

Self-Healing and Interlayer Repair in Photopolymer Additive Manufacturing: Mechanisms, Network Mobility and Validation Limits

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ER-013 · Engineering Review · Version 1.4 · 2026

Statement of Significance

Self-healing is frequently presented as a single material attribute, yet a printed photopolymer can recover apparent continuity through very different mechanisms. Additional curing can strengthen an incompletely converted interface, mobile chains can diffuse and entangle across adjacent layers, dynamic covalent bonds can exchange, supramolecular interactions can reform, and encapsulated agents can create a one-time repair zone. These outcomes are not equivalent. This review separates interlayer strengthening from post-damage repair and proposes a mechanics-first qualification architecture in which crack closure, rebonding, load transfer and repeated functional recovery are demonstrated independently. The central engineering question is therefore not whether a resin is labelled self-healing, but which network process restores which property, under what activation conditions, and with what limit on repeatability and dimensional stability.

Keywords: self-healing photopolymers; vat photopolymerisation; DLP; SLA; covalent adaptable networks; vitrimers; disulfide exchange; imine exchange; boronate esters; supramolecular networks; interlayer welding; mechanical anisotropy; repair; stress relaxation

Abstract

Photopolymer additive manufacturing normally converts a low-viscosity reactive formulation into a permanently crosslinked object. That transformation is advantageous for geometric fidelity and green strength, but it also restricts molecular mobility after cure and can leave layer interfaces, crack surfaces and damaged regions unable to re-establish load-bearing connectivity. A growing literature addresses this limitation through intrinsic dynamic covalent networks, supramolecular interactions, mobile linear-polymer phases, extrinsic healing agents and hybrid elastomer architectures. These approaches are often grouped under the term self-healing even though they solve different problems. Interlayer welding during or after fabrication is not the same experiment as restoring a severed specimen; visual crack closure does not prove recovery of fracture resistance; and a single tensile-strength ratio does not establish fatigue life, autonomous function or repeated reparability. This review organises photopolymer repair around four coupled variables: network mobility, interfacial contact, exchange or rebonding kinetics, and the mechanical quantity used to define recovery. Primary studies demonstrate that DLP- and stereolithography-compatible systems can incorporate disulfide exchange, transesterification, imine exchange, boronate-ester metathesis, ionic or hydrogen-bonded associations, and extrinsic solvent-welding strategies. Recent work also shows that dynamic chemistry can reduce, rather than universally eliminate, layer-dependent mechanical anisotropy. A minimum reporting framework is proposed for damage state, activation protocol, specimen orientation, controls, recovery metric, number of cycles, failure location and dimensional stability. The resulting framework defines a defensible boundary between post-cure strengthening, interlayer repair, intrinsic self-healing, reprocessing and functional recovery.

1. Introduction

Vat photopolymerisation and related light-based additive-manufacturing methods obtain their speed and spatial resolution by rapidly converting multifunctional liquid monomers and oligomers into a crosslinked solid. The same network formation that provides shape retention can suppress the long-range molecular motion normally required for two damaged polymer surfaces to interpenetrate, entangle or react. Repair therefore requires a mechanism that remains active after the primary photopolymerisation step, or a deliberately retained mobile phase that can reconnect an interface when suitable contact and activation are supplied.

The layerwise process adds a second problem. A printed object is not necessarily mechanically homogeneous through its build direction. Nanoscale mapping of a DLP-printed photopolymer by Gojzewski and co-workers identified local mechanical heterogeneity at layer interfaces, supporting the view that the interface is a material state that should be measured rather than assumed to be identical to the layer interior [1]. This does not mean that every Z-direction failure is caused by a universally weak boundary. Orientation, exposure history, conversion, geometry, residual stress, pixel or voxel architecture and post-processing can all contribute. It does mean that interlayer connectivity is a legitimate design and qualification variable.

