

Embedded Components and Hybrid Functional Assemblies

In-Process Embedding in Vat-Photopolymerised Parts: Pause, Placement, Resume, Interfacial Cure and Verification

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Statement of Significance

Embedding a component during vat photopolymerisation is not ordinary assembly performed earlier in time. The inserted object changes the optical, chemical and mechanical boundary conditions of the unfinished build. Direct SLA studies show that pause-place-resume fabrication can integrate glass, membranes, paper, steel, silicone elements, silicon microdevices and fibrous scaffolds, but they also expose failure modes that are invisible in a monolithic print: platform realignment error, trapped resin, shadowed interfaces, oxygen inhibition, suction loading, deformation and incomplete sealing [1,2]. ER-169 converts those observations into a bounded qualification framework. It does not claim universal compatibility or industrial readiness.

Abstract

Vat photopolymerisation normally builds a monolithic object from successive exposures of one liquid formulation. A pause-place-resume route changes that architecture by interrupting the build, placing a prefabricated component on or within the partially cured part, and resuming layerwise exposure so that the component becomes enclosed or functionally coupled to the printed structure. Sagot et al. demonstrated this strategy in SLA microfluidics with glass coverslips, soluble films, paper pads, steel balls, silicone O-rings, elastic and nanoporous membranes, and silicon microfilters [1]. Ng et al. separately inserted a three-dimensional fibrous scaffold into a partially printed SLA perfusion chamber before resuming fabrication [2]. These studies establish technical feasibility, but only for specified printers, transparent methacrylate resins, component preparations and device geometries. They also identify important limits. Opaque inserts can shadow the interface; oxygen-permeable materials can inhibit local cure; higher resin viscosity can increase immersion and separation forces; platform removal can disturb registration; and cure shrinkage can deform an insert. ER-169 therefore treats embedded-component manufacture as a controlled hybrid process. Qualification must preserve component identity and orientation, interface geometry, pause state, resin condition, optical access, placement accuracy, restart alignment, cleaning, post-cure, sealing and functional verification. No single successful prototype qualifies another component, resin, printer or service condition.

Keywords: vat photopolymerisation; stereolithography; embedded components; print-pause-print; hybrid manufacturing; interfacial cure; microfluidics; process qualification

1. Scope and ownership

ER-169 addresses the in-process insertion of prefabricated functional components into parts made by vat photopolymerisation. Its central sequence is print, pause, expose the unfinished build, place the component, restore the build to the printer and resume exposure. It owns the manufacturing decisions created by that interruption: insert geometry and compatibility, placement features, interface resin state, optical access, restart registration, enclosure, cleaning, post-cure and verification of the resulting hybrid part.

Post-print adhesive assembly remains within ER-165. Load introduction through inserts, threads, press fits and overmoulded interfaces remains within ER-166, whereas ER-169 owns in-process enclosure of a prefabricated component during the build. Coating or encapsulating a completed reactive photopolymer substrate remains within ER-168. The paper also excludes conductive or functional fillers dispersed in the

resin, voxel-level formulation switching, and the design and regulatory qualification of a medical or microfluidic device; those subjects are outside this article's scope and are not reassigned here. ER-169 concerns a discrete component that exists before insertion and remains distinguishable from the surrounding printed matrix.

The direct evidence core is intentionally narrow. Sagot et al. used two commercial SLA systems and two transparent resins for the completed integrations, with a third and more viscous resin attempted but not completed, to investigate a broad set of objects in microfluidic chips [1]. Ng et al. used an Asiga SLA system and a methacrylate resin to integrate a PLGA fibrous scaffold and PDMS inserts into a perfusion culture device [2]. The evidence supports a qualification architecture, not universal materials or process values.

2. Embedding changes the process state

A monolithic VPP build remains within a repeated exposure-separation cycle. Embedding introduces a discontinuity. The platform may be removed, uncured resin is disturbed, the partially cured surface is cleaned or exposed to air, a foreign solid is positioned, and the build is returned to the machine. The next layers must attach across a boundary that may differ in surface chemistry, oxygen content, roughness, wetting, stiffness, optical transmission and thermal expansion.

