

Direct and Indirect Additive Manufacturing for Advanced Ceramics and Metals: Evidence-Based Route Selection

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Statement of Significance

A route is not “direct” merely because printing is its most visible step. Ceramic and metal VPP normally print a binder-containing green body that still requires cleaning, debinding and sintering; investment casting prints a sacrificial pattern and adds investment, evacuation/burnout and casting. Selection should compare the complete chains by accepted-part performance, yield, lead time and cost—not resin price, print time or catalogue labels alone.

Keywords: ceramics; metals; VPP; investment casting; route selection; debinding; sintering; accepted-part cost.

Abstract

This targeted engineering review defines an evidence-based comparison of direct and indirect additive-manufacturing routes for advanced ceramic and metal parts. Current literature shows multiple VPP strategies for particle-filled and precursor systems, strong coupling between optical cure depth and ceramic processing, demonstrated large sacrificial patterns for investment casting, and one route-pair techno-economic analysis. These sources do not support a universal winner. The paper instead freezes the functional requirement, maps every transformation from feedstock to inspected part, and compares dimensional compensation, defect modes, yield, rework, capacity, outsourced operations and cost per accepted part. A route-selection matrix and minimum validation record are provided. Manufacturer product descriptions are treated as candidate-process information until the complete workflow is validated. RP-02 supplies the shared evidence-to-decision method.

1. Definitions and evidence boundary

Here, a direct route creates the intended ceramic or metal geometry as a particle-filled or precursor-containing green body that is subsequently converted to the final inorganic article. An indirect route prints a disposable pattern or a mould used to shape another material. Both are multi-step manufacturing chains; “direct” does not mean one-step, net-shape or free of tooling.

Zeng and Saccone review VPP strategies for metals and ceramics and the central roles of suspension, cure, debinding and densification [1]. Li et al. analyse selection of cure depth for Al₂O₃ VPP [2]. Sameni et al. demonstrate large VPP master patterns in an investment-casting workflow [3]. Sartini et al. compare rapid investment casting with VPP routes techno-economically for a defined case [4]. Only [4] supplies a route-pair economic result; none establishes universal superiority across materials, geometries or production volumes.

2. Where risk enters each process chain

Direct ceramic/metal VPP concentrates risk in feedstock stability, recoating, light scattering/absorption, cure-depth control, green strength, support removal, debinding and sintering. Polymer removal can generate pressure, cracking or contamination; densification produces shrinkage and may distort unsupported or non-uniform sections. Final properties depend on porosity, phase state and thermal history, not on green-body appearance alone [1,2].

Indirect pattern–investment–casting routes move risk into pattern accuracy and drainage, assembly, investment compatibility, pattern removal/burnout, mould integrity, metal fill and solidification. Sameni et al. show that large VPP master patterns can be viable, but that demonstration is a route example rather than proof for every geometry or foundry chain [3]. Printed mould routes add mould life, release, seams and injection/casting pressure to the control plan.

The appropriate question is therefore not which route has fewer named steps, but which chain has the highest probability of delivering the frozen requirement with controlled variation. A route that prints quickly can lose on cracking, casting rejection, machining allowance or inspection burden; a slower print can win if downstream yield and repeatability are superior.

3. Cure depth, compensation and transfer of geometry

Ceramic cure depth must support layer bonding and green handling without excessive lateral cure or trapped defects. Li et al. demonstrate that cure-depth selection is a process-design decision in Al₂O₃ VPP [2]. Exposure cannot be optimised independently of particle loading, optical attenuation, layer thickness and downstream shrinkage. Working curves are useful controls only for the frozen formulation and measurement state.

Every route needs a dimensional-transfer model. Direct routes require green-to-fired scale factors, anisotropic shrinkage and distortion maps. Indirect routes require printed-pattern error, investment expansion, pattern-removal effects, alloy contraction and any finishing allowance. Compensation derived from one geometry or section thickness should not be transferred without verification. Final metrology—not CAD-to-pattern agreement—closes the route decision.

