residue or cracking. Sintering changes dimensions, pores, phases and grain structure and may require material-specific atmospheres, setters and finishing. `DIW`, `robocasting` and `paste extrusion` therefore identify a process family, not one implementation or operating window. Rotational rheometry, capillary/nozzle flow and deposited-filament response probe different states; a scalar viscosity, yield stress or storage modulus cannot establish printability. Pneumatic pressure is not volumetric flow, nozzle diameter is not final resolution, and green shape retention is not final dimensional capability. Higher solids loading, interlayer drying and support-bath printing each create conditional benefits with opposing risks. Oxide demonstrations do not transfer automatically to SiC, Si₃N₄, ZrB₂-based, refractory or functional ceramics. Brittle qualification requires state-, orientation- and surface-labelled tests, flaw-population statistics, fractography and inspection capability rather than density or mean strength alone. This qualitative engineering review connects incoming material, ink preparation, rheology, metering, nozzle flow, filament deposition, drying, thermal processing, finishing, safety, economics and part-linked qualification. It excludes concrete and other macroscopic construction deposition, and it makes acceptance depend on the complete powder-to-delivered-ceramic chain.

Keywords: *ceramic direct ink writing; robocasting; ceramic paste extrusion; rheology; yield stress; thixotropy; filament deposition; drying; green body; debinding; sintering; technical ceramics; qualification*

1. Purpose, scope and terminology

ISO/ASTM 52900 places direct ink writing within material extrusion: material is selectively dispensed through a nozzle or orifice [1]. The standard category is useful, but it does not identify the feedstock chemistry, metering mechanism, free-filament behaviour or delivered state. In ceramic DIW, the deposited material is normally ceramic powder held by a liquid phase, colloidal structure, gel, temporary binder or combination of these. The object leaving the build stage is therefore a wet or dry green body. NIST explicitly identifies the non-dense printed state and subsequent sintering as a distinctive source of ceramic-AM cost and complexity [12].

`Direct ink writing` is the broad term used here for ambient or moderately conditioned extrusion of a complex fluid without relying on melting as the principal deposition mechanism. `Robocasting` is retained when an implementation or source uses that established ceramic label. `Paste extrusion`, `slurry extrusion`, `microextrusion`, `direct-write assembly` and supplier-specific terms may describe related variants. None proves identical powder loading, organic content, reservoir, pressure control, nozzle, drying or thermal route. Sauret, Ray and Compton usefully frame robocasting as a ceramic- or metal-suspension implementation within DIW while showing that the family includes materially different complex fluids and solidification routes [34].

The scope starts at incoming ceramic powder, liquid, dispersant, rheology modifier, binder or gelling constituent, antifoam, sintering aid and any support medium. It covers identity and release, addition sequence, wetting, dispersion, deagglomeration, mixing, degassing, storage and remix; reservoir loading; pneumatic, piston, syringe, screw or other declared metering; line and nozzle flow; start, corner, stop and restart; filament deposition, fusion and stacking; controlled drying and green handling; organic

removal where applicable; brown-state inspection where meaningful; sintering, cooling, setter interaction and atmosphere; finishing, cleaning, inspection, testing, economics, safety and qualification.

ER-144 controls DIW and paste-extrusion systems delivered as polymers, silicones, hydrogels or highly filled polymer composites. ER-152 owns ceramic-particle routes through final thermal consolidation. ER-151 controls ceramic vat photopolymerisation, ER-153 ceramic and sand binder jetting, ER-154 bound-ceramic filament and pellet extrusion, and ER-155 polymer-binder powder-bed routes. This paper excludes cement, concrete, geopolymer, regolith and other macroscopic high-volume construction deposition. It also excludes food, pharmaceutical and cell-laden printing. A bioceramic demonstration, if encountered, remains a material/process experiment and cannot establish device safety, sterility, biological performance or regulatory approval.

Four ink families are kept distinct. A `colloidal ink` relies substantially on particle interactions and liquid removal to acquire green strength. A `hydrogel-carrier ink` uses a temporary aqueous polymer network or gel-forming phase to assist extrusion and shape retention. A `binder/solvent paste` contains a more substantial temporary organic phase that later dries and burns out. A `preceramic-polymer ink` converts an organic or hybrid precursor into a ceramic rather than merely removing a binder from an existing powder compact. The last route is mentioned only where needed to interpret embedded-DIW evidence; its chemistry and yield are not interchangeable with powder-sintering routes.

ISO/ASTM 52901 requires the customer and provider to define delivered state, requirements, inspection and documentation for purchased AM parts [4]. `Robocast alumina`, `DIW SiC` or `printed zirconia` is insufficient. A useful requirement identifies powder/ceramic grade and phase, intentionally dense or porous architecture, final heat-treatment and surface state, critical geometry, cleanliness, functional properties, test methods, inspection coverage, traceability and use environment. ISO/ASTM 52910 supports requirements-led design communication [3], while ISO/ASTM 52927 helps organise characteristics and test methods [5]. None supplies a formulation or process window.

This review deliberately does not prescribe powder grade, particle distribution, solids basis, dispersant, pH, ionic strength, binder, liquid, mixing sequence, rheology range, storage life, reservoir, pressure, flow, nozzle geometry, standoff, path speed, line spacing, layer height, support medium, humidity, temperature, drying time, burnout, atmosphere, sintering aid, furnace schedule, setter, compensation, finishing or acceptance threshold. Each belongs to a declared powder-ink-delivery-geometry-drying-thermal-intended-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 state-resolved route

The phrase `print a ceramic` compresses a sequence of material identities. Released powders and additives first become an ink with a history-dependent particle network. Metering pressurises or displaces that ink through a reservoir, connectors and nozzle. The confined material accelerates and shears near contractions, may slip at walls or segregate, and then enters an extensional and free-surface state at the nozzle exit. A deposited filament wets or contacts a substrate and prior filaments, relaxes and recovers structure, carries subsequent layers, and loses liquid or undergoes gelation. The green structure is dried, handled and, if needed, debound. Only sintering or another declared conversion creates the intended final ceramic state.

Table 1. State-resolved ceramic DIW/robocasting chain

Stage	Controlled state	Principal evidence	Invalid shortcut
Powder and ingredient release	Ceramic identity, phase/surface, additives, liquid/binder, moisture and sampling	Certificates plus verified incoming tests and change control	`Correct ceramic paste`
Ink release	Composition basis, dispersed/agglomerate state, gas, rheology histories, aging, evaporation and homogeneity	Representative tests under preparation, rest, shear and use histories	`Viscosity passed`
Reservoir, line and nozzle	Fill state, compliance, pressure/displacement, temperature, geometry, wear, residence, slip, clogging and actual flow	Registered delivery signals plus extrudate and maintenance evidence	`Set pressure equals flow`
Filament and layer	Exit shape, swell/contraction, continuity, placement, wetting, fusion, spreading, recovery, stacking and time	Feature tests across starts, paths, corners, stops, height and build duration	`Nozzle diameter equals resolution`
Wet-to-dry green body	Evaporation, gel/binder state, capillary stress, shrinkage, warpage, delamination, strength and handling	Geometry/environment-specific drying record and green inspection	`Shape retained at deposition`
Burnout/brown state	Organic removal, gas paths, residue, reaction, cracks, shape and residual strength	Ink/geometry/load/atmosphere-specific thermal evidence and hold point	`Low binder means no debinding risk`
Sintering and cooling	Densification or pore target, phase, grain, shrinkage, gravity, setter, atmosphere and furnace position	Load-linked material, dimensional and defect evidence	`Apply one scale factor`
Delivered acceptance	Geometry, surface, cleanliness, pore/flaw population and functional properties	Part-linked tests, uncertainty, genealogy and authorised disposition	`Density or mean strength passed`



Figure 1. State-resolved ceramic direct-ink-writing route.