Sagot et al. formalised a print-pause-print sequence comprising design of a slot where required, printing the first section, pausing, removing excess resin, positioning the object, restoring the platform, resuming the print, cleaning and post-curing [1]. Ng et al. likewise inserted a fibrous scaffold into a partially printed perfusion chamber and resumed SLA fabrication, avoiding a separate chamber-bonding step [2]. These are direct demonstrations that insertion can occur inside the build sequence. They do not show that interruption is neutral.

The controlled process record must therefore distinguish the pre-pause part, the exposed interface, the insert and the post-pause structure. A completed hybrid part cannot be interpreted as if all four had shared one uninterrupted cure history.

3. The insert is an optical boundary

The inserted component can transmit, absorb, scatter or reflect the exposure wavelength. That optical behaviour determines whether resin beneath or adjacent to the object receives sufficient dose during resumed printing and post-cure.

Sagot et al. observed imperfect bonding and limited delamination around opaque silicon microfilters. The printer laser did not reach resin trapped between the insert and pre-pause layers; some of that resin was removed during development, while remaining resin was polymerised during post-cure [1]. This establishes two separate risks: an interface may contain underexposed material before cleaning, and later post-cure may reinforce what remains without proving complete conversion throughout the shadowed region.

Qualification should define insert transmission at the relevant wavelength, projected shadow area, intended cure path, interface gap and whether post-cure radiation can reach the obscured volume. A visually enclosed insert is not evidence that the interface received the same dose as an unobstructed layer. Opaque, reflective or highly scattering inserts require an alternate bonding or geometrical strategy and direct verification.

4. Oxygen permeability and sorption can prevent local cure

The insert may alter local radical polymerisation through gas transport or sorption. Sagot et al. reported that PDMS could not be incorporated even after silanisation and vacuum treatment because its high oxygen permeability and sorption inhibited curing of resin near the material [1]. This is direct evidence that nominal adhesion treatment cannot overcome an incompatible interfacial reaction environment.

The failure should not be reduced to a generic statement that one polymer is incompatible with every resin. The tested PDMS, resins, geometry and exposure conditions define the observation. The transferable engineering rule is narrower: component selection must consider oxygen permeability, absorbed species, extractables and the ability of the interface to achieve cure under the actual exposure path.

The same study nevertheless integrated PDMS successfully after masking the membrane faces with adhesive frames, which shows that an incompatible interfacial environment may be isolated rather than accepted as an exclusion [1]. The masking material, its removal and its residue then become controlled variables, as discussed in Section 8.

A qualification coupon should reproduce insert material, surface preparation, thickness, storage, preconditioning and contact time with resin. Cure at the interface should be assessed separately from bulk cure. Passing a pull test after post-cure does not by itself show that no mobile or under-reacted interfacial material remains.

5. Placement geometry is part of the digital definition

An insert thicker than a layer needs a receiving feature. Sagot et al. used a slot corresponding to the object shape, with stated margins, to facilitate manual positioning [1]. Thin objects could be placed on the pre-pause surface. Ng et al. fabricated the miniaturised scaffold to fit the culture chamber without folding [2].

The build definition should therefore include the insert envelope, tolerance, insertion direction, datum, retention feature, clearance and the volume expected to contain resin. Excess clearance can produce positional uncertainty or a thick resin gap. Insufficient clearance can damage the pre-pause structure or insert. A compliant, porous or fragile insert also needs a defined handling condition because its installed geometry may differ from its free geometry.

Placement should be verified against functional datums, not merely the outer part. Where the insert provides a flow restriction, optical window, membrane, electrode or mechanical stop, its active region and orientation determine performance.

6. Platform removal creates a restart-registration problem

Removing the platform for insertion can change position and angle before printing resumes. Sagot et al. measured the alignment between pre-pause and post-pause structures on one printer and cautioned that the result depends on how the platform is attached and secured. They did not measure alignment between the insert and pre-pause layers, and stated that results may differ on other printers [1].

This distinction is essential. Restart registration and insert-placement accuracy are separate quantities. A printer may return the platform reproducibly while an operator places the component inaccurately, or the insert may be well positioned while the platform reseats with angular or translational error.

A process capability study should measure both. It should include repeated platform removal and replacement, multiple operators where manual placement is used, representative insert sizes and an inspection method sensitive to the functional tolerance. The capability belongs to the specific platform interface and work instruction. It cannot be assumed from nominal pixel size or layer thickness.