Two distinct research questions have consequently converged. The first asks whether a damaged photopolymer can restore structural or functional performance after fracture. The second asks whether mobility or exchange chemistry can improve connectivity across interfaces created by the additive process itself. The literature uses terms such as self-healing, mending, welding, rebonding, reprocessing and repair across both questions. Without a stricter definition, impressive results in a soft elastomer can be transferred rhetorically to a rigid thermoset, or a thermally strengthened layer interface can be described as autonomous healing even when no post-damage experiment was performed.

This review focuses on photopolymer-based additive manufacturing, with particular emphasis on DLP, stereolithography and vat photopolymerisation. It synthesises public primary literature on intrinsic and extrinsic healing, dynamic covalent networks, physical or supramolecular rebonding and interlayer welding. It does not map commercial formulations, product activation windows or proprietary additive dosages. The objective is to define mechanism-specific evidence and the limits of the claims that can be made from it.

2. Repair terminology: different phenomena require different evidence

2.1 Post-cure strengthening is not self-healing

A photopolymer can become stronger after additional light or thermal treatment because conversion increases, residual reactive groups are consumed, solvent is removed or physical ageing changes the network. Such a change may improve an interface and is often useful in manufacturing, but it is not by itself evidence that a damaged network can heal. A self-healing claim requires a defined damage event followed by a defined recovery step and a comparison between pristine, damaged and repaired states. Otherwise, ordinary maturation of the cured network is being conflated with repair.

2.2 Crack closure, bonding and load transfer are separate observables

A cut that visually disappears demonstrates geometric closure at the observation scale. Adhesion across the closed surface demonstrates a second level of evidence. Recovery of strength, strain-to-failure, toughness or fracture resistance demonstrates a third. These outcomes can diverge. A compliant material may close a cut because the surfaces remain tacky while still failing prematurely under load; conversely, a stiff dynamic network may weld two accurately aligned pieces and restore substantial load transfer without showing autonomous crack closure. Qualification should therefore report what was actually recovered rather than assigning one global healing percentage.

2.3 Intrinsic, extrinsic and interfacial repair

Intrinsic systems retain reversible or exchangeable interactions in the printed network itself. Dynamic covalent bonds, hydrogen bonding, ionic associations and other supramolecular interactions can reform when mobility and contact are sufficient. Extrinsic systems store a separate healing agent in capsules or reservoirs and release it when damage occurs. Interfacial welding is broader: it includes chain diffusion, entanglement, dynamic bond exchange or new covalent reaction across an interface, whether that interface was created by layerwise printing, deliberate assembly or fracture. These categories overlap mechanistically but impose different limits on repeatability, activation and geometry.

Term	What changes	Minimum evidence	Misinterpretation to avoid
Post-cure strengthening	Conversion, residual stress or network state after fabrication.	Before/after mechanical data without a damage event.	Calling ordinary post-cure improvement self-healing.
Physical crack closure	Damaged faces return to apparent contact.	Time-resolved imaging and controlled contact conditions.	Assuming a closed crack has recovered load transfer.
Interfacial welding	Connectivity is created across a pre-existing interface.	Interface-specific mechanical test and failure-location analysis.	Assuming welding of assembled parts proves autonomous repair.
Intrinsic self-healing	Network interactions reform after damage.	Defined damage, healing protocol and recovered property.	Reporting only a qualitative photograph.
Extrinsic self-healing	Stored healing agent is released into damage zone.	Agent-release mechanism plus mechanical recovery.	Assuming the mechanism is indefinitely repeatable.
Reprocessing / recycling	Topology or chemistry permits reshaping or material recovery.	Repeated processing or chemical recovery with retained properties.	Using recyclability as a synonym for crack healing.

Table 1. Terms that should be separated in photopolymer repair studies.

3. Layer interfaces are a distinct qualification problem

3.1 Why a layer boundary can differ from bulk material

Layerwise photopolymerisation produces a periodic exposure history. Each newly exposed layer is formed against material that has already undergone some combination of polymerisation, oxygen contact, light attenuation, shrinkage and mechanical separation. Gojzewski et al. used atomic-force-microscopy-based mechanical mapping to resolve interfacial regions of locally reduced modulus - up to about 30% below the layer interior - between consecutively deposited layers in a printed photopolymer [1]. The result is important because a nominally monolithic CAD body can contain a repeated material history at the layer pitch. The relevant interface thickness and severity remain resin- and process-dependent, so the finding should not be converted into a universal Z-strength penalty.