The chain prevents five category errors. First, extrusion establishes a powder distribution and green geometry; it does not create final ceramic bonds. Second, an ink that passes a rotational test may behave differently in a nozzle because wall slip, entrance flow, pressure, extensional history and residence are different. Third, a filament that stands for seconds may collapse during a long build or crack during drying. Fourth, dimensions change locally as liquid leaves and particles densify. Fifth, a high-density final coupon can coexist with critical planar or rare defects in a component.

The genealogy links material lots to final disposition. It includes powder and additive identity, preparation vessel and media, order/energy/time and temperature, measured solids basis, degassing and screening, storage/remix/age, reservoir and cartridge identity, fill method and trapped gas, line and nozzle geometry, machine and software/file version, coordinate system and orientation, environmental history, delivery and build records, green handling, drying, burnout/debinding load, sintering load and furnace position, atmosphere, setter/contact, finishing, inspection, test specimens and final serial or batch. ISO/ASTM 52951 supports part-linked data packages [7], while ISO 17295 supports explicit orientation and coordinates [6].

Hold points separate states. Ink release authorises use only inside its validated age, temperature and replenishment boundaries. Build completion authorises controlled drying, not final use. Dry-green release confirms handling and furnace eligibility, not sintered conformance. A brown-state hold is used only where inspection can detect a relevant defect without damaging the fragile compact. Final release requires the intended ceramic identity, geometry, surface, pore/ flaw state and properties. A deviation is never erased merely because the component survives the next stage.

Material balances also follow the chain. Supplied powder is divided among accepted parts, retained ink, line/nozzle hold-up, purge, cleaning residue, supports or sacrificial media, green and thermal rejects, finishing removal and specimens. Recovered paste is not automatically released paste; it can acquire dried fragments, contaminants, evaporation, air, segregated particles or a different shear history. Reuse therefore needs identification, segregation, mixing and requalification rules.

3. Ceramic powder, surfaces, additives and ink families

Powder establishes composition, phase, impurity, particle shape, distribution, surface area, surface chemistry, agglomeration, packing and sintering response. The liquid and organic system establishes wetting, dispersion, viscosity, yield, recovery, drying, green strength and removal burden. Sintering aids, pH modifiers, salts, surfactants, thickeners, gelling species, lubricants and antifoams can change both states. Ceramic ink is therefore a coupled material with preparation history, not a neutral carrier plus a powder label.

Incoming control may include phase and dopant, moisture or loss on ignition, carbon/oxygen or other impurity, particle morphology, size distribution, specific surface, hard agglomerates and sintering-aid distribution. The relevant in-process distribution is the dispersed state after the controlled mixing operation. A supplier certificate on dry powder cannot reveal whether mixing leaves large agglomerates, adds wear debris or changes surface chemistry.

Particle size creates conflicting demands. Finer material can support smaller features, packing or sintering kinetics but increases surface area, liquid and dispersant demand, agglomeration, viscosity and inhalation concern. Coarser particles can lower specific-surface burden while increasing surface roughness, settling and clogging risk. A broad or multimodal distribution can improve packing in one formulation yet segregate under another shear or settling history. Particle-to-nozzle ratio is relevant but not sufficient because soft agglomerates, fibre length, nozzle entrance and local concentration also govern blockage [34].

Surface charge and adsorption are central in aqueous colloidal inks. pH, ionic strength, dispersant chemistry, powder dissolution and contamination can shift the interparticle potential and change flow with time. Feldbauer, Cramer and Gilmer investigated aqueous SiC slurry loading through zeta-potential and dispersant controls in a current non-oxide robocasting study [23]. Their measurements support the need to treat powder surface and formulation state together. Their selected chemistry and operating values do not transfer to another SiC lot, furnace route or ceramic.

Colloidal inks can minimise temporary organics by using a highly concentrated, shear-thinning particle network that rapidly resists flow after deposition. Smay, Cesarano and Lewis demonstrated directed assembly with colloidal inks and connected ink design to filament retention and periodic architecture [16]. Li and Lewis extended directed assembly to nanoparticle inks [17]. These foundational results establish mechanisms and possibilities, not a universal solids loading, dispersant or nozzle window.

Hydrogel-carrier inks introduce a temporary network that can improve shape retention, green handling or composition flexibility. Feilden and co-workers used hydrogel inks for structural Al₂O₃ and SiC robocasting and followed the route through drying, binder removal, oxide or non-oxide sintering and fracture analysis [20]. The useful lesson is the coupling of formulation, drying, thermal route and defects. A hydrogel formulation optimised for alumina is not automatically suitable for SiC; a material-specific atmosphere and sintering response remain essential.

Binder/solvent pastes can increase green cohesion and broaden acceptable powder packing or handling, but they increase volatile and organic transport, burnout burden, residue risk and furnace emissions. The term `paste` does not reveal whether shape retention arises from particle jamming, yield-stress additives, solvent loss, polymer gelation or a combination. Every thermal model begins with measured or otherwise controlled composition and decomposition behaviour, not a generic DIW label.

Solids loading is reported on an unambiguous basis. Mass fraction can appear high for a dense ceramic while corresponding to a different volume fraction than another material. When conversion is reliable, both bases improve comparison. Higher ceramic volume fraction can reduce liquid loss, organic removal and sintering shrinkage and can shorten particle-to-particle distance. It can also increase mixing torque, trapped gas, pressure, wall slip, clogging, particle migration and sensitivity to small composition changes. Xia and Duan showed loading-dependent zirconia outcomes in one DIW system [27]; Kovač and co-workers emphasised preparation optimisation and defect control in a Ce-TZP ink [26]. Neither defines a maximum-loading rule.

Mixing is controlled as an operation. Addition order can determine whether a dispersant reaches powder surfaces before a thickener or binder occupies them. Energy and time can break soft agglomerates while heating the batch or eroding media. Vacuum mixing can remove gas but also accelerate evaporation or foaming under the wrong conditions. Screening can remove large contaminants while altering composition or rejecting useful agglomerate information. The record includes vessel, impeller/media, fill, atmosphere where relevant, sequence, energy or speed/time, temperature, vacuum, filtration/screening and hold time.

Ink homogeneity is sampled in space and time. A bulk sample can hide a top-to-bottom concentration gradient, a wall-rich phase or a late-build change. Density, solids, particle/agglomerate state, moisture, pH or conductivity where relevant, and rheological responses are sampled from positions and histories that represent loading and use. Aging may improve adsorption equilibration or thixotropic structure in one formulation while promoting settling, hydrolysis, evaporation or irreversible aggregation in another.