7. Resin viscosity and component area govern mechanical disturbance

The insert and unfinished part re-enter liquid resin after placement. Displaced resin and subsequent separation can load the component, its interface and the partially cured structure. Sagot et al. could not complete some large-overhang coverslip integrations with a more viscous resin because the insert experienced large forces during re-entry and suction during platform movement [1].

The observation links component projected area, clearance, resin viscosity, immersion path and separation mechanics. It does not establish a universal viscosity limit. A qualification build should reproduce the worst

credible resin temperature, viscosity and insert area, and should observe movement, fracture, lift or delamination during the first resumed cycles.

Drainage and vent paths may be necessary so that resin is not hydraulically trapped beneath a broad insert. Resumed lift speed and separation distance may need to differ from the monolithic process. Any change must be qualified against layer formation as well as insert stability.

8. Surface preparation must match the component and function

In the Sagot study, glass coverslips were cleaned, plasma treated and silanised with a methacrylate-functional silane to increase resin-glass adhesion [1]. Other incorporated objects did not all require the same preparation. The study therefore supports component-specific interface preparation, not a universal primer.

Preparation can serve different purposes: remove contamination, improve wetting, create covalent coupling, control resin intrusion, preserve pore openness or keep an optical area clear. Those purposes can conflict. A treatment that improves adhesion may alter optical transmission, membrane selectivity, electrical contact or biological surface function.

The process specification should define preparation chemistry, concentration, time, drying, maximum storage interval and acceptance check. The component must be handled after preparation without recontaminating the active interface. If masking is used to protect an active region, its removal and residue become additional controlled steps.

9. Porous and permeable inserts require function-preservation tests

Embedding can occlude the feature that justifies the insert. Sagot et al. compared nanoporous PET and Nafion membranes incorporated by print-pause-print with clamped controls. PET electrical behaviour was close between configurations, while Nafion selectivity was retained but total chip resistance was slightly higher, which the authors attributed to possible resin blockage of some pores [1]. Silicon microfilters also contained defined pores and integrated electrodes; electrical access was demonstrated, but the authors stated that substantial optimisation was still required for cell sensing [1].

Ng et al. evaluated an embedded fibrous scaffold and found minimal decreases in measured pore size and porosity after perfusion, while reporting cell infiltration and functional biological responses in the specific device [2].

These results show why enclosure integrity and insert function must be verified separately. A leak-free part can still contain a blinded membrane, insulated electrode, obstructed filter or compressed scaffold. Qualification should compare the insert before and after embedding using the property relevant to its function.

10. Cleaning is a controlled challenge to the hybrid interface

The hybrid part must survive removal of uncured resin. Sagot et al. used isopropanol or acetone, flushed channels, applied ultrasonic cleaning and then post-cured under defined conditions [1]. Ng et al. used a biological device whose construction and subsequent culture imposed a different process sequence [2].

Cleaning can extract or swell the insert, penetrate a porous component, weaken an adhesive frame, transport uncured resin into protected regions or dislodge a poorly retained object. A solvent compatible with the printed matrix is not automatically compatible with the insert.

The cleaning qualification should include solvent identity and purity, bath loading, time, agitation, temperature, flushing pressure, drying and the time between insertion and post-cure. The acceptance test should look for residue, movement, swelling, cracking, loss of function and contamination of inaccessible cavities. The evidence reviewed here does not justify a universal wash time or solvent.

11. Post-cure can strengthen an interface and distort it

Post-cure is not merely completion of the surrounding matrix. It can polymerise resin remaining in a shadowed gap, increase shrinkage stress, heat the insert and change dimensional alignment. Sagot et al. reported that post-cure reinforced bonding around opaque objects, but also observed higher deformation in some chips, probably related to shrinkage, including deformation of integrated coverslips. The effect was not reproducible between batches and was not investigated further [1].

That uncertainty must remain visible. Post-cure may improve retention while worsening optical flatness, membrane stress, seal geometry or component calibration. Qualification should measure the relevant geometry and function before and after post-cure where practicable. Cure schedule, support state and thermal boundary condition are part of the hybrid process specification.