3.2 Interlayer strengthening can occur without a self-healing network

Zhu and co-workers addressed layer adhesion through a different mechanism: linear polymers were introduced into DLP resins and a subsequent heat treatment allowed diffusion and entanglement to weld adjacent layers [10]. The important concept is mobility across the interface. A permanently crosslinked matrix can benefit from a mobile polymer fraction even if the crosslinked network itself does not undergo dynamic covalent exchange. This route should be classified as post-print interlayer welding rather than autonomous self-healing.

3.3 Dynamic exchange can reduce anisotropy without erasing process history

Dynamic covalent chemistry provides another path. Bonacini et al. incorporated boronate-ester-based dynamic crosslinks into photocurable vat-printing networks and used stress-relaxation and creep-recovery measurements to connect bond exchange with post-print network rearrangement [16]. Their work explicitly targeted reduction of mechanical anisotropy. This is a more defensible formulation than claiming elimination of Z-axis anisotropy: the printed object still has an orientation, a layer architecture and an exposure history, while dynamic exchange changes how strongly those features remain encoded in the mechanical response.

4. Dynamic covalent networks: permanent connectivity with exchangeable topology

Dynamic covalent networks retain covalent connectivity while allowing bonds to exchange, dissociate and reform, or reorganise under a stimulus. For photopolymer additive manufacturing, the design challenge is unusually strict: the liquid formulation must remain stable enough to process, the primary cure must be fast enough to resolve the intended geometry, and the cured network must later recover sufficient mobility for repair. A chemistry that exchanges too slowly provides little practical healing; one that exchanges too readily can produce creep, dimensional drift or loss of service stiffness.

4.1 Transesterification and vitrimer-like photopolymers

Rossegger et al. demonstrated DLP printing of thiol-acrylate vitrimer systems in which thermo-activated transesterification enabled topology rearrangement, shape-memory behaviour and thermal mending [7]. A subsequent study from the same group introduced a photolabile transesterification catalyst so that dynamic exchange could be activated locally with a second wavelength, separating primary 405 nm printing from 365 nm catalyst activation [8]. This orthogonality illustrates an important engineering route: curing and repair need not be driven by the same trigger.

Transesterification-based repair has also been demonstrated in other printable architectures. Grauzeliene et al. developed a DLP-printable vitrimer from glycerol 1,3-diglycerolate diacrylate and tetrahydrofurfuryl methacrylate and evaluated weldability and repairability after cure [14]. Ye et al. later reported acrylate and methacrylate photopolymer resins based on low-activation-energy adaptable covalent bonding, showing that repair can be retained in high-resolution printed structures when the exchange chemistry is activated thermally [17]. These studies establish feasibility, but their activation temperatures, catalyst systems and mechanical baselines are formulation-specific rather than universal design windows.

4.2 Disulfide and imine exchange

Disulfide metathesis is particularly attractive for elastomeric systems because exchange can occur without destroying the permanent network architecture. Yu et al. combined thiol-ene photopolymerisation with disulfide-containing crosslink regions to print self-healable elastomeric structures by projection stereolithography [3]. In a different architecture, Kamble and Asha combined disulfide and imine dynamics in a biobased DLP photopolymer and demonstrated both self-healing and reprintability [18]. The presence of two exchange chemistries does not automatically improve every property; it increases the number of kinetic processes that must be controlled during storage, printing, service and repair.

Imine exchange provides another route to adaptable printed networks. Stouten et al. demonstrated a biobased DLP photopolymer containing dynamic imine bonds with rapid thermal reprocessability [11]. More recently, Kollwitz, Balszuweit and co-workers investigated imine-containing adaptive materials for 3D printing and explicitly examined molecular welding by imine bond formation [20]. These examples reinforce the need to distinguish repair of a local interface from full material recycling: both exploit network dynamics, but their test geometries and evidentiary burdens differ.