The 3Dresyns technical-ceramics page identifies a current manufacturer-declared direct-printing scope and explicitly places formulation and process validation on the implementation [35]. It is not independent evidence for DIW performance, and its product values are not reproduced. A commercial starting material becomes a released factory ink only after the user identifies the actual powder, preparation, delivery architecture, thermal route and acceptance evidence.

4. Rheology, measurement history and printability

Ceramic DIW asks the ink to behave differently in sequence. It must remain sufficiently uniform in storage and the reservoir; yield and flow through contractions and a nozzle without unacceptable pressure, segregation or damage; form a continuous filament; recover or solidify rapidly enough to resist spreading and self-weight; and still wet and fuse with adjacent material. No single rheological number represents this time- and geometry-dependent cycle.

The NIST guide to rheological nomenclature for ceramic particulate systems distinguishes measured quantities, constitutive descriptions and instrument artefacts and emphasises explicit geometry and procedure [14]. That discipline matters because dense ceramic suspensions can slip at smooth tools, shear localise, evaporate at an exposed rim, sediment, fracture, trap bubbles or exceed instrument torque. A clean curve is not automatically a material property.

Steady or ramped shear tests can describe apparent shear thinning over a declared range, but order and dwell affect thixotropic systems. A descending ramp after strong preshear may show a lower structure than the material experiences at reservoir start-up. A long dwell can allow sedimentation or evaporation. Herschel–Bulkley, Bingham, power-law or other fits are compact descriptions inside the measured range; fit parameters are not universal constants and should not be extrapolated blindly to a nozzle or near-zero shear.

Yield stress is especially protocol-dependent. Static yield can describe the stress needed to initiate flow from a rested structure. Dynamic yield can describe an extrapolated or sustained-flow state. Stress ramp, creep, stress growth, oscillatory amplitude sweep and vane methods can produce different operational values. Shape retention also depends on elastic and time-dependent response, geometry, gravity, capillarity and drying, so a yield number alone cannot certify a tall wall or span.

Oscillatory tests can probe storage and loss response inside an identified linear region and can follow recovery after shear. The crossover of moduli, an arbitrary modulus ratio or a recovery percentage has meaning only with strain, frequency, preshear, rest, temperature and test geometry. Rapid recovery can help stacking yet reduce wetting or interdiffusion at a filament interface. Conversely, a low-rest modulus may improve fusion but permit sagging. The relevant window is two-sided.

Wall slip can make rotational data appear less viscous and can decouple pressure from bulk deformation in the nozzle. Measurements with different gaps or roughened tools, vane geometries or capillary comparisons can reveal it. Estelle and Gozen demonstrated nozzle-size-dependent wall-slip and transient-flow limitations in a non-ceramic model ink [33]. The material is not transferred to ceramics; the primary evidence supports the broader warning that pressure-flow models which omit slip and compliance can mispredict actual delivery.

Extensional response and free-surface behaviour are often undermeasured. At the nozzle entrance and exit, ink elements accelerate, reorient and stretch. Elastic recoil can cause die swell; surface tension can round or neck a filament; particles or fibres can orient; an unstable stream can pulse, coil or break. Sauret, Ray and Compton identify nozzle flow, clogging, extensional filament formation and post-deposition dynamics as coupled DIW fluid-mechanics problems [34]. Rotational shear data alone cannot close them.

M'Barki, Bocquet and Stevenson explicitly linked rheology with printability and final dense/strong ceramic outcomes in a tested system [19]. The durable conclusion is methodological: ink measurements should be tested against a geometry- and post-

process-defined outcome. It is unsafe to extract their rheological window as a universal criterion because powder, particle interactions, nozzle, path, drying and sintering differ.

A useful characterisation ladder therefore includes, as risk requires; preparation and rest histories; apparent steady and transient shear with slip checks; oscillatory structure and recovery; creep or stress growth; temperature and evaporation sensitivity; capillary or actual-nozzle pressure–flow tests; start/stop and residence tests; extrudate continuity and swell; single-filament geometry and spreading; multilayer stacking; drying and shrinkage; and final ceramic defects/properties. The ladder is shortened only when evidence shows that a measurement cannot influence the intended product.

‘Printability’ is not a free-standing material property. It is a statement that a declared ink, age, delivery system, nozzle, environment, path family, feature, build duration, drying strategy and post-process can meet declared acceptance. The same ink can be printable for an open lattice with a large nozzle and unprintable for a thin sealed wall. A successful calibration spiral cannot qualify a component with long pauses, tight corners, mass transitions or inaccessible interiors.

Rheology release limits are tied to outcomes. A control chart may use a measured response as a sensitive batch indicator, but its acceptance band is validated against extrusion, geometry, drying and final-state evidence. If the process relies on wall slip, the wall material and wear are controlled. If it relies on aging, time and mixing history are controlled. If ambient moisture or temperature shifts the result, the cell controls or compensates those variables through a validated rule rather than operator judgement.

5. Reservoir, metering, nozzle flow and start/stop control

The printhead begins upstream of the visible tip. Reservoir geometry, free volume, follower or plunger, trapped gas, tubing length and compliance, connectors, filters, valve, pressure sensor location, nozzle entrance and temperature form one delivery system. Changing a syringe size, hose, cartridge material or fill procedure can change the transient even when the same nominal pressure and nozzle are retained.

Pneumatic systems regulate gas pressure or pressure on a follower. They can be simple and fast to command, but pressure is the cause, not the delivered volume. Flow changes with ink resistance, temperature, age, fill height, trapped-gas compression, line expansion, nozzle state and motion. At a start, some command energy first compresses gas, ink and flexible components. At a stop, stored pressure can continue extrusion. Retraction or negative pressure can reduce ooze while introducing cavitation, air or composition change. A pressure recipe is therefore inseparable from the complete delivery configuration.

Piston, syringe-pump or lead-screw displacement can provide a better estimate of displaced volume once leakage and compliance are controlled. It still does not guarantee immediate exit flow. Ink compressibility, trapped gas, mechanical backlash, wall slip and elastic storage create delay. Estelle and Gozen showed long and nozzle-dependent transients in a displacement-controlled model-ink system [33]. Their implementation is not a ceramic setting; it demonstrates why start-up, steady state and restart must be measured separately.

Screw, auger, progressive-cavity or other positive-displacement systems can process larger reservoirs or highly filled pastes and can reduce some pneumatic sensitivities. They add shear, residence distribution, leakage/backflow, wear, heat, dead zones and possible particle or fibre damage. Screw speed is not automatically outlet flow when fill, slip or backpressure varies. A change of feed architecture is a material/process change, not a maintenance-neutral substitution.

Nozzle geometry includes inlet contraction, taper, straight length, internal diameter, surface, roundness, wear and exit condition. A tapered nozzle can reduce some pressure loss or residence while increasing convergent flow and orientation. A long straight section can stabilise a developed flow but raises pressure and history. Roughness can suppress slip or nucleate build-up. Abrasive ceramic powders can enlarge or score the bore, altering flow and filament size during a campaign.