12. Verification requires multiple independent acceptance limbs

A defensible acceptance decision should not collapse hybrid-part evaluation into one test. At minimum, the following limbs should be considered:

1. component identity, lot and preconditioning;
2. correct orientation and placement relative to functional datums;
3. pre-pause and post-pause registration;
4. interfacial cure or absence of mobile resin where relevant;
5. retention and seal integrity;
6. preservation of optical, electrical, fluidic, porous, mechanical or biological function;
7. dimensional state after cleaning and post-cure;
8. absence of damage introduced by immersion and separation;
9. traceability of operator, printer, resin, programme and interruption history.

Sagot et al. used X-ray tomography, pressure testing, flow measurements, electrical measurements, microscopy and functional assays for different inserted objects [1]. Ng et al. used dimensional measurements, scaffold morphology and porosity, cell assays and gene-expression measurements for its specific biological device [2]. These examples support selecting tests by failure mechanism. They do not define one universal inspection suite.

13. A staged qualification strategy

Qualification should advance from interface coupon to representative subassembly and then to the complete part. An interface coupon can isolate optical shadowing, cure inhibition, adhesion and solvent compatibility. A placement coupon can measure human or automated positioning and restart registration. A representative subassembly can reproduce projected area, trapped volume, drainage and separation forces. The complete part confirms integrated function.

Repeated builds are necessary because the process includes manual operations and platform reseating. Challenge conditions should include the limits of resin temperature and age, insert tolerance, placement delay, platform-removal duration and post-cure state that are intended for production. Failure modes should be defined before testing so that a successful function test does not conceal an unacceptable interface.

Bridging to a new insert, resin or printer is justified only when the changed variable is outside the mechanism controlling the original evidence or when direct comparison shows equivalence. A new colour, filler or opaque component can change the cure path even if geometry is unchanged.

14. Evidence limitations

Both direct studies concern microfluidic or biological proof-of-concept devices and use specified commercial SLA systems and transparent methacrylate resins [1,2]. They do not establish capability for load-bearing

inserts, high-voltage electronics, sealed energy-storage devices, long-term environmental exposure or regulated production.

The broadest study tested most conditions on one printer, evaluated restart alignment only on that platform, used two transparent resins for the completed integrations, attempted but did not complete coverslip integration with a third and more viscous resin, and did not measure insert-to-pre-pause placement accuracy [1]. Some reliability statements were supported by triplicates while other observations were reported without complete production-scale statistics. The scaffold study was application-specific, included sealant at a printed-to-PDMS interface, and identified build-area and mass-production limits [2].

Neither study supplies universal allowable gaps, adhesion strength, conversion thresholds, leak criteria, fatigue life or service-temperature limits. The evidence supports the process architecture and its known failure mechanisms. It does not qualify any untested combination.

15. Conclusions

Direct SLA evidence demonstrates that prefabricated components can be inserted into a paused build and enclosed or coupled by resumed vat photopolymerisation [1,2]. The demonstrated objects range from glass, paper and steel to membranes, silicon microdevices and fibrous scaffolds. Their successful use depends on more than geometric fit.

The insert changes optical access, oxygen transport, wetting, resin flow, separation force, cure shrinkage and the functional boundary of the part. Restart registration and component placement must be measured separately. Opaque interfaces may remain shadowed, oxygen-permeable materials may inhibit cure, viscous resin can overload broad inserts, post-cure can reinforce or deform the interface, and cleaning can challenge both retention and function.

ER-169 therefore treats pause-place-resume fabrication as a hybrid manufacturing process with its own qualification record. Acceptance requires proof of identity, placement, cure, retention, sealing, dimensional state and retained component function under the specific printer, resin, insert and post-processing conditions. A successful prototype is evidence of feasibility, not a universal process window.

Related Engineering Review boundaries

ER-169 owns in-process insertion and enclosure of discrete prefabricated components during a VPP build. ER-165 retains post-print adhesive assembly. ER-166 retains load introduction through an insert interface, including inserts, threads, press fits and overmoulded interfaces; ER-169 differs by addressing enclosure during the interrupted build. ER-168 retains coating and encapsulation of a completed reactive photopolymer substrate. Dispersed fillers, multimaterial resin exchange as an end in itself, device-specific regulatory qualification, and separately owned chemistry, exposure, washing, post-cure or service mechanisms remain outside ER-169; no unnamed Engineering Review is reassigned here.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. This review does not claim that any 3Dresyns resin, printer, embedded component, interface or hybrid process is qualified for a specific industrial, medical or regulated use.

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Data availability

No new experimental dataset was generated for this review.