

Vat Photopolymerisation of Ceramics

LCM and CDP, Suspension Optics, Green Handling, Debinding, Sintering and Qualification

Juan Seguro

3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

Correspondence: info@3Dresyns.com · Website: www.3Dresyns.com

ER-151 · Engineering Review · Version 0.4 · 6 September 2026

Statement of Significance

Ceramic vat photopolymerisation can shape intricate technical-ceramic green bodies without a mould, but projected or scanned light does not directly create a finished ceramic. It freezes a powder distribution inside a temporary polymer network. The apparent precision of the green print survives only if a highly filled suspension can be prepared, renewed and exposed reproducibly; the green body can be separated, cleaned and dried without damage; organic matter can escape without generating pressure cracks or residue; and the powder compact can shrink, densify and cool without unacceptable warpage, reaction, pores, phase change or setter damage. These constraints are coupled. Increasing ceramic loading can reduce organic burden while making dispersion, recoating and optical cure harder. Increasing exposure can improve depth or adhesion while broadening features and trapping material. A support-free print can still need a furnace setter. A high mean strength can still conceal a critical flaw population. This review provides a state-resolved factory framework for advanced oxide, nitride, bioceramic and functional-ceramic routes. It distinguishes stereolithography, DLP, LCD, LCM and supplier-labelled ceramic direct production, bounds published demonstrations to their materials and cells, and makes final acceptance depend on the complete suspension-to-sintered-component chain.

Abstract

Vat photopolymerisation of ceramics selectively cures a photoactive ceramic-powder suspension or paste to form a polymer-bound green body that is subsequently recovered, cleaned, debound and sintered. Labels including ceramic stereolithography, ceramic DLP, LCD ceramic printing, lithography-based ceramic manufacturing (LCM), CerAM VPP and ceramic direct production (CDP) describe related implementations but do not guarantee an identical optical engine, layer-delivery mechanism, feedstock state or thermal route. Powder refractive index, absorption, particle and agglomerate size, surface chemistry, solids loading, resin spectrum and initiator response govern light transport. Rheology, sedimentation, thixotropic recovery and aging govern layer renewal and composition. Cure depth, lateral overcure, conversion, green strength and interlayer contact are separate responses; nominal wavelength, pixel pitch or scalar exposure cannot establish final feature capability. Green recovery and cleaning can damage thin walls or trap uncured suspension. Debinding is a geometry-dependent heat-, mass-transfer- and reaction process, while sintering introduces three-dimensional shrinkage, phase and grain evolution, gravity, setter interaction and atmosphere sensitivity. Oxide evidence does not transfer automatically to silicon nitride, aluminium nitride, calcium phosphate or other advanced ceramics. Brittle-component qualification requires flaw-population statistics, fractography and inspection capability rather than density or mean strength alone. This qualitative engineering review connects material release, formulation, optics, layer delivery, green handling, thermal processing, finishing, safety, productivity and part-linked qualification. It supplies no transferable formulation, exposure, cleaning, debinding, sintering, scale-factor or acceptance recipe.

Keywords: *ceramic vat photopolymerisation; lithography-based ceramic manufacturing; ceramic direct production; ceramic DLP; ceramic stereolithography; powder-loaded photoresin; green body; debinding; sintering; technical ceramics; qualification*

1. Purpose, scope and terminology

ISO/ASTM 52900 defines vat photopolymerisation as an additive-manufacturing category in which liquid photopolymer in a vat is selectively cured by light-activated polymerisation [1]. Ceramic implementations suspend or disperse ceramic powder in the photoactive phase. The selectively cured object is therefore a ceramic-powder/polymer green composite. It is not a dense alumina, zirconia, silicon nitride, aluminium nitride or hydroxyapatite component when it leaves the printer. NIST explicitly identifies post-build sintering as a distinctive source of cost and complexity in ceramic AM [12].

The scope begins with ceramic powder, sintering aid where applicable, resin constituents, dispersant, initiator, absorber, cleaning media, setter and furnace consumables. It covers identification, release, mixing, deagglomeration, degassing, storage, remixing, layer formation, optical exposure, platform or vat motion, separation, green-part recovery, cleaning, drying, green inspection, support handling, debinding, brown-state control, sintering, cooling, finishing, cleaning, inspection, testing, economics, safety and qualification. ISO/ASTM 52920 supplies a general site/process qualification architecture [2], while ISO/ASTM 52910 supports requirements-led design communication [3]. Neither document provides a ceramic feedstock or furnace window.

‘Stereolithography’ or ‘SLA’ is used here for a scanned optical path only when the implementation actually scans a focused beam. ‘DLP’ denotes a projected digital image produced by a digital micromirror or equivalent projector. ‘LCD’ denotes an image mask based on a liquid-crystal panel. Projected and masked systems can expose a layer nominally in parallel, but spectrum, irradiance field, pixel imaging, optical blur and material response remain machine-specific. ‘Top-down’, ‘bottom-up’, ‘film transport’, ‘recoated film’, ‘free surface’, ‘squeeze flow’ and ‘paste’ describe materially different layer and separation conditions.

`Lithography-based ceramic manufacturing` (LCM), `CerAM VPP`, `ceramic DLP`, `ceramic stereolithography` and `ceramic direct production` (CDP) are retained as implementation or supplier labels, not treated as synonyms with one shared process window. A current 3Dresyns IFU uses CDP and related labels for direct shaping of sinterable materials and requires user validation [35]. That page is used only to establish manufacturer terminology and the declared validation boundary. Its numerical starting formulations and settings are deliberately not reproduced here and do not constitute independent evidence.

The paper focuses on advanced technical ceramics and highly specialised 3D-resin systems: structural oxides, transformation-toughened zirconia, nitrides, thermal-management ceramics, calcium phosphates and selected functional ceramics. It excludes cement, concrete, regolith and other macroscopic high-volume construction. It also excludes ceramic binder jetting, extrusion/direct-ink writing, ceramic powder-bed fusion and metal-filled lithography. Polymer-derived ceramics are mentioned only to prevent category confusion because conversion of a preceramic polymer is not the same material route as debinding and sintering a powder-loaded green body. Metal-filled vat-photopolymerisation is controlled by ER-149; ER-151 retains the ceramic-powder VPP route and its ceramic-specific thermal-conversion evidence.

ISO/ASTM 52901 requires customer and provider to define the delivered state, required characteristics, inspection and documentation for purchased AM parts [4]. A purchase order that asks only for `3D-printed zirconia` or `LCM alumina` is underdefined. It should identify ceramic grade and phase, delivered density or pore architecture, surface and cleanliness condition, heat-treatment state, critical geometry, functional properties, inspection coverage, traceability and any regulatory or service constraints.

This review does not prescribe powder grade, particle size, solids loading, binder chemistry, dispersant, mixing sequence, rheological range, storage life, wavelength, irradiance, exposure, layer thickness, separation motion, cleaning chemistry, drying route, debinding cycle, atmosphere, sintering aid, furnace schedule, setter, scale factor, finishing method or acceptance threshold. Each belongs to a declared powder–resin–optics–layer–delivery–geometry–thermal–route–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 word `printing` compresses several material identities. Released powder and photoactive ingredients first become a formulated suspension or paste. Layer delivery then creates a temporary spatial distribution of solids at an exposure interface. Patterned light forms a polymer network that holds some of that distribution. The recovered green part contains ceramic powder, crosslinked binder, potentially unreacted species and process-created interfaces. Debinding removes or converts organic matter, leaving a fragile porous powder compact commonly called a brown body. Sintering then changes pore geometry, grain and phase state while shrinking the component.