Clogging is not limited to one particle larger than the bore. Agglomerates, fibres, debris, dried skins, gas, concentration fluctuations and bridging among smaller particles can interrupt flow. A ratio of nozzle diameter to particle or fibre size helps screen risk but cannot establish freedom from blockage [34]. Prevention includes powder/agglomerate control, clean preparation, compatible screening, sealed storage, appropriate nozzle geometry, controlled pauses and defined cleaning. Purging until flow ‘looks right’ is uncontrolled if the purge state and waste are not recorded.

Pressure monitoring can reveal changes in resistance, trapped gas, depletion, obstruction or start/stop behaviour. Kopatz and co-workers investigated pressure-based monitoring in DIW material extrusion [31]. A pressure trace becomes process evidence only after its coordinate/time registration, sensor range, location, uncertainty and relationship to flow, geometry and defects are validated. The same pressure rise can reflect colder ink, nozzle build-up, altered loading or a longer path residence; it is not a unique defect label.

Flow calibration measures output over relevant time scales. Gravimetric or volumetric collection can support steady-state mapping when density and evaporation are known. Imaging can measure extrudate diameter or discontinuity. Neither alone captures deposition against a surface. The controlled map covers command-to-flow delay, steady flow, corner speed changes, short segment, dwell, stop, restart and end-of-cartridge state. It is repeated after variables that materially affect compliance or resistance change.

The machine coordinate system and deposition path are linked to the delivered material. Acceleration and jerk alter relative nozzle speed while the ink transient lags. In corners, continuous flow can accumulate material; overly aggressive deceleration or retraction can thin or break the filament. At a seam, pressure residue can create a blob and restart delay can create a void. Toolpath planning therefore uses the identified delivery dynamics rather than a constant line-width assumption.

Maintenance is part of control. Nozzles and seals are identified, inspected and replaced against evidence; cleaning does not change surface or leave incompatible residue; sensor zero and calibration are checked; reservoirs and lines are protected from dried

material; and disassembly/reassembly has a verified return-to-service test. A trace that differs after maintenance triggers evaluation rather than manual pressure adjustment until appearance recovers.

6. Filament geometry, fusion, stacking and shape retention

At the exit, confined flow becomes a free filament. Its diameter and cross-section can differ from the nozzle because of swell, contraction, draw-down, surface tension, standoff and contact with the substrate. The final deposited bead depends jointly on volumetric flow and relative speed. Too much material for the programmed path creates lateral spread, ridges, nozzle ploughing or accumulation. Too little creates necking, gaps, weak contact and discontinuity.

Nozzle standoff is a forming variable. A small gap can mechanically compress the filament, improve contact or smear previous material, but can also scrape, overfill or transmit force to a weak build. A large gap can allow stretching, lateral placement error, coiling or breakage. Layer height is not simply selected as a fraction of nozzle diameter; it is qualified with the actual ink, flow, speed, support, prior-layer state and desired interface.

Neighbouring filaments need controlled contact. Adequate overlap can eliminate open gaps, but excessive overlap displaces material and changes wall thickness or surface. Contact depends on the time between paths and on recovery or drying. A newly deposited filament that has already rebuilt a strong structure may resist wetting by the next line. A very fluid interface may fuse while losing the intended pore or wall geometry. `Shape retention` and `fusion` are therefore opposing constraints within a usable window.

Stacking adds time-dependent load. Lower filaments carry increasing weight while their liquid, gel or binder state evolves. A wall that appears stable after five layers can slump after fifty; a tall slender element can buckle even when each local filament retains its section. Span sag depends on unsupported length, filament state, time and temperature. Build qualification uses representative height, duration, pauses and mass transitions rather than a small demonstration.

Path pattern becomes a material architecture. Continuous roads can leave interfilament interfaces, pores and orientation. Alternating directions can redistribute defects or create repeated crossings. Baltazar and co-workers examined filament patterning and structural properties in dense robocast alumina [21]. Their result supports explicit pattern/orientation control and final-state testing, not a universal preferred raster.

Particles, platelets, whiskers or chopped fibres can align in convergent and nozzle flow, and their orientation can affect shrinkage, thermal transport, crack paths and strength. Kemp and co-workers reported DIW of ZrB₂-SiC chopped-fibre composites, including orientation and process-created defects in a specific ultrahigh-temperature route [25]. The demonstration shows that reinforcement and extrusion history must be qualified together. It does not establish that a fibre added to another ceramic will improve an isotropic property.

Open lattices deliberately preserve interfilament voids; nominally dense walls attempt to remove them. These are different products. A pore that is designed and connected can be functional; an unintended crack-like gap at a road interface can be critical. Density targets, toolpath, inspection and property tests therefore distinguish designed architecture from process porosity. A micrograph of one polished plane cannot prove three-dimensional pore connectivity or absence of rare planar flaws.

Feature capability is measured after each relevant state. Wet line width, dry-green width and sintered width can change differently. Vertical and horizontal holes, slots, thin walls, corners, junctions, overhangs, enclosed passages and mixed-mass regions present different flow, drying, support and inspection challenges. Nominal nozzle diameter is neither minimum positive feature nor minimum cleanable gap.

Start and stop artefacts are included in test features. A long continuous wall can hide seam defects, while a lattice contains thousands of accelerations and crossings. A qualification artefact includes the process events that dominate the real component. A toolpath edit that moves seams or changes path order can alter drying time, support and flaw orientation and therefore enters change control.

7. Drying, interlayer drying and green-body handling

Drying converts a deposited wet body into a transportable green compact, but it also creates capillary pressure, concentration gradients, particle rearrangement and shrinkage. Evaporation begins at exposed surfaces and can form a skin while the interior remains mobile. Differential shrinkage can warp a plate, open a filament interface, crack a mass transition or detach the body from its substrate.

Drying rate is controlled through liquid system, temperature, humidity, airflow, platform, enclosure, geometry and time. Faster evaporation can help a fresh layer support the next, yet increase gradients and surface stress. Slower evaporation can improve uniformity while extending the period of slumping or sedimentation. The correct comparison is not `fast versus slow` in isolation but the final green and sintered outcome for the represented geometry.

Interlayer drying intentionally changes the state before subsequent deposition. Davie and co-workers showed in a ceramic paste-extrusion system that interlayer drying could improve tall or overhanging geometry while also changing vertical shrinkage, subsequent layer dimensions and void formation; compensation reduced void fraction within their tested implementation [22]. This is strong evidence for a coupled strategy, not a transferable drying time, temperature or compensation factor.

Interlayer drying also changes interfaces. A partially dried filament can resist deformation and reduce collapse, but its surface may be less able to wet and fuse with the next layer. Repeated dry/wet cycles can create moisture gradients or periodic pore structures. If a nozzle contacts a drier layer, it may scrape or fracture rather than gently compress it. Drying and toolpath order are therefore co-qualified.

The substrate or build plate participates. Adhesion must resist early shrinkage and nozzle forces, but excessive restraint can generate warpage or cracking. A porous substrate can wick liquid and create a bottom-to-top gradient. A heated platform can accelerate local drying. A release film, sacrificial layer or lubricant can contaminate the green body or furnace. Removal timing and method affect the stress state.