4.3 Boronate esters and other exchange mechanisms

Boronate esters can exchange under comparatively mild conditions and have been incorporated into photocurable networks. Robinson et al. used boronate esters to create catalyst-free 3D-printing resins with tunable fractions of dynamic and static crosslinks [9]. Bonacini et al. subsequently brought boronate-ester dynamics directly into a vat-photopolymerisation anisotropy problem [16]. Fang et al. used a different dynamic-covalent architecture based on exchangeable hindered urea chemistry to create DLP-printed networks with post-print geometric and mechanical reprogrammability [12]. Collectively, these studies show that dynamic exchange is a design axis rather than one chemistry class.

5. Supramolecular and physical self-healing

Covalent exchange is not required for repair. Reversible ionic associations, hydrogen bonds and chain interdiffusion can restore cohesion when damaged surfaces are brought into contact. Zhu et al. reported DLP-printable polymers crosslinked by ionic and hydrogen-bonding interactions, using the dynamic physical network to enable healing, recycling and assembly [5]. Huang et al. combined complementary network components in a DLP-printable polymer composite designed to balance robustness with self-healing and recyclability [13]. These systems demonstrate that reversible physical interactions can be compatible with light-based printing, but their behaviour is strongly dependent on temperature, moisture, contact pressure and segmental mobility.

Soft elastomers make the distinction especially clear. Gomez et al. developed vat-photopolymerisable self-healing elastomers for modular soft robotics [6], and Beckett et al. later reported a hybrid acrylate/thiol-ene elastomer capable of rapid autonomous interfacial healing in soft devices [19]. Such results are valuable for compliant architectures, where large deformation can press damaged faces together and reversible interactions remain mobile near service temperature. They cannot be transferred directly to a glassy structural photopolymer whose crack faces separate, whose chain mobility is low, or whose service temperature is far below the relevant relaxation regime.

Hydrogels occupy another distinct regime. Caprioli et al. demonstrated DLP-printed self-healing hydrogels using a dynamic network compatible with commercial printing [4]. Water plasticises the network and changes diffusion, interfacial contact and bond-exchange kinetics. A hydrogel healing protocol should therefore not be treated as a generic validation route for dry engineering resins. The material state during damage and healing is part of the mechanism.

6. Extrinsic healing: stored agent rather than reversible network

Extrinsic self-healing places a separate healing phase inside the printed material. Sanders et al. incorporated solvent-containing microcapsules into a commercial stereolithography resin and demonstrated recovery of fracture performance through solvent welding after capsule rupture [2]. The approach is conceptually different from dynamic covalent or supramolecular healing. The matrix itself need not remain exchangeable; damage activates a local reservoir that modifies the crack interface.

The engineering advantage is that a relatively conventional crosslinked matrix can acquire a repair pathway. The limitations are equally important. Capsules alter resin rheology, optical scattering and local stress concentration; the available agent is finite; and a crack must intersect a reservoir for the mechanism to operate. Repeated healing of the same location is therefore not an automatic consequence of a successful first repair. For VPP, capsule size and optical interaction can also constrain feature fidelity. Extrinsic and intrinsic systems should not be ranked by one healing-efficiency number without accounting for these architectural differences.

7. From damage closure to interlayer welding

Interlayer welding is the bridge between additive-process anisotropy and post-damage repair. In the linear-polymer strategy of Zhu et al., heat enables polymer diffusion and entanglement across layer boundaries [10]. In vitrimer systems, dynamic covalent exchange can reconnect two cured surfaces when contact and activation are sufficient [7,14,17]. In imine-containing systems, molecular welding can be driven by dynamic bond formation at the interface [20]. The common variable is not the chemical label but the availability of mobile or exchangeable species across a contacting boundary.