Table 1. State-resolved ceramic vat-photopolymerisation chain

Stage	Controlled state	Principal evidence	Invalid shortcut
Powder and ingredient release	Ceramic identity, phase/surface, sintering aids, resin, initiator, dispersant, absorber, storage and sampling	Certificates plus verified identity and specified incoming tests	`Correct ceramic resin`
Suspension or paste release	Solids basis, dispersion, agglomerates, rheology, stability, optical response, gas/moisture and history	Representative batch tests under relevant histories	`Looks homogeneous`
Layer and exposure	Renewal, thickness, temperature, interface, separation, spectrum, irradiance field and exposure sequence	Registered machine/material evidence linked to build position	`Correct wavelength and dose`
Green formation	Conversion, depth/width, layer contact, packing, geometry, strength, residue and internal clearance	State-specific coupons, features and inspection	`Pixel-perfect ceramic`
Recovery and drying	Separation, cleaning, support handling, solvent/water removal, damage and contamination	Qualified handling and cleanliness evidence	`Wash until clean`
Debinding/brown state	Organic removal, gas paths, residue, reaction, cracks, shape and residual strength	Geometry/load/atmosphere-specific record and hold point	`Binder removed`
Sintering and cooling	Densification, phase, grain, pores, chemistry, shrinkage, gravity, setter and furnace position	Furnace/load record plus mapped material and dimensional evidence	`Apply one scale factor`
Delivered acceptance	Final geometry, surface, cleanliness, flaw populations and functional properties	Part-linked tests, uncertainty, genealogy and disposition	`Density or coupon passed`



Figure 1. State-resolved ceramic vat-photopolymerisation route.

The chain prevents four recurring category errors. First, photopolymerisation retains particles; it does not sinter them. Second, apparent green accuracy is not final accuracy because polymer removal, densification and cooling remain open. Third, uncured suspension can temporarily support geometry in a vat without proving that cavities can be cleaned or that the shape will survive the furnace. Fourth, a nominally single debind-and-sinter programme still contains distinct transformations with separate failure modes.

Traceability crosses batch and load boundaries. One powder lot can enter several formulation batches. A suspension can age during multiple builds. One build can span different optical-field positions and recoating histories. A furnace load can combine parts from several builds, setters and orientations. The controlled genealogy links powder and ingredient lots, mixing energy and sequence, formulation age, storage/remix history, machine and file version, layer/exposure state, build position, green handling, cleaning and drying, debinding load/position, sintering load/position, setter/contact, finishing, tests and final serial or batch.

ISO/ASTM 52951 supports part-linked data packages [7]. ISO/ASTM 52953 addresses registration of monitoring data in metal AM [6]; only its general registration principle is borrowed here. It does not qualify ceramic sensors or acceptance logic. The process owner defines which records are raw, which are validated summaries, how clocks and coordinates are synchronised, and how a deviation in mixing, exposure, cleaning or furnace history is linked to affected parts.

The production chain contains explicit holds. A suspension release does not authorise unlimited use after aging or replenishment. Green release confirms handling and thermal eligibility, not final conformance. Brown-state release confirms safe continuation only when that inspection is technically meaningful. Sintered release requires final geometry, material and functional evidence. Bypassing a hold because the part will be 'fixed in sintering' converts an assumption into hidden rework risk.

3. Ceramic powder, surface chemistry and photoactive binder

The powder establishes ceramic chemistry, phase, impurity burden, particle morphology, size distribution, surface area, surface hydroxylation or oxidation, agglomeration, packing and sintering response. The organic phase establishes viscosity, wetting, dispersion, photochemical response, green network, cleaning compatibility and the mass that must later leave. Sintering aids, pigments, absorbers and other additives can influence both stages. A formulation is therefore a coupled material, not ceramic powder mixed with an inert carrier.

Powder identity is verified beyond a commercial name. Relevant attributes can include phase and polymorph, dopant level, moisture, loss on ignition, carbon/oxygen or other impurity, specific surface, morphology, particle-size distribution before and after dispersion, hard agglomerates, and sintering-aid distribution. A zirconia labelled only by oxide name leaves stabiliser content and phase behaviour unresolved. A silicon-nitride or aluminium-nitride powder brings oxygen, surface chemistry and atmosphere sensitivity that cannot be inferred from an alumina route.

Particle size presents a multi-objective trade. Finer particles can improve packing and sintering kinetics or support thinner green features, but increase surface area, dispersant demand, viscosity, adsorbed species and powder-handling exposure. Coarser particles can reduce specific surface and alter scattering while limiting layer uniformity and fine-feature formation. Bimodal or multimodal distributions can improve packing in one system while increasing segregation or formulation complexity. The useful distribution is the dispersed in-process state, not merely the supplier's dry-powder certificate.

Surface chemistry controls wetting and adsorption. A dispersant that works for alumina in one acrylate system may not adsorb or remain stable on zirconia, hydroxyapatite, Si₃N₄ or AlN. Competitive adsorption among dispersant, initiator, inhibitor, monomer and adventitious water can change rheology or cure with time. Milling and mixing can expose fresh surfaces, heat the formulation and introduce wear debris. The batch record therefore includes vessel, media, order of addition, energy/time, temperature, atmosphere where relevant, degassing and screening.

The photoactive phase is selected for more than low initial viscosity. Monomer functionality and molecular structure influence network formation, cure rate, shrinkage, green strength, glass transition, cleaning resistance and thermal decomposition. Kuang and co-workers varied monofunctional, bifunctional and multifunctional resin constituents in a zirconia DLP study [30]. Their reported optimum belongs to their powder, resin, initiator, printer and test method. The transferable result is the need to optimise rheology, cure and thermal removal jointly, not the recipe.

Solids loading must be reported unambiguously, preferably with both mass and volume basis when conversion data are reliable. Higher ceramic volume fraction can reduce organic content, shorten particle-to-particle distance and lower densification shrinkage. It can also increase viscosity, yield stress, trapped-gas risk, blade or squeeze force, incomplete levelling and the sensitivity to agglomerates. Lower loading can make coating and cure easier while increasing binder-removal burden, shrinkage and the chance that the particle network loses continuity.

Griffith and Halloran established early particle-filled stereolithography foundations [18], while Chartier and co-workers demonstrated the coupled demands of high loading, rheology, cure and structural ceramic shaping [19]. These studies remain important because the physical conflicts persist. They do not define modern machine parameters. Halloran's later review synthesises ceramic photopolymerisation mechanisms and process boundaries [16]; it likewise supports engineering models, not universal operating numbers.

Formulation release includes homogeneity and stability. A visually uniform vat can contain agglomerates, entrained gas, settling gradients or binder-rich regions. Samples are taken from positions and times that represent actual layer delivery. Particle/agglomerate distribution, rheology, density or solids content, optical response and aging are assessed with uncertainty and repeatability appropriate to the risk. Zocca and co-workers emphasised that ceramic AM opportunities remain inseparable from feedstock, post-process and defect challenges [17].

Unexposed feedstock is not automatically virgin-equivalent after a build. It can acquire cured debris, contamination, cleaning carryover, evaporative change, initiator depletion, altered agglomeration or a different light/temperature history. Reuse requires a controlled rule for segregation, screening, refresh, requalification and maximum history. Recoverable mass is not the same as released mass, and released mass is not the same as accepted-part material efficiency. Generic ageing, storage, reuse and requalification logic is inherited from ER-032; ER-151 applies it to ceramic photoactive suspensions and pastes.

4. Suspension optics, scattering and cure–loading trade-offs

Light transport through a ceramic suspension depends on absorption and scattering by the liquid and solids. Refractive-index mismatch between particle and organic phase, particle and agglomerate size relative to wavelength, volume fraction, pigment, porosity or bubbles, surface state, optical spectrum and geometry all contribute. A white oxide can scatter strongly; a dark or high-index non-oxide can absorb and scatter enough to make cure shallow or laterally complex. The generic refractive-index-contrast and particle-scattering framework is inherited from ER-076, while absorber, pigment and initiator effects on cure depth are inherited from ER-044; ER-151 applies both to ceramic VPP suspensions.

A simple working curve can be useful when its measurement method and range are declared, but it is an empirical representation of a specific formulation, age, temperature, optical engine and geometry. It does not prove conversion, green strength or dimensional fidelity. Cure depth is the vertical extent meeting a measurement criterion. Lateral cure or overcure describes boundary growth in the plane. Conversion describes reaction extent. Interlayer adhesion concerns contact between successive states. These responses may move differently with exposure.

More dose can increase cured depth or green strength until other effects dominate, yet it can also broaden walls, close channels, bond to a window or film, add heat and change stress. Less dose can sharpen a nominal boundary while leaving weak interlayer contact or fragile green material. The usable window is bounded on both sides and validated with representative features: vertical and horizontal walls, holes, channels, lattices, unsupported spans, mass transitions and field-edge locations.