Green-body handling includes support removal where used, transfer, dimensional measurement, cleaning and furnace loading. A part can possess enough strength for static lifting yet fail under peel, vibration or local grip. Thin and thick regions require different support. Handling fixtures, trays and setters are designed to distribute load without imprinting or contamination. If the part changes shape during the wait before the furnace, queue time is a controlled variable.

Dry-green inspection can include mass, dimensions, surface, optical imaging, microscopy, radiography or CT where technically capable. Its purpose is to intercept defects that will not heal and to measure shrinkage inputs. A clean surface does not reveal an internal interface; a dense-looking image does not establish binder removal. Inspection limits and false-reject/false-accept risks are documented.

Drying evidence covers positions and seasons or cell conditions that matter. Airflow near a door, enclosure load, neighbouring parts and batch spacing can change evaporation. Tall parts can shade lower regions; cavities can trap vapour. A recipe validated on a single open wall does not close a thick junction or enclosed channel. Moisture or mass endpoints are used only when their sampling and relationship to internal state are established.

8. Burnout/debinding and the brown state

Not every ceramic ink contains the same organic burden, but almost every route contains something that must leave or transform: water or solvent, dispersant, rheology modifier, hydrogel, binder, lubricant, antifoam or support residue. Low total organic content reduces one risk; it does not prove that decomposition is harmless. A small amount concentrated at interfaces can still leave carbon, gas or weak planes. 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-152 retains DIW-specific drying, ink chemistry, geometry, atmosphere and sintering evidence.

Drying and thermal burnout are separated unless validated evidence supports a combined operation. Residual liquid can boil or accelerate gas evolution. Organic decomposition can be endothermic or exothermic, oxygen-limited, catalytic on the powder surface or altered by part thickness. The safe programme depends on formulation, green packing, geometry, furnace flow and load.

Gas must travel from its generation site through a pore network that changes with temperature. Thick regions and enclosed paths increase transport length. A surface can become less permeable while the interior continues to evolve gas. Pressure can open a road interface, blister a wall or create an internal crack invisible after sintering until fracture. Thermogravimetric or evolved-gas evidence can inform stages but cannot by itself qualify a component geometry.

Hydrogel-carrier and binder/solvent systems have different decomposition pathways. Feilden and co-workers followed hydrogel-derived Al₂O₃ and SiC structures through material-specific thermal routes and identified defects affecting strength [20]. Their evidence supports full-chain analysis. It does not justify copying an oxide burnout programme to a non-oxide or changing atmosphere without requalification.

Atmosphere affects decomposition, residue and powder chemistry. Oxidising conditions can assist removal of some organics while oxidising a non-oxide powder or additive. Inert atmosphere can protect chemistry while retaining carbon or changing decomposition. Purge rate, oxygen potential, gas purity, load arrangement and exhaust are part of the record. Furnace off-gas and contamination can affect subsequent loads.

The brown body is the porous ceramic compact after the relevant organic removal and before densification. It can be weaker than the dry green body because the temporary network has gone. Handling, inspection and transfer are minimised and supported. A combined debind-and-sinter cycle may pass continuously through this state, but the material transformation still exists and its risk is not removed by eliminating a manual hold.

Acceptance at this stage can use mass change, witness material, off-gas response, visual or non-destructive inspection and controlled residual analysis where these are validated. 'Cycle completed' is not evidence that all parts experienced the same removal. Furnace position, packing, setter, gas path and load mass can change the result. A deviation in one thermocouple or exhaust signal is linked to affected components, not averaged into the load.

Support media, sacrificial materials and embedded baths introduce additional residues. Their removal must not erode the green body, occlude channels or react during firing. If a support burns out, its gas and ash join the thermal mass balance. If it is washed out, the wash can rewet and stress the green ceramic. Support removal is a manufacturing stage with its own evidence.

9. Sintering, shrinkage, atmosphere, setters and finishing

Sintering converts a porous particle compact toward a denser or deliberately porous ceramic through surface, grain-boundary and volume transport. Shrinkage is a consequence of pore and particle rearrangement, neck growth and densification; it is not a simple printer correction. Local green density, particle orientation, road interfaces, drying and additives can create local sintering-rate differences.

One global scale factor is unsafe when shrinkage differs by axis, location, feature, build orientation or furnace contact. Compensation is a model tied to a material lot family, ink preparation, path strategy, green density, geometry class, thermal load, atmosphere, setter and measurement system. It is validated across the range, and its residuals are examined rather than hidden behind a mean.

The setter supports a body whose stiffness and shape change with temperature. Contact can restrain shrinkage, transfer contamination, imprint a surface or promote reaction. Powder beds, coatings, sacrificial supports or shaped setters can reduce one risk while affecting heat/gas transfer or cleanup. A print claimed to need no build support can still require a furnace setter.

Gravity and capillarity remain relevant during thermal softening or liquid-phase sintering. Tall slender features, spans and asymmetric mass can sag. A feature that is self-supporting while wet can distort near peak temperature. Orientation is selected for deposition, drying, burnout, sintering and finishing together, not for printer convenience alone.

Oxide and non-oxide atmospheres are not interchangeable. Alumina or zirconia may tolerate an oxidising route that would alter SiC or Si₃N₄. Non-oxide densification can depend on powder surface oxygen, sintering aids, gas chemistry and pressure. Faria and co-workers reported a proof-of-concept Si₃N₄ robocasting route [24], and Feldbauer and co-workers reported current aqueous SiC loading and pressureless-sintering work [23]. These demonstrate feasibility within declared systems; neither authorises a shared furnace schedule.

Phase and chemistry can change during firing. Zirconia stabiliser and thermal history affect phase balance. BaTiO₃-based functional ceramics can be sensitive to stoichiometry, grain and atmosphere. Refractories can react or vitrify. Ultrahigh-temperature composites can form interfacial products. Final acceptance therefore measures the property-relevant material state rather than assuming the powder certificate survives unchanged.

Furnace control includes calibrated temperature range, uniformity, atmosphere or vacuum, gas purity/flow, pressure where applicable, load arrangement, thermal mass, setters, ramp/hold/cool history and alarms. A programmed setpoint is not the component temperature. Qualification maps positions and load families; routine records identify the actual load. A furnace or controller change enters process change control.

Cooling can generate gradients, transformation stress and setter interaction. The part remains vulnerable until its temperature and phase are safe for handling. Unloading early to improve throughput can exchange furnace occupancy for cracking or distortion. Queueing and cooling capacity are part of complete-cell economics.

Finishing can remove road texture, setter contact, support scars or dimensional stock and can create new surface flaws. Grinding direction, grit, coolant, force, edge preparation, residual stress and cleanliness affect brittle strength. If test bars are machined while production surfaces are as-sintered, the property evidence does not directly represent the component. Dimensional acceptance identifies whether datums are as-sintered or created during finishing.

Final cleaning removes abrasive, setter, support and process residues without damaging or chemically changing the ceramic. Functional routes may require controlled electrodes, poling, infiltration or coating after sintering; those states are separately identified. The delivered object is accepted only after every mandatory post-process, not at the first dense-looking condition.