A qualification protocol should therefore define the interface itself. A layer boundary created during printing differs from a saw-cut surface, a razor cut, a tensile fracture surface and a deliberately assembled joint. Surface roughness, oxidation, residual uncured species, contamination and geometric fit change the real contact area. Healing a clean cut immediately after damage can overestimate repair of an aged service crack. Conversely, a deliberately pressed joint can underestimate the difficulty of autonomous repair when no external force is available to maintain contact.

The same logic applies to post-print assembly. If two independently printed parts are welded into a strong joint, that is valuable evidence for adaptable-network joining. It does not by itself show that a crack inside a complex component will close, align and restore its original fracture path. The claim should match the interface that was actually tested.

Study / route	Network or repair mechanism	Demonstrated phenomenon	Claim boundary
Sanders et al. [2]	Extrinsic solvent-containing microcapsules.	SLA-printable composite with fracture-performance recovery.	Agent is finite; mechanism is not intrinsically repeatable.
Yu et al. [3]	Disulfide exchange in a photoelastomer.	Printed self-healable elastomeric structures.	Soft elastomer regime; kinetics and contact are system-specific.
Rossegger et al. [7,8]	Thermo-activated transesterification.	Mending and locally switchable network rearrangement.	Requires defined thermal/photo activation.
Zhu et al. [10]	Diffusion and entanglement of linear polymer.	Post-print interlayer welding.	Strengthening mechanism is not autonomous crack healing.
Fang et al. [12]	Dynamic covalent hindered-urea network.	Mechanical and geometric reprogrammability.	Reprogrammability is broader than local damage repair.
Bonacini et al. [16]	Dynamic boronate-ester crosslinks.	Stress relaxation and reduced mechanical anisotropy.	Reduction should not be described as universal elimination.
Ye et al. [17]	Catalysed transesterification in adaptable photopolymer.	Thermoactivated repair after printing.	Repair temperature and baseline are resin-specific.
Beckett et al. [19]	Dynamic physical interactions in hybrid elastomer.	Rapid autonomous healing in soft-device context.	Not directly transferable to rigid glassy networks.

Table 2. Representative photopolymer repair mechanisms and the evidence they provide.

8. A mechanics-first validation architecture

8.1 Define damage before defining healing

The starting damage state controls the difficulty of repair. A shallow notch, full severing, fatigue crack, delamination and interlayer defect create different amounts of new surface and different constraints on realignment. The test should record the damage method, crack orientation relative to the build layers, crack opening or removed material, time between damage and healing, and whether the surfaces remained in contact. Without these details, a healing ratio is not transferable between studies.

8.2 Define the activation state

Dynamic networks require a mobility window. Temperature, irradiation, humidity, solvent exposure, pressure and healing time can all change the rate and extent of recovery. Reporting only a nominal healing temperature omits whether the specimen was clamped, compressed or freely annealed and whether the activation condition also changes an undamaged control. A thermal treatment can both promote exchange and further post-cure the material. A valid control should experience the same activation without the damage-repair cycle.

8.3 Recover the relevant mechanical quantity

Strength recovery is not equivalent to toughness recovery. A healed interface may carry a high peak stress yet fail at low strain; a highly extensible material may recover elongation while remaining weaker; and a crack-arrest mechanism may improve fracture energy without restoring modulus. For structural repair, at least the property governing the intended failure mode should be measured. For an interface-sensitive question, fracture toughness, work of fracture, lap-shear or another interface-specific method can be more informative than a bulk tensile specimen.

8.4 Track where the repaired specimen fails

Failure location is an underused diagnostic. If a healed specimen breaks again along the same interface, the joint remains the limiting link even if its peak strength appears high. If failure moves into the bulk, the interface has at least reached the strength scale of the surrounding material under that test. This observation should be reported together with the recovery metric. It provides mechanistic evidence that a numerical ratio alone cannot supply.

8.5 Demonstrate repeatability rather than extrapolating it

A one-cycle repair does not establish multi-cycle durability. Intrinsic dynamic networks may be repeatedly exchangeable in principle, but repeated heating can cause oxidation, residual post-cure, catalyst migration, plasticiser loss or dimensional change. Extrinsic reservoirs may be depleted. Supramolecular networks may accumulate permanent damage. Each claimed cycle should therefore be tested, and the property trajectory should be shown rather than converting the first-cycle result into a projected service-life extension.