Griffith and Halloran linked scattering to powder/resin optical contrast in early ceramic stereolithography [18]. Halloran later reviewed how scattering and absorption constrain ceramic photopolymerisation [16]. Wu and co-workers specifically engineered a high-refractive-index liquid phase for Si₃N₄ mask stereolithography [29]. Their result shows that optical contrast can be designed; it does not establish one resin index or wavelength for other nitride powders.

The optical engine is characterised by more than a nominal wavelength and rated power. Relevant evidence includes spectrum, irradiance map, focus or point-spread behaviour, magnification/distortion, pixel or scan registration, temporal stability, exposure sequence, window transmission and contamination. A DLP pixel, LCD pixel or laser spot is a command element, not final ceramic resolution. Optical blur, scattering, polymerisation, layer mechanics, cleaning damage and sintering all separate the final edge from the digital boundary.

Absorbers and pigments can improve depth control while reducing cure margin or creating wavelength sensitivity. Photoinitiator concentration can increase radical generation while changing optical attenuation, conversion gradients, yellowing or thermal residue. Oxygen inhibition can matter near interfaces or free surfaces, depending on chemistry and architecture. Because ceramic powders present large surfaces, adsorption or quenching can change the effective initiator response. The material and light package are therefore released together.

Alumina offers useful but bounded examples. Zhang and co-workers took one alumina DLP formulation through shaping and sintering [21]. Verza and co-workers demonstrated alumina components with a cost-effective LCD printer [22]. These studies show that different image engines can produce ceramic green bodies when the suspension and process are engineered. They do not prove that an LCD and DLP system share exposure, layer, accuracy, throughput or thermal results.

Non-oxides expose the limit of transfer. Altun and co-workers reported an LCM route for a Si₃N₄-based ceramic [27], while Cramer and co-workers later studied the rheology, printing and sintering of silicon-nitride/resin slurries [26]. Both required material-specific formulation and thermal control. The presence of a successful Si₃N₄ article is evidence of feasibility in that system, not evidence that a generic ‘ceramic resin’ can carry every nitride or that oxide windows are conservative.

5. Rheology, sedimentation, aging and layer delivery

Rheology determines whether the feedstock mixes, transfers, coats, levels, resists sedimentation, releases from a film and stops moving before exposure. The relevant material may be a low-viscosity suspension, a shear-thinning liquid, a yield-stress paste or a thixotropic system delivered as a discrete film. One viscosity measured at one shear rate and temperature cannot describe all these

operations. General rheology, sedimentation, thixotropy and recoating controls for highly filled suspensions are inherited from ER-036; ER-151 owns their ceramic-VPP implementation and qualification consequences.

The process history includes mixing, pumping or recirculation, blade passage, squeeze flow under a platform, separation from a transparent interface, transport between reservoir and exposure zone, and rest before cure. Each produces different shear rate, duration and recovery time. A rheological test plan reproduces the relevant rate and time windows, controls wall slip and evaporation where needed, and reports temperature, geometry, loading and preconditioning. NIST's current ceramic-AM programme places dense-suspension rheology and interlaboratory measurement variability among its priority metrology needs [12].

Sedimentation and agglomeration alter both solids content and optical response through the build. A binder-rich upper region can cure differently from a powder-rich lower region. Slow settling can still matter during a long print. Yield stress can reduce settling while increasing layer force and trapping prior-layer topography. Thixotropic recovery can be beneficial if the feedstock flows during delivery and rebuilds structure before exposure, but harmful if recovery is too fast for levelling or too slow to prevent drift.

Age is not merely time since mixing. Storage temperature, light exposure, container headspace, repeated opening, remixing energy, recirculation, volatile loss, surface reactions and partial polymerisation contribute. Cramer and co-workers observed time-dependent and formulation-dependent behaviour while developing Si₃N₄ VPP slurries [26]. Their study illustrates why apparent initial printability does not establish a stable production feedstock and why a re-mix can change, rather than simply restore, the state.

Layer-delivery architecture determines the rheological demand. A free-surface top-down vat needs surface levelling and immersion control. A bottom-up liquid vat introduces separation forces at the transparent window and may rely on replenishment after peel. Film-transport or recoated-film systems impose doctor-blade and transport histories. Paste-based systems can tolerate higher yield stress but require controlled metering, gap and pressure. LCM implementations often use purpose-designed highly filled suspensions and layer delivery; the label alone does not reveal the mechanism.

Layer thickness is a commanded gap or motion, not automatically deposited ceramic thickness. It interacts with particle/agglomerate size, prior-layer roughness, platform parallelism, feedstock compressibility, blade deflection, squeeze pressure, window/film motion and cured-depth overlap. A thin nominal layer can exclude agglomerates, increase force or magnify debris. A thick layer can fail to renew or cure through. Measurement includes the actual green layer and feature response, not only machine position.

Gas can enter during powder addition, mixing, degassing failure, pumping or recoating. Bubbles affect optics, local packing and green strength and can become pores or crack origins. Vacuum degassing can remove gas while promoting volatile loss or foaming; centrifugal mixing can heat the batch; rest can permit settling. The selected method is validated against the formulation and production time rather than declared by equipment name.

Table 2. Coupled feedstock, optical and layer-delivery controls

Control variable	Potential benefit	Coupled penalty or failure mode	Evidence required before transfer
Higher ceramic volume fraction	Lower organic burden; closer particle packing; potentially lower shrinkage	Higher viscosity/yield stress; harder dispersion and levelling; shallower cure; trapped gas	Solids basis, rheology, stability, cure, green handling and full thermal-route comparison
Finer powder or broken agglomerates	Thin layers; sintering activity; potentially finer features	Higher surface/dispersant demand; powder exposure; optical and aging changes	Dispersed distribution, surface chemistry, rheology, optics and contamination control
Increased exposure	Greater depth or green margin within a bounded range	Lateral overcure, feature closure, interface adhesion, heat or stress	Depth, width, conversion, strength and representative feature map
Strong yield stress/thixotropy	Reduced settling; shape retention before cure	Blade/squeeze force, slow levelling, history dependence and trapped interfaces	Rate/time sweep, recovery, delivery simulation and build-duration stability
Fast recoating or short wait	Lower nominal print time	Nonuniform layer, unrecovered rheology, waves, voids or composition gradients	Registered layer metrology and defect/property correlation
More aggressive cleaning	Faster visible feedstock removal	Green erosion, swelling, cracking, trapped contamination or support damage	Material-removal/compatibility window and cavity-specific cleanliness evidence
Faster thermal cycle	Shorter nominal furnace occupancy	Pressure cracks, residue, delamination, thermal gradients or distortion	Geometry/load-specific gas, mass-loss, dimensional and defect evidence

Feedstock release criteria are tied to the layer architecture. A suspension that passes a cup-viscosity check may fail under a transport film. A paste that holds a vertical bead may not fill a fine recessed layer. A low-shear stability result may not predict high-shear agglomeration or wall slip. Technology selection therefore begins with the cell's actual material path, not with an isolated datasheet value.

6. Exposure architecture, working windows and feature formation

Scanned and projected exposure divide time and optical energy differently. A scanned beam can vary path, velocity and local dwell, but introduces scan order, acceleration, hatch, focus and overlap. A projected image exposes many locations nominally together, but field uniformity, pixel imaging, grey-level behaviour, temporal sequence and optics matter. LCD masks add panel transmission, pixel aperture, heat and aging considerations. None of these architectures eliminates formulation or layer-delivery limits.

A process window is established from controlled test articles and representative geometries, not from one cured puck. At minimum it maps layer adhesion, vertical and lateral response, line/gap fidelity, hole/channel clearance, thin walls, unsupported or weakly supported regions, mass transitions, surface orientation and build-field position. Green dimensional metrology is paired with post-debind and post-sinter results so a compensation model is not fitted to the wrong state. The working-curve principle as a formulation-specific, non-transferable calibration is inherited from ER-002; ER-151 uses it only within the ceramic VPP state chain.

Working curves are measured with the same formulation state, interface and spectrum used in production. Threshold and penetration-like parameters can help compare batches or detect drift, but they do not replace representative parts. A formulation can show acceptable cure depth while producing weak interfaces, lateral closure or excessive adhesion to a window. Conversely, a shallow cure result can be acceptable for a thin controlled layer if interlayer overlap and green properties close.