10. Oxide, non-oxide, refractory, ultrahigh-temperature and functional ceramics

Ceramic DIW is attractive partly because nozzle deposition can accommodate materials that are difficult to melt or optically expose. That breadth is conditional. Powder surface, liquid compatibility, particle morphology, rheology, drying, atmosphere and densification must be rebuilt for each family. Lewis's foundational review shows the breadth of functional materials accessible to DIW while making ink design central to the process [18]. Material breadth is a research capability, not evidence of a common production window.

Alumina is frequently used as a structural model because powder, aqueous processing and sintering knowledge are extensive. It supports systematic study of filament pattern, drying and brittle flaws. Baltazar and co-workers found structural consequences of filament patterning in dense robocast alumina [21]. Those observations justify orientation-labelled evidence. They do not prove that every alumina ink has the same dominant interface or that an alumina pattern transfers to another ceramic.

Zirconia adds stabiliser and phase-transformation concerns. Ink preparation affects agglomerates and defects; sintering and cooling affect phase and grain; finishing affects surface flaws and transformation. Kovač and co-workers investigated preparation for high-density Ce-TZP DIW [26], while Xia and Duan examined solids-loading effects in a zirconia route [27]. Their results support formulation-specific optimisation and final-state verification rather than a generic zirconia recipe.

Silicon carbide and silicon nitride illustrate the non-oxide boundary. Aqueous preparation can alter surface oxygen and dispersant response; organic removal and sintering atmosphere can affect carbon, oxide layers, aids and final phases. Feldbauer and co-workers address current high-loading aqueous SiC robocasting [23]. Feilden and co-workers include a hydrogel-carrier SiC route [20], and Faria and co-workers report a Si₃N₄ proof of concept [24]. These systems cannot be merged into one 'non-oxide' formulation or furnace cycle.

ZrB₂-SiC and related ultrahigh-temperature ceramics create further pressure, abrasion, oxidation and densification challenges. Chopped reinforcement can align and agglomerate, and a preceramic or temporary organic phase can change conversion and defect formation. Kemp and co-workers provide a bounded composite demonstration [25]. Qualification would still need intended-environment oxidation, thermal shock, joint/interface and long-term evidence beyond a successful print and room-temperature coupon.

SiO₂-Al₂O₃ refractory products can favour DIW where composition and internal architecture are valuable, but refractory acceptance concerns high-temperature phase, creep, thermal cycling, slag or atmosphere interaction and dimensional stability. Zhu and co-workers demonstrated one refractory DIW route [29]. It does not establish suitability for a furnace duty or transfer to construction-scale deposition, which is outside this review.

Functional ceramics add properties not captured by density and strength. Gadea and co-workers used hybrid inks to form tall BaTiO₃-based ceramics [28]. The work supports formulation/geometry coupling in one functional material. Electrical or

electromechanical acceptance still depends on final phase, porosity, grain state, electrode, poling where applicable, frequency, field, temperature, humidity and aging. A tall green or sintered shape is not a qualified device.

Designed density gradients can be functional but create shrinkage mismatch. Kanno, Kurita and Narita reported bending-strength evidence for density-controlled DIW alumina and identified interface cracking associated with differential shrinkage in the studied architecture [32]. The factory implication is general: composition, solids, path or pore transitions are interfaces requiring local dimensional and fracture evidence. The numerical result and geometry remain study-specific.

Hybrid or multimaterial deposition increases the genealogy burden. Every material needs a released feed path, and interfaces need chemical, thermal and shrinkage compatibility. Switching can leave mixed dead volume or cross-contamination. A graded command is not necessarily a graded composition at the nozzle because residence and mixing smear the transition. Final tests map actual composition and property across the interface.

Table 2. Material-family opportunities and non-transfer boundaries

Family	Conditional opportunity	Dominant additional controls	Transfer that is not allowed
Alumina/structural oxides	Dense or designed-porous shapes, lattices and low-tooling geometry	Dispersion, road interfaces, drying, sintering/setter and brittle flaw populations	Alumina rheology or pattern as a universal ceramic window
Zirconia systems	Complex transformation-toughened or functional shapes	Stabiliser/phase, agglomerates, green density, sintering/cooling and finishing	Powder name as proof of phase or service properties
SiC and Si ₃ N ₄	Non-oxide geometry without melting; high-temperature potential	Surface oxygen, additives, atmosphere, residue, densification and oxidation	Oxide binder-removal or furnace route
Refractory/UHTC composites	Near-net refractory or extreme-temperature architecture	Abrasion, fibre/particle orientation, atmosphere, reaction, thermal shock and service oxidation	Successful green print as extreme-service approval
Functional oxides	Dielectric, ferroelectric or other designed function in complex shapes	Stoichiometry, phase, grain, pores, electrodes/poling and field/environment test	Density or room-temperature strength as functional evidence
Graded/multimaterial	Spatial composition, density or pore architecture	Dead volume, transition fidelity, differential drying/sintering and interface fracture	Commanded gradient as measured final gradient

11. Defects, orientation, fractography and brittle statistics

Defects are classified by formation stage. Powder and preparation can create hard agglomerates, contamination, gas and composition gradients. Delivery can create segregation, clog-release debris, pulsation and start/stop voids. Deposition can create road gaps, overfill, poor fusion, folded filaments, orientation and inclusions. Drying can create skin, warpage, delamination and capillary cracks. Burnout can create pressure cracks and residue. Sintering can create pores, abnormal grain, reaction, phase error, distortion and setter damage. Finishing can add surface cracks or edge damage.

An inspection image is interpreted against that mechanism map. Surface imaging cannot exclude a buried road interface. A polished section is local and may cut parallel to a planar defect. Bulk density averages the component and can miss a rare critical crack. CT capability depends on attenuation, size, voxel, contrast, reconstruction and artefact. The inspection plan states the relevant indication, required coverage and demonstrated detection capability.

Orientation matters from nozzle to test. ISO 17295 supports explicit part position, coordinate and orientation [6]. The record links road direction, build axis, surface normal, furnace orientation, specimen axis and loading. A label such as `XY` without a defined coordinate origin and toolpath can be ambiguous. If specimens are extracted or machined, their location and direction remain linked to the component.

Brittle strength is controlled by the most severe effective flaw in the stressed surface or volume. Scatter is therefore process information. ASTM C1161 defines a flexural-strength method for advanced ceramics [8], and ISO 14704 supplies a standard method for monolithic fine ceramics [11]. The chosen method, specimen size, preparation, surface, chamfer, orientation, loading and environment accompany every value.

ASTM C1239 provides a framework for reporting uniaxial strength and estimating Weibull parameters [9]. Sample size, confidence, censoring and mixed populations matter. Combining different path patterns, furnace positions or surface states into one attractive distribution can hide multiple failure mechanisms. Statistics support a defined population; they do not replace process understanding.

Fractography connects the distribution to manufacturing. ASTM C1322 structures identification and characterisation of fracture origins [10]. Fracture surfaces are retained, protected and examined with knowledge of stress and process history. Road-interface flaws, agglomerates, pores, inclusions, machining damage and corners are classified and fed back to preparation, deposition, drying, firing or finishing controls.