Evidence level	Measurement	What it supports	What it does not yet support
1\.. Visual	Crack closure, surface continuity, optical microscopy.	Geometric contact at the observation scale.	Restored mechanical or functional performance.
2\.. Interfacial	Adhesion, lap shear, peel or interface fracture.	Re-established load transfer across the repaired boundary.	Bulk property recovery or durability.
3\.. Mechanical	Strength, modulus, elongation, toughness or fracture metric.	Recovery of the stated property under the stated test.	Other properties, other orientations or long-term life.
4\.. Functional	Leak tightness, actuation, conductivity, sealing or device output.	Recovery of application-relevant function.	Structural equivalence unless mechanics are also measured.
5\.. Repeated-cycle	Property after multiple damage/repair cycles.	Demonstrated repeatability over the tested cycle count.	Indefinite healing or lifetime extension.
6\.. Service-state	Repair after ageing, fatigue or environmental exposure.	Performance under a defined use-relevant history.	Transfer to untested environments or geometries.

Table 3. Evidence ladder for a self-healing or interlayer-repair claim.

9. Trade-offs and failure modes of dynamic repair networks

9.1 Mobility versus dimensional stability

The molecular motion that enables repair can also enable creep, stress relaxation and loss of dimensional stability. This trade-off is especially important in vat-printed parts because the same geometry that must heal may also carry tight dimensional tolerances. Dynamic boronate-ester and vitrimer studies commonly characterise stress relaxation precisely because the exchange process changes time-dependent mechanical behaviour [7,9,16,17]. A repairable network should therefore be qualified both below and within its activation regime.

9.2 Repair temperature versus thermal ageing

Thermal activation is experimentally convenient but can introduce confounding changes. Elevated temperature may further polymerise residual groups, relax residual stress, accelerate oxidation, alter pigments or fillers, and change crystallinity in mobile thermoplastic phases. A repaired specimen that becomes stronger than its original baseline may reflect more than interfacial healing. Matched undamaged annealing controls are essential when the repair trigger is thermal.

9.3 Dynamic chemistry versus printability

Repair chemistry is present before printing, so it can influence the liquid resin as well as the cured part. Catalysts and dynamic functional groups can change viscosity, dark stability, polymerisation rate, optical absorption and network conversion. Rossegger et al. explicitly addressed catalyst compatibility and resin stability in DLP-printable thiol-acrylate vitrimers [7,8]. The appropriate formulation question is therefore not whether a dynamic bond can heal in a cast polymer, but whether the complete resin remains printable and stable while retaining the intended post-cure exchange behaviour.

9.4 Stronger interfaces do not guarantee better structures

Eliminating one weak interface can expose another failure mode. Increasing interlayer connectivity may shift fracture to the bulk, raise residual stress, reduce energy dissipation or increase creep. In soft devices, high interfacial adhesion may be desirable; in sacrificial assemblies or intentionally separable joints it may not be. Interlayer repair should be linked to the load path and failure mode of the final part rather than treated as a universal objective.

10. Application-specific implications

Soft robotics and compliant devices are the most mature demonstration space because large deformation and intimate surface contact favour reversible physical interactions. Yu et al., Gomez et al. and Beckett et al. show that photopolymerisable elastomer architectures can combine complex geometry with post-damage recovery [3,6,19]. The relevant qualification metrics include not only tensile recovery but also actuation amplitude, leak tightness, adhesion and recovery time under the actual deformation cycle.

For rigid structural photopolymers, the evidentiary bar is different. High modulus reduces spontaneous crack-face contact and can concentrate stress at incompletely repaired boundaries. Thermally activated vitrimer or adaptable-network approaches [7,14,17] are therefore better interpreted as controlled repair or welding technologies unless autonomous closure is directly demonstrated. Fracture-sensitive metrics and dimensional stability become more important than a simple visual repair test.