Conversion and green network affect later thermal behaviour. Heterogeneous cure can leave residual monomer or weak regions that react differently on heating. Bae and Halloran linked residual monomer to cracking in stereolithography-fabricated ceramics [20]. Their result establishes a credible mechanism and the need to control the green chemical state; it does not define a universal post-cure or furnace ramp.

Exposure-induced polymerisation shrinkage and internal stress can distort the green body or weaken interfaces even before debinding. Large cross-sections, abrupt changes and constrained contact with a build plate or film can accumulate different histories. An additional post-cure can increase conversion or handling strength while increasing dimensional change, embrittlement or thermal burden. It is treated as a controlled process step with an intended response and limits.

Feature capability is state-labelled. `Green minimum wall`, `cleanable green channel`, `debound minimum wall` and `sintered accepted wall` are not interchangeable. A cavity may print but retain uncured suspension. A thin lattice may clean but collapse during debinding. A channel may survive sintering but be uninspectable. Marketing-level `resolution` is replaced by a feature catalogue with orientation, position, dimensions, surface, probability of success and inspection capability. The replacement of generic resolution claims by state-labelled feature capability is inherited from ER-010; ER-151 extends that discipline through green, debound and sintered ceramic states.

Exposure-field calibration is maintained. Reference artefacts or sensor maps establish uniformity and registration after light-engine service, window replacement, contamination events, software changes or material changes. A stable optical reading is supporting evidence, not final acceptance, until correlated with layer, green and sintered outcomes. Monitoring signals are versioned and linked to the build rather than stored as unregistered screenshots.

Process optimisation respects multiple objectives. Maximising green strength can increase cleaning difficulty or burnout burden. Minimising lateral cure can reduce interlayer margin. Maximising exposure throughput can increase peel force or leave insufficient layer recovery. The selected window is the smallest defensible region that meets the complete chain, with guard bands and documented reaction plans for drift.

7. Green recovery, cleaning, drying, support and inspection

The green body is a fragile composite whose strength, toughness, swelling response and surface condition depend on conversion, powder loading and geometry. Removal from the platform, window, film or surrounding feedstock applies bending, peel, suction, pressure and handling loads. A part that survives automated separation may still be damaged by manual cleaning. Recovery tooling and operator method therefore belong to qualification.

Uncured suspension must be removed from external surfaces, holes, blind cavities, lattices and internal channels without eroding cured material or redistributing powder-rich residue. Visual cleanliness at an accessible face is not evidence for an internal passage. The cleaning method declares medium, temperature, flow or agitation, pressure, time, orientation, number of cycles, refresh/filtration, drainage and endpoint. Compatibility is evaluated for swelling, extraction of unreacted species, stress cracking, delamination and contamination. General washing- and drying-induced extraction, swelling and dimensional-response controls are inherited from ER-033; ER-151 applies them to ceramic-loaded green bodies and trapped suspension.

Cleaning is also a geometry-selection gate. A channel that cannot be drained, flushed, inspected and dried is not production-feasible merely because the exposure engine can form it. Escape holes and access paths are designed around suspension rheology and cleaning. Trapped feedstock can become a dense inclusion, internal pressure source or uncontrolled local composition after heat treatment. Sectioned development parts, mass balance, flow evidence or imaging can establish a bounded clearance capability.

Drying can create gradients and capillary stress. Rapid surface drying may trap solvent or water inside a thick or enclosed section. Slow drying can extend swelling or contamination. Temperature can soften the green binder, accelerate reaction or change dimensions. The part is held and oriented to avoid sagging, adhesion or contact marks. A dry-to-touch criterion is insufficient when retained liquid affects debinding.

Printer supports carry green loads and can aid platform attachment, separation and cleaning access. Their interfaces can concentrate stress, leave scars or create thick organic junctions. Removal before debinding can damage the green body; removal after sintering can require abrasive or diamond finishing and may introduce surface flaws. The support strategy specifies when and how interfaces are removed and how the resulting surface is accepted.

Furnace support is a separate design problem. A geometry printed without green supports can sag or warp during binder softening and sintering. Setters, sacrificial supports, powder beds or membranes can distribute load and allow shrinkage, but also cause friction, reaction, imprinting, contamination or constrained distortion. `Support-free printing` is therefore not `support-free manufacturing`.

Green inspection targets defects that later processing cannot reliably repair: missing features, delamination, gross bubbles, trapped feedstock, cracks, cleaning erosion, contamination, blocked channels and unacceptable warpage. Dimensional measurements establish the state needed for shrinkage modelling. Detection is limited by opacity, roughness and geometry. A clean external image cannot close internal packing or interface quality.

The green hold point records mass, dimensions, orientation, visible/accessible defects, cleaning and drying history, support state, elapsed time, handling damage and authority to enter thermal processing. It does not accept the final ceramic. Parts that fail are segregated with feedstock and waste controls; they are not quietly returned to the vat or furnace load.

8. Debinding, gas transport and the brown state

Debinding removes the temporary organic network without destroying the powder architecture it created. On heating, the binder can soften, expand, shrink, depolymerise, crosslink, volatilise, oxidise or leave carbonaceous residue. The evolving gases must reach an external sink through pathways that change as liquid or polymer disappears. Heat transfer, reaction kinetics and mass transport are therefore coupled to section thickness, surface area, internal cavities, powder packing and atmosphere. ER-037 is the controlling corpus owner for the generic binder-removal, gas-transport and brown-body defect architecture; ER-151 retains the ceramic-VPP-specific formulation, geometry, atmosphere and acceptance consequences. 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-151 retains vat-photopolymerisation-specific green cure state, residual monomer and conversion, geometry, atmosphere, setter and sintering evidence.

Thermogravimetric, calorimetric and evolved-gas measurements can identify mass-loss regions and reactions for representative material. They do not alone define a safe part cycle. A small open specimen has shorter escape paths and lower thermal gradient than a thick hub, enclosed channel or compact furnace load. A cycle is qualified against the largest relevant transport length, geometry family, green density, support/contact condition and furnace loading.

Residual monomer and heterogeneous conversion can create local reactions before an open pore network forms. Bae and Halloran's ceramic-stereolithography study showed how residual monomer could contribute to cracking during thermal treatment [20]. This mechanism is a warning against treating exposure and debinding as independent. Green cure, any post-cure, aging and cleaning all influence the material entering the furnace.

Fast heating can generate gas faster than it escapes, producing blisters, delamination, internal cracks or distortion. Excessively slow heating can increase furnace occupancy, oxidation or unwanted reaction and still fail if the chemistry or gas path is wrong. Holds and ramps are justified by material and geometry evidence rather than copied from a resin datasheet. Furnace temperature calibration, load thermocouples where appropriate, atmosphere flow and exhaust condition are part of the record.

Atmosphere affects both organic removal and ceramic chemistry. Air can support oxidative removal for compatible oxide systems, yet local oxygen depletion can change decomposition. Inert or reactive atmospheres can be necessary for sensitive powders but may increase carbon-retention or off-gas risk. Switching atmospheres introduces purge and asphyxiation controls. The same nominal gas does not guarantee the same oxygen/moisture potential at every load position.

The brown body is usually more porous and mechanically fragile than the green body because the polymer skeleton has been removed before ceramic necking or full densification. Handling, transfer between furnaces and setter adjustment can initiate cracks that become difficult to distinguish after sintering. When debinding and sintering occur in one uninterrupted programme, a conceptual brown-state hold remains: the process record must still demonstrate adequate organic removal and safe transition into densification.

Brown-state inspection is selected for value and feasibility. Mass change, residual carbon or other chemical analysis, accessible microscopy, dimensional change and carefully designed witnesses can support release. A target mass loss is not sufficient by itself because evaporation, moisture or oxidation can confound it, and spatially trapped residue can coexist with an acceptable total. Witnesses represent actual section, green density, location and thermal shielding rather than only loose material.

Debinding defects are not repaired by sintering. A pressure crack can partly close at the surface while remaining a strength-limiting planar flaw. Residual carbon can alter colour, grain boundaries, dielectric or thermal behaviour. Delamination can produce a local pore band. The furnace decision therefore includes a stop rule when off-gas, temperature, mass loss, atmosphere or witness evidence departs from the qualified range.