Hydrogel-ink structural-ceramic work identified strength-limiting defects after the complete route [20]. Patterned alumina evidence shows that filament architecture can change structural response [21]. Differential-density alumina evidence shows interface cracks can arise from shrinkage mismatch [32]. Together, these sources support mechanism-led investigation, not a pooled ceramic-DIW strength expectation.

NIST's current ceramic-AM programme reports that interlaboratory work found a small set of flaw types dominating failures while populations differed among laboratories under nominally similar conditions [12]. Allen, Levin and Maier call for curated feedstock/end-product data and an international round-robin tied to standards [13]. The production lesson is direct: a published ink name, CAD file or nominal process does not reproduce a local flaw population. Site-specific evidence remains mandatory.

Property testing follows service failure modes. Flexural strength does not establish fracture toughness, fatigue, creep, wear, thermal shock, dielectric breakdown, permeability or oxidation life. Dense and porous products need different models. A lattice may fail by strut bending or a junction flaw; a sealed component may fail by a leak path; a functional ceramic may fail by electrode or domain degradation. The qualification plan tests the delivered state and relevant environment.

Witness specimens are useful only when representative. A small bar placed beside a tall component can experience a different deposition history, drying gradient and furnace constraint. A specimen cut from a part may destroy the evidence it is meant to represent or sample only one location. Representativeness is justified through geometry, position and process mapping, with destructive correlation where necessary.

12. Geometry, scale, embedded support, productivity, economics and safety

Ceramic DIW can create open lattices, curved walls, internal passages, graded porosity and near-net shapes without a hard mould. It can also change composition along a path when multiple controlled feeds are available. These are mechanistic opportunities. A geometry is manufacturable only when it can be deposited, dried, handled, thermally processed, cleaned, inspected and used within tolerance.

Scale creates new physics rather than merely longer toolpaths. Tall structures accumulate weight and time; broad parts accumulate drying and thermal gradients; thick junctions retain liquid and organics; long builds increase ink aging and nozzle wear. Larger nozzles can increase deposition rate while reducing feature access and increasing surface stock. Smaller nozzles can improve nominal path scale while raising pressure, clogging, residence and transient sensitivity.

Interlayer drying can enable height at the cost of periodic shrinkage and interface change [22]. Hybrid inks enabled tall BaTiO₃-based demonstrations within a declared system [28]. Neither result supports unbounded scale. Qualification establishes maximum represented height, span, wall, mass transition, duration, pause and environmental range. A tall vase is not automatically a structural or functional large part. Embedded/support-bath architectures and sacrificial-support recovery are inherited from ER-163; ER-152 addresses only their use and qualification within ceramic DIW.

Embedded DIW deposits into a support medium that yields around the moving nozzle and recovers around the filament. Huang and co-workers demonstrated freeform ceramic components using embedded DIW, primarily in a preceramic-polymer implementation while also exploring powder-containing inks [30]. The architecture can reduce gravity-driven sag and enable freeform paths, but it adds bath rheology, ink–bath interface, buoyancy, contamination, nozzle drag, path closure, recovery and bath removal. It is an alternate process chain, not a universal solution to ceramic support.

Conventional sacrificial supports also add material compatibility, path time, drying and removal. A support that is mechanically effective while wet can restrain shrinkage or leave residue. An internal support can become inaccessible after drying. Unsupported geometry in the printer can still need a setter in the furnace. Design reviews therefore map support and contact at every state.

Complete-cell time includes powder and ink release, preparation, degassing, loading, priming, deposition, pauses/interlayer drying, unloading, controlled drying, support or bath removal, green inspection, burnout/debinding, sintering and cooling, finishing, inspection, maintenance, cleaning, rework and queueing. Furnace and drying capacity can dominate even when deposition is fast.

$$\text{Effective cell throughput} = \text{accepted components} \div \text{complete elapsed and capacity-constrained cell time}$$

Economics compare accepted function with realistic alternatives: pressing plus green machining, slip or gel casting, injection moulding, tape assembly, conventional machining of fired stock, vat photopolymerisation or another AM route. DIW can avoid tooling and retain high material utilisation for changing or low volumes. Surface finishing, manual loading, long drying/firing and qualification can reverse the advantage. Purchase price or programmed print time is not cost per accepted component.

Yield is state-resolved. An ink loss, nozzle failure, green crack, burnout crack, sintering distortion and final-test reject have different costs. Late failures consume all prior capacity and can dominate economics. Scrap mass is separated from recoverable and re-released material. Furnace furniture, support bath, filters, cleaning media, abrasives, test specimens and waste treatment are included.

Safety assessment follows tasks and substances. Fine ceramic powders and dry finishing can create inhalation exposure; liquids, dispersants, binders and cleaners can create skin, eye, inhalation, flammability or incompatibility hazards; pressurised reservoirs can release material; moving axes, screws and pinch points require guarding. NIOSH's current additive-manufacturing resource supports task-based exposure assessment, hierarchy of controls and attention to the complete workflow [15]. It does not replace powder-, chemical- or process-specific hazard information.

Powder addition, mixing, cartridge filling, purging, nozzle clearing and dry cleanup are controlled rather than treated as brief exceptions. Enclosure, local exhaust, closed transfer, compatible tools, housekeeping and protective equipment are selected from the actual exposure assessment. Compressed gas is not used to disperse deposited powder or clear contamination into the room. Gloves are chosen for the relevant chemicals and changed before contamination spreads to controls or documents.

Thermal processing adds hot surfaces, combustible or toxic decomposition products, furnace energy, pressure/vacuum where used and inert, reducing or reactive atmospheres. Inert gas can displace oxygen; reducing or process gases can add fire, toxicity or reaction hazards. Off-gas and purge logic consider the measured formulation and worst credible load. Setters and furnace maintenance can expose dust and residues.

Safety qualification covers normal operation, refill, jam, pressure fault, nozzle clearing, spill, failed print, power loss, exhaust failure, furnace alarm, maintenance and waste. Increasing scale changes stored pressure, powder/solvent inventory, off-gas load and manual handling. A laboratory control is not assumed adequate for production throughput.

13. Qualification architecture and technology-selection gate

Qualification begins with final requirements and works backward. The specification defines material identity and phase, intentionally dense or porous architecture, geometry, surface, cleanliness, mechanical or functional performance, environment, reliability, inspection, traceability and regulatory constraints. The route is selected only if each state can be controlled and evidenced. ISO/ASTM 52920 provides the general production-site and process qualification architecture [2]. Cross-process direct/indirect route comparison is inherited from ER-049; ER-152 contributes the ceramic DIW evidence used within that selection architecture.

Material qualification identifies powder and additive specifications, formulation identity, preparation and aging, allowed adjustment/reuse, rheological and extrusion responses, drying and thermal transformations. Equipment qualification identifies reservoir/metering/nozzle architecture, calibrated signals, environmental control, software/file state, maintenance and critical consumables. Personnel qualification covers material preparation, loading, machine operation, green handling, furnace operation, finishing, inspection and deviation authority.

