

Vat Photopolymerisation of Implantable Ceramics: Processing, Sintering, Bioactivity and Qualification Constraints

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Statement of Significance

In ceramic VPP the printed photopolymer is only an intermediate. Slurry rheology and cure determine the green body; debinding determines defect formation; sintering determines density, phase, shrinkage and porosity; and only the final ceramic can be evaluated for mechanical or biological performance. This review focuses on that processing-to-implant interface and prevents green-body printability or nominal ceramic identity from being converted directly into implant claims.

Keywords: ceramic vat photopolymerisation; zirconia; hydroxyapatite; bioceramic; debinding; sintering; green body; porosity; bioactivity; implant; DLP

Abstract

VPP of ceramic-filled resins enables complex zirconia, alumina, hydroxyapatite and related bioceramic geometries, but qualification spans several material states. High-solids slurry must remain printable and homogeneous; the green body must survive cleaning; debinding must remove organics without cracking; sintering must control shrinkage, phase and porosity; and the final ceramic must meet application-specific mechanical, chemical and biological requirements. Recent studies on DLP 3YSZ, hydroxyapatite scaffolds and porous bone-regeneration structures illustrate the importance of formulation, cleaning, debinding and sintering. This review defines a six-state evidence chain from feedstock to final device and separates dense zirconia-type requirements from porous bioactive scaffold requirements. Ceramic 3Dresyn CDP zirconia/YSZ and alumina products are included as commercial process examples only, with no implant or clinical suitability inferred.

1. Introduction

Ceramic VPP is an indirect additive-manufacturing route. The liquid is a suspension of ceramic particles in a photocurable binder system; the printed object is a polymer-bound green body; and the final ceramic emerges only after debinding and sintering. Every transition can create defects. Therefore a high-resolution green print does not establish final dimensional accuracy, density, strength, phase stability or biological performance.

This distinction is particularly important for implant-oriented ceramics. Dense zirconia components prioritise densification, phase stability, strength and ageing, whereas hydroxyapatite and bioactive scaffolds may intentionally retain interconnected porosity to support transport and tissue ingrowth. A single “implantable ceramic” category would hide those opposing design targets.

2. Six material states

Domain	Measured output	Primary dependency	Claim boundary
Slurry	Rheology, stability, solids, optical cure.	Particle size/loading, dispersant, binder, wavelength.	No green or sintered property.
Green body	Geometry, conversion and handling strength.	Exposure, cleaning, layer bonding.	No final ceramic dimensions.
Debound body	Organic removal and defect state.	Heating rate, atmosphere, part size.	No final density/phase.
Sintered ceramic	Density, porosity, phase, grain size, dimensions.	Sintering schedule and powder chemistry.	No biological suitability by identity alone.
Conditioned test article	Surface, sterilisation/cleaning, machining.	Final device processing.	No application performance without testing.
Qualified device/material	Mechanical, chemical and biological endpoints.	Intended contact, load, environment, standards.	Cannot be inferred from slurry or product name.

Table 1. Engineering distinctions that must be preserved.

3. Slurry design and cure

Ceramic loading raises viscosity and light scattering while reducing binder fraction. Dispersion quality controls sedimentation and local solids content. Goulas and co-workers demonstrated formulation-driven DLP manufacture of 3YSZ ceramics, illustrating that feedstock formulation is not separable from final ceramic quality. Working-curve calibration should therefore be performed on the actual slurry, and solids loading should be reported on a clear mass or volume basis. [1]

4. Cleaning and green-body integrity

Porous and lattice geometries create a cleaning problem because uncured slurry can remain trapped inside channels. Cleaning forces can also fracture thin green features. Recent work specifically addressing cleaning strategies for VPP porous scaffolds shows that post-print removal is part of ceramic manufacturing, not a cosmetic step. Internal residual slurry can alter local composition and become a defect during debinding. [4]

5. Debinding

Debinding is frequently the highest-risk thermal stage because gases must leave the part while the ceramic skeleton remains fragile. Heating too quickly can produce pressure, cracking or delamination; thick sections require longer diffusion paths. Thermogravimetric information about the organic fraction can inform a schedule, but the schedule must be validated on representative geometry because gas transport and thermal gradients scale with thickness. [1,4,5]

Stage	Dominant risk	Observable	Control
Cleaning	Trapped slurry or feature damage.	Mass/CT/sectioning and visual defects.	Access paths, solvent/process and gentle handling.
Drying	Warping or binder migration.	Dimensions and surface state.	Controlled drying conditions.
Debinding	Cracks, blisters, residual carbon.	Mass change, microscopy and defect inspection.	Geometry-specific thermal ramp and atmosphere.
Sintering	Anisotropic shrinkage, warpage, grain/phase change.	Dimensions, density, phase, microscopy.	Validated support and thermal cycle.
Finishing	Surface damage or contamination.	Roughness, chemistry and dimensions.	Application-specific finishing/cleaning.

Table 2. Processing risks from green body to sintered ceramic.