Combustible decomposition products and furnace exhaust are safety and environmental controls, not merely odour issues. Off-gas composition, ignition potential, condensable residue, duct compatibility and treatment are assessed for the actual binder and load. Maintenance can expose operators to condensed organics and ceramic dust. A programme that makes visually sound parts but overloads exhaust or leaves hazardous deposits is not qualified.

9. Sintering, shrinkage, setters, atmosphere and finishing

Sintering converts the porous powder compact into a ceramic through neck growth, pore evolution, grain-boundary motion, phase change and densification. Shrinkage reflects the difference between green packing and the final microstructure, but it is not necessarily uniform or isotropic. Local green-density gradients, interfaces, geometry, gravity, thermal gradients, setter friction, atmosphere and grain growth can produce region-specific strain.

A linear scale factor fitted to one coupon is therefore a provisional model, not a universal material property. Validation includes different sizes, wall directions, section transitions, orientations, build-field locations, furnace positions and support/contact states.

The compensation workflow retains the unscaled CAD, intended final geometry, compensated build geometry, software version and measured residual error. Iterative compensation remains controlled engineering, not manual file correction without genealogy.

Setter design balances support and freedom to shrink. A flat plate can support a face while friction restrains in-plane motion. Powder beds can distribute load but imprint, contaminate or inhibit gas exchange. Sacrificial ceramic structures can shrink at a different rate. Membranes and point supports can reduce contact while increasing stress concentration. Setter composition can react with the part or scavenge/introduce species. Contact surfaces are part of the material route and final surface plan.

Oxide ceramics can often tolerate oxidising stages, but the correct oxygen potential, sintering aid, temperature and dwell remain grade-specific. Zirconia phase balance and grain evolution can change transformation behaviour. Alumina strength depends on flaw population, grain and surface condition, not density alone. Nitrides require more stringent atmosphere and chemistry control. Altun and co-workers used a material-specific route for Si₃N₄-based LCM [27], and Cramer and co-workers separately documented formulation and sintering challenges for silicon nitride VPP [26]. Their different systems illustrate why 'non-oxide ceramic' is not one furnace recipe.

Aluminium nitride adds thermal-conductivity and oxygen-control sensitivity. Schwarzer-Fischer, Scheithauer and Michaelis demonstrated a CerAM VPP route for AlN with a specific powder, formulation, sintering additions and atmosphere [28]. The result establishes feasibility of complex AlN in that chain. It does not transfer its thermal conductivity, density, formulation or furnace conditions to another AlN grade, component or supplier.

Final density is measured and interpreted carefully. Archimedes-type methods, geometrical density, helium pycnometry and image analysis address different volumes and pore populations. Surface-connected pores, closed pores, roughness and trapped fluid can bias results. A high relative-density number can coexist with a critical planar flaw, inclusion, weak surface or undesirable phase. Density is one state variable, not acceptance by itself.

Cooling can change phase, stress and dimensions. Large temperature gradients, transformation strains and fixture release can produce cracks or warpage after the peak hold. Furnace opening, gas change and transfer are controlled. The final furnace record includes calibrated programme, actual relevant temperatures, atmosphere/pressure/flow, load map, setter, witness positions, alarms, deviations and cooling history.

Finishing removes support scars, setter contact, surface reaction, roughness or excess stock and creates functional dimensions. Grinding, lapping, polishing, laser processing, blasting or machining can introduce subsurface damage, residual stress, contamination or phase change. Yoo and co-workers showed that alumina air abrasion changed the measured mechanical response of additively manufactured zirconia specimens [31]. The conclusion is not that abrasion is universally beneficial; it is that surface treatment and test state must accompany any property claim.

Cleaning after finishing removes abrasive, coolant, dust and setter residue. Functional ceramics may require controlled metallisation, coating, sterilisation or joining after sintering; those steps can alter surfaces and properties. Delivered acceptance names the exact state. A polished test bar does not certify an as-sintered lattice, and an as-sintered density specimen does not certify a machined seal face.

10. Material families and bounded application evidence

Ceramic VPP is attractive because one shaping architecture can potentially carry multiple powders, but the process does not erase material science. Powder optical response, surface chemistry, sintering aid, atmosphere, phase evolution, grain growth, defect sensitivity and functional tests differ among material families. Technology selection starts with the required final ceramic state rather than with a generic 'ceramic-compatible printer' claim.

Alumina is widely used for structural, electrical, wear and high-temperature components and is a common process-development material. Zhang and co-workers reported one alumina DLP route [21], while Verza and co-workers showed a cost-effective LCD implementation [22]. Scheithauer and co-workers applied LCM to a ceramic heat-exchanger case and discussed both opportunities and limits [25]. These demonstrations support mould-free complex shaping. They do not prove universal pressure integrity, thermal-shock resistance, cleanability or economic advantage for every heat-exchanger geometry.

Zirconia requires stabiliser, phase and aging context. Green and sintered dimensions, translucency, strength and surface response depend on powder chemistry, grain and heat treatment. Kuang and co-workers' formulation study [30] and Yoo and co-workers' surface-treatment study [31] show that resin design and finishing can each affect the result. A supplier's 'zirconia resin' label is not a material specification, and a high test-bar strength does not establish hydrothermal-aging resistance or device approval.

Dental evidence is especially easy to overgeneralise. Patil and co-workers studied wear behaviour of lithography-manufactured dental zirconia in a defined experiment [32]. Such work can inform test hypotheses and material comparisons. It does not establish fit, fatigue, antagonist wear, translucency, sterilisation, aging, patient safety or regulatory conformity for a different formulation, printer or restoration.

Silicon nitride and related SiAlON systems offer high-temperature, wear and thermal-shock potential but present optical and sintering difficulties. High refractive index and darker powder response can constrain cure, while nitrogen atmosphere, sintering aids and phase evolution control densification. Wu and co-workers addressed refractive-index engineering for a Si₃N₄ mask-stereolithography slurry [29]; Altun and co-workers demonstrated a dense Si₃N₄-based LCM route [27]; Cramer and co-workers exposed continuing rheology and sintering challenges [26]. These are complementary bounded studies, not one transferable recipe.

Aluminium nitride is valued for thermal conductivity with electrical insulation, but oxygen, secondary phases, porosity and grain boundaries can degrade performance. The AlN CerAM VPP study by Schwarzer-Fischer and co-workers [28] connects

suspension development to a measured sintered property. A factory qualification must repeat chemistry, density, microstructure, thermal conductivity, dielectric behaviour and reliability for its own grade, geometry, atmosphere and finishing state.

Calcium-phosphate and hydroxyapatite systems require a distinction among ceramic, composite and reactive-conversion routes. Zeng and co-workers reported DLP-formed hydroxyapatite scaffolds with mechanical and biological tests in their defined system [33]. Another study produced hydroxyapatite–resin composites through vat photopolymerisation and post-processing by in-situ hydrolysis of alpha-tricalcium phosphate [34]. The latter is not automatically equivalent to a fully debound and sintered hydroxyapatite ceramic. Material identity, retained polymer, phase conversion, porosity and test state must be named. Application bounding for bioceramic, hydroxyapatite and dental-zirconia evidence is inherited from ER-023; ER-151 does not extend those demonstrations into device-level safety or regulatory claims.

Biological test language remains bounded. A cell assay, short animal study or literature history of the base ceramic does not confer biocompatibility on residual monomer, dispersant, pigment, cleaning residue, sintering aid, surface treatment or final device. Medical or dental use needs application-specific chemistry, cleanliness, sterilisation, mechanical, aging, biological and regulatory evidence. `Bioceramic` is a material/use category, not approval.

Functional ceramics add properties that density and strength cannot represent. Thermal conductivity depends on porosity, impurities, grain boundaries and direction. Dielectric loss and permittivity depend on phase, frequency, temperature and electrodes. Piezoelectric response requires composition, poling and orientation. Optical translucency depends on scattering centres, phase and surface. Porous filters and scaffolds require permeability, connectivity and cleanability. Each property is measured in the delivered state and linked to the relevant manufacturing variables.