For printed assemblies and multi-material structures, interfacial welding can be a manufacturing function independent of damage tolerance. Linear-polymer diffusion [10], dynamic covalent exchange [20] and other adaptable-network mechanisms can enable post-print joining, modular repair or replacement of local sections. These workflows may be strategically valuable even when the material is not autonomously self-healing in service.

For circular manufacturing, chemical recovery and reprocessing form a separate axis. Stouten et al. demonstrated rapid reprocessing of imine-containing printed networks [11], Nguyen and Du Prez demonstrated restoration of photocurable crosslinkers for repeated light-based printing [15], Kamble and Asha combined dynamic bonds with reprinting [18], and Liu et al. reported a sulfur-mediated dynamic network supporting chemical recovery in a high-resolution photopolymer [21]. These studies should support circularity claims only at the level of the demonstrated recovery loop; they should not be used as indirect evidence of crack healing unless such an experiment was performed.

11. Proposed minimum reporting framework

A reproducible repair study should report enough information to reconstruct both the material state and the damage-repair trajectory. Proprietary formulations need not disclose exact composition, but the network class, exchange mechanism and activation logic must be explicit. The minimum set below is intended for literature comparison and engineering qualification rather than as a new standard.

Reporting block	Minimum information	Why it matters	Claim boundary
Printed state	Process type, wavelength, layer thickness, orientation, post-cure and conditioning.	Defines the starting network and layer history.	Prevents transfer across different cure states.
Network mechanism	Dynamic covalent, supramolecular, mobile phase or extrinsic agent; trigger.	Identifies the physical route to recovery.	Avoids treating all self-healing labels as equivalent.
Damage protocol	Notch/cut/fracture/delamination, orientation, crack size, time before repair.	Defines the created interface and severity.	Prevents comparison of fundamentally different damage states.
Repair protocol	Temperature, light, humidity/solvent, pressure/contact, duration and fixtures.	Defines mobility and interfacial contact.	Separates autonomous from externally assisted repair.
Controls	Pristine, damaged-unhealed and activation-only controls.	Separates healing from post-cure or annealing effects.	Prevents inflated recovery attribution.
Mechanical metric	Strength, strain, modulus, toughness/fracture or interface test; n and scatter.	Defines what was actually recovered.	One metric does not represent complete mechanical equivalence.
Failure analysis	Failure location and fracture-surface observation where relevant.	Shows whether the repaired interface remains limiting.	A high ratio alone can hide interfacial weakness.
Cycle / ageing state	Number of repair cycles and environmental or fatigue history.	Tests persistence of the mechanism.	No extrapolation beyond tested cycles or conditions.
Geometry stability	Dimensions before/after activation where tolerance matters.	Captures creep, flow or thermal distortion.	Repairability cannot substitute for dimensional qualification.

Table 4. Minimum reporting set for self-healing and interlayer-repair studies in photopolymer additive manufacturing.

12. Research priorities

12.1 Interface-specific fracture methods for VPP

Many studies continue to rely on bulk tensile bars even when the proposed mechanism acts at layer boundaries. Purpose-designed fracture or adhesion geometries that isolate a known printed interface would make it easier to separate bulk toughening from true interlayer repair. Orientation, layer pitch and interface location should be controlled explicitly.

12.2 Direct mapping of network mobility across printed interfaces

Mechanical mapping has already shown that interfaces can be locally distinct [1]. The next step is to couple local mechanical measurements with conversion, spectroscopy, chemical mapping or relaxation measurements before and after welding. Such experiments could determine whether an apparent gain in Z-direction performance arises from new covalent exchange, chain interpenetration, additional cure or stress redistribution.

12.3 Cycle-resolved repair under service load

The field needs fewer isolated maximum recovery values and more trajectories. Repeated damage at the same site, fatigue before repair, delayed repair after surface ageing and repair under constrained geometry are closer to engineering service. These protocols would reveal depletion, catalyst ageing, irreversible chain scission and accumulated dimensional drift that a first-cycle result cannot show.