Installation and operational qualification show that equipment and utilities can operate and control their intended ranges. Performance qualification uses representative and worst-case combinations of ink age, cartridge state, nozzle, starts/stops, build duration, height, span, road pattern, mass transition, drying path, support, furnace load/position, setter, atmosphere and finishing. The test family includes adverse but permitted conditions rather than one favourable nominal build.

Table 3. Ceramic DIW qualification and selection gate

Gate	Question that must close	Minimum evidence family	Stop condition
Requirement	Is the final ceramic state, geometry, function and inspection defined?	Drawing/specification, use environment, failure modes and acceptance plan	Generic '3D-printed ceramic' requirement
Ink	Is powder-to-ink identity and history stable through the allowed use period?	Composition basis, dispersion/agglomerates, gas, rheology histories, age/reuse and sampling	Visual homogeneity or one viscosity only
Delivery	Can the actual reservoir/line/nozzle meter reproducibly through starts, paths and stops?	Pressure/displacement/flow, nozzle state, transients, maintenance and deposited-filament evidence	Set pressure, screw speed or nozzle diameter used as proof
Green geometry	Can representative features fuse and retain shape through the full build and drying path?	Height/span/corner/seam/mass-transition tests, drying record and green inspection	Small short print or immediate visual pass
Thermal route	Can organics leave and ceramic densify without unacceptable reaction or distortion?	Geometry/load/atmosphere/setter records, phase, pores, dimensions and defects	Copied burnout/sintering cycle or one scale factor
Properties	Are final flaw populations and functional properties acceptable?	Standard-labelled statistics, orientation/surface, fractography and application tests	Density or mean strength alone
Inspection	Can critical dimensions and defect hypotheses be detected with known capability?	Validated method, coverage, uncertainty and destructive correlation	'CT inspected' or 'no visible cracks' without capability
Production	Is the full cell safe, repeatable and economic at accepted-part level?	Yield, constrained time/cost, maintenance, exposure and change control	Deposition-only speed or material-use claim

The control plan connects inputs, leading indicators and final outcomes. Rheology can detect batch drift; pressure can detect delivery change; images can detect some deposition defects; mass or moisture can track drying; furnace signals can track thermal history. None is a final-quality surrogate until correlated with the relevant geometry, defect and property inside a validated range.

Change control is conservative because variables are coupled. Powder supplier or surface state, dispersant, binder, liquid, water quality, mixing tool, storage, reservoir, tubing, nozzle geometry/material, sensor, software, path order, environment, drying, support bath, furnace, atmosphere, setter or finishing can affect multiple stages. A risk review identifies which prior evidence remains representative and which qualification elements repeat.

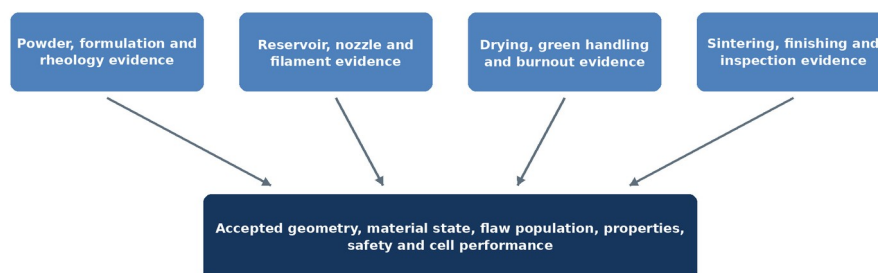


Figure 2. Evidence closure for an accepted ceramic DIW component.

The technology-selection gate asks what DIW uniquely enables and what it costs to close the evidence. It is favoured when mould avoidance, path-defined architecture, open porosity, graded material, rapid design change or low-volume geometry outweigh nozzle scale, surface, drying, thermal and inspection burdens. Slip casting, pressing, injection moulding or green machining can dominate repeatable simple shapes and high volumes. Ceramic VPP can dominate smaller intricate features when

optical suspension and cleaning are acceptable. Binder jetting can dominate some powder-bed geometries and batch nesting. The result depends on the final component and cell, not on a universal ranking.

No-go conditions include a required feature that cannot be deposited, fused, dried, cleaned or inspected; a formulation whose time-dependent state cannot be controlled; excessive pressure or clogging; inaccessible support medium; unacceptable drying or thermal gradients; atmosphere or setter incompatibility; an unobservable critical flaw; a required property unsupported in the delivered state; or complete-cell safety, yield or economics outside the programme boundary. A promising green print does not override a closed stop condition.

14. Conclusions and research priorities

Ceramic DIW and robocasting are powerful because they translate a controlled complex-fluid path into a ceramic green architecture without a hard mould. Their central limitation is the same coupling: the path is formed by a suspension whose structure changes during preparation, confinement, extension, deposition, rest and drying, and the useful material is created only after further thermal transformations.

The ink cannot be qualified with one viscosity or yield value. Rheometry must preserve protocol and artefact controls, then connect to actual nozzle flow, start/stop dynamics, filament geometry, multilayer stability, drying and final defects. Pressure is not flow; nozzle diameter is not final resolution; immediate shape retention is not long-build or dry-green stability.

Higher loading, stronger recovery, interlayer drying and embedded support are conditional tools. Each improves one part of the process while potentially worsening mixing, pressure, fusion, shrinkage, voids, contamination or removal. Their benefit belongs to a declared material–delivery–geometry–environment–thermal system and comparator.

The printer creates a green ceramic body. Drying can introduce capillary stress and periodic interfaces. Organic removal is chemistry- and geometry-dependent even at low binder content. Sintering introduces local shrinkage, phase, grain, gravity, atmosphere and setter effects. Oxide evidence does not transfer automatically to non-oxides, refractories, UHTCs or functional ceramics.

Qualification therefore follows defects and states. Density and mean strength are insufficient for brittle components. Orientation-labelled testing, population statistics, fractography and inspection capability connect powder, preparation, roads, drying, firing and finishing to reliability. Functional ceramics require final electrical, thermal, optical or other application-relevant evidence rather than structural proxies.

Priority research should close the gap between laboratory rheometry and actual high-solids nozzle histories; quantify slip, extensional response, clogging and transient flow; develop reference inks and interlaboratory procedures; link registered pressure and imaging signals to defect mechanisms; model filament fusion and drying across long builds; predict anisotropic shrinkage and setter contact; and build shared flaw-population databases tied to standard tests. NIST and the 2022 industrialisation panel identify feedstock metrology, public data and round-robin comparison as immediate needs [12,13].

Scale-up research should report accepted-part throughput, not only travel or deposition rate. It should include preparation, cartridge change, cleaning, drying, furnace utilisation, finishing, inspection, yield, exposure and waste. Embedded and multimaterial routes need quantitative bath/interface removal and composition-transition evidence. Non-oxide and functional routes need atmosphere-, chemistry- and property-specific closure.

Factory adoption should proceed through a requirements-led gate: define the final ceramic and failure modes; release powder and ink through their real histories; characterise the actual delivery and filament process; prove representative geometry through drying and handling; validate organic removal, atmosphere, setter and sintering; identify flaw populations; demonstrate final properties and inspection capability; then calculate safety, yield and complete-cell economics. Only this chain supports an accepted ceramic component.

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