Advanced or exotic powders can also create new incompatibilities. A pigment that improves optical control may contaminate a dielectric ceramic. A sintering aid that enables densification can reduce thermal conductivity. A dispersant that stabilises a suspension can leave an element at grain boundaries. A high-index liquid that improves Si₃N₄ cure can change debinding. The benefit is accepted only after the complete property set closes, not after a successful green print.

11. Defects, fractography, brittle statistics and property evidence

Ceramic defects must be classified by mechanism and state. Feedstock defects include hard agglomerates, contamination, gas and composition gradients. Layer defects include incomplete renewal, trapped interfaces, debris and thickness variation. Exposure defects include undercure, lateral overcure, weak interfaces and spatially variable conversion. Green-handling defects include cracks, erosion, trapped feedstock and drying damage. Thermal defects include pressure cracks, delamination, residual carbon, distortion, pores, reaction, phase error and grain abnormality.

These defects differ in orientation, size, location and detectability. A density result averages volume and can miss a planar interface or rare inclusion. A polished section is local. A surface image cannot show a buried crack. Computed tomography can be powerful, but its capability depends on material attenuation, part size, voxel size, contrast, reconstruction, beam-hardening and artefacts. Cramer and co-workers compared CT-observed flaws with critical-flaw estimates and fracture surfaces in one paste-stereolithography alumina route [24]. Their bounded result does not authorise `CT inspected` as a universal defect-free claim.

Strength in brittle ceramics is governed by the most severe effective flaw in the stressed volume and surface. Scatter is therefore information about the flaw population, not noise to be averaged away. ASTM C1161 defines a controlled ambient flexural-strength method [8], and ISO 14704 provides another standardised fine-ceramic flexural method [11]. The selected method, specimen geometry, preparation, loading, orientation and environment accompany the result.

ASTM C1239 addresses reporting uniaxial strength data and estimation of Weibull parameters [9]. Sample size, censoring, confidence intervals and population mixing matter. Pooling different orientations, surfaces, furnace loads or failure origins can create a misleading single distribution. A high characteristic strength with a broad or mixed flaw population may be less useful than a lower but stable and explainable process.

Fractography closes the link between strength and manufacturing mechanism. ASTM C1322 structures fracture-origin characterisation [10]. Fracture surfaces are preserved, protected and examined with knowledge of load direction and specimen history. Origins such as agglomerates, pores, layer interfaces, machining damage, inclusions or corners are classified and mapped to build, furnace and finishing variables.

Maier, Allen, Cox and Levin reported an interlaboratory study of additively manufactured alumina flexural strength [23]. NIST's current summary notes that a small number of flaw types accounted for most failures while flaw populations varied significantly among laboratories even under nominally identical conditions [12]. The important factory conclusion is that nominally shared powder, design or process labels do not create identical reliability. Local process and flaw-population evidence remain necessary.

Mechanical testing is state- and location-aware. Orientation relative to layers, position in the optical field, height, proximity to supports or mass transitions, setter contact and furnace position can change defects and surfaces. Machined bars can remove the as-sintered surface population; as-sintered bars can retain surface roughness unrepresentative of a polished component. Both can be useful if their purpose and state are explicit.

Fracture toughness, fatigue, creep, wear, thermal shock and environmental aging require separate methods and cannot be inferred from flexural strength. Functional components may fail from permeability, dielectric breakdown, thermal cycling or contact damage rather than monotonic bending. Test selection follows service failure modes. A published demonstration with good density and one strength result is feasibility evidence, not a design allowable.

Inspection capability is validated against critical flaw hypotheses. Artificial defects, reference standards, destructive correlation and probability-of-detection approaches may be necessary. The minimum detectable indication is not automatically the minimum critical flaw, and detectability can change across thick and thin regions. When inspection cannot cover a critical internal region, design, process control, witness strategy or use restriction must close the gap.

12. Geometry, inspection, productivity, economics and safety

Ceramic VPP can produce thin walls, lattices, channels and complex surfaces that are expensive to machine from dense ceramic. Geometry is beneficial only when the complete chain can coat, expose, clean, debind, support, sinter, finish and inspect it. A hidden channel that prints but retains slurry, or a lattice that survives cleaning but warps in the furnace, is not a manufacturable feature.

Design rules are state-resolved. Minimum wall, gap, hole and unsupported span are measured in green, debound and sintered states. Thick-to-thin transitions are checked for cure, drying and gas-transport gradients. Enclosed volumes need removal and inspection access. Sharp inside corners can concentrate stress; large flat areas can stick to setters; tall slender features can sag. Orientation is chosen for all stages, not only for exposure speed or green supports.

Dimensional inspection follows datum survival. A build-platform reference may be removed during support separation. Shrinkage can move features relative to one another. Finishing creates new datums. The measurement plan connects green, sintered and final coordinate systems with uncertainty. Local compensation is accepted only within a validated design family and software/change-control state.

The useful inspection stack can include mass and dimensions, surface microscopy, optical or X-ray CT, ultrasonic or resonance methods where appropriate, density, chemistry, phase analysis, microstructure, leak/permeability, functional tests and destructive witnesses. Each method has access and resolution limits. Testing every part is not automatically sufficient when the method cannot detect the critical mechanism; conversely, destructive testing cannot be applied blindly without a sampling and linkage strategy.

Nominal projected-layer exposure can be fast, but printer cycle time includes layer renewal, platform motion, separation, wait and recoating. Complete-cell time also includes formulation, conditioning, loading, recovery, cleaning, drying, green inspection, support handling, long debinding/sintering/cooling cycles, finishing, inspection, maintenance and rework. Furnace loading and yield can dominate economics even when optical exposure is short.

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

Material efficiency distinguishes powder or suspension supplied, suspension remaining, suspension released for reuse, green-part mass, debinding loss, finishing removal, witness/test material, rejects and accepted ceramic mass. Surrounding slurry that can be collected but requires requalification is not zero waste. Setters, cleaning media, filters, furnace consumables and abrasive finishing add cost and environmental burden.

LCM heat-exchanger work illustrates the correct economic boundary: complex geometry can be enabled, but process and material limits remain [25]. The comparison is against realistic alternatives such as machining, pressing plus green machining, injection moulding, gel casting, tape-based assembly or joining. Tooling avoidance can favour low or changing volume; long thermal cycles and manual cleaning can reverse the advantage at scale. Cost is evaluated per accepted function, not per green build.

Safety begins with the specific ingredients and tasks. Ceramic powders can be respirable or sensitising depending on composition and size. Uncured resins can present skin, eye and inhalation hazards. Mixing, powder addition, scraping, cleaning, compressed gas, ultrasonic agitation and dry finishing can generate exposure. NIOSH's safe-VPP guidance supports enclosure, ventilation, task control, protective equipment and housekeeping principles [15], but a ceramic cell needs additional powder-, chemical-, furnace- and material-specific assessment.

Optical sources, moving platforms, pinch points, heated vats, electrical systems and automated motion require guarding and interlocks. Cleaning liquids bring flammability, incompatibility and waste issues. Gloves are selected for the actual chemicals and changed before permeation or contamination spreads. UV-blocking covers do not control powder or solvent exposure.

Thermal processing adds combustible off-gas, hot surfaces, furnace energy, pressure or vacuum where used, inert/reactive atmospheres and heavy fragile loads. Nitrogen or argon can create asphyxiation risk; other gases can be reactive or toxic. Off-gas treatment and purge logic are designed for decomposition products. Furnace maintenance and setter cleaning can expose dust and condensed residue. Safety review covers normal operation, refill, jam, spill, failed build, power loss, alarm, maintenance and waste.

The 2026 NIST photopolymer workshop report identifies continuing needs in material characterisation, measurement, standards, safety and regulation [14]. NIST's VPP programme similarly frames photopolymer AM around voxel-scale and process-stage metrology rather than printer claims [13]. These public sources support a cautious evidence architecture: the system is qualified through measured states, not assumed mature because the optical hardware is commercially available.

13. Qualification and the technology-selection gate

Qualification starts from the delivered requirement. Geometry, surface, chemistry, phase, pore architecture, mechanical or functional properties, environment, reliability, inspection and regulatory constraints are translated into process evidence. The chosen route must close every state from incoming powder to final disposition. ISO/ASTM 52927 helps organise characteristics and tests [5], but the application determines acceptance. The direct-versus-indirect manufacturing axis is inherited from ER-049; ER-151 contributes only the ceramic-VPP route evidence required to place this process on that axis.