12.4 Separating anisotropy reduction from anisotropy elimination

Dynamic exchange can redistribute stress and improve connectivity, as the recent boronate-ester work illustrates [16]. A stronger claim requires directional mechanical testing across multiple orientations and geometries after the complete print and activation workflow. Until such evidence exists, reduced anisotropy is the defensible engineering language.

12.5 Functional repair beyond tensile specimens

A repaired seal should be tested for leakage, a soft actuator for recovered displacement and pressure response, a conductive element for resistance stability, and a structural joint for the relevant fracture mode. Mechanical and functional recovery should be reported together when a device-level claim is made. This prevents a material from appearing fully recovered because one easy-to-measure property returned to baseline.

3Dresyns implementation examples

3Dresyns currently commercialises both a repairable resin and additive routes intended to introduce self-repair or interlayer-welding behaviour. These examples illustrate implementation pathways discussed in this review, but their product positioning does not replace mechanism-specific measurements of damage state, activation conditions, recovered mechanical property, fracture location and cycle retention.

3Dresyn Vitimer 3R-D70. Manufacturer documentation positions this as a reprocessable, repairable and recyclable self-healing resin for SLA, DLP and LCD printing. It is an implementation example of a network-level repair concept and still requires the property-specific recovery qualification proposed in this review [M1].

3D-ADD SH. Manufacturer documentation describes a family of temperature-targeted self-healing additives for compatible UV-curable 3D-printing resins. The family illustrates assisted repair at controlled activation conditions rather than autonomous healing at service temperature [M2].

3D-ADD ReBond Weld series. Manufacturer documentation positions this additive family for cure-stress relief, interlayer welding and post-print repair at controlled activation conditions. It does not by itself establish recovery of a predefined damaged specimen [M3].

Source basis: current 3Dresyns product and Technical Data Sheet documentation, August 2026. These commercial examples are included to connect the review framework to implementation and are not substitutes for independent application-specific validation.

13. Conclusions

- Self-healing, interlayer welding, post-cure strengthening, reprocessing and recycling are related but distinct phenomena. Each requires a different experimental comparison.
- Layer interfaces in photopolymer additive manufacturing can be mechanically distinct, but no universal Z-axis penalty or single interlayer failure mechanism should be assumed.
- Repair requires both a mechanism for molecular rebonding or transport and sufficient physical contact across the damaged interface. Dynamic chemistry alone cannot compensate for an open, contaminated or misaligned crack.
- Dynamic covalent approaches demonstrated in light-based printing include transesterification, disulfide exchange, imine exchange, boronate-ester exchange and other adaptable networks. Supramolecular and mobile-polymer strategies provide noncovalent alternatives.
- Interlayer welding can be achieved by chain diffusion and entanglement or by dynamic bond exchange. This manufacturing function should not automatically be labelled autonomous self-healing.
- A healing percentage has meaning only when the denominator, damage state, recovery property, activation protocol, orientation, controls and number of cycles are reported.
- Dynamic network mobility creates engineering trade-offs with creep, stress relaxation, dimensional stability, resin shelf stability and cure behaviour. Repairability should therefore be qualified together with printability and service-state mechanics.
- The most defensible path to structural claims is a mechanics-first framework that progresses from visual closure to interfacial load transfer, property recovery, repeated cycles and application-relevant function.

Limitations

This review is a literature-based engineering synthesis rather than a preregistered systematic review. The cited studies span soft elastomers, hydrogels, rigid networks, extrinsic composites and adaptable thermosets with different printers, damage protocols and recovery metrics. Their numerical healing efficiencies are therefore intentionally not pooled into a universal ranking. The proposed terminology and reporting architecture have not yet been validated through a dedicated interlaboratory study.

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. The review discusses public materials-science evidence and does not disclose proprietary formulation composition, additive dosage, activation windows or internal product-performance data. Commercial products are not used as substitutes for peer-reviewed evidence.

Data availability

No new experimental dataset was generated for this review. Quantitative and mechanistic examples derive from the cited primary literature and remain subject to the specimen geometry, process state, activation protocol and test method reported in those studies.

Company information

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