6. Sintering, shrinkage and phase

Sintering converts the porous debound skeleton into a dense or intentionally porous ceramic. Shrinkage is substantial and may be anisotropic, so final dimensions should be measured rather than derived from one universal scale factor. For zirconia, phase composition and grain size influence ageing and mechanical behaviour. For hydroxyapatite, excessive thermal treatment can alter chemistry while insufficient densification changes strength. Final ceramic density and phase should therefore accompany dimensional results. [1,3,5–9,11]

7. Dense zirconia and porous bioactive scaffolds are different problems

Dense dental or structural zirconia seeks low defect content and high densification. Bone-regeneration scaffolds intentionally introduce pore networks and therefore trade strength for transport and biological interface. Recent VPP HA and HA/3Y-ZrO₂ research demonstrates the value of evaluating mechanical response and cytocompatibility on the final sintered scaffold. Those results should not be transferred to dense zirconia components or vice versa. [2,3,6]

Class	Structural target	Biological/chemical target	Key evidence
Dense zirconia component	High density, strength, phase stability and accuracy.	Application-specific surface/biological evaluation if contacting tissue.	Density, phase, strength, ageing, dimensions.
Porous HA scaffold	Interconnected porosity with adequate mechanical integrity.	Cytocompatibility/bioactivity and relevant degradation/ion behaviour.	Porosity/connectivity, mechanics, chemistry, biological tests.
Composite bioceramic	Controlled phase fractions and interfaces.	Response linked to actual final composition.	Phase mapping, mechanics and biological evaluation.
Non-implant ceramic tooling	Thermal/mechanical function.	No implant biology required.	Application mechanical/thermal qualification.

Table 3. Divergent qualification targets for ceramic application classes.

8. Bioactivity and biological qualification

Bioactivity is a measured response, not an adjective attached automatically to a ceramic family. Apatite formation in a simulated fluid, cell response and in vivo bone integration are different evidence levels. For an implant-oriented printed ceramic, the final sintered/finished material state, sterilisation and extractables or surface chemistry must be considered. Compliance with one materials standard does not mean that a finished implant meets all clinical or regulatory requirements. [7–12]

9. Minimum reporting framework

Block	Minimum information	Reason	Claim limit
Powder/slurry	Ceramic identity, particle distribution, solids, dispersant/binder class.	Defines feedstock and scattering/rheology.	No final property from nominal powder alone.
VPP	Wavelength, layer, exposure, orientation and cleaning.	Defines green body.	No final dimension claim yet.
Debinding	Thermal profile, atmosphere, geometry.	Controls gas-removal defects.	No universal residual-carbon claim.
Sintering	Temperature/time/atmosphere/support.	Defines density, phase and shrinkage.	One shrink factor is not universal.
Final material	Density/porosity, phase, dimensions, surface, mechanics.	Defines actual ceramic state.	Green data cannot substitute.
Biological qualification	Final-state test article and application-relevant endpoints.	Connects material to intended implant use.	No “meets all clinical standards” shortcut.

Table 4. Minimum reporting set for implant-oriented ceramic VPP.

3Dresyns implementation examples

3Dresyns ceramic feedstock products provide commercial examples of indirect VPP processing routes. They should be treated as manufacturing materials, not as finished implant claims.

- The Ceramic 3Dresyn CDP platform provides a manufacturer-documented binder/feedstock route for ceramic powders, including zirconia-oriented workflows, followed by user-controlled debinding and sintering. Final density, phase, shrinkage and mechanical properties depend on the validated powder and thermal process [M1].
- The same CDP platform can be used as manufacturing context for alumina-oriented workflows, whose final-material requirements must be assessed independently from zirconia and against the relevant final-ceramic standard [M1].

• 3Dresyn Bio Scaffolds1 is retained only as a boundary example for scaffold research. Its manufacturer positioning does not establish that a sintered ceramic construct is an implant or meets clinical standards [M2].

No 3Dresyns feedstock is treated here as evidence of implant approval, universal final accuracy, bioactivity or patient-specific performance. Qualification belongs to the final processed ceramic/device.

10. Conclusions

- Ceramic VPP is a multi-state indirect manufacturing route; the green body is not the final ceramic.
- Slurry dispersion and optical cure determine green-body quality but not final implant properties.
- Cleaning and debinding are critical defect-generating stages, especially in thick or porous geometries.
- Sintering controls final shrinkage, density, phase and porosity and must be validated on representative geometry.
- Dense zirconia components and porous bioactive scaffolds have different, often opposing design targets.
- Bioactivity and biological suitability require tests on the final processed material state.
- Commercial ceramic feedstocks are implementation examples, not finished implant claims.

Limitations

This review is limited to ceramic VPP/related lithographic routes and does not constitute medical-device regulatory guidance. Numerical performance is not pooled across powders, thermal cycles or application classes.

Author contributions

Juan Segurola: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. Commercial 3Dresyns materials are identified only as implementation examples supported by controlled product documentation. They are not treated as independent peer-reviewed evidence and no proprietary formulation composition is disclosed.

Data availability

No new experimental dataset was generated for this review. Scientific statements are attributed to the cited literature and standards; commercial examples are separated from the independent evidence base.

Company information

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