The material specification identifies powder grade, stabiliser/dopant or sintering aid, phase and impurity limits, feedstock formulation identity, allowed reuse and delivered thermal/finishing state. The equipment specification identifies layer-delivery and optical architecture, calibrated ranges, critical consumables, software/file control, environment and maintenance. Personnel qualification covers powder/resin handling, formulation, machine operation, green recovery, furnace operation, finishing, inspection and deviation authority.

Installation and operational qualification demonstrate that the cell can control the intended ranges. Performance qualification uses representative or worst-case geometries, materials, field positions, orientations, build durations, cleaning challenges, debinding transport lengths, furnace positions, setters and finishing states. Coupons accompany parts only when their representativeness is justified. A small bar in an open location cannot automatically qualify a thick enclosed component.

Table 3. Ceramic VPP qualification and selection gate

Gate	Question that must close	Minimum evidence family	Stop condition
Requirement	Is final ceramic identity, state, function and inspection defined?	Drawing/specification, use environment, failure modes and acceptance plan	Generic 'printed ceramic' requirement
Feedstock	Is the powder/resin batch stable and representative through use?	Identity, dispersed state, rheology, optics, age/reuse and sampling evidence	Uncontrolled agglomeration, drift or reuse
Layer/exposure	Can the actual cell form the required green features across its field and duration?	Layer, spectrum/irradiance, depth/width, conversion, adhesion and feature maps	Pixel/spot or scalar dose used as proof
Green handling	Can all regions be recovered, cleaned, dried and inspected without damage?	Geometry-specific handling, residue, mass/dimension and defect evidence	Trapped feedstock or inaccessible damage risk
Thermal route	Can binder leave and ceramic densify without unacceptable reaction or distortion?	Geometry/load/atmosphere/setter records, witnesses, phase, pores and dimensions	Coupon-only or copied furnace cycle
Properties	Are flaw populations and functional properties acceptable in the delivered state?	Statistics, fractography, microstructure, location/orientation and application tests	Density or mean strength alone
Inspection	Can specified critical flaws and dimensions be detected with known capability?	Validated methods, coverage, uncertainty and destructive correlation	'CT inspected' or 'no visible defect' without capability
Production	Is the route safe, repeatable and economic at accepted-part level?	Complete-cell time/cost, yield, maintenance, exposure and change control	Printer-only rate or recoverable-material claim

Change control is conservative because variables are coupled. Powder supplier or surface state, resin ingredient, initiator, pigment, mixing media, formulation age, layer film, window, light engine, software, cleaning solvent, furnace, atmosphere, setter, geometry family or finishing method can affect multiple stages. A risk assessment identifies which prior evidence remains valid and which tests must be repeated.

Process monitoring can support control when its coordinate, time base, measurement uncertainty and correlation are known. Images can detect recoating or gross green anomalies; force or motion signals can reveal separation changes; optical sensors can track exposure; furnace sensors can track temperature and atmosphere. No signal is accepted as a final-quality surrogate until validated against relevant defects and properties.

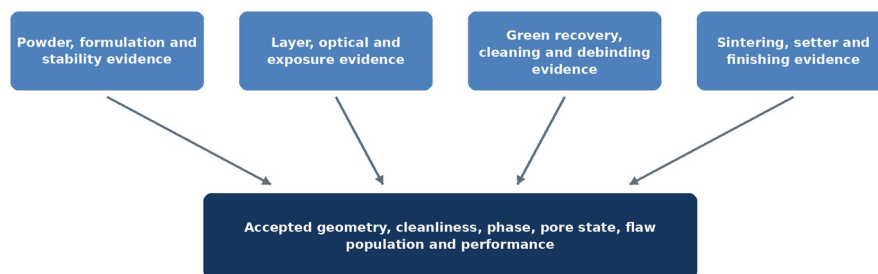


Figure 2. Evidence closure for an accepted ceramic VPP component.

Technology selection compares ceramic VPP with conventional and additive alternatives at the delivered-part level. VPP is favoured when geometry, surface, fine features, low-to-moderate volume or design change offset formulation, cleaning and furnace burden. Pressing, injection moulding, gel casting or green machining can dominate for stable high volume or simpler shapes. Extrusion can favour larger features and very high solids loading. Binder jetting can avoid light-scattering limits but introduces powder-bed and infiltration/sintering trade-offs. No route is intrinsically best without the requirement and production scale.

Supplier-labelled CDP or LCM can be a useful starting architecture when its materials, layer mechanism and IFU are current. The user remains responsible for verifying compatibility and performance in the intended system. The 3Dresyns IFU explicitly positions its values as a workflow requiring validation [35]. This review reinforces that boundary and does not turn those values into publication claims or production instructions.

The release package includes final approved file, material and ingredient lots, formulation/reuse history, machine state, build log, green handling, cleaning/drying, thermal load and setter maps, finishing, inspection, tests, deviations, concessions and authorising signatures. Independent technical review challenges the claim boundaries.

14. Conclusions and research priorities

Ceramic vat photopolymerisation is best understood as an indirect shaping-and-consolidation chain. Its principal advantage is the ability to define intricate green geometry by patterned light. Its principal limitation is that the green geometry must survive material removal, organic removal, densification and cooling before it becomes the specified ceramic. Every claimed benefit is conditional on that complete route.

LCM, ceramic stereolithography, DLP, LCD, CerAM VPP and CDP should be named precisely rather than merged. Optical architecture does not define layer delivery, suspension state or thermal route. Powder loading, rheology, stability and optical cure are coupled. Cure depth, lateral cure, conversion, strength and adhesion remain separate. Nominal pixel or spot size is not delivered resolution.

Green handling is a manufacturing stage, not an afterthought. Recovery, cleaning, drainage and drying determine whether thin features and internal channels are real, cleanable components or trapped-feedstock demonstrations. Printer supports do not replace furnace setters. Debinding is limited by reaction and gas transport; sintering is limited by chemistry, phase, pores, shrinkage, gravity and contact. A transferable recipe or one scale factor is therefore unsafe.

Material families remain distinct. Alumina and zirconia evidence does not establish Si₃N₄ or AlN processing. Biological familiarity of hydroxyapatite or zirconia does not establish a formulation, device or regulatory claim. Functional properties require final-state measurement. The strongest technology paper is one that states where its evidence stops.

Brittle qualification depends on flaw populations. Density and mean strength are insufficient. Standardised testing, Weibull-aware reporting, fractography, location/orientation control and inspection capability are needed to connect process variation to reliability. NIST's current ceramic-AM programme and interlaboratory evidence show that ostensibly similar routes can produce different controlling flaws [12,23].

Priority research should focus on traceable dense-suspension rheology across real layer histories; spectrum- and geometry-resolved cure measurement; in-situ detection linked to critical defects; non-destructive inspection with probability-of-detection evidence; geometry-aware debinding models; shrinkage and setter/contact models; non-oxide atmosphere and chemistry control; and shared round-robin artefacts that include cleaning and thermal processing rather than exposure alone.

Factory adoption should proceed through a requirements-led gate: define the final ceramic; declare the actual optical and layer architecture; release the powder-loaded resin through the complete use period; prove green recovery and internal cleanliness; validate geometry-specific debinding and sintering; identify flaw populations; demonstrate relevant properties and inspection capability; then calculate safety, yield and complete-cell economics. Only that evidence supports an accepted advanced-ceramic component.