4. Route-selection architecture

Decision field	Direct ceramic/metal VPP	Indirect pattern or mould	Required evidence
Material/function	Final phase from loaded or precursor feedstock	Wider casting/injection material choice	Composition, density/porosity and end-use tests
Geometry transfer	Cure plus debind/sinter shrinkage and distortion	Pattern/mould plus investment/casting contraction	Stage-by-stage metrology and compensation map
Primary defects	Sedimentation, cure error, green crack, debind crack, warp, residual porosity	Drainage, pattern damage, shell crack, ash/residue, misrun, shrinkage porosity	Defect taxonomy with rejection criteria
Scale/volume	Build packing and furnace capacity can dominate	Pattern rate, tooling route and foundry batch dominate	Capacity model at target mix and utilisation
Changeover	Feedstock/printer/furnace cleaning and qualification	Pattern or mould change plus casting setup	Measured changeover, learning and validation cost
Economics	All printing, cleaning, thermal processing, finishing and inspection	Pattern/mould, investment, burnout, casting, finishing and inspection	Cost per accepted part with uncertainty
Qualification	Frozen feedstock-to-fired article	Frozen pattern/mould-to-cast article	Traceable lots, process versions and final acceptance

5. Yield and cost per accepted part

The denominator must be accepted final parts, not successful prints. At minimum, report started builds or batches; green, post-debind, post-sinter or post-cast quantities; rework; scrap reason; inspection result; and time to disposition. A practical model is $C_{\text{accepted}} = (\text{material} + \text{machine} + \text{labour} + \text{energy} + \text{tooling/investment} + \text{outsourced processing} + \text{inspection} + \text{rework} + \text{allocated scrap}) / \text{accepted parts}$. Assumptions for utilisation, batch size, depreciation, labour and energy require sensitivity ranges.

Sartini et al. support this logic for the route pair and case they examined [4]. Their result should not be extrapolated as a break-even threshold for other machines, countries, geometries or quality levels. Qualification batches should generate empirical yield distributions before production forecasts are presented as established cost.

6. Minimum validation record

- Freeze material, geometry, tolerances, surface, properties, inspection and annual demand before scoring routes.
- Map every step, transfer, queue, outsourced operation and inspection gate from feedstock receipt to release.
- Record formulation/pattern lot, equipment, software, exposure, cleaning, thermal cycles, atmosphere and fixtures.
- Measure geometry at the green/pattern, intermediate and final states; retain orientation and section-thickness effects.
- Define defect classes and acceptance before trials; report scrap and rework separately from first-pass yield.
- Compare cost, lead time and capacity per accepted final part with uncertainty and sensitivity analysis.
- Regualify material, supplier, formulation, machine, furnace/foundry, geometry or process changes according to risk.

7. 3Dresyns implementation boundary

3Dresyns offers materials for ceramic/metal feedstocks and indirect casting pathways, including heat-meltable LMM Perfect Cast PC1 and top-down VPP Perfect Cast HS1 Bio. Their product pages describe intended process roles and internal or standardized test results, but do not make either pathway a universal winner. “Zero ash”, gravity removal, exposure guidance or a material property remains bound to the stated product and test conditions. The user must validate printer, geometry, investment, evacuation/burnout, casting or debinding/sintering and final inspection as one controlled workflow. Sources: <https://www.3dresyns.com/products/3dresyn-lmm-perfect-cast-pc1-castable-solid-photopolymer-for-printing-heat-meltable-castings-for-jewelry-by-lithography-based-metal-manufacturing-lmm> and <https://www.3dresyns.com/products/3dresyn-perfect-cast-hs1-heat-soluble-meltable-flowable-castable-photopolymer-wax>

8. Limitations and research priorities

Comparative studies spanning identical geometries, acceptance criteria and production volumes remain limited. Priorities are matched direct/indirect trials; section-dependent dimensional transfer; debinding and burnout gas evolution; furnace and foundry capacity; first-pass yield; automated defect classification; environmental inventory per accepted part; and transparent techno-economic sensitivity analyses. Until such evidence exists, selection outputs should be presented as project decisions, not rankings of technologies.

9. Conclusions

- Direct and indirect AM are complete process chains with differently located risks.
- Route selection begins with frozen final-part requirements and ends with final inspection.
- Print success, green-body quality or pattern accuracy cannot substitute for accepted final-part yield.
- Cost comparisons must include every downstream step, rework, scrap, capacity and uncertainty.
- 3Dresyns materials define candidate pathways; qualification belongs to the exact validated workflow.

Declarations

References

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