References

- [1] ISO/ASTM 52900:2021. *Additive manufacturing — General principles — Fundamentals and vocabulary*. Edition 2; confirmed in 2025. <https://www.iso.org/standard/74514.html>
- [2] ISO/ASTM 52920:2023. *Additive manufacturing — Qualification principles — Requirements for industrial additive manufacturing processes and production sites*. Edition 1. <https://www.iso.org/standard/76911.html>
- [3] ISO/ASTM 52910:2018. *Additive manufacturing — Design — Requirements, guidelines and recommendations*. Edition 1. <https://www.iso.org/standard/67289.html>
- [4] ISO/ASTM 52901:2017. *Additive manufacturing — General principles — Requirements for purchased AM parts*. Edition 1; confirmed in 2023. <https://www.iso.org/standard/67288.html>
- [5] ISO/ASTM 52927:2024. *Additive manufacturing — General principles — Main characteristics and corresponding test methods*. Edition 1. <https://www.iso.org/standard/81802.html>
- [6] ISO/ASTM 52953:2025. *Additive manufacturing for metals — General principles — Registration of data acquired from process monitoring and for quality control*. Edition 1. <https://www.iso.org/standard/84117.html>
- [7] ISO/ASTM 52951:2026. *Additive manufacturing — Data — Data packages for AM parts*. Edition 1. <https://www.iso.org/standard/76828.html>
- [8] ASTM C1161-18(2023). *Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature*. <https://www.astm.org/c1161-18r23.html>
- [9] ASTM C1239-26a. *Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics*. <https://www.astm.org/c1239-26a.html>
- [10] ASTM C1322-25. *Standard Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics*. <https://www.astm.org/c1322-25.html>
- [11] ISO 14704:2016. *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for flexural strength of monolithic ceramics at room temperature*. <https://www.iso.org/standard/65411.html>
- [12] National Institute of Standards and Technology. *Additive Manufacturing of Ceramics*. Updated 10 June 2026. <https://www.nist.gov/programs-projects/additive-manufacturing-ceramics>
- [13] National Institute of Standards and Technology. *Vat Photopolymerization*. Updated 15 May 2025. <https://www.nist.gov/additive-manufacturing/research-areas/technologies/vat-photopolymerization>
- [14] Higgins, C., Killgore, J., Idacavage, M. et al. *Photopolymer Additive Manufacturing 2025 Workshop Report: Building a Unified Vision from Research to Regulation*. NIST Advanced Manufacturing Series 100-78 (2026). <https://doi.org/10.6028/NIST.AMS.100-78>
- [15] National Institute for Occupational Safety and Health. *Safe Desktop Vat Photopolymerization 3-D Printing*. January 2025. <https://www.cdc.gov/niosh/media/pdfs/2025/01/Safe-3D-Printing.pdf>
- [16] Halloran, J.W. *Ceramic stereolithography: Additive manufacturing for ceramics by photopolymerization*. *Annual Review of Materials Research* 46 (2016) 19–40. <https://doi.org/10.1146/annurev-matsci-070115-031841>
- [17] Zocca, A., Colombo, P., Gomes, C.M. and Günster, J. *Additive Manufacturing of Ceramics: Issues, Potentialities, and Opportunities*. *Journal of the American Ceramic Society* 98 (2015) 1983–2001. <https://doi.org/10.1111/jace.13700>
- [18] Griffith, M.L. and Halloran, J.W. *Freeform fabrication of ceramics via stereolithography*. *Journal of the American Ceramic Society* 79 (1996) 2601–2608. <https://doi.org/10.1111/j.1151-2916.1996.tb09022.x>
- [19] Chartier, T., Chaput, C., Doreau, F. and Loiseau, M. *Stereolithography of structural complex ceramic parts*. *Journal of Materials Science* 37 (2002) 3141–3147. <https://doi.org/10.1023/A:1016102210277>
- [20] Bae, C.-J. and Halloran, J.W. *Influence of Residual Monomer on Cracking in Ceramics Fabricated by Stereolithography*. *International Journal of Applied Ceramic Technology* 8 (2011) 1289–1295. <https://doi.org/10.1111/j.1744-7402.2010.02578.x>
- [21] Zhang, L., Huang, J., He, Y., Liu, K., Xiang, B., Zhai, J., Kong, L.B., Zhang, T. and Liu, Y. *Fabrication and properties of alumina ceramics shaped by digital light processing as an additive manufacturing technology*. *International Journal of Applied Ceramic Technology* 19 (2022) 281–288. <https://doi.org/10.1111/ijac.13895>
- [22] Verza, J.R., de Camargo, I.L., Morelli, M.R. and da Luz, A.P. *Development of photosensitive slurries and fabrication of alumina components using a cost-effective liquid crystal display printer*. *International Journal of Applied Ceramic Technology* 22(4) (2025) e15123. <https://doi.org/10.1111/ijac.15123>
- [23] Maier, R.A., Allen, A.J., Cox, B. and Levin, I. *Interlaboratory study of flexural strength in additively manufactured alumina*. *Journal of the American Ceramic Society* 108(2) (2025) e20133. <https://doi.org/10.1111/jace.20133>
- [24] Cramer, C.L., Márquez Rosay, A., Dehoff, R.R. and Nelson, A.T. *Ability of x-ray computed tomography to resolve critical flaw size in laser-based, paste stereolithography ceramic printing of alumina*. *International Journal of Ceramic Engineering & Science* 6 (2024) e10233. <https://doi.org/10.1002/ces2.10233>

- [25] Scheithauer, U., Schwarzer, E., Moritz, T. and Michaelis, A. *Additive Manufacturing of Ceramic Heat Exchanger: Opportunities and Limits of the Lithography-Based Ceramic Manufacturing (LCM)*. Journal of Materials Engineering and Performance 27 (2018) 14–20. <https://doi.org/10.1007/s11665-017-2843-z>
- [26] Cramer, C.L., Hmeidat, N.S., Mitchell, D.J. et al. *Rheology improvement for silicon nitride and resin slurries for vat photopolymerization printing and sintering*. npj Advanced Manufacturing 2 (2025) 36. <https://doi.org/10.1038/s44334-025-00051-y>
- [27] Altun, A.A., Prochaska, T., Konegger, T. and Schwentenwein, M. *Dense, Strong, and Precise Silicon Nitride-Based Ceramic Parts by Lithography-Based Ceramic Manufacturing*. Applied Sciences 10 (2020) 996. <https://doi.org/10.3390/app10030996>
- [28] Schwarzer-Fischer, E., Scheithauer, U. and Michaelis, A. *CerAMfacturing of Aluminum Nitride with High Thermal Conductivity via Lithography-Based Ceramic Vat Photopolymerization (CerAM VPP)*. Ceramics 6 (2023) 416–431. <https://doi.org/10.3390/ceramics6010024>
- [29] Wu, X., Xu, C. and Zhang, Z. *Development and analysis of a high refractive index liquid phase Si₃N₄ slurry for mask stereolithography*. Ceramics International 48 (2022) 120–129. <https://doi.org/10.1016/j.ceramint.2021.09.087>
- [30] Kuang, N., Xiao, M., Qi, H., Zhao, W. and Wu, J. *Optimization of Resin Composition for Zirconia Ceramic Digital Light Processing Additive Manufacturing*. Polymers 17 (2025) 797. <https://doi.org/10.3390/polym17060797>
- [31] Yoo, L.-G. et al. *Mechanical properties of additively manufactured zirconia with alumina air abrasion surface treatment*. Scientific Reports 13 (2023) 9153. <https://doi.org/10.1038/s41598-023-36181-6>
- [32] Patil, A. et al. *Wear behaviour of lithography ceramic manufactured dental zirconia*. BMC Oral Health 23 (2023) 276. <https://doi.org/10.1186/s12903-023-02974-4>
- [33] Zeng, Y., Yan, Y., Yan, H., Liu, C., Li, P., Dong, P., Zhao, Y. and Chen, J. *3D printing of hydroxyapatite scaffolds with good mechanical and biocompatible properties by digital light processing*. Journal of Materials Science 53 (2018) 6291–6301. <https://doi.org/10.1007/s10853-018-1992-2>
- [34] Oliver-Urrutia, C., Drotárová, L., Gascón-Pérez, S., Slámečka, K., Ravaszová, S., Čelko, L. and Montufar, E.B. *Hydroxyapatite-Resin Composites Produced by Vat Photopolymerization and Post-Processing via In Situ Hydrolysis of Alpha Tricalcium Phosphate*. Ceramics 6 (2023) 2282–2294. <https://doi.org/10.3390/ceramics6040139>
- [35] 3Dresyns. *Fast Instructions for Use (IFU) for Direct Printing of Sintering Ceramics, Metals and Exotic Materials*. Accessed 1 September 2026. <https://www.3dresyns.com/pages/fast-instructions-for-use-ifu-for-direct-printing-of-sintering-ceramics-metals-and-exotic